Universität Siegen

Violations of Lorentz Invariance and Their Connections to Cosmic Particles

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Photo by S. Saffi (Univ. of Adelaide)

Outline

- Introduction
- Lorentz Violation in the Photon Sector
- Previous Bounds from Cosmic Particles
- Interlude: Extensive Air Showers and Their Detection
- Bounds on Lorentz Violation Using Extensive Air Showers
- Summary

Introduction

Introduction

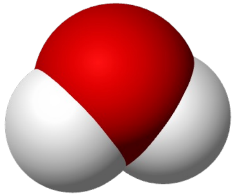
Nature around us

$\mathcal{O}(1\,\mathrm{m})$ and above

Water drop

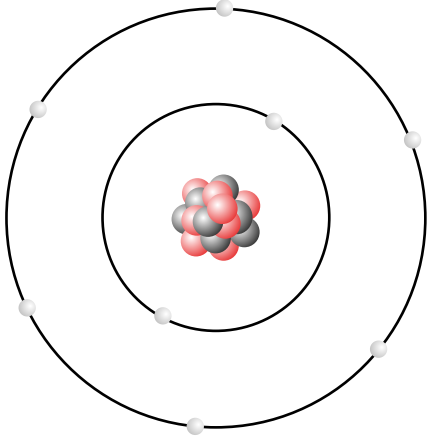
$\mathcal{O}(10^{-3}\,\mathrm{m})$

Water molecule



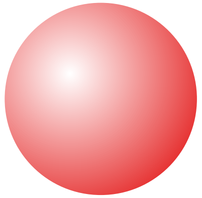
$\mathcal{O}(10^{-10}\,\mathrm{m})$

Oxygen atom



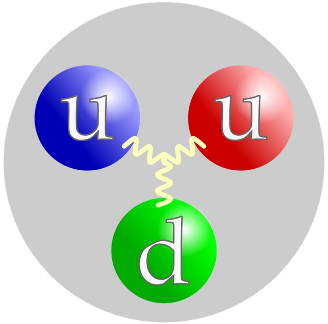
$\mathcal{O}(10^{-11}\,\mathrm{m})$

Proton



$\mathcal{O}(10^{-15}\,\mathrm{m})$

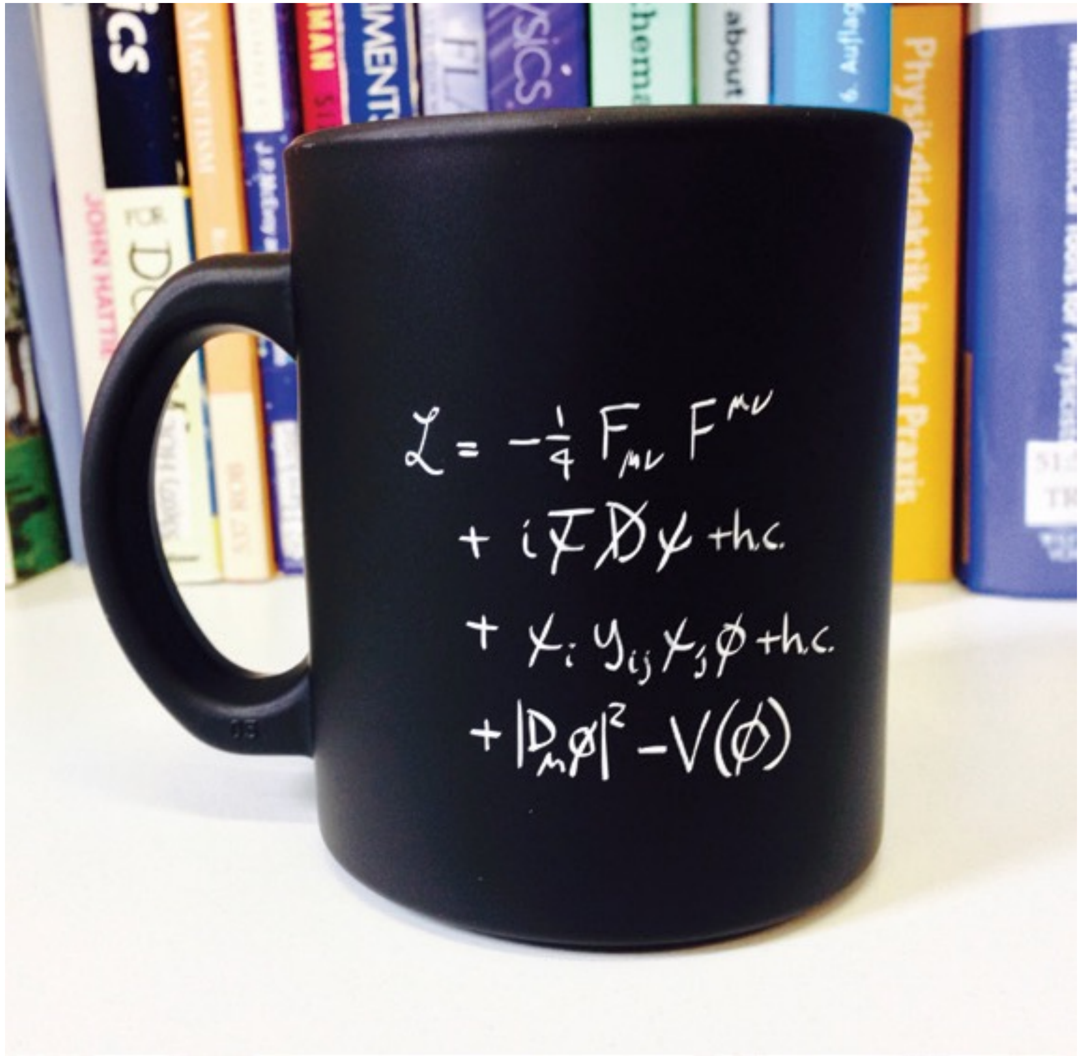
Quarks and Gluons



below $\mathcal{O}(10^{-18}\,\mathrm{m})$

[Wikipedia]

Standard Model of Particle Physics

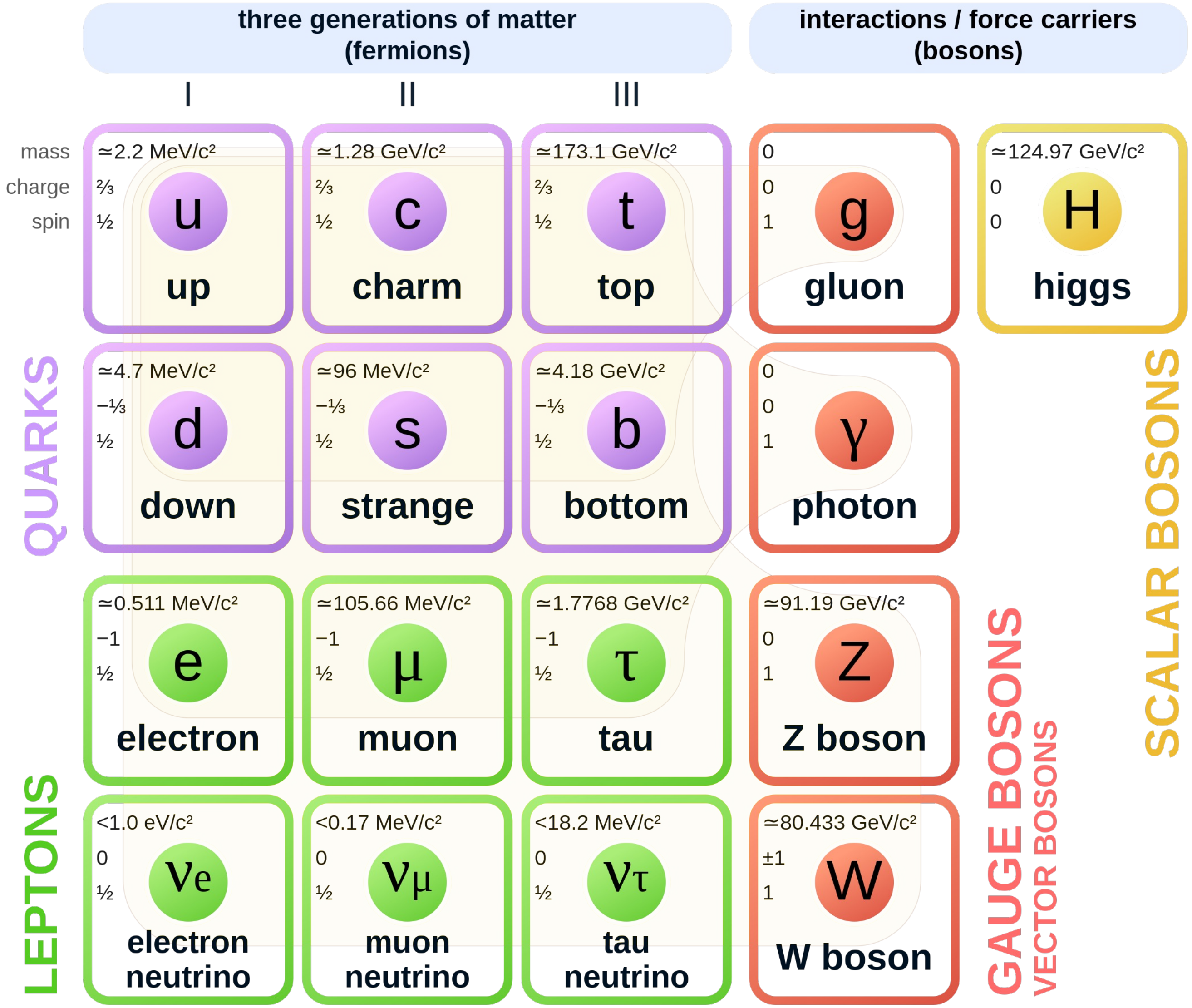


[Woithe, Wiener, van der Veken; Phys. Educ. 52 (2017) 034001]

$$\begin{gathered}
\mathcal{L}_{SM} = -\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g^2_s f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
M^2 W^+_\mu W^-_\mu - \frac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \frac{1}{2c^2_w} M^2 Z^0_\mu Z^0_\mu - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - igc_w(\partial_\nu Z^0_\mu (W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)) - \\
igs_w(\partial_\nu A_\mu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + A_\mu(W^+_\nu \partial_\nu W^-_\mu - \\
W^-_\nu \partial_\nu W^+_\mu)) - \frac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \frac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c^2_w (Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - \\
Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s^2_w (A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w (A_\mu Z^0_\nu (W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu) - \frac{1}{2}\partial_\mu H \partial_\mu H - 2M^2\alpha_h H^2 - \partial_\mu\phi^+\partial_\mu\phi^- - \frac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0 - \\
\beta_h\left(\frac{2M^2}{g^2} + \frac{2M}{g}H + \frac{1}{2}(H^2+\phi^0\phi^0+2\phi^+\phi^-)\right) + \frac{2M^4}{g^2}\alpha_h - \\
g\alpha_h M \left(H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-\right) - \\
\frac{1}{8}g^2\alpha_h \left(H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2\right) - \\
gMW^+_\mu W^-_\mu H - \frac{1}{2}g\frac{M}{c^2_w} Z^0_\mu Z^0_\mu H - \\
\frac{1}{2}ig\left(W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)\right) + \\
\frac{1}{2}g\left(W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) + W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)\right) + \frac{1}{2}g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) + \\
M\left(\frac{1}{c_w}Z^0_\mu\partial_\mu\phi^0 + W^+_\mu\partial_\mu\phi^- + W^-_\mu\partial_\mu\phi^+\right) - ig\frac{s^2_w}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_wMA_\mu(W^+_\mu\phi^- - \\
W^-_\mu\phi^+) - ig\frac{1-2c^2_w}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_wA_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \\
\frac{1}{4}g^2W^+_\mu W^-_\mu\left(H^2+(\phi^0)^2+2\phi^+\phi^-\right) - \frac{1}{8}g^2\frac{1}{c^2_w}Z^0_\mu Z^0_\mu\left(H^2+(\phi^0)^2+2(2s^2_w-1)^2\phi^+\phi^-\right) - \\
\frac{1}{2}g^2\frac{s^2_w}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) - \frac{1}{2}ig^2\frac{s^2_w}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac{1}{2}g^2s_wA_\mu\phi^0(W^+_\mu\phi^- + \\
W^-_\mu\phi^+) + \frac{1}{2}ig^2s_wA_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\frac{s_w}{c_w}(2c^2_w-1)Z^0_\mu A_\mu\phi^+\phi^- - \\
g^2s^2_wA_\mu A_\mu\phi^+\phi^- + \frac{1}{2}ig_s\,\lambda^a_{ij}(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu - \bar{e}^\lambda(\gamma\partial+m^\lambda_e)e^\lambda - \bar{\nu}^\lambda(\gamma\partial+m^\lambda_\nu)\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + \\
m^\lambda_u)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial+m^\lambda_d)d^\lambda_j + igs_wA_\mu\left(-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \frac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)\right) + \\
\frac{ig}{4c_w}Z^0_\mu\{(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s^2_w-1-\gamma^5)e^\lambda) + (\bar{d}^\lambda_j\gamma^\mu(\frac{4}{3}s^2_w-1-\gamma^5)d^\lambda_j) + \\
(\bar{u}^\lambda_j\gamma^\mu(1-\frac{8}{3}s^2_w+\gamma^5)u^\lambda_j)\} + \frac{ig}{2\sqrt{2}}W^+_\mu\left((\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)U^{lep}{}_{\lambda\kappa}e^\kappa) + (\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)\right) + \\
\frac{ig}{2\sqrt{2}}W^-_\mu\left((\bar{e}^\kappa U^{lep\dagger}{}_{\kappa\lambda}\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\kappa\lambda}\gamma^\mu(1+\gamma^5)u^\lambda_j)\right) + \\
\frac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_e(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1-\gamma^5)e^\kappa) + m^\lambda_\nu(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1+\gamma^5)e^\kappa\right) + \\
\frac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_e(\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1+\gamma^5)\nu^\kappa) - m^\kappa_\nu(\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1-\gamma^5)\nu^\kappa\right) - \frac{g}{2}\frac{m^\lambda_\nu}{M}H(\bar{\nu}^\lambda\nu^\lambda) - \\
\frac{g}{2}\frac{m^\lambda_e}{M}H(\bar{e}^\lambda e^\lambda) + \frac{ig}{2}\frac{m^\lambda_\nu}{M}\phi^0(\bar{\nu}^\lambda\gamma^5\nu^\lambda) - \frac{ig}{2}\frac{m^\lambda_e}{M}\phi^0(\bar{e}^\lambda\gamma^5e^\lambda) - \frac{1}{4}\,\bar{\nu}_\lambda\,M^R_{\lambda\kappa}\,(1-\gamma_5)\hat{\nu}_\kappa - \\
\frac{1}{4}\,\bar{\nu}_\lambda\,M^R_{\lambda\kappa}\,(1-\gamma_5)\hat{\nu}_\kappa + \frac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_d(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m^\lambda_u(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j\right) + \\
\frac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_d(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m^\kappa_u(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j\right) - \frac{g}{2}\frac{m^\lambda_u}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \\
\frac{g}{2}\frac{m^\lambda_d}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \frac{ig}{2}\frac{m^\lambda_u}{M}\phi^0(\bar{u}^\lambda_j\gamma^5u^\lambda_j) - \frac{ig}{2}\frac{m^\lambda_d}{M}\phi^0(\bar{d}^\lambda_j\gamma^5d^\lambda_j) + \bar{G}^a\partial^2G^a + g_sf^{abc}\partial_\mu\bar{G}^aG^bg^c_\mu + \\
\bar{X}^+(\partial^2-M^2)X^+ + \bar{X}^-(\partial^2-M^2)X^- + \bar{X}^0(\partial^2-\frac{M^2}{c^2_w})X^0 + \bar{Y}\partial^2Y + igc_wW^+_\mu(\partial_\mu\bar{X}^0X^- - \\
\partial_\mu\bar{X}^+X^0) + igs_wW^+_\mu(\partial_\mu\bar{Y}X^- - \partial_\mu\bar{X}^+Y) + igc_wW^-_\mu(\partial_\mu\bar{X}^-X^0 - \\
\partial_\mu\bar{X}^0X^+) + igs_wW^-_\mu(\partial_\mu\bar{X}^-Y - \partial_\mu\bar{Y}X^+) + igc_wZ^0_\mu(\partial_\mu\bar{X}^+X^+ - \\
\partial_\mu\bar{X}^-X^-) + igs_wA_\mu(\partial_\mu\bar{X}^+X^+ - \\
\partial_\mu\bar{X}^-X^-) - \frac{1}{2}gM\left(\bar{X}^+X^+H + \bar{X}^-X^-H + \frac{1}{c^2_w}\bar{X}^0X^0H\right) + \frac{1-2c^2_w}{2c_w}igM\left(\bar{X}^+X^0\phi^+ - \bar{X}^-X^0\phi^-\right) + \\
\frac{1}{2c_w}igM\left(\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-\right) + igMs_w\left(\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-\right) + \\
\frac{1}{2}igM\left(\bar{X}^+X^+\phi^0 - \bar{X}^-X^-\phi^0\right) .
\end{gathered}$$

[M. Marcolli]

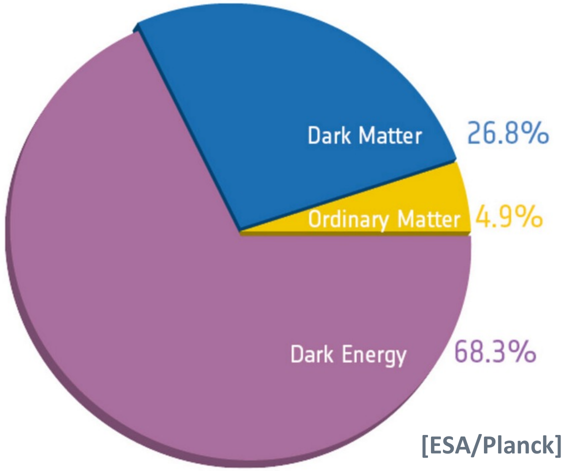
Standard Model of Particle Physics



[Wikipedia]

Beyond the Standard Model

- The Standard Model (SM) works **incredibly well**, but it does not offer a **complete description** of our Universe
  - Only $\sim 5\%$ of our Universe consists of "ordinary" matter, $\sim 27\%$ **dark matter** and $\sim 68\%$ **dark energy** are not described by the SM
  - **Gravity** is not included in the SM!



[ESA/Planck]

- We need a **more comprehensive** (and **fundamental**) theory
  - In **current approaches** to construct such a theory (e.g. based on string theory or loop-quantum gravity), **deviations from exact Lorentz invariance** may well be possible [Jacobson, Liberati, Mattingly; Ann. Phys. 321 (2006) 150] [Addazi et al. (incl. MN); Prog. Part. Nucl. Phys. 125 (2022) 103948]
  - **Reminder:** Lorentz invariance means that the **laws of physics are the same** for all observers moving w.r.t. each other in an inertial frame – a **pillar** of (modern) physics
  - **Small effects** should become apparent already below the Planck scale: possibility to **test Lorentz violation (LV) experimentally**

Lorentz Violation in the Photon Sector

How to Test LV?

- Two different *ansätze*: [Jacobson, Liberati, Mattingly; Ann. Phys. 321 (2006) 150] [Addazi et al. (incl. MN); Prog. Part. Nucl. Phys. 125 (2022) 103948]
  - Modify/expand the **dispersion relation** for different particles directly
  - Construct an **effective field theory** containing Lorentz-violating operators

- Specific realization of the latter *ansatz*: **Standard Model Extension** (SME)

  [Colladay, Kostelecký; Phys. Rev. D 58 (1998) 116002]
  - Provides a **general framework** to study LV in any sector of the SM
  - Here: focus on the **photon sector** (“modified Maxwell theory”)

LV in the Photon Sector

- Look at the **Lagrangian density:**

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

  - First two terms correspond to **conventional quantum electrodynamics (QED)**
  - **Last term** introduces a dimension-four operator that gives rise to LV while preserving CPT and gauge invariance **[Chadha, Nielsen; Nucl. Phys. B 217 (1983) 125]** **[Kostelecký, Mewes; Phys. Rev. D 66 (2002) 056005]**
  - **Notes on notation:** natural units $\hbar = c = 1$ and the Minkowski metric $\eta_{\mu\nu} = [\mathrm{diag}(+1,-1,-1,-1)]_{\mu\nu}$ are used; the Maxwell field strength tensor is defined as usual through $F_{\mu\nu} \equiv \partial_{\mu}A_{\nu} - \partial_{\nu}A_{\mu}$

LV in the Photon Sector

- The fixed 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; Phys. Rev. D 41 (1990) 1231] [Kostelecký, Mewes; Phys. Rev. D 87 (2001) 251304]
  - [Klinkhamer, Risse; Phys. Rev. D 77 (2008) 117901] 8 components lead to **direction-dependent** modifications of the photon-propagation properties: not discussed here
  - Focus on the last remaining component, which leads to an **isotropic** modification of the photon-propagation properties
- Isotropic, non-birefringent LV in the photon sector is ultimately controlled by a **single, dimensionless parameter κ**, which relates to k_F through:

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

Isotropic, Nonbirefringent LV

- **Restriction on κ** from microcausality and unitarity: $\kappa \in (-1, 1]$ [Klinkhamer, Schreck; Nucl. Phys. B 848 (2011) 90]
- Photon propagation is determined by the field equations obtained from the previous equations: look specifically at the **phase velocity of the photon**

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

  - **Note:** c refers here to the maximum attainable velocity of a massive Dirac fermion (but still $c = 1$ in natural units)
- For **non-zero values** of κ, certain processes **forbidden** in the conventional, Lorentz-invariant theory ($\kappa = 0$) become **allowed** [Jacobson, Liberati, Mattingly; Ann. Phys. 321 (2006) 150] [Kaufhold, Klinkhamer; Nucl. Phys. B 734 (2006) 1]
  - $\kappa > 0$: **vacuum Cherenkov radiation** (VCh), $f^{\pm} \rightarrow f^{\pm} + \tilde{\gamma}$
  - $\kappa < 0$: **photon decay** (PhD), $\tilde{\gamma} \rightarrow e^- + e^+$

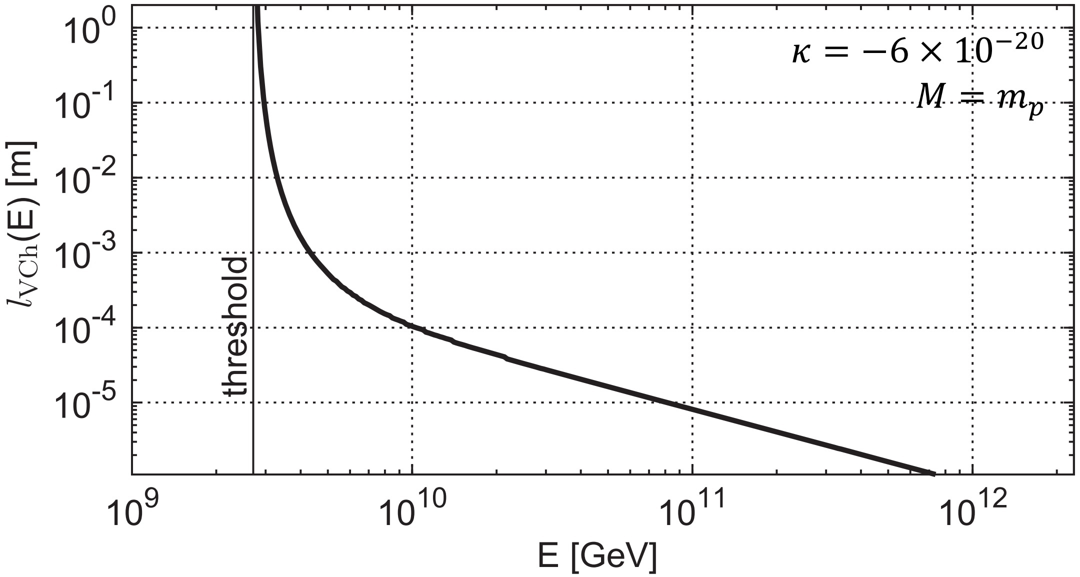
} Look for signatures of these non-standard processes in measurements!

Vacuum Cherenkov Radiation ($\kappa > 0$)

- Charged particles of mass M emit vacuum Cherenkov radiation above the **threshold**

$$E_{\mathrm{thr}}^{\mathrm{VCh}}(\kappa) = M\sqrt{\frac{1+\kappa}{2\kappa}}$$

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



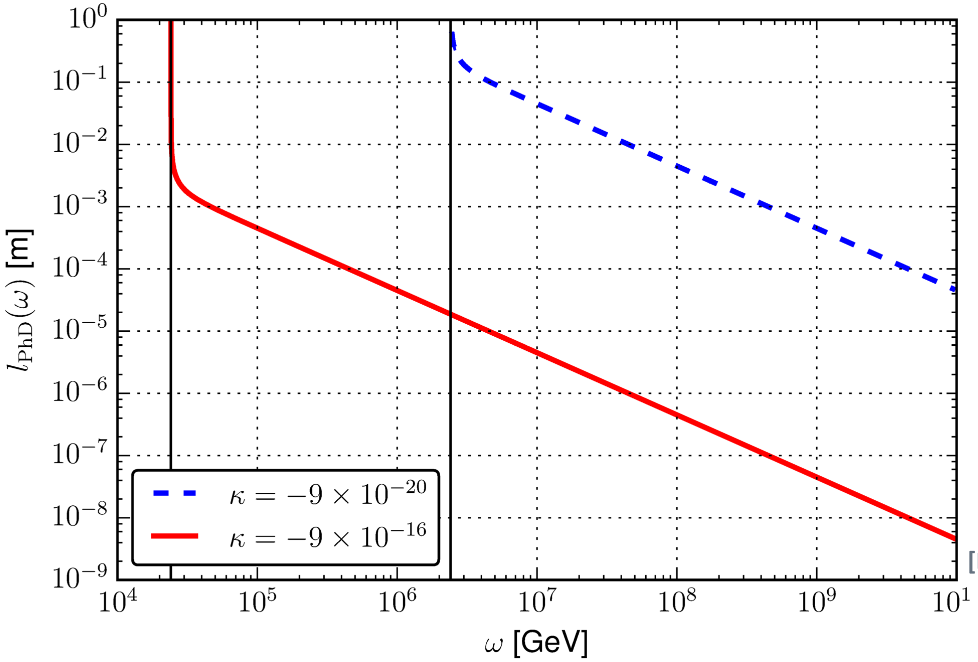
[Díaz, Klinkhamer; Phys. Rev. D 92 (2015) 025007; mod.]

Photon Decay ($\kappa < 0$)

- Photons decay above the **threshold**

$$E_{\text{thr}}^{\text{PhD}}(\kappa) = 2m_e\sqrt{\frac{1-\kappa}{-2\kappa}}$$

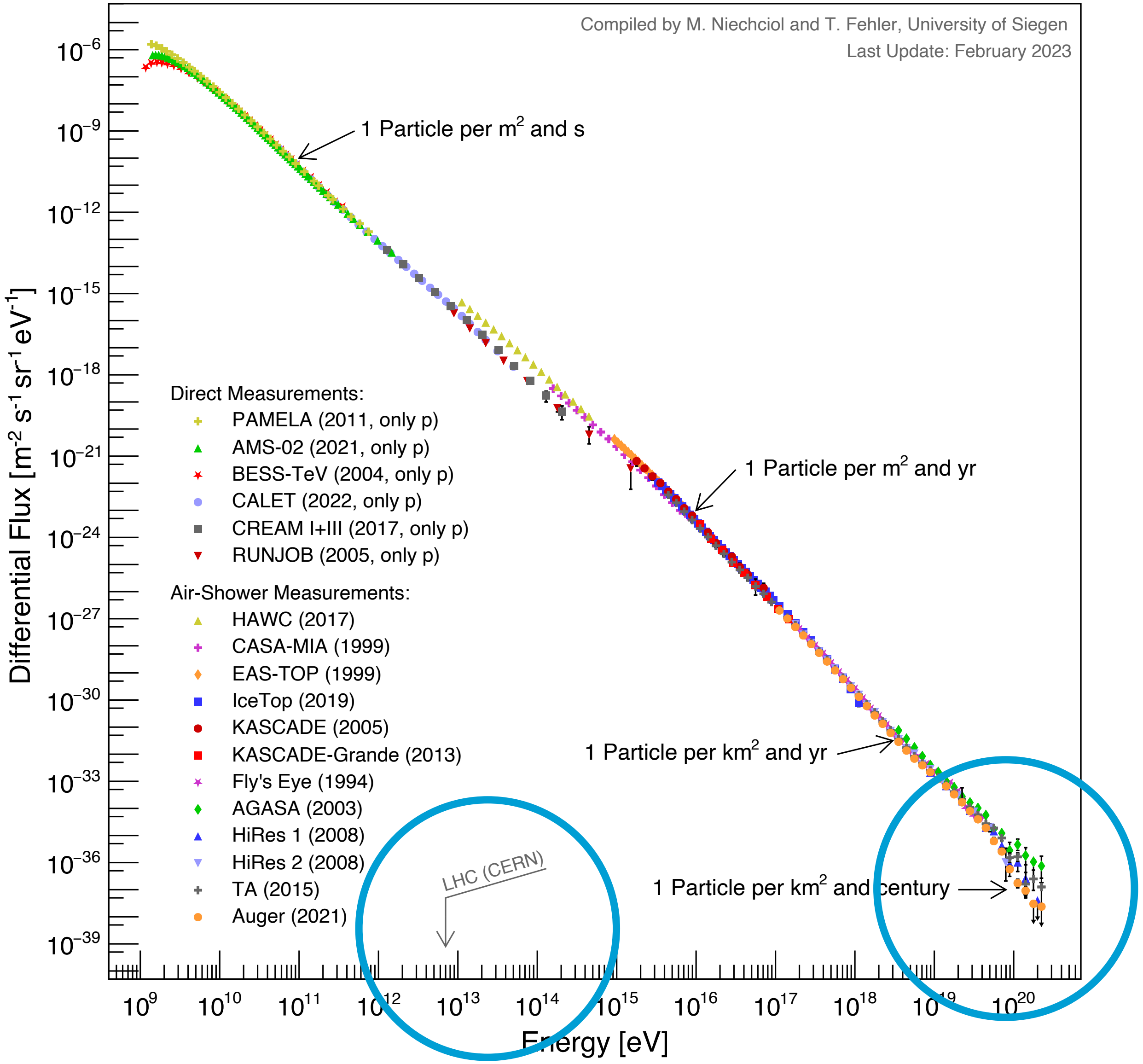
- Decay length drops to cm-scales right at the threshold: essentially **instantaneous decay**



[Díaz, Klinkhamer, Risse; Phys. Rev. D 94 (2016) 085025]

Previous Bounds from Cosmic Particles

Cosmic Rays


Compiled by M. Niechciol and T. Fehler, University of Siegen
Last Update: February 2023
1 Particle per m^2 and s
1 Particle per m^2 and yr
1 Particle per km^2 and yr
1 Particle per km^2 and century
LHC (CERN)
Direct Measurements:
PAMELA (2011, only p)
AMS-02 (2021, only p)
BESS-TeV (2004, only p)
CALET (2022, only p)
CREAM I+III (2017, only p)
RUNJOB (2005, only p)
Air-Shower Measurements:
HAWC (2017)
CASA-MIA (1999)
EAS-TOP (1999)
IceTop (2019)
KASCADE (2005)
KASCADE-Grande (2013)
Fly's Eye (1994)
AGASA (2003)
HiRes 1 (2008)
HiRes 2 (2008)
TA (2015)
Auger (2021)
Differential Flux [m^{-2} s^{-1} sr^{-1} eV^{-1}]
10^{-6}
10^{-9}
10^{-12}
10^{-15}
10^{-18}
10^{-21}
10^{-24}
10^{-27}
10^{-30}
10^{-33}
10^{-36}
10^{-39}
Energy [eV]
10^{9}
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}

Bounds on $\kappa > 0$

[Beall; Phys. Rev. D 1 (1970) 961]
[Coleman, Glashow; Phys. Lett. B 405 (1997) 249]

- Exploit the **mere existence** of ultra-high-energy cosmic rays to derive a bound on $\kappa > 0$
  - **Simple argument**: if a particle with energy E (and mass M) originating in a far-away cosmic source is measured at Earth, then the LV threshold must be higher than E and a bound on κ can be derived
- Use measurements from the **Pierre Auger Observatory** [Pierre Auger Coll.; Astropart. Phys. 27 (2007) 155]
  - UHECR event with $E = 212\,\mathrm{EeV} \pm 25\,\%$, conservatively assuming an iron nucleus ($M = 52\,\mathrm{GeV}$):

$$\boldsymbol{\kappa < 6 \times 10^{-20}} \text{ (at } 98\,\% \text{ C.L.)}$$

[Klinkhamer, Risse; Phys. Rev. D 77 (2008) 117901]
[Klinkhamer, Schreck; Phys. Rev. D 78 (2008) 085026]

[Bird et al.; Astrophys. J. 441 (1995) 144]

- **NB:** Using the $320\,\mathrm{EeV}$ Fly's Eye event from 1991 (and ignoring the energy uncertainty) would yield a bound at the level of 1.3×10^{-20}


[Pierre Auger Coll.]

Bounds on $\kappa < 0$

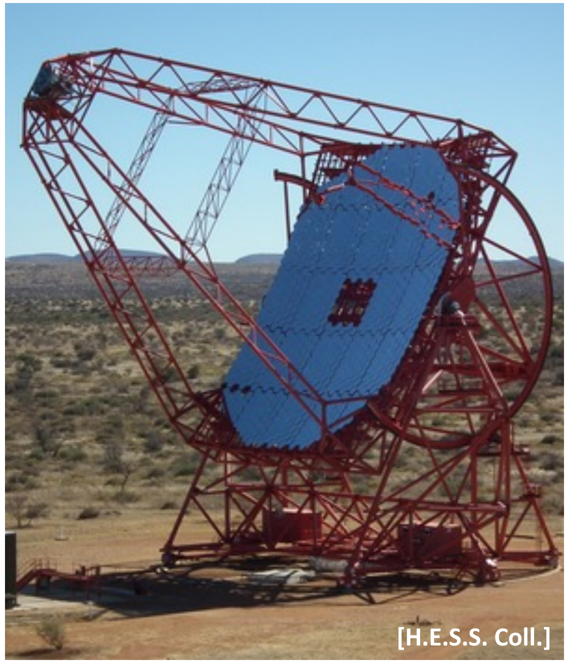
- **Same argument** as before: exploit the mere existence of **cosmic photons** to derive a bound on $\kappa < 0$

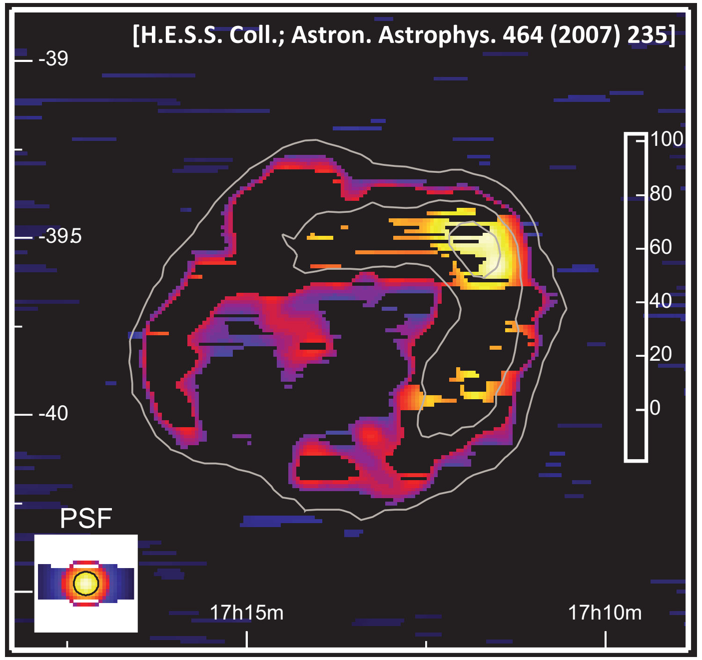
[H.E.S.S. Coll.; Astron. Astrophys. 464 (2007) 235]

- Use **H.E.S.S. measurements** of the supernova remnant **RX J1713.7–3946** (distance $\sim 1\,\mathrm{pc}$)
  - With $E_\gamma = 30\,\mathrm{TeV} \pm 15\,\%$: $\boldsymbol{\kappa > -9 \times 10^{-16}}$ (at $98\,\%$ C.L.) [Klinkhamer, Schreck; Phys. Rev. D 78 (2008) 085026]

[LHAASO Coll.; Nature 594 (2021) 33]

- **NB:** LHAASO detected photons up to $1.4\,\mathrm{PeV}$ from a galactic source, which would translate to a bound at the level of -2.7×10^{-19} (again ignoring uncertainties)


[H.E.S.S. Coll.]


[H.E.S.S. Coll.; Astron. Astrophys. 464 (2007) 235]

Bounds on $\kappa < 0$

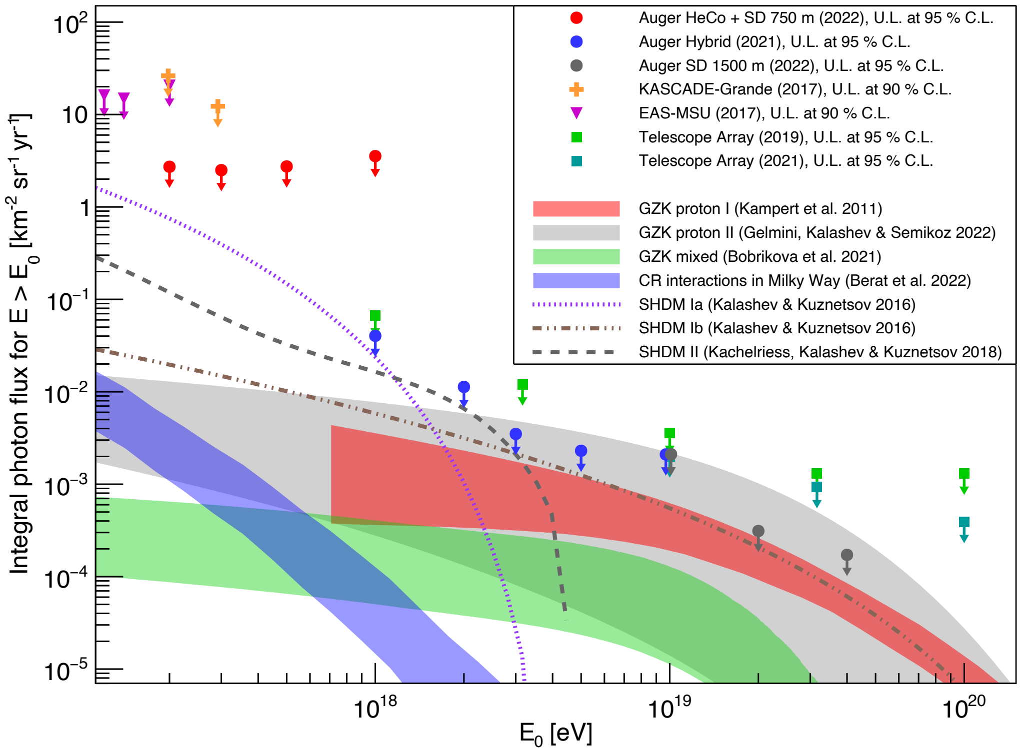
- **Further improving** the bound on $\kappa < 0$ would require higher-energy (primary) photons
- **But:** no photons observed in the ultra-high-energy regime (yet)

- Alternative approach: exploit the secondary particles in **extensive air showers**
  - LV can have an impact on the **shower development**

    → **“indirect” bounds** on LV

    [Díaz, Klinkhamer, Risse; Phys. Rev. D 94 (2016) 085025]
    [Klinkhamer, MN, Risse; Phys. Rev. D 96 (2017) 116011]

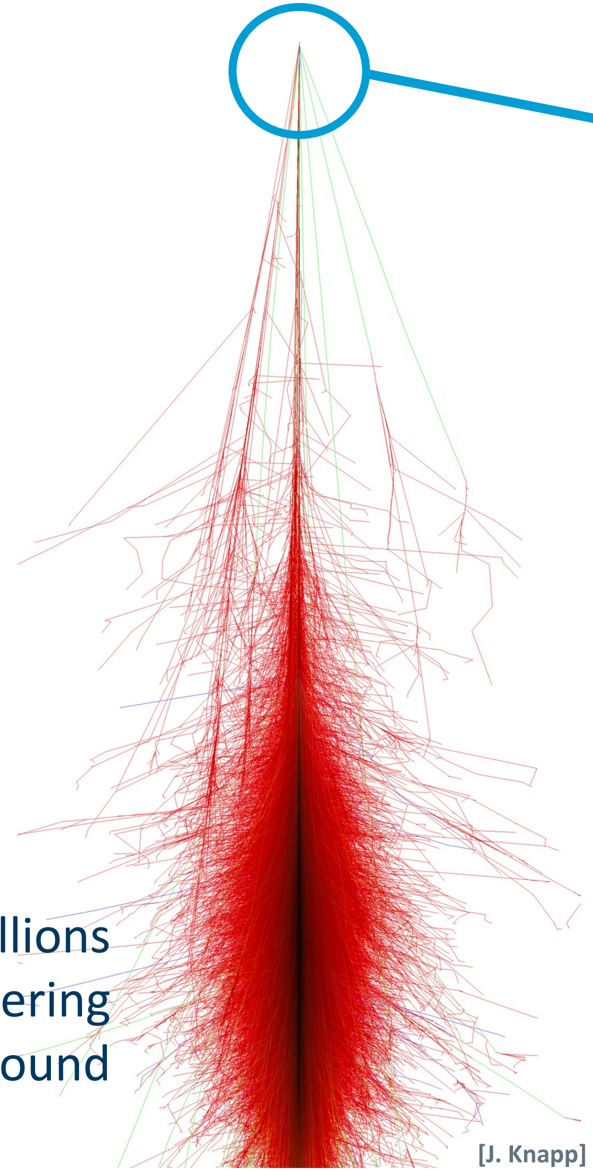
[Pierre Auger Coll.; Universe 8 (2022) 579]



Extensive Air Showers and Their Detection

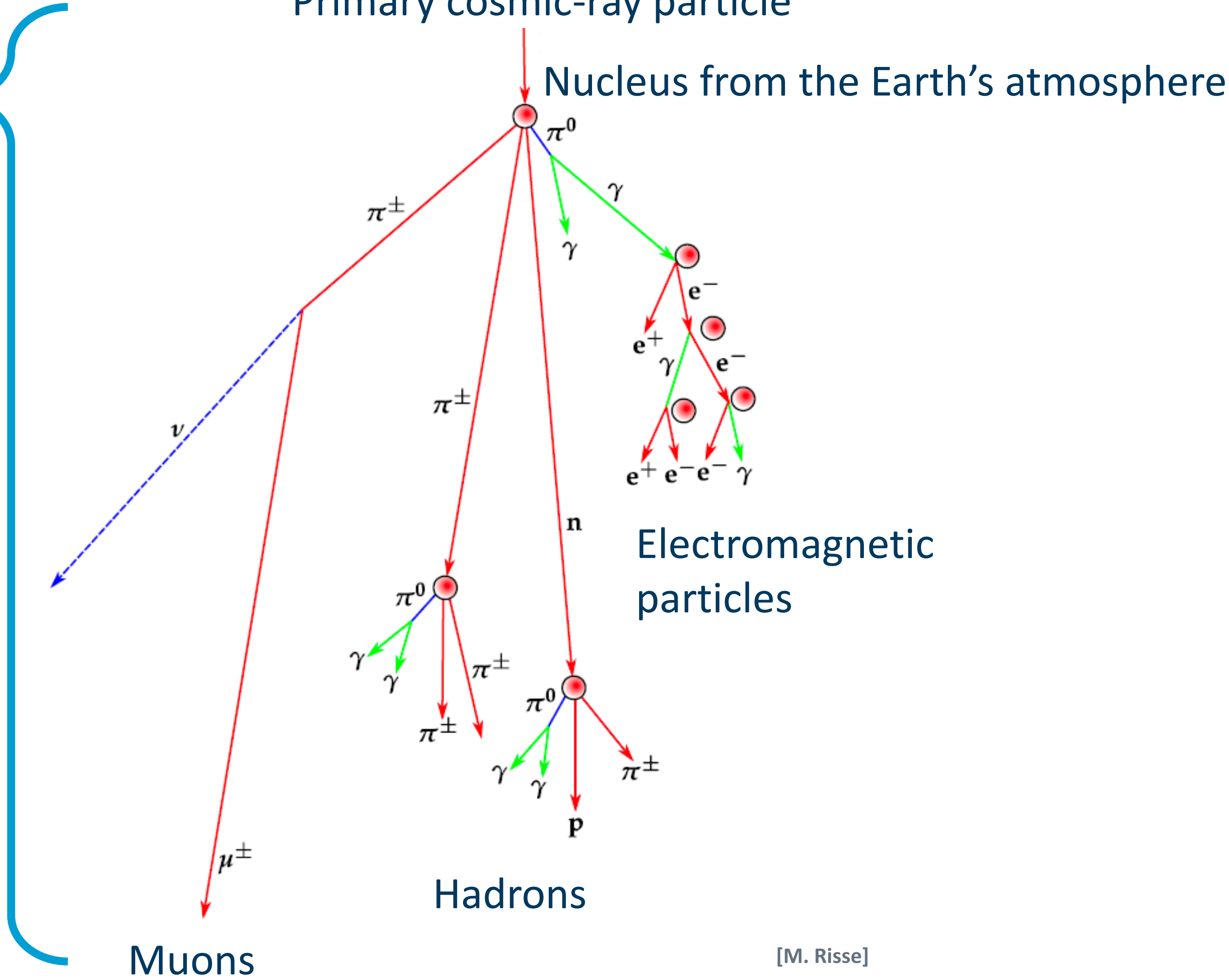
Interlude

Extensive Air Showers



Cascade of billions
of particles, covering
a large area on ground

[J. Knapp]



Primary cosmic-ray particle

Nucleus from the Earth’s atmosphere

Electromagnetic
particles

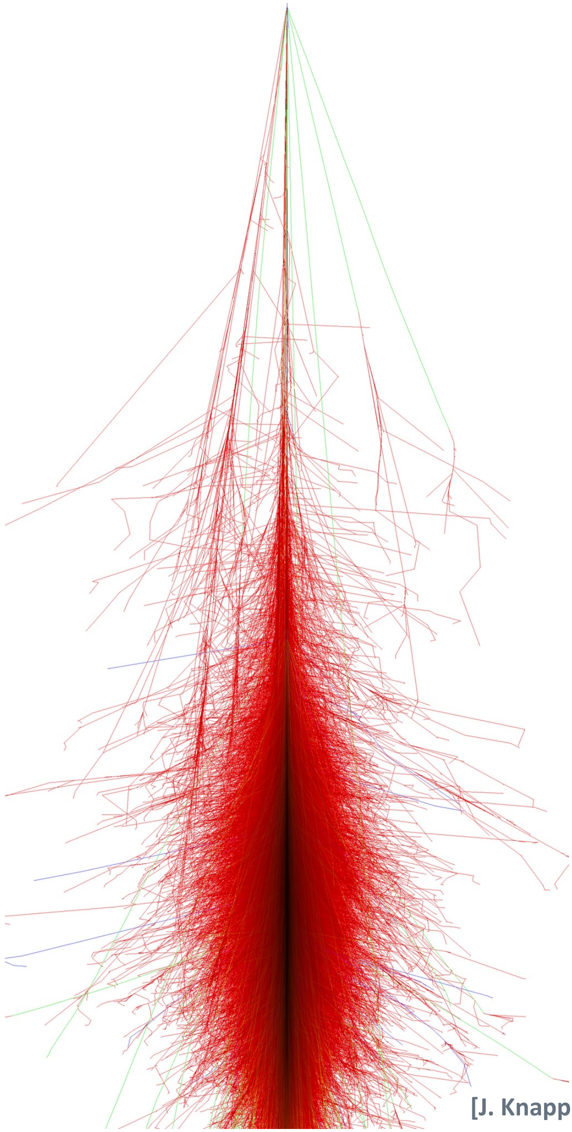
Hadrons

Muons

[M. Risse]

Measuring Extensive Air Showers

- Two main **measurement techniques** currently
  - Measuring the (lateral distribution of) **secondary particles on ground** with a sparse detector array
    - Possibility to cover large areas in a cost-effective way
    - Duty cycle close to $100\,\%$
  - Measuring the **fluorescence light** emitted in the atmosphere when the air shower passes through (proxy for the longitudinal development)
    - Good knowledge of the atmosphere needed to interpret the data
    - Measurement only possible in clear, moonless nights (duty cycle reduced to $\sim 15\,\%$)
- **Future**: radio measurements of air showers?



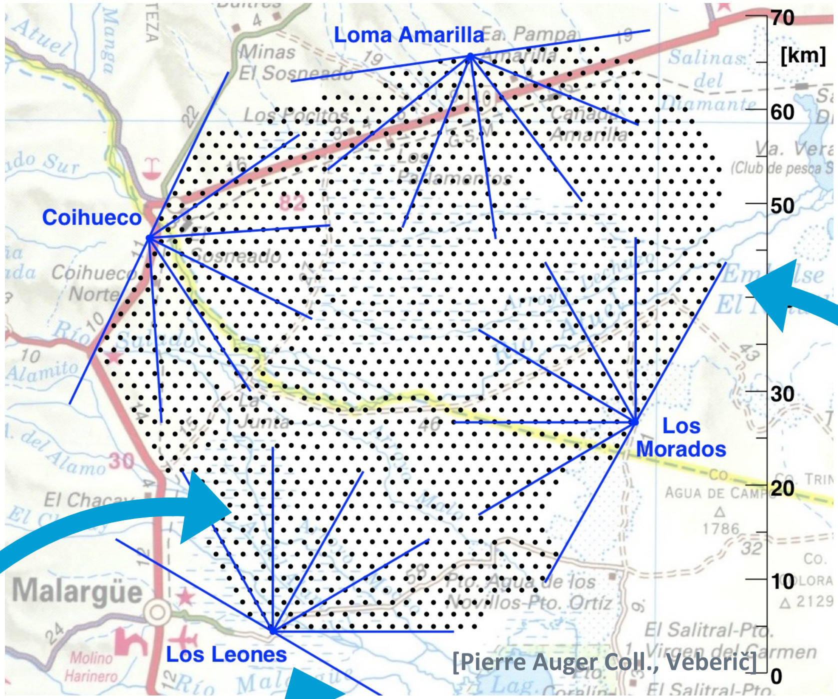
[J. Knapp]

Example: Pierre Auger Observatory

- **Surface Detector (SD)**
  - ~1660 water Cherenkov detector stations, covering about $3000\,\text{km}^2$
- **Fluorescence Detector (FD)**
  - Four FD stations with 27 telescopes
- Data taking started in **2004**
- Detector upgrade (**AugerPrime**) ongoing

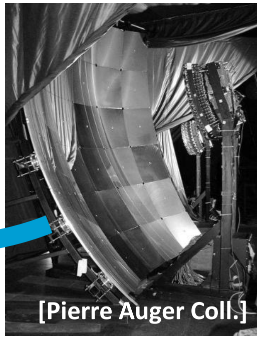
PIERRE
AUGER
OBSERVATORY


[Pierre Auger Coll.]



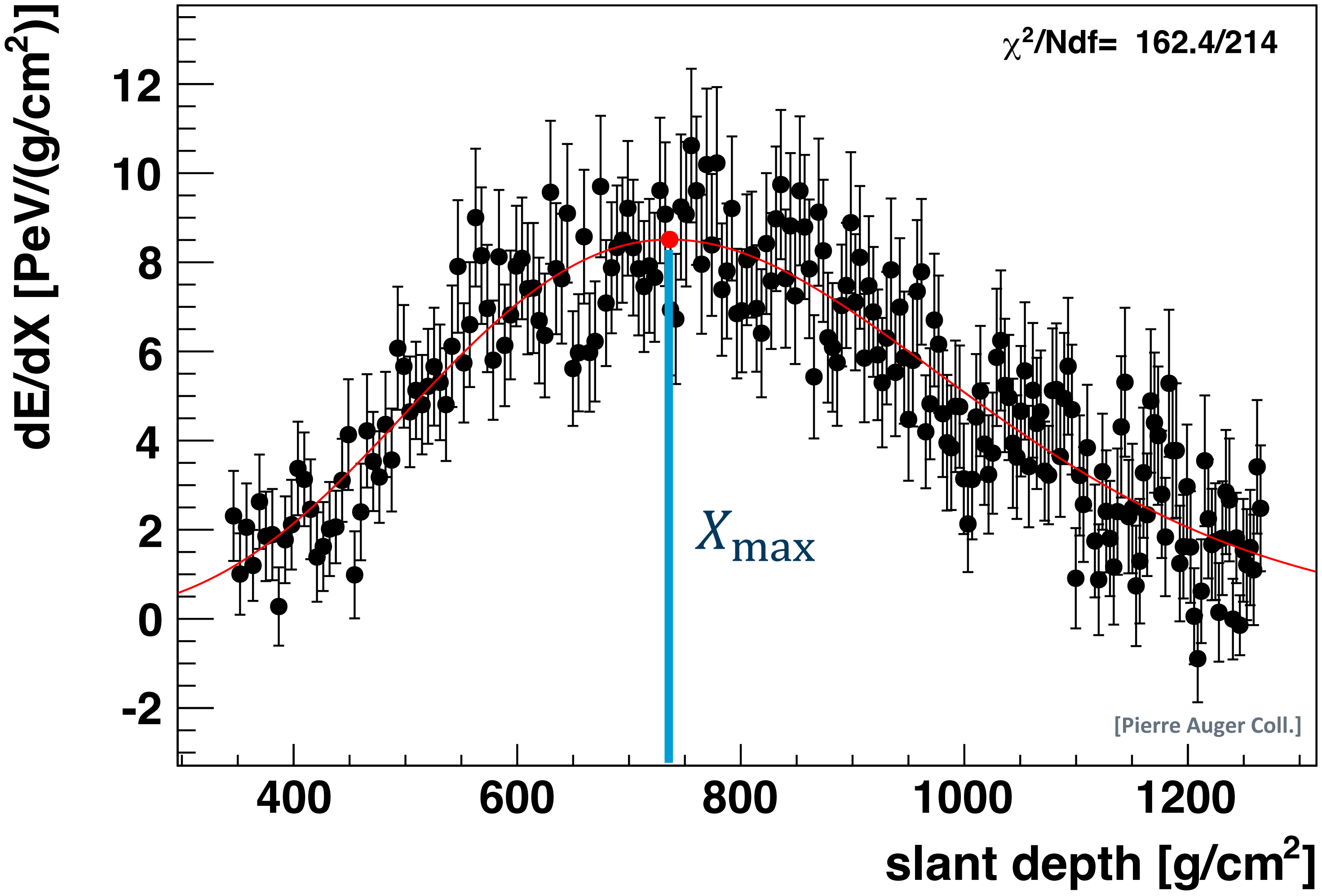
[Pierre Auger Coll., Veberič]


[Pierre Auger Coll.]


[Pierre Auger Coll.]

[CIA]

Measured Air-Shower Profile

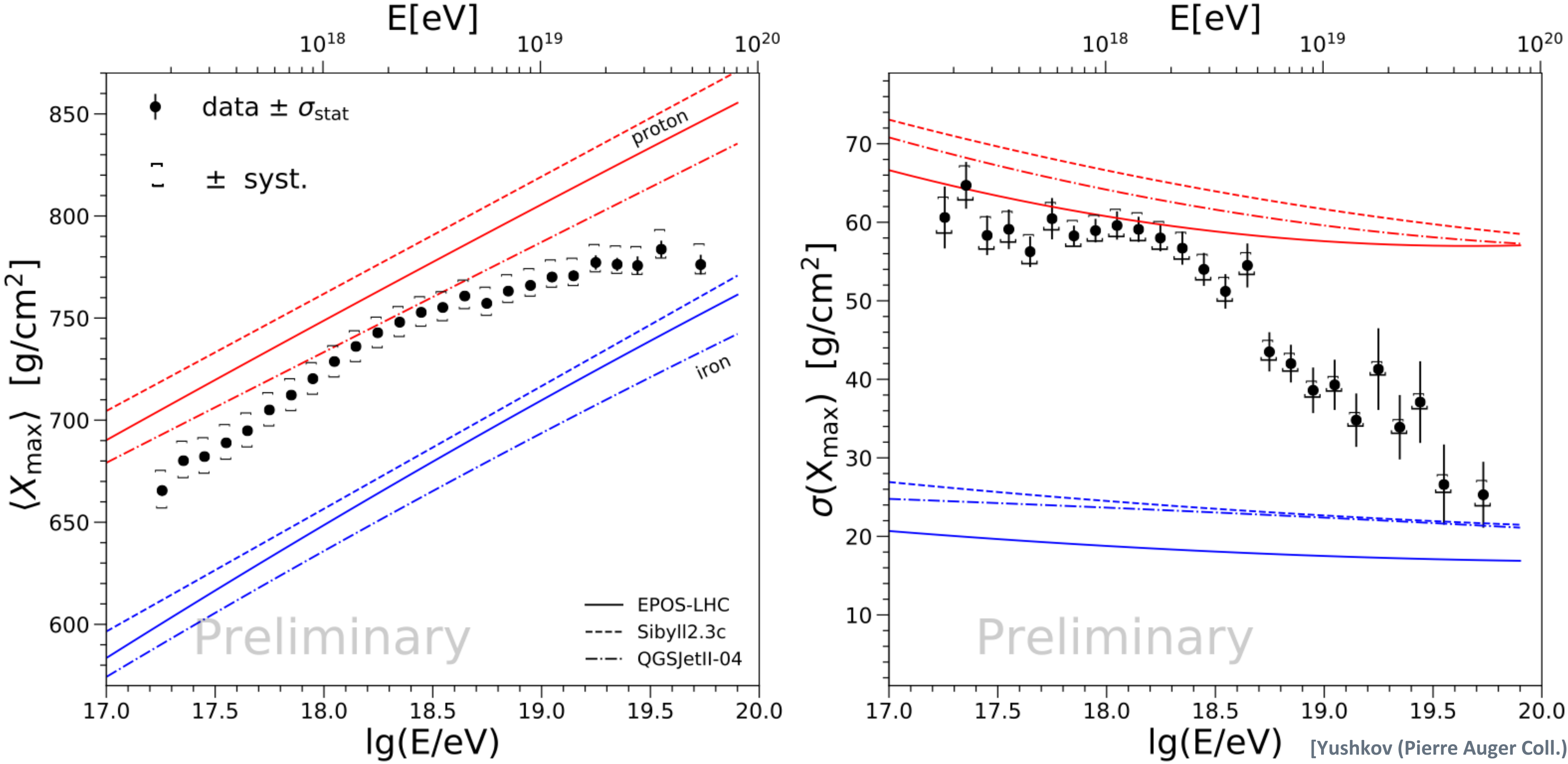


Atmospheric depth of shower maximum $X_{\max}$ directly from profile, important observable for composition studies

Primary energy E from integration of shower profile:

$$E = \int \frac{\mathrm{d}E}{\mathrm{d}X} \mathrm{d}X$$

Measurements of $\langle X_{\mathrm{max}} \rangle$ and $\sigma(X_{\mathrm{max}})$



[Yushkov (Pierre Auger Coll.); PoS (ICRC 2019) 482]

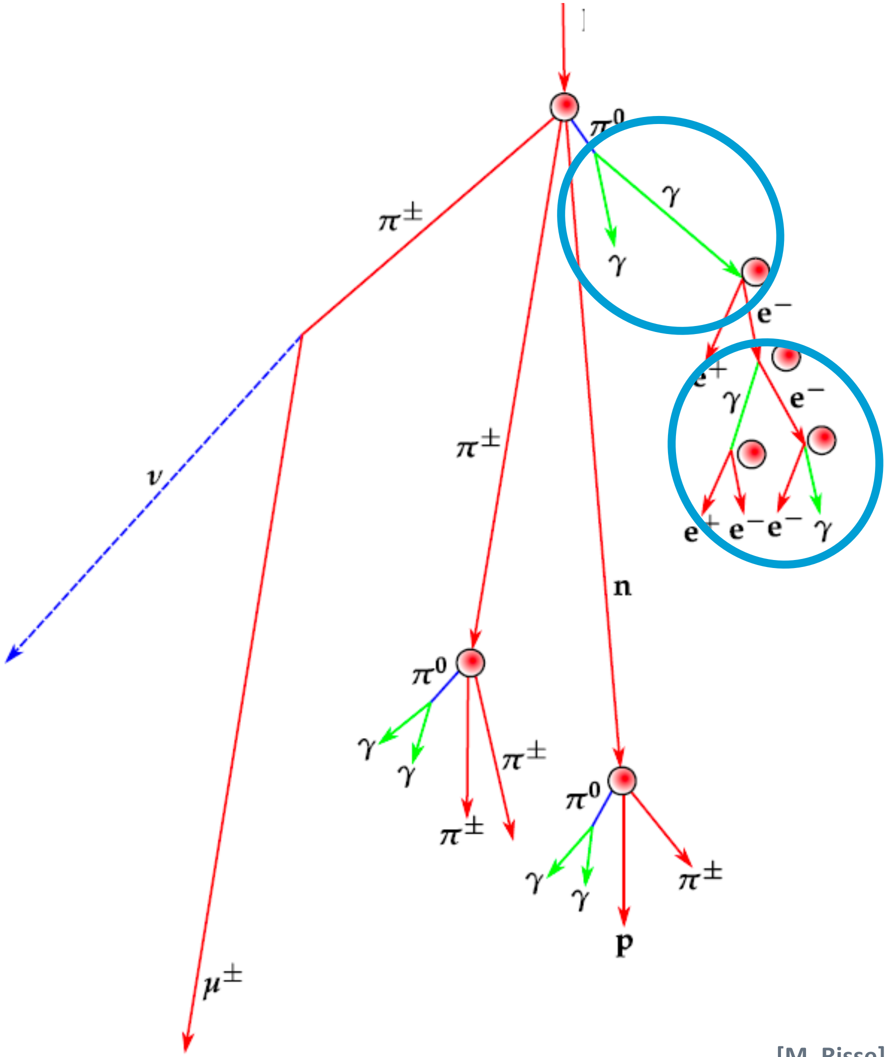
- **Interpretation** of the measurements of $\langle X_{\mathrm{max}} \rangle$ and $\sigma(X_{\mathrm{max}})$ depends on air-shower simulations – **what would change** in the presence of LV?

Bounds on Lorentz Violation Using Extensive Air Showers

What if Photons in an Air Shower Decay?

- If photons above the threshold decay immediately into electron-positron pairs: expect **shorter showers (smaller $X_{\max}$)**
  - **NB:** secondary photons with up to $\sim 10\,\%$ of the primary energy possible:
    $1\ \mathrm{EeV}$ cosmic ray → $100\ \mathrm{PeV}$ photons

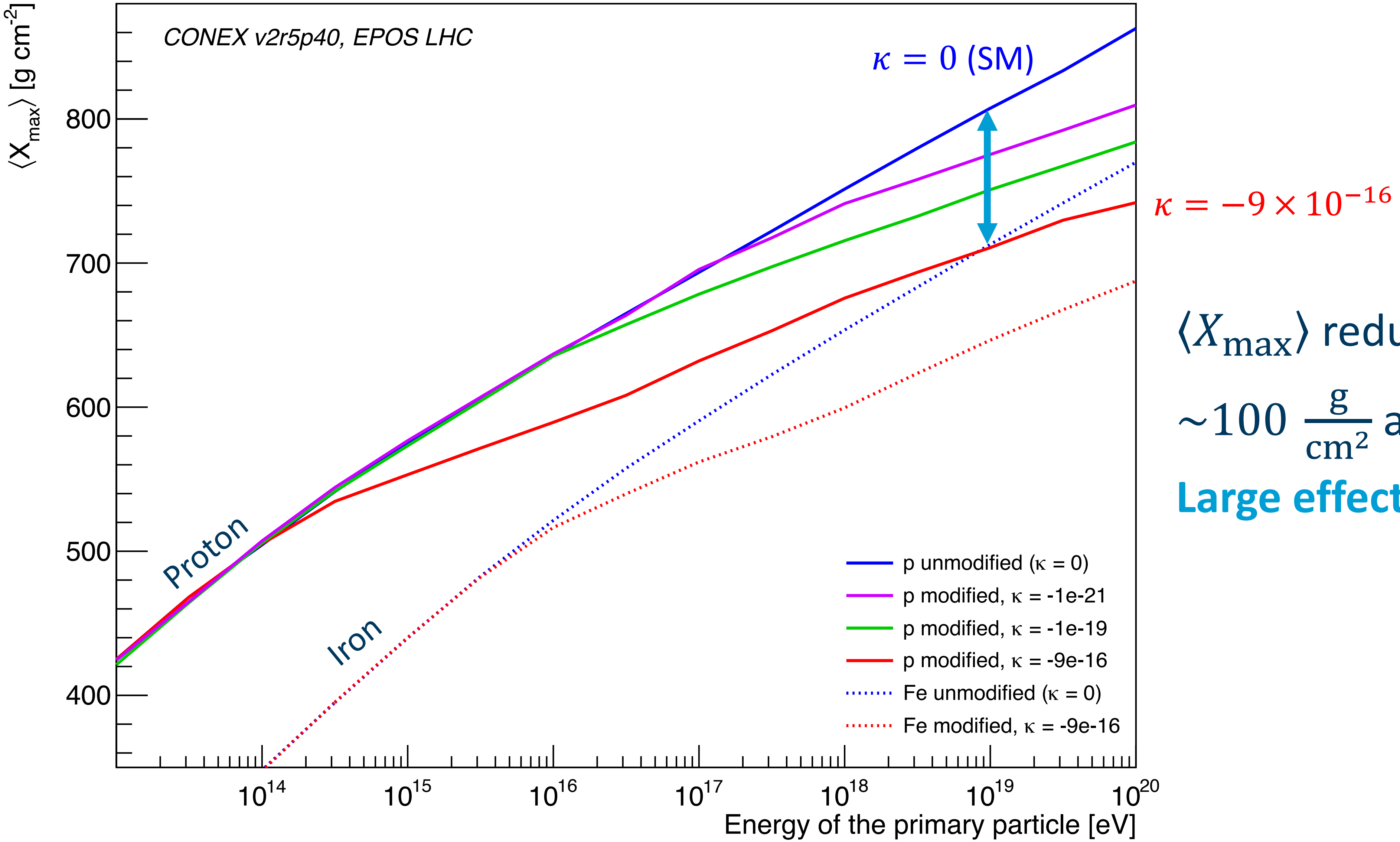
- How large is the **impact of LV on $\langle X_{\max} \rangle$**?
  - **Simulation study** using the Monte Carlo code CONEX, extended to include LV processes
    [Bergmann et al.; Astropart. Phys. 26 (2007) 420]
    [Pierog et al.; Nucl. Phys. B, Proc. Suppl. 151 (2006) 159]
    [Klinkhamer, MN, Risse; Phys. Rev. D 96 (2017) 116011]



[M. Risse]

Impact of LV on $\langle X_{\max} \rangle$

[Klinkhamer, MN, Risse; Phys. Rev. D 96 (2017) 116011]



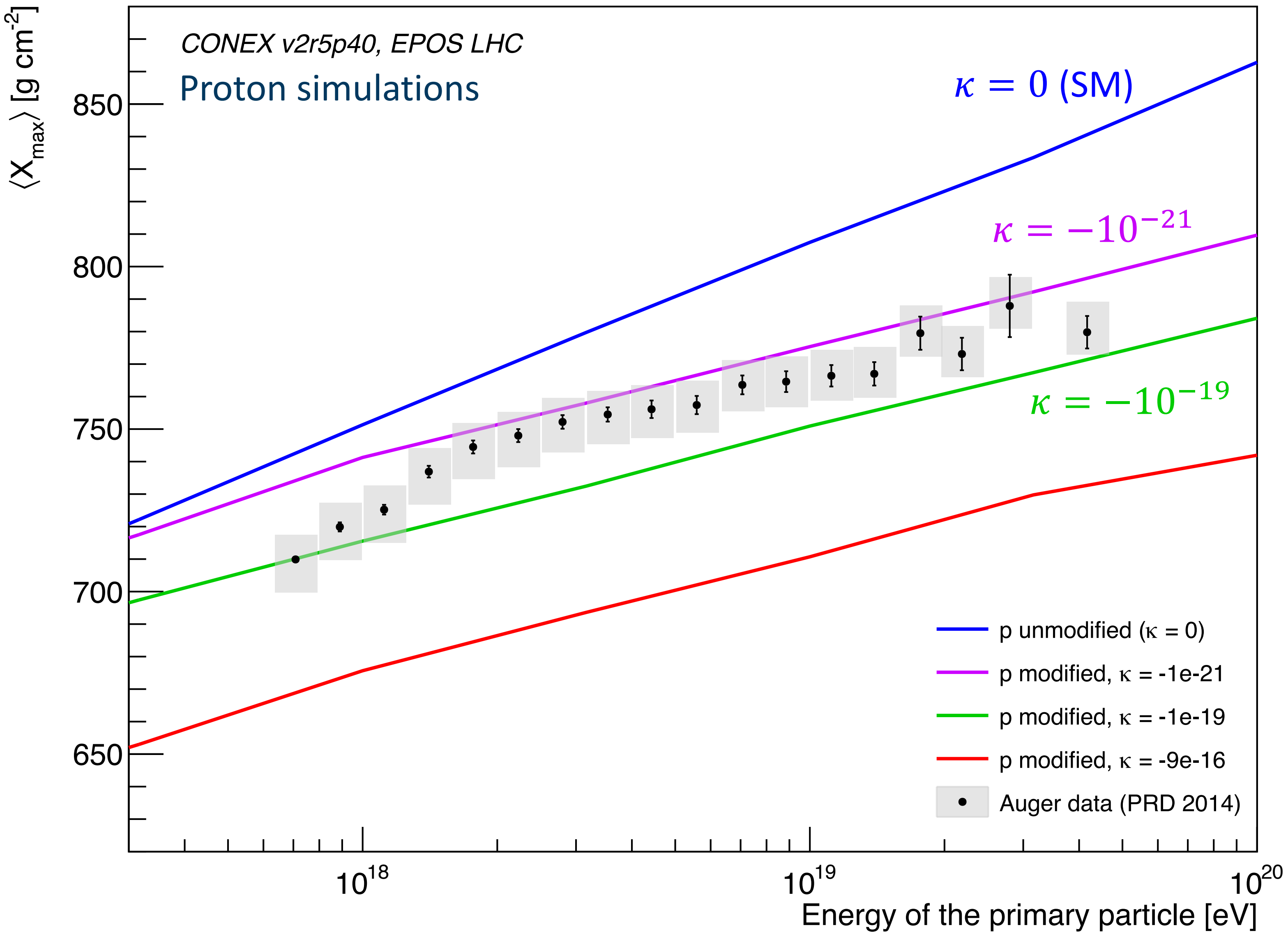
$\langle X_{\max} \rangle$ reduced by

$\sim 100 \ \frac{\mathrm{g}}{\mathrm{cm}^2}$ at 10^{19} eV:

Large effect!

Comparison to $\langle X_{\max} \rangle$ Data

[Klinkhamer, MN, Risse; Phys. Rev. D 96 (2017) 116011]



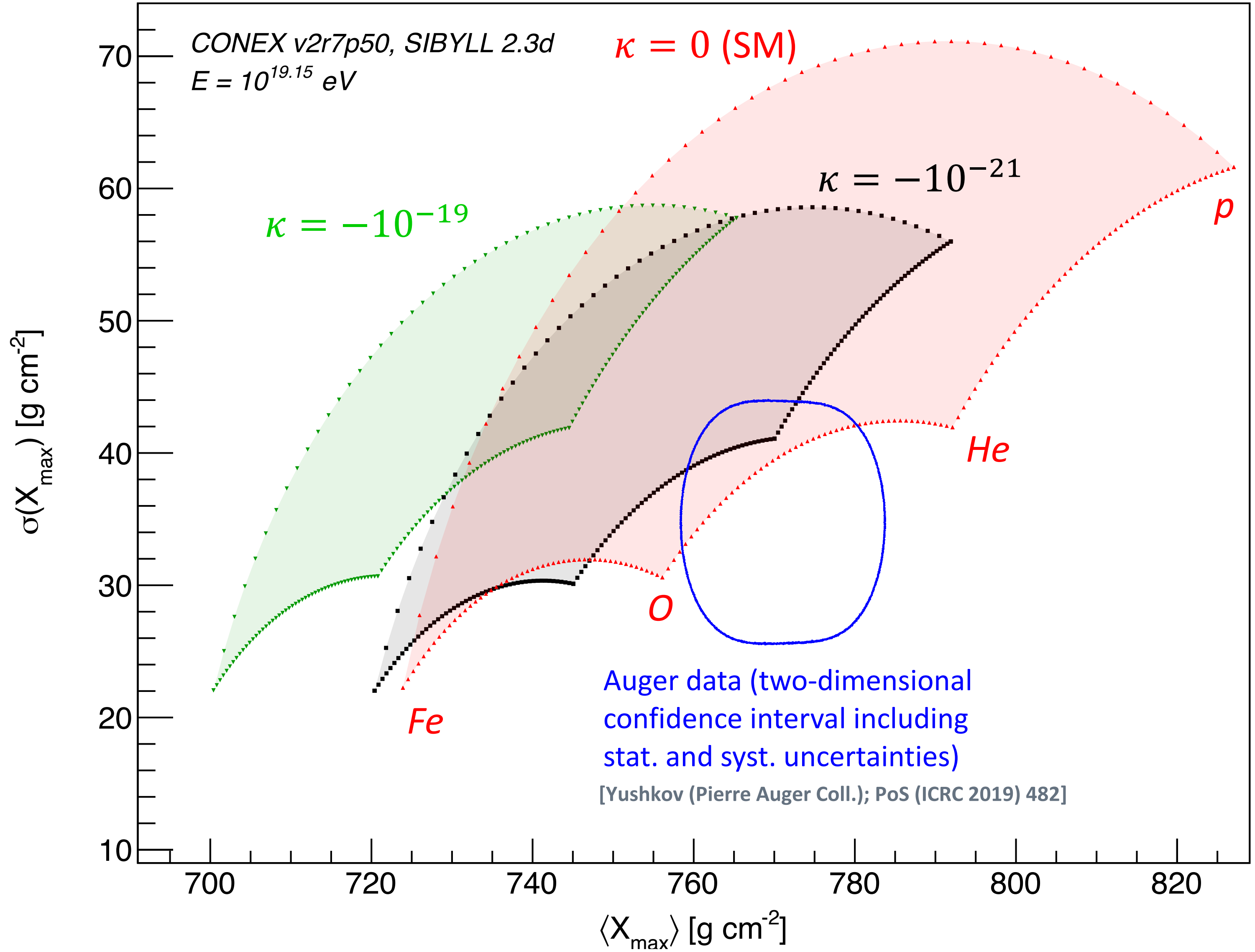
If **deeper showers** are observed than expected for a given κ for primary protons: exclude this κ

Full analysis yields a bound $\boldsymbol{\kappa > -3 \times 10^{-19}}$ (98 % C.L.)

Only protons so far taken into account (conservative assumption)

Including $\sigma(X_{\max})$

[Duenkel, MN, Risse; Phys. Rev. D 104 (2021) 015010]



Auger data (two-dimensional confidence interval including stat. and syst. uncertainties)

[Yushkov (Pierre Auger Coll.); PoS (ICRC 2019) 482]

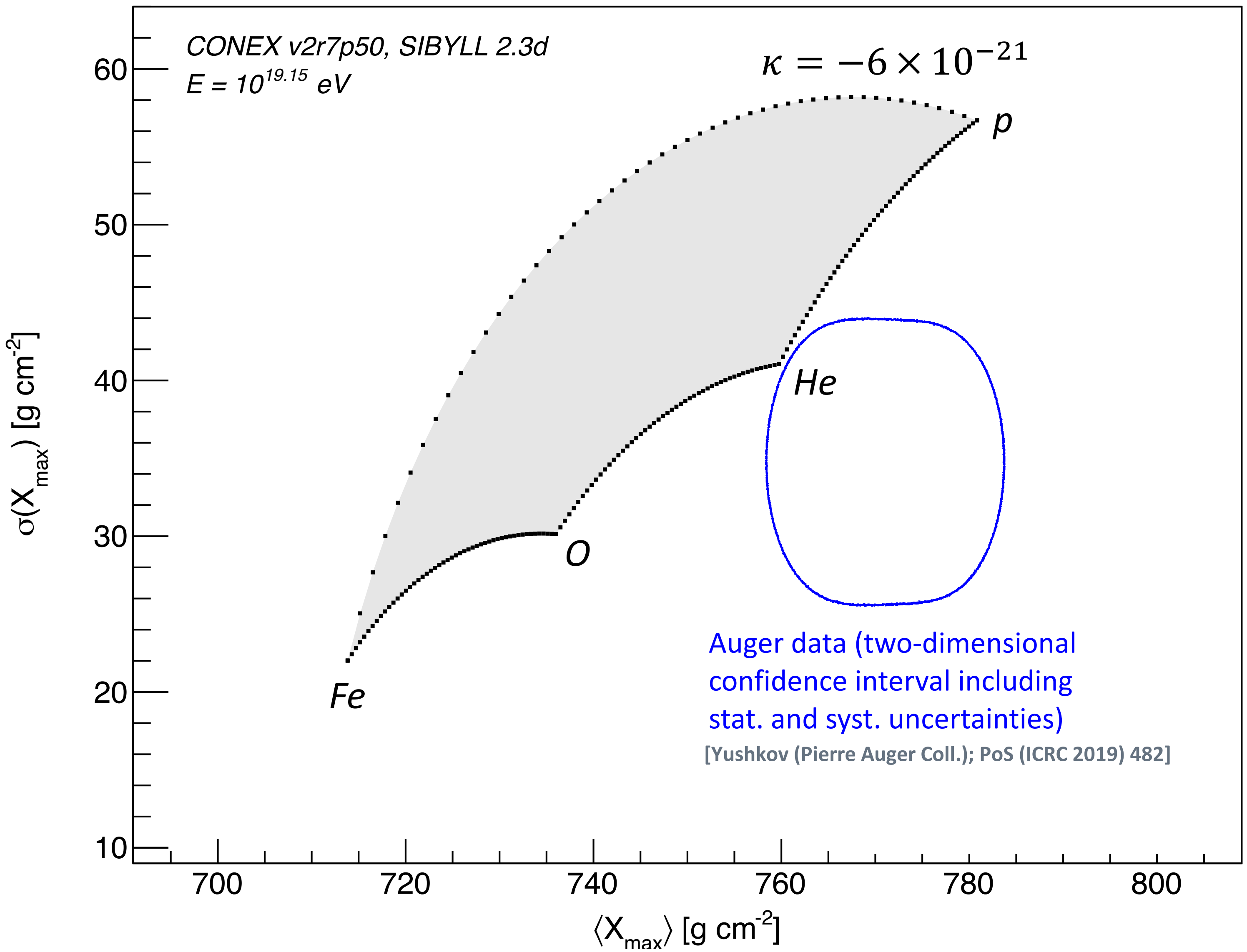
Simulate **mixtures** of protons and heavier nuclei (He, O, Fe)

The **“umbrellas”** bracket the range of allowed values in the $\langle X_{\max}\rangle/\sigma(X_{\max})$ space for a given κ (and energy)

If there is **no overlap** with data in any energy bin, then this κ can be **excluded**

A New Bound on $\kappa < 0$

[Duenkel, MN, Risse; Phys. Rev. D 104 (2021) 015010]



Auger data (two-dimensional confidence interval including stat. and syst. uncertainties)

[Yushkov (Pierre Auger Coll.); PoS (ICRC 2019) 482]

Full analysis yields a bound

$\kappa > -6 \times 10^{-21}$ (98 % C.L.)

More **general takeaway**:

shower profile at ultra-high energies are quite “normal”

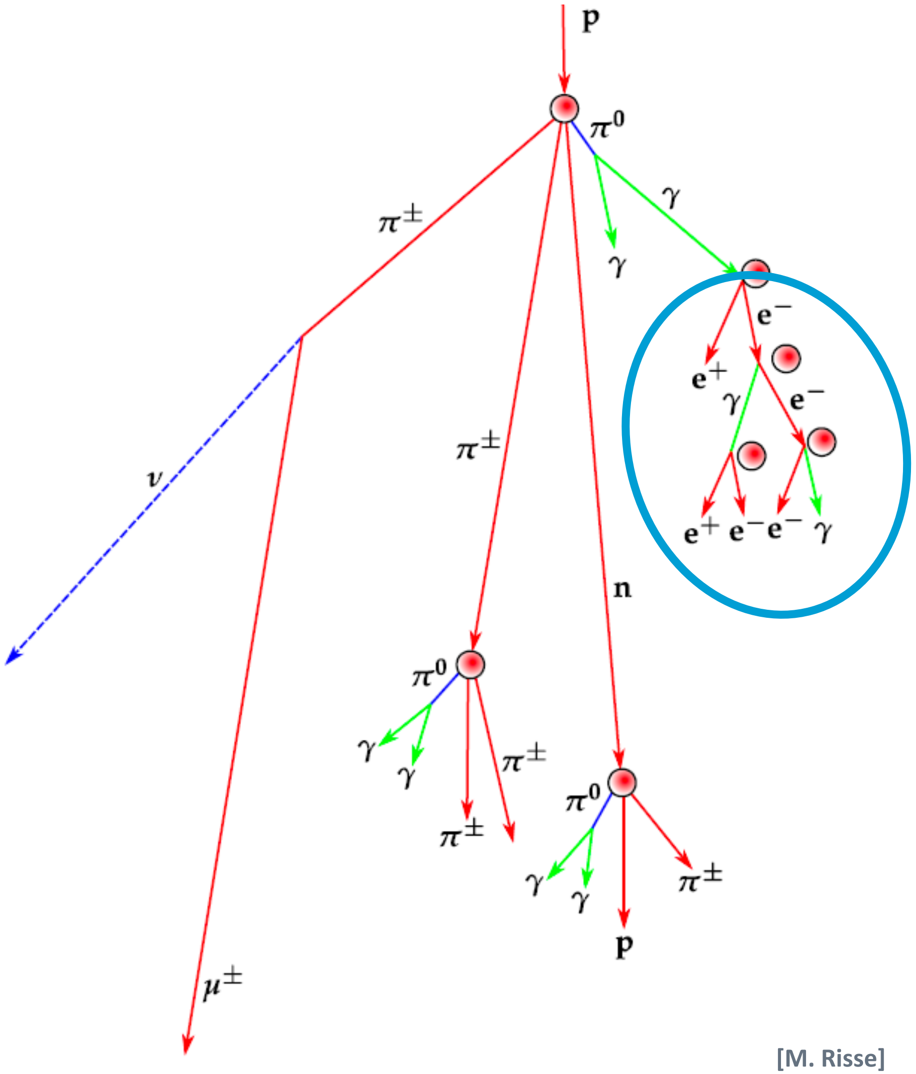
Bounds on κ so Far

	Bounds based on primary cosmic particles	Bounds based on secondary particles in air showers
$\kappa > 0$ Vac. Cherenkov rad. $f^{\pm} \rightarrow f^{\pm} + \tilde{\gamma}$	$< 6 \times 10^{-20}$ [Klinkhamer, Risse; Phys. Rev. D 77 (2008) 117901] [Klinkhamer, Schreck; Phys. Rev. D 78 (2008) 085026]	?
$\kappa < 0$ Photon decay $\tilde{\gamma} \rightarrow e^{-} + e^{+}$	$> -9 \times 10^{-16}$ [Klinkhamer, Schreck; Phys. Rev. D 78 (2008) 085026]	$> -6 \times 10^{-21}$ [Duenkel, MN, Risse; Phys. Rev. D 104 (2021) 015010]

All bounds at $98\,\%$ C.L.

Vacuum Cherenkov Radiation in Air Showers

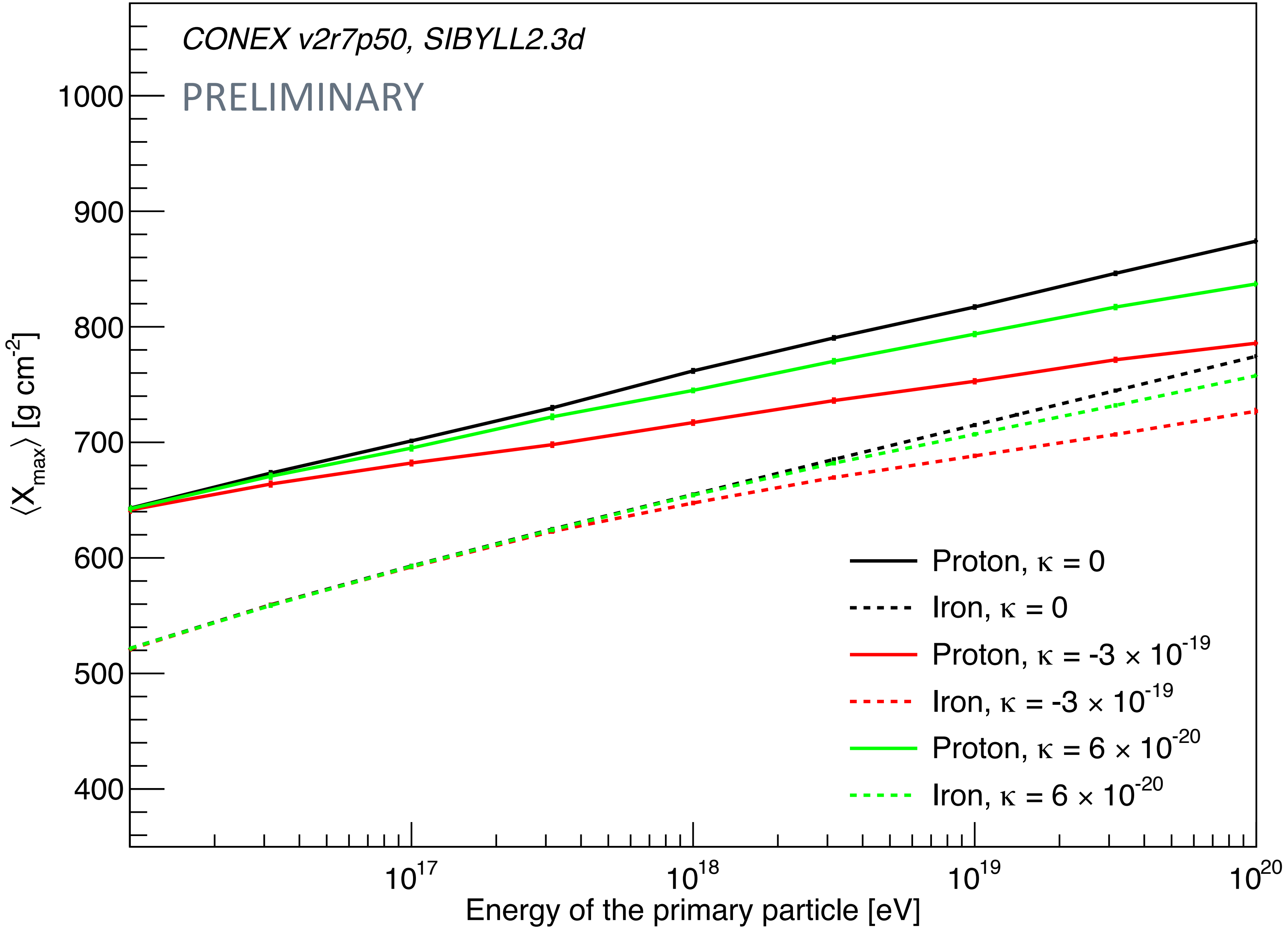
- What if **electrons and positrons** (most numerous and lightest charged particles in an air shower) lose their energy immediately due to vacuum Cherenkov radiation?
  - Expect again **shorter showers** with smaller $X_{\max}$!
- Perform again a **simulation study** with CONEX



[M. Risse]

Vacuum Cherenkov Radiation in Air Showers: $\langle X_{\mathbf{max}} \rangle$

[Duenkel, MN, Risse; Proc. UHECR 2022, to be published]



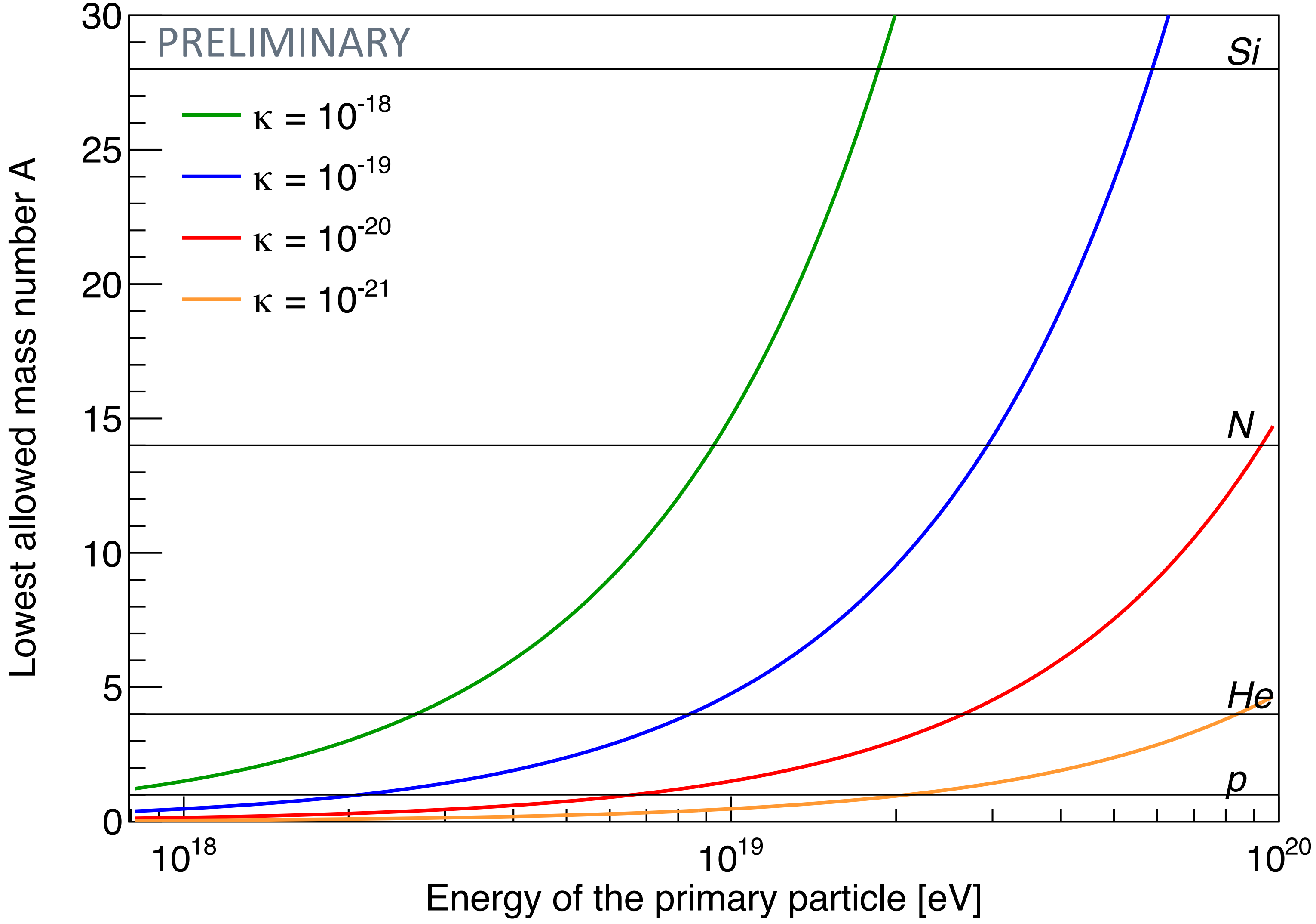
Smaller effect compared to the case of photon decay ($\kappa < 0$)

Still: possible to constrain $\kappa > 0$ with this approach

NB: complementary to previous approach (different particles and method)

Which Primaries Can Actually Reach Earth?

[Duenkel, MN, Risse; publ. in preparation]



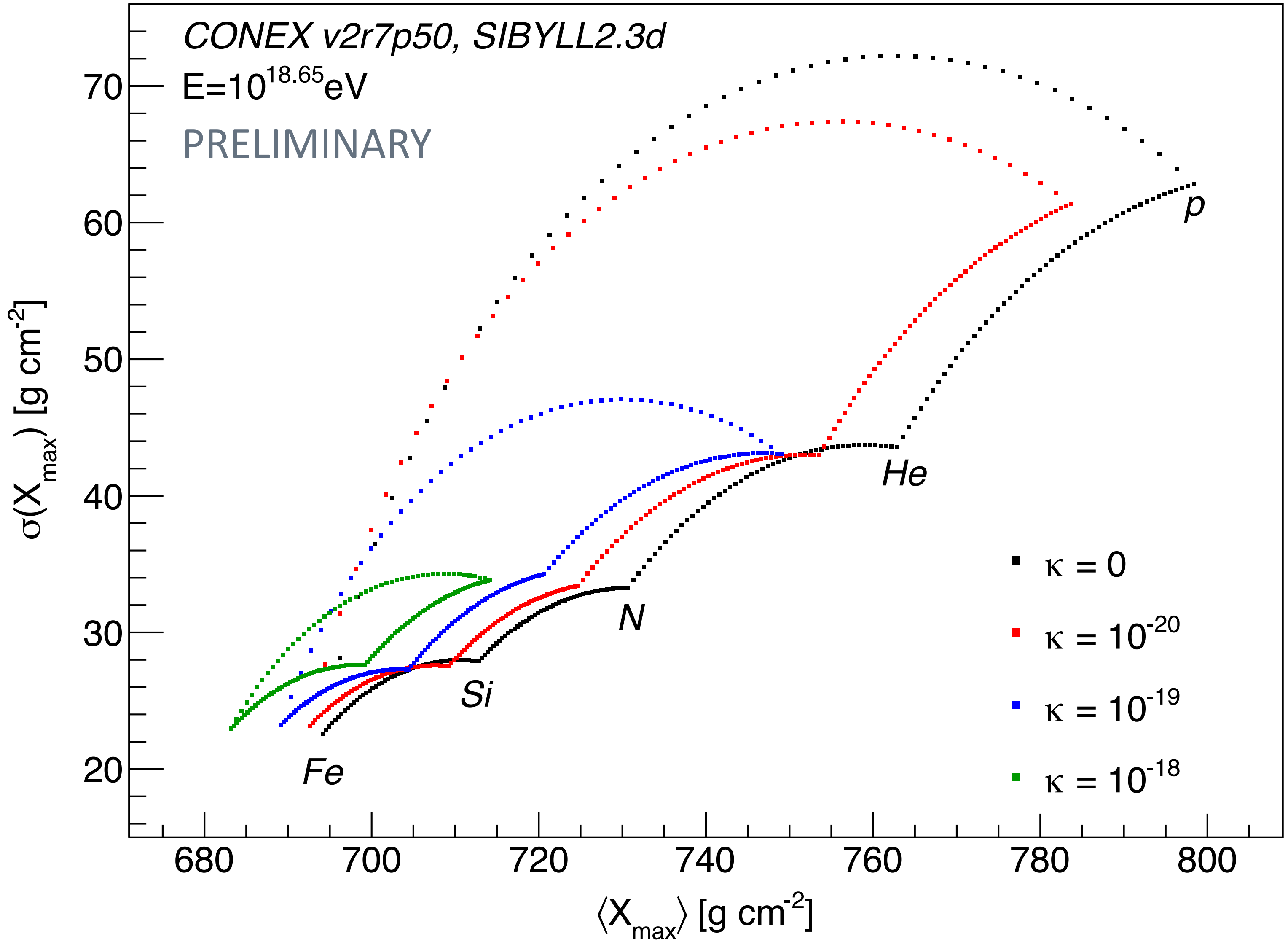
Need to take into account that the **primary particle** also emits vacuum Cherenkov radiation to be **consistent**:

Not all primaries can actually reach Earth

→ composition constraint

Back to the Umbrella Plots

[Duenkel, MN, Risse; publ. in preparation]



Consequence:

Umbrellas get smaller as more primaries drop out

Preliminary result after comparison with Auger data:

$\boldsymbol{\kappa < 3 \times 10^{-20}}$ (98 % C.L.)

All Bounds on κ Together

	Bounds based on primary cosmic particles	Bounds based on secondary particles in air showers
$\kappa > 0$ Vac. Cherenkov rad. $f^{\pm} \rightarrow f^{\pm} + \tilde{\gamma}$	$< 6 \times 10^{-20}$ [Klinkhamer, Risse; Phys. Rev. D 77 (2008) 117901] [Klinkhamer, Schreck; Phys. Rev. D 78 (2008) 085026]	$< 3 \times 10^{-20}$ PRELIMINARY [Duenkel, MN, Risse; publ. in preparation]
$\kappa < 0$ Photon decay $\tilde{\gamma} \rightarrow e^{-} + e^{+}$	$> -9 \times 10^{-16}$ [Klinkhamer, Schreck; Phys. Rev. D 78 (2008) 085026]	$> -6 \times 10^{-21}$ [Duenkel, MN, Risse; Phys. Rev. D 104 (2021) 015010]

All bounds at $98\ \%$ C.L.

Summary

Summary

- **Cosmic particles** with their ultra-high energies provide a **unique opportunity to test Lorentz invariance** at energy scales beyond the reach of man-made accelerators
- **Bounds on LV** can be placed from the absence of non-standard processes that become allowed in the LV case
  - In particular: **vacuum Cherenkov radiation** and **photon decay** (in extensive air showers)
- **Current bounds** on isotropic, non-birefringent LV in the photon sector:

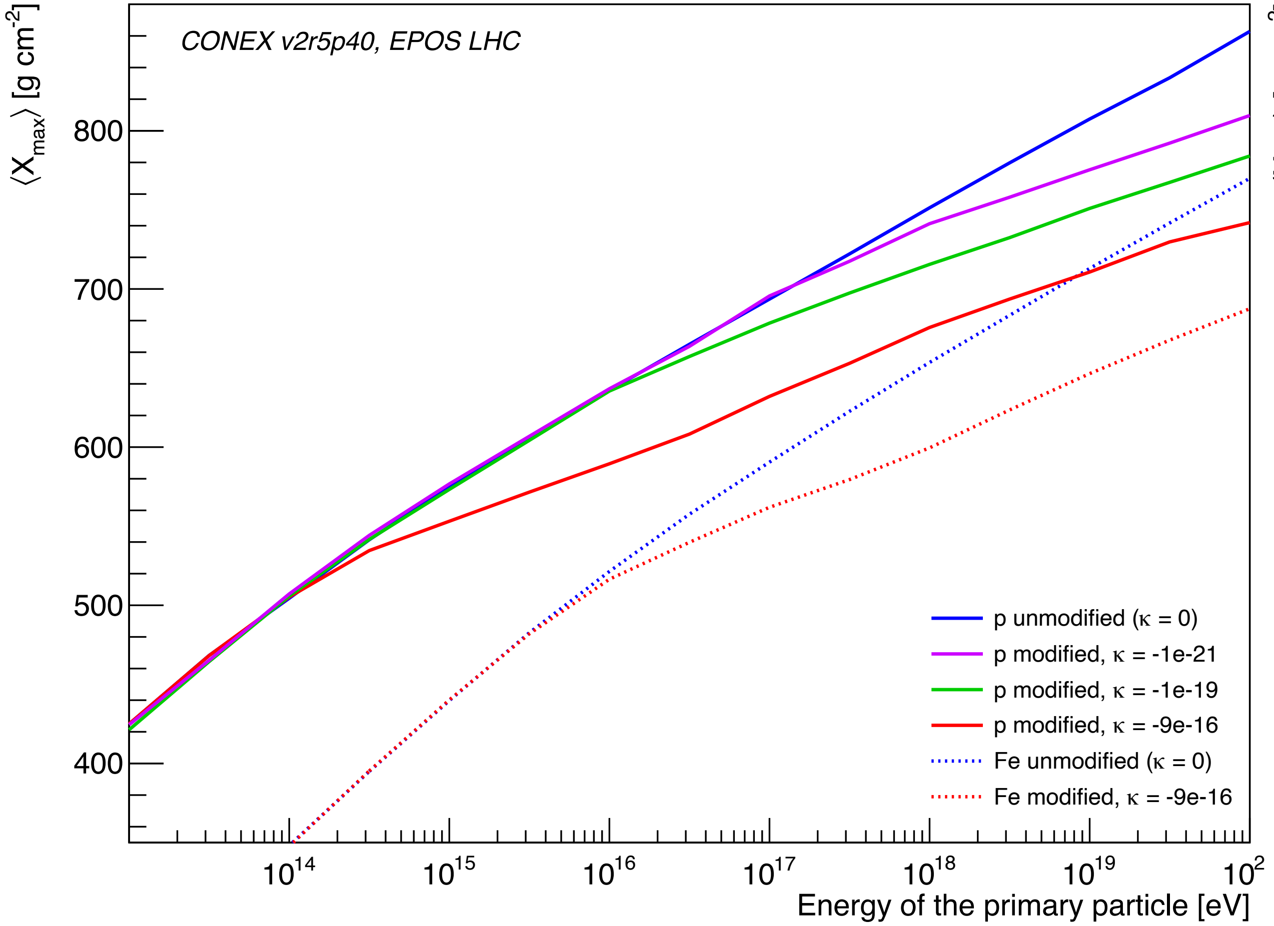
$$-6 \times 10^{-21} < \kappa < 3 \times 10^{-20} \text{ (98 \% C.L.)}$$

- Numerous **improvements** of these bounds possible if, e.g.,…
  - UHE photons observed; uncertainties on $\langle X_{\max} \rangle / \sigma(X_{\max})$ reduced, more composition constraints…
- Lorentz invariance apparently **holds to a large extent** – but we're ready to finally see experimental evidence for **new physics beyond the SM**

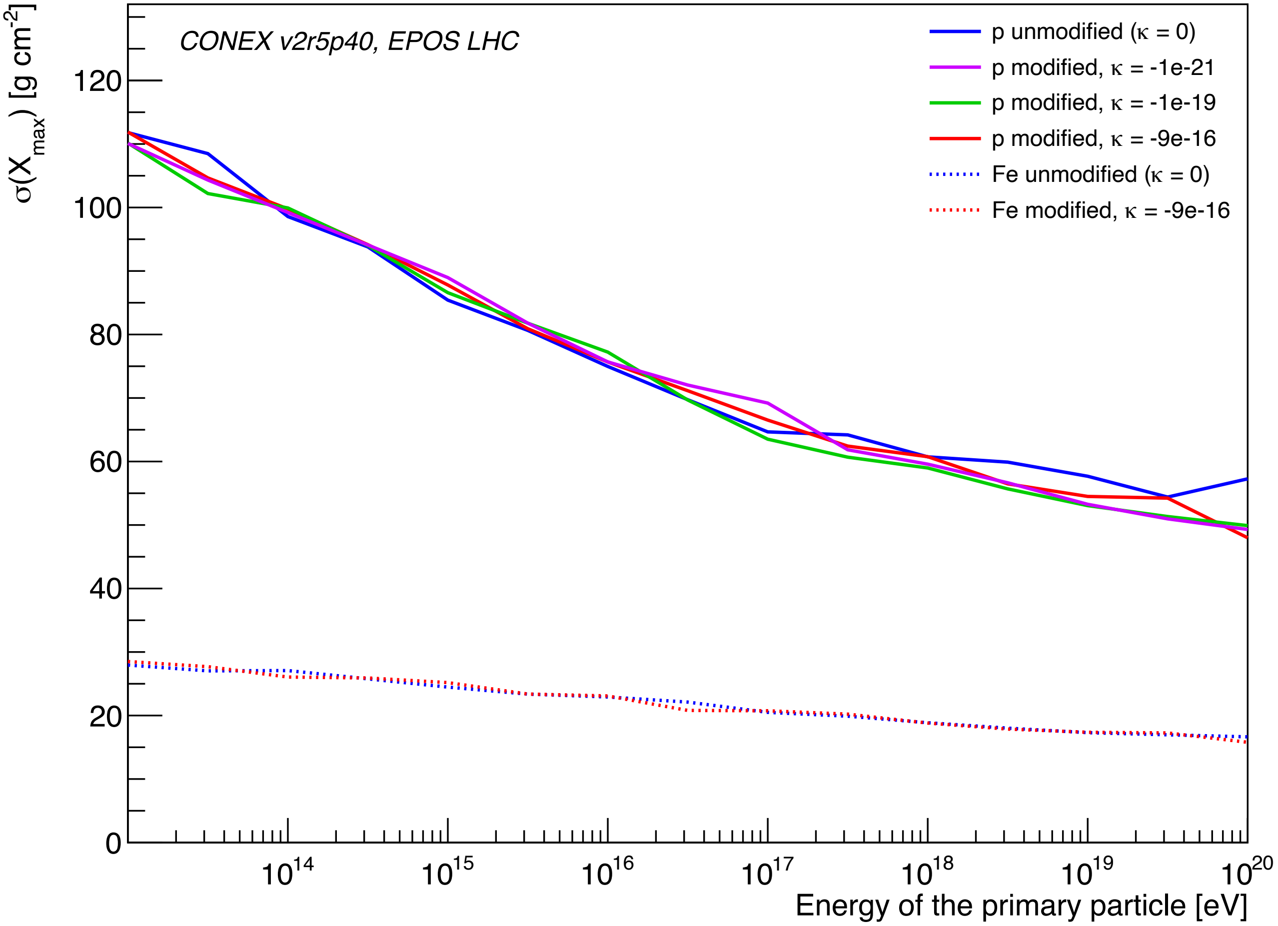
Appendix / Backup

Impact of LV on $\langle X_{\max}\rangle$ and $\sigma(X_{\max})$ (Separately)

[Klinkhamer, MN, Risse; Phys. Rev. D 96 (2017) 116011]

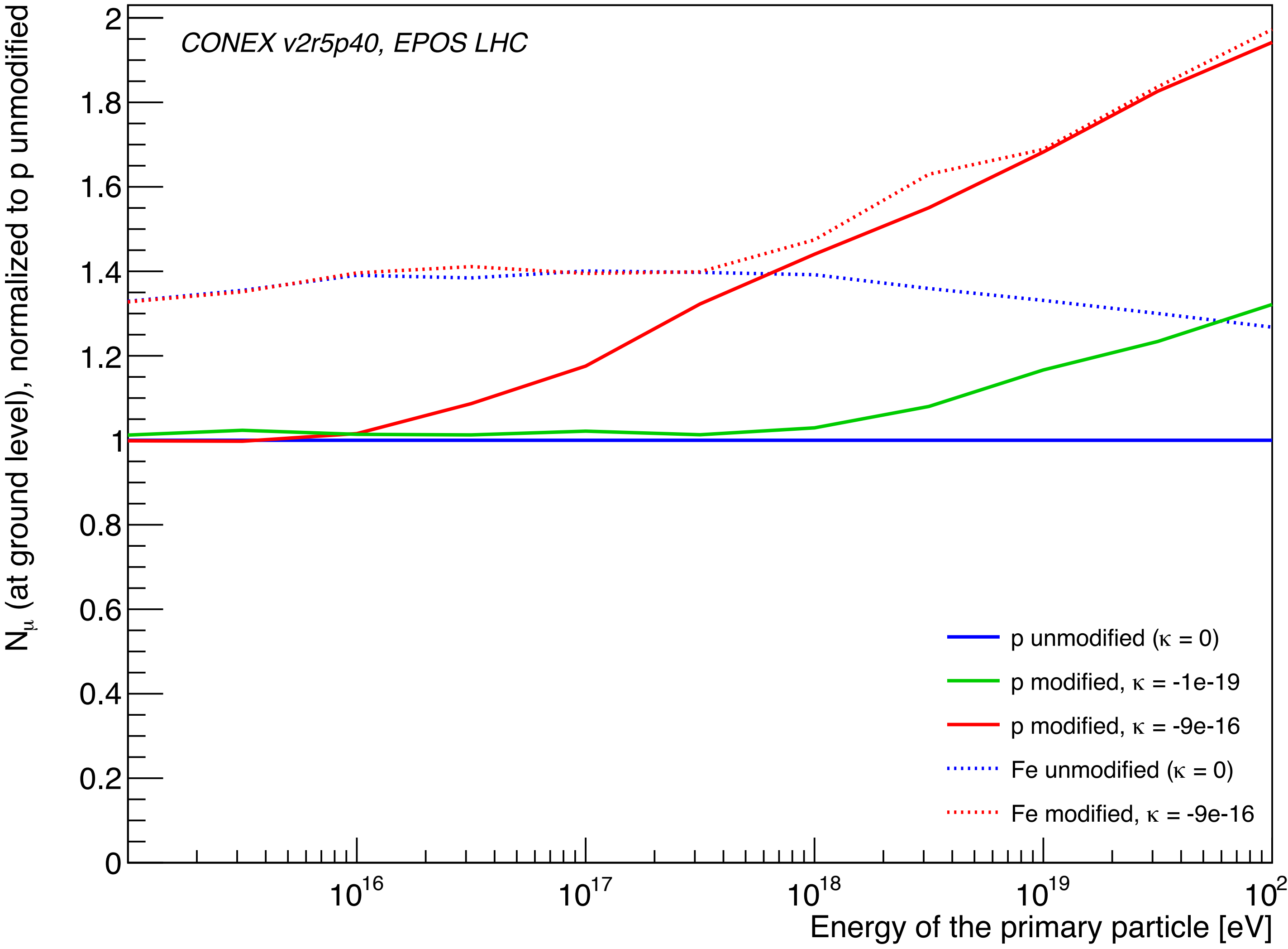


[Klinkhamer, MN, Risse; Phys. Rev. D 96 (2017) 116011]



Impact of LV on the Number of Muons in Air Showers

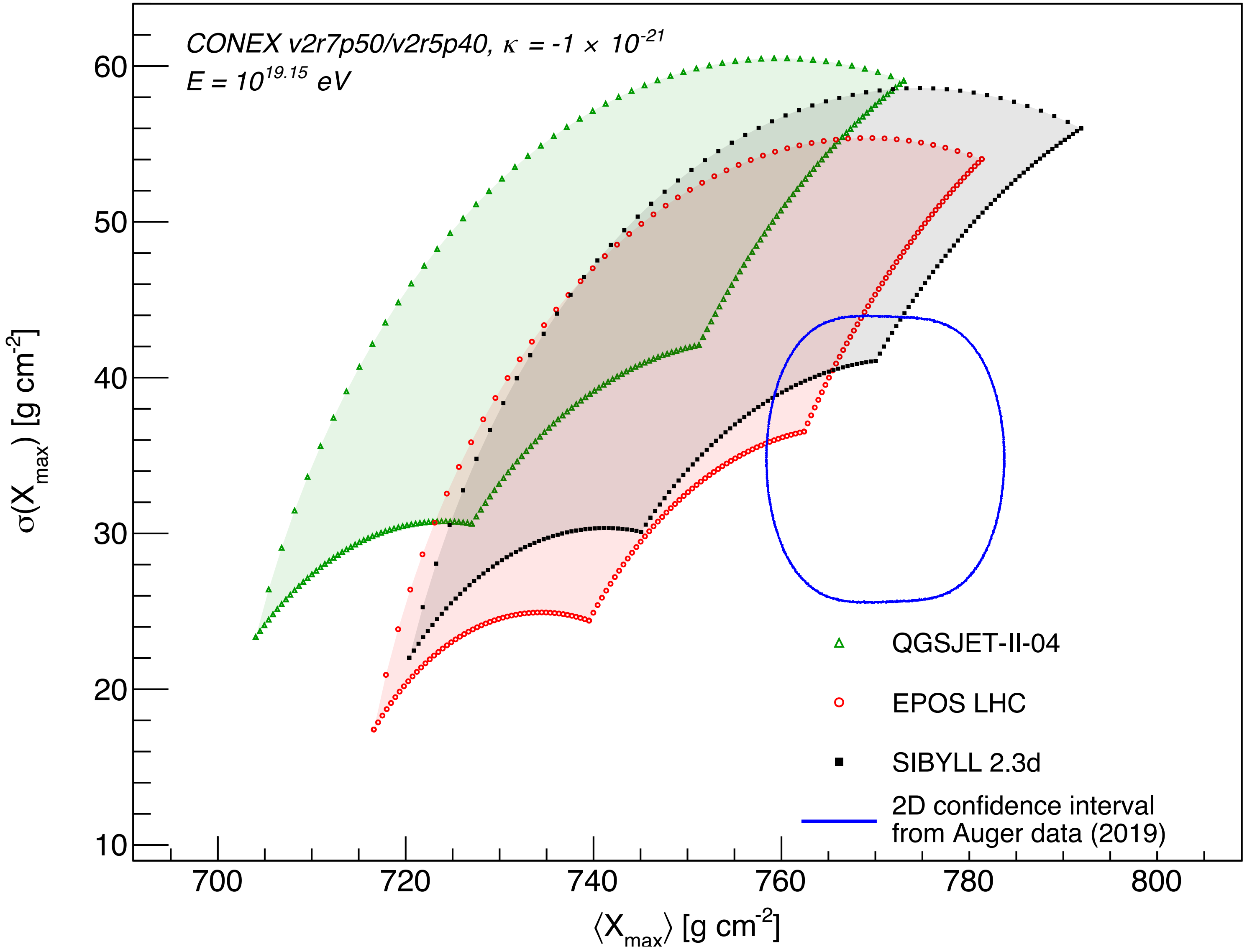
- Also production of (non-standard) photons via π^0 decay affected
- Effectively, **π^0 decay suppressed** at high energies
  → **more muons**
- Already implemented in the MC simulations with CONEX



[Klinkhamer, MN, Risse; Phys. Rev. D 96 (2017) 116011]

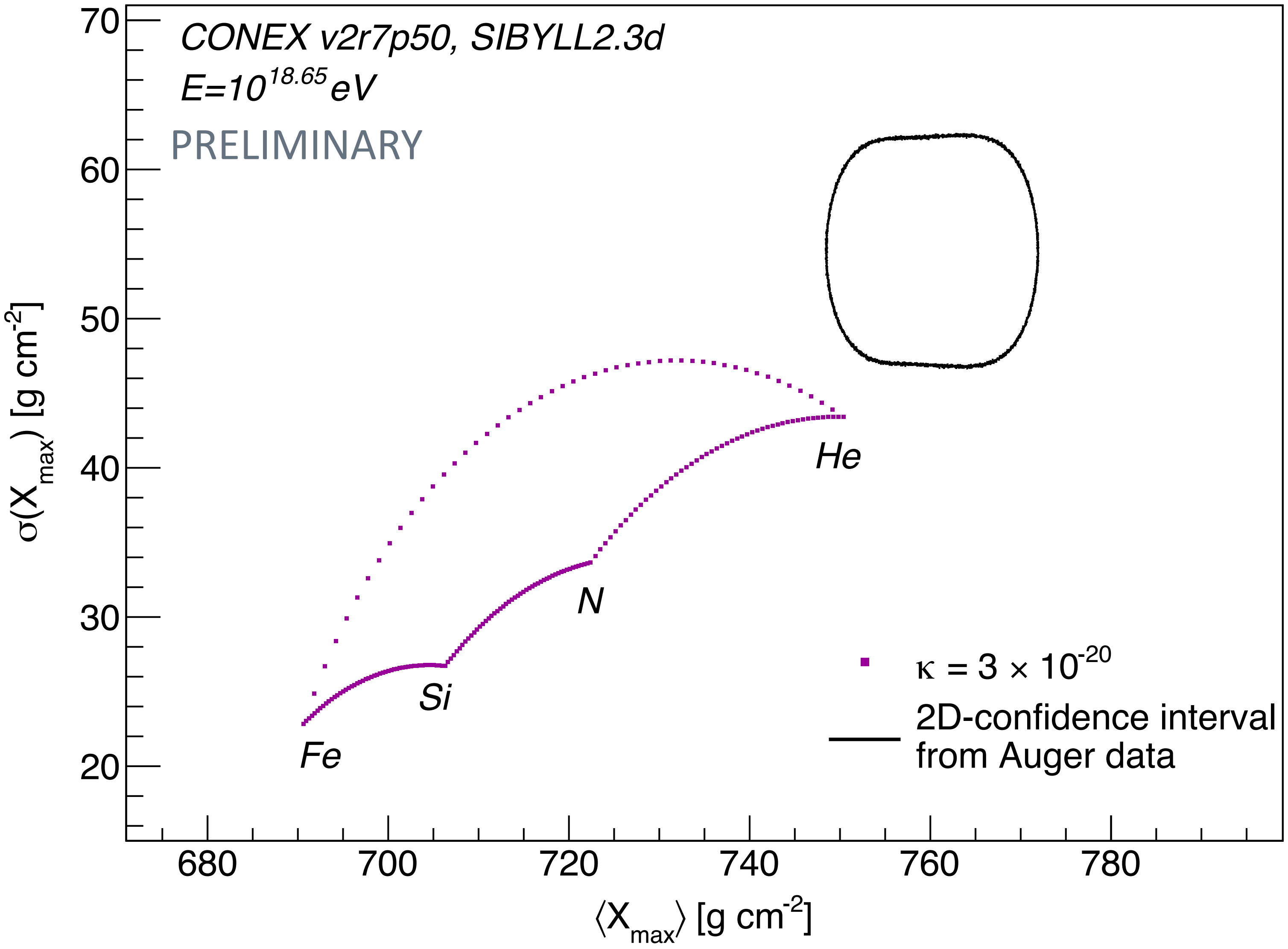
Hadronic interaction models

[Duenkel, MN, Risse; Phys. Rev. D 104 (2021) 015010]

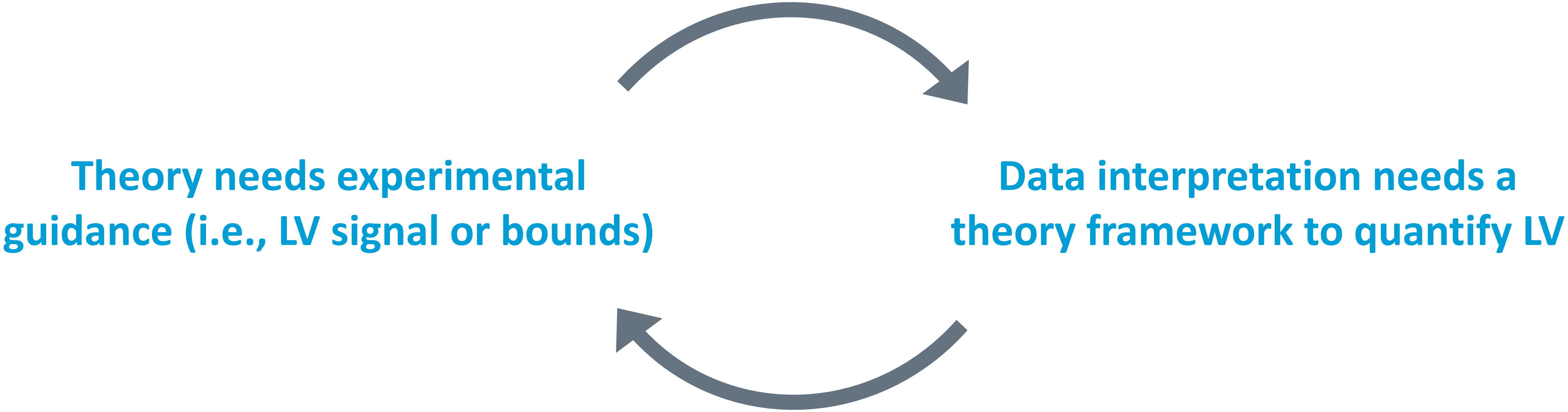


Critical Energy bin ($\kappa > 0$)

[Duenkel, MN, Risse; publ. in preparation]



Testing LV: Interplay Theory ↔ Experiment



Theory needs experimental guidance (i.e., LV signal or bounds)

Data interpretation needs a theory framework to quantify LV