Universität Siegen

HEP Experimental High Energy Physics

CPPS Center for Particle Physics Siegen

Violations of Lorentz Invariance and Extensive Air Showers

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CPPS Retreat

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Photo by S. Saffi (Univ. of Adelaide)

LV in the Photon Sector in the Standard Model Extension

[Colladay, Kostelecký; Phys. Rev. D 58 (1998) 116002]

- Look at the **Lagrangian density:**

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

  - 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 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]
  - 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

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

- 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**

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

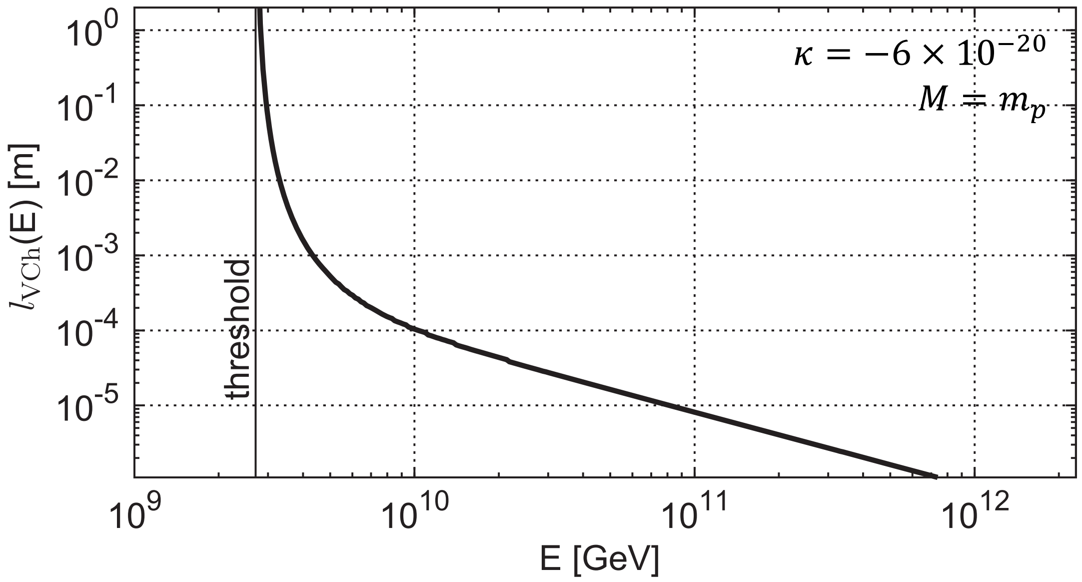
  - **Note:** c refers here to the maximum attainable velocity of a massive Dirac fermion (but still $c = 1$ in natural units)
- For **non-zero values** of κ, certain processes **forbidden** in the conventional, Lorentz-invariant theory ($\kappa = 0$) become **allowed** [Jacobson, Liberati, Mattingly; 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), $\tilde{\gamma} \rightarrow e^{-} + e^{+}$

Vacuum Cherenkov Radiation ($\kappa > 0$)

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

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

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



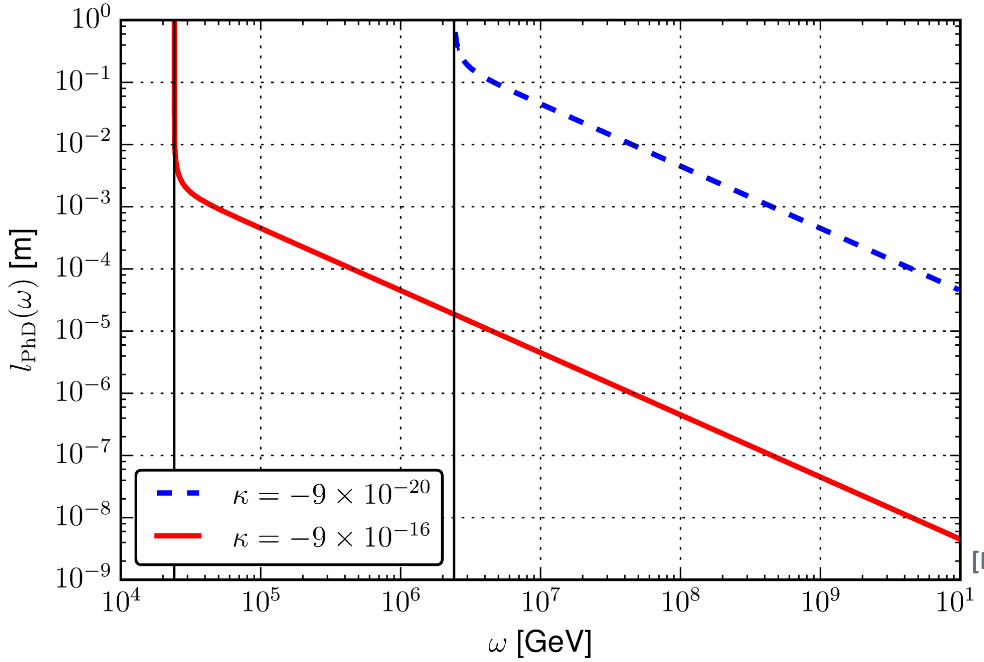
[Díaz, Klinkhamer; Phys. Rev. D 92 (2015) 025007; mod.]

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**



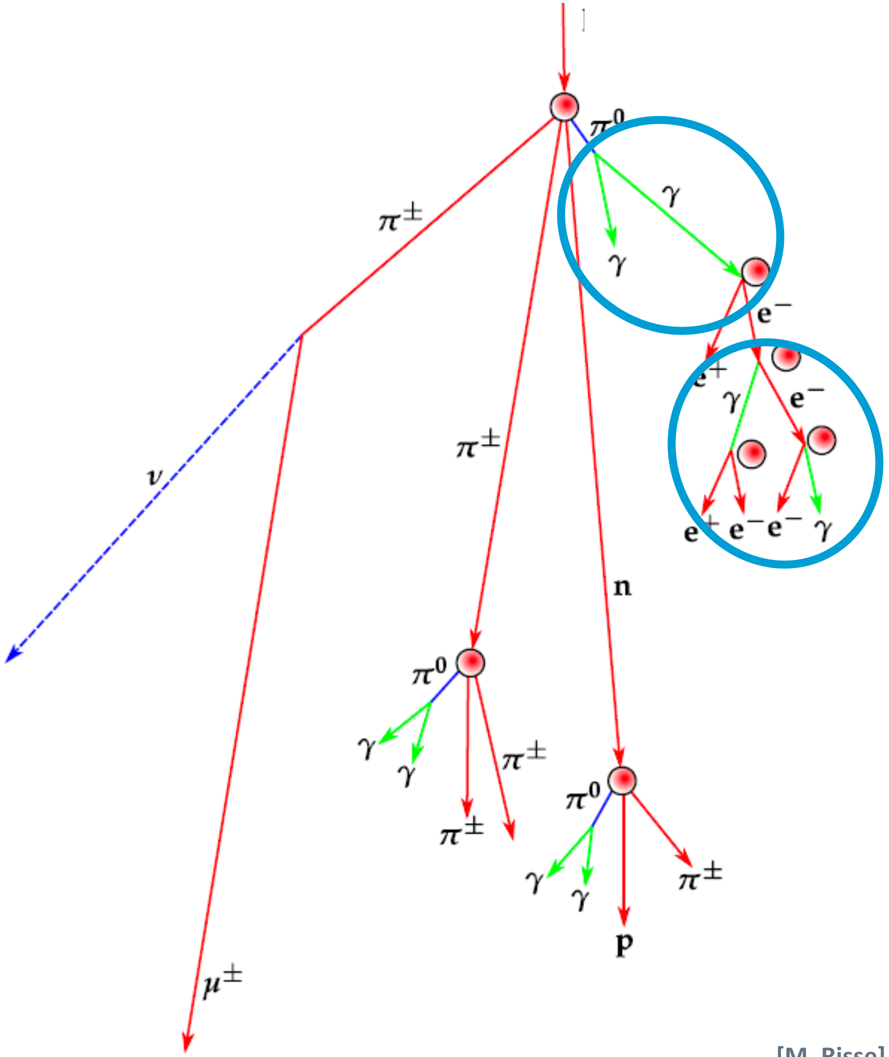
[Díaz, Klinkhamer, Risse; Phys. Rev. D 94 (2016) 085025]

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 $\rightarrow$ $100\,\mathrm{PeV}$ photons

- How large is the **impact of LV on $\langle X_{\mathrm{max}} \rangle$**?
  - **Simulation study** using the Monte Carlo code CONEX, extended to include LV processes

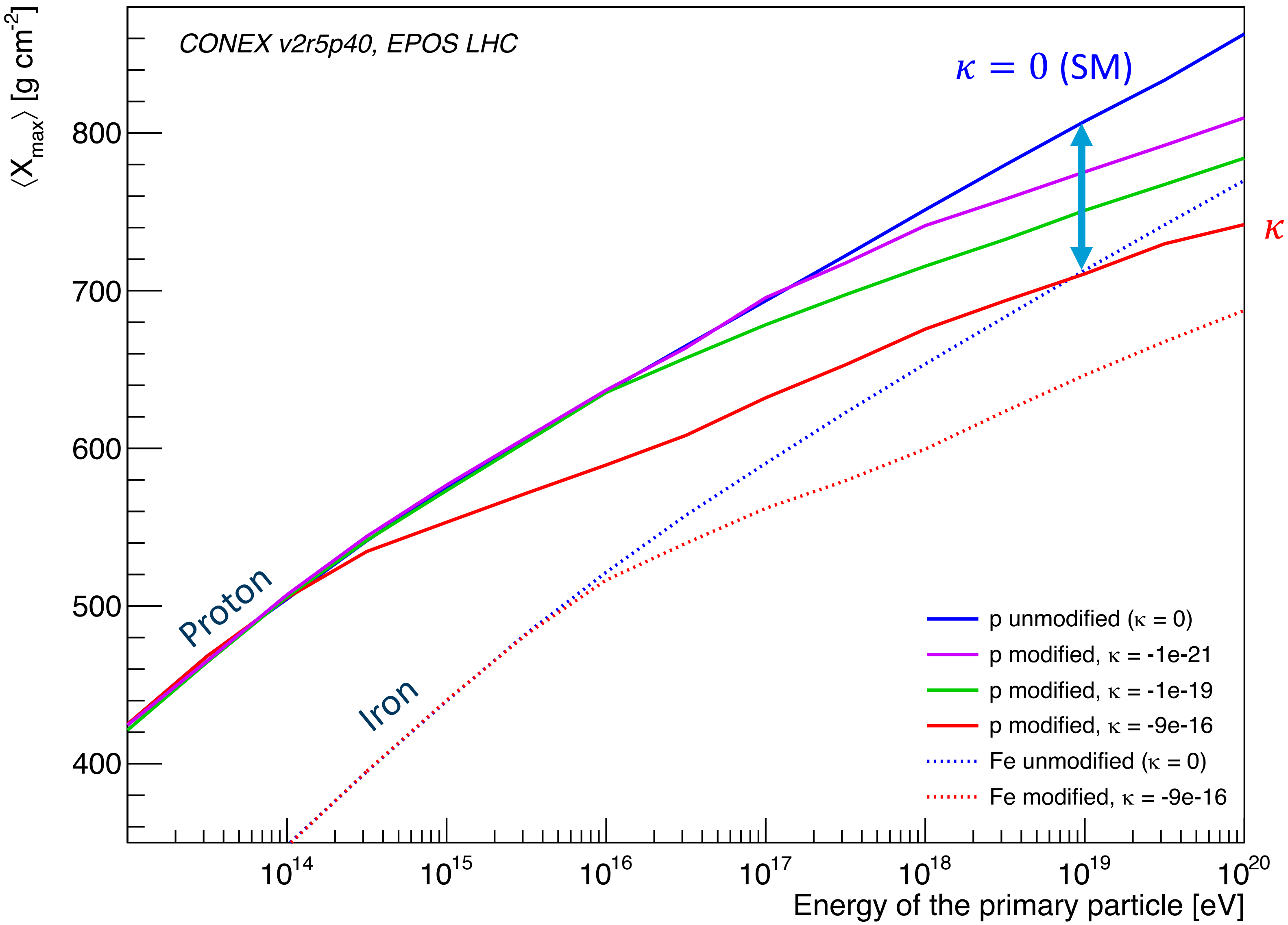
[Bergmann et al.; Astropart. Phys. 26 (2007) 420]
[Pierog et al.; Nucl. Phys. B, Proc. Suppl. 151 (2006) 159]
[Klinkhamer, MN, Risse; Phys. Rev. D 96 (2017) 116011]



[M. Risse]

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

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

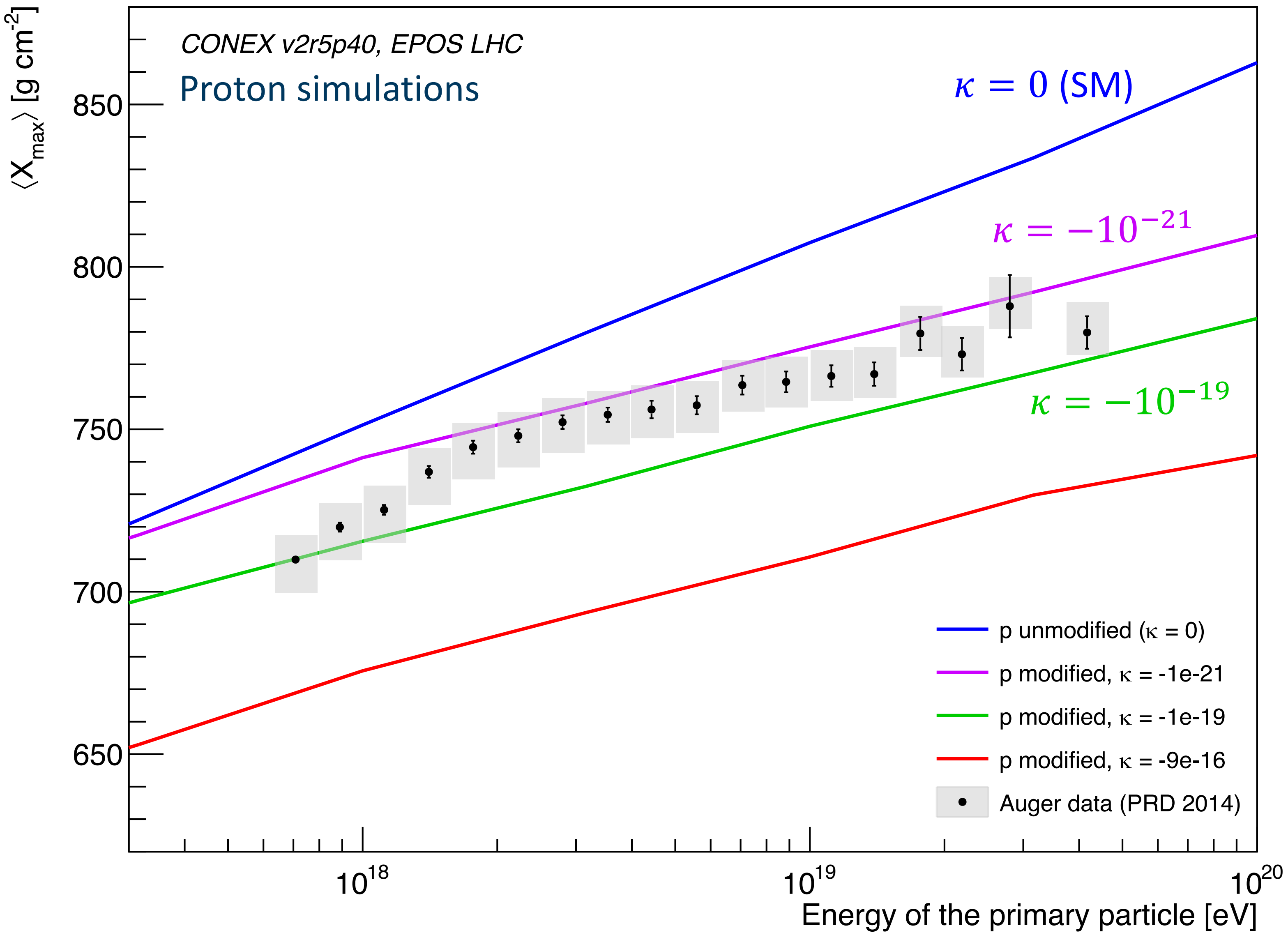


$\langle X_{\max} \rangle$ reduced by $\sim 100 \frac{g}{cm^2}$ at 10^{19} eV:

Large effect!

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

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



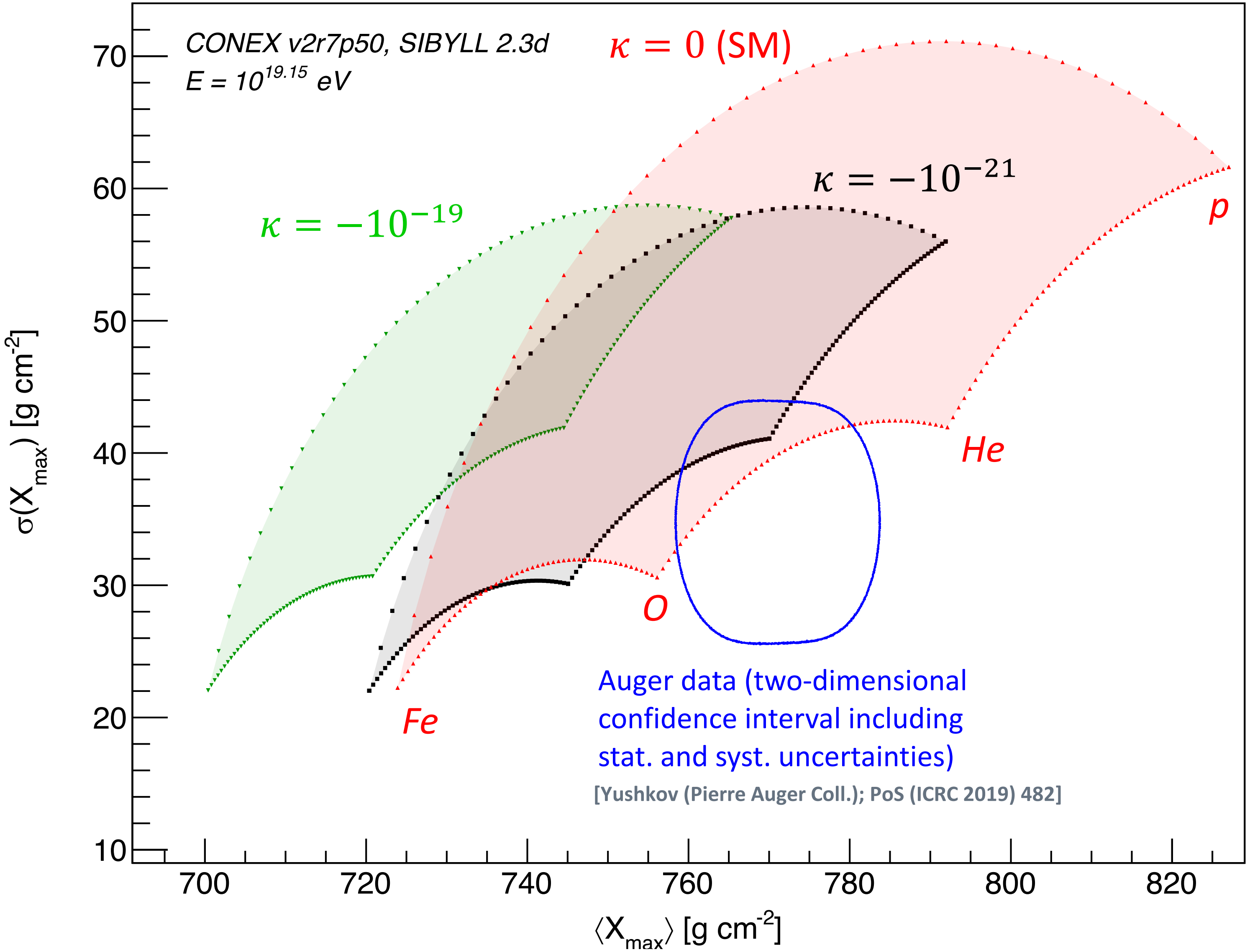
If **deeper showers** are observed than expected for a given κ for primary protons: exclude this κ

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]



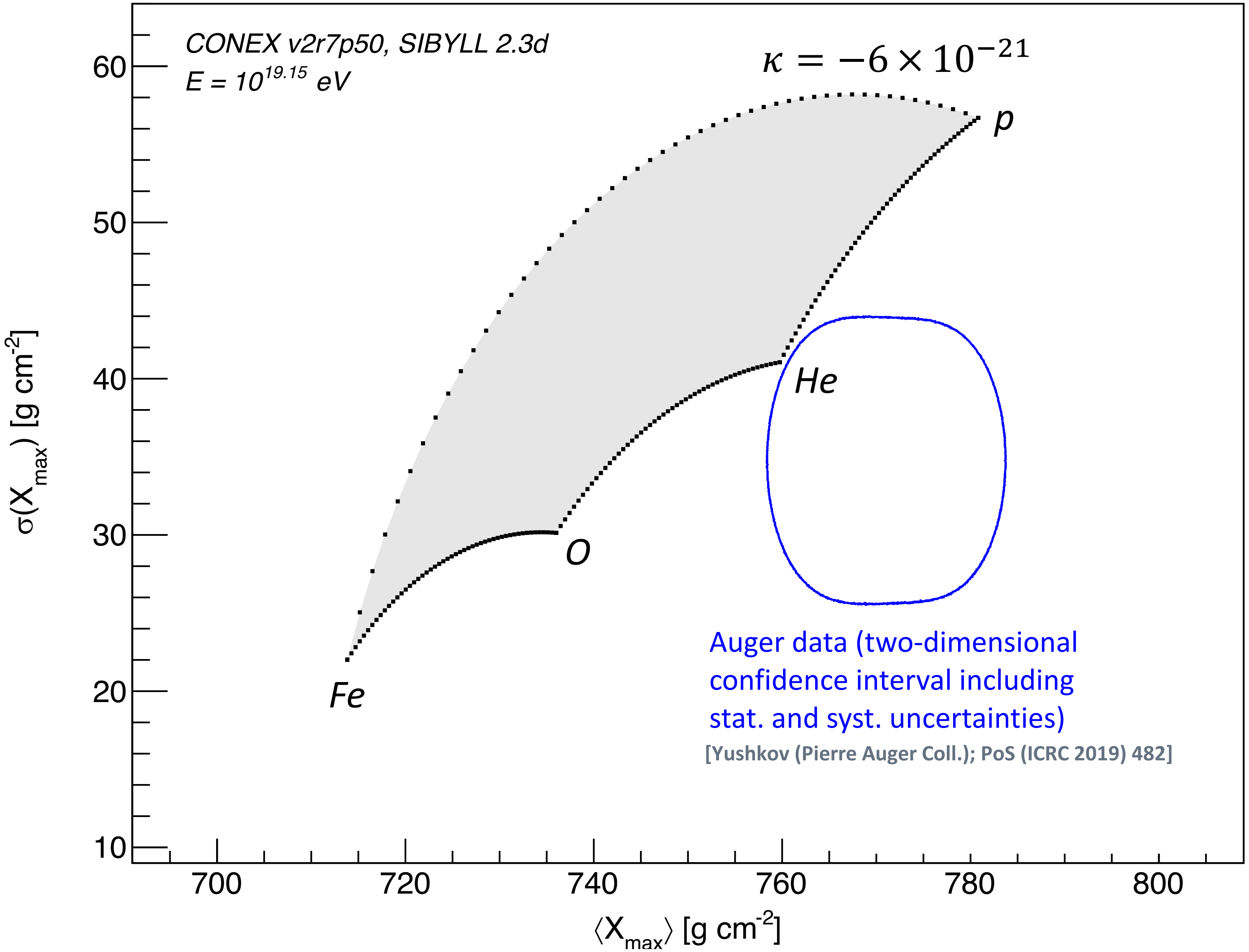
Simulate **mixtures** of protons and heavier nuclei (He, O, Fe)

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]



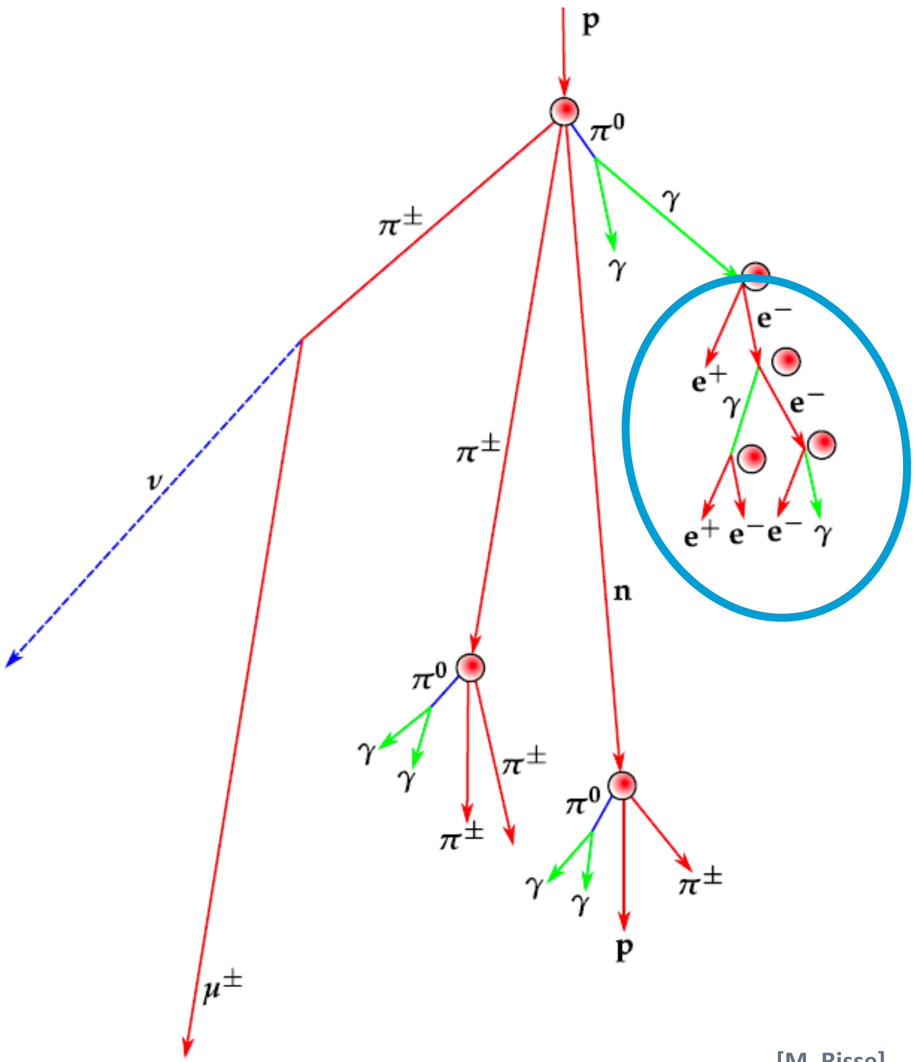
Full analysis yields a bound $\boldsymbol{\kappa > -6 \times 10^{-21}}$ (98 % C.L.)

More **general takeaway**: shower profiles at ultra-high energies are quite "normal"

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 $X_{\max}$!

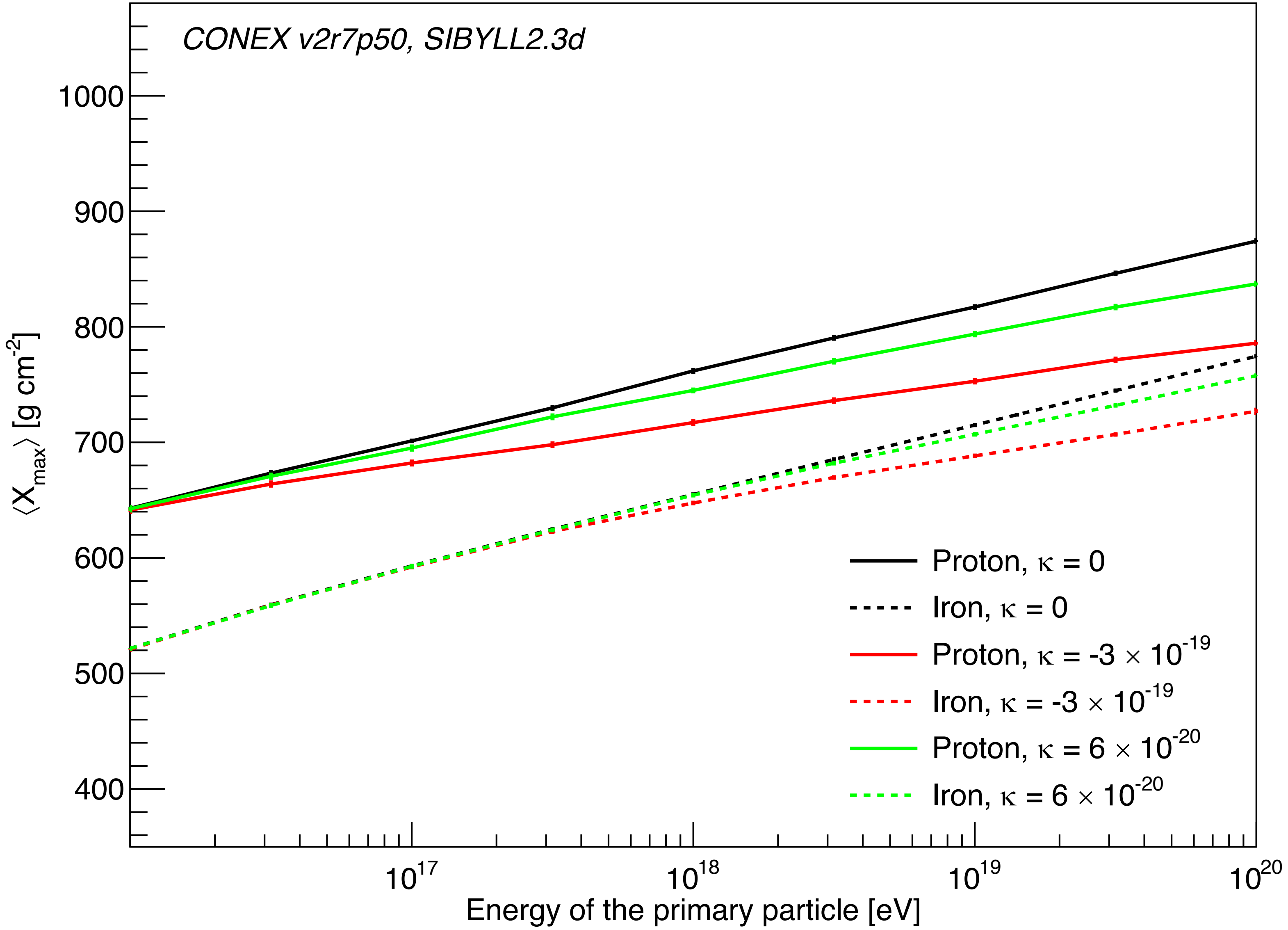
- Perform again a **simulation study** with CONEX



[M. Risse]

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

[Duenkel, MN, Risse; Proc. UHECR 2022]



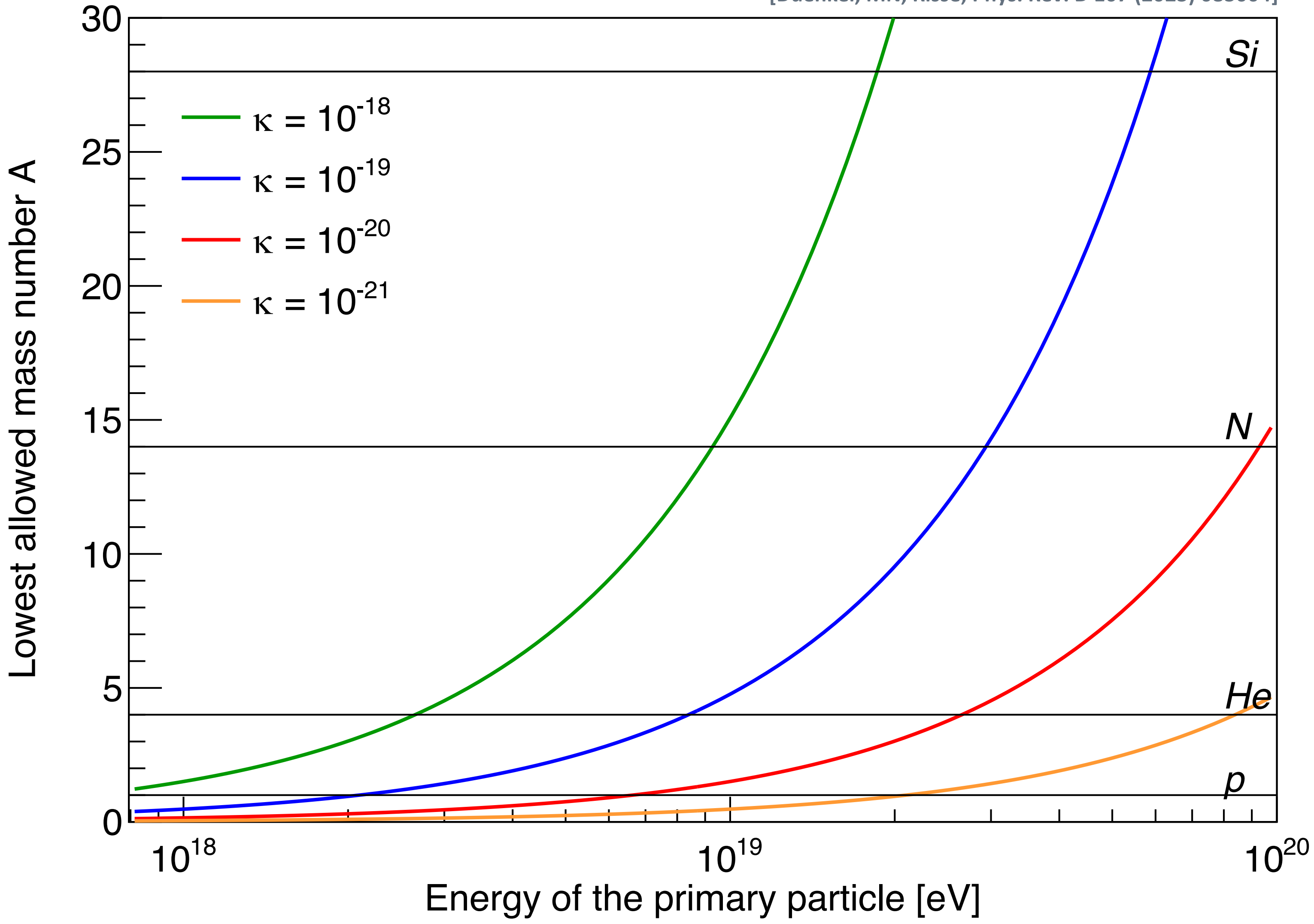
Smaller effect compared to the case of photon decay ($\kappa < 0$)

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; Phys. Rev. D 107 (2023) 083004]



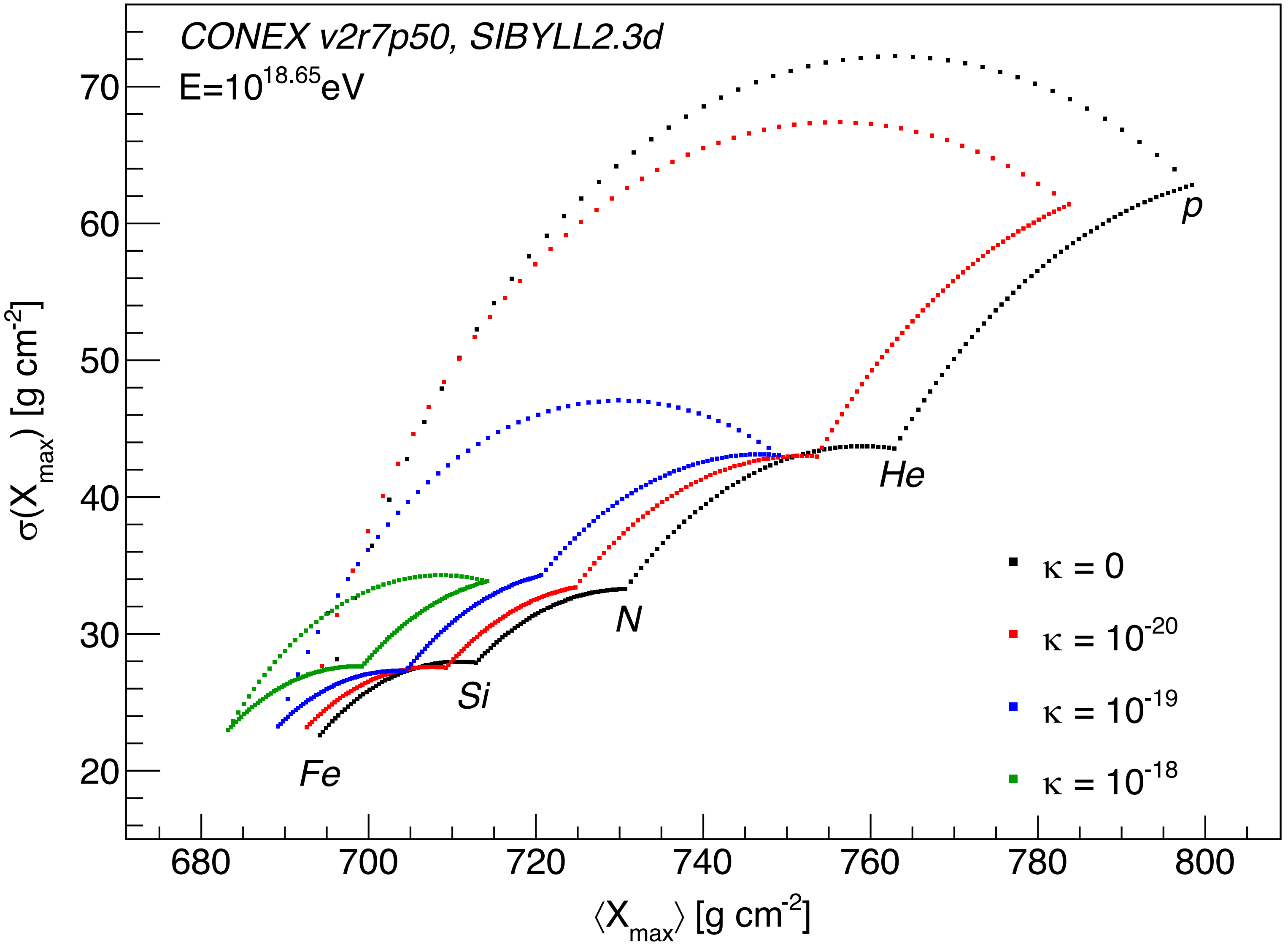
Need to take into account that the **primary particle** also emits vacuum Cherenkov radiation to be **consistent**:

Not all primaries can actually reach Earth

→ composition constraint

Back to the Umbrella Plots

[Duenkel, MN, Risse; Phys. Rev. D 107 (2023) 083004]



Consequence:

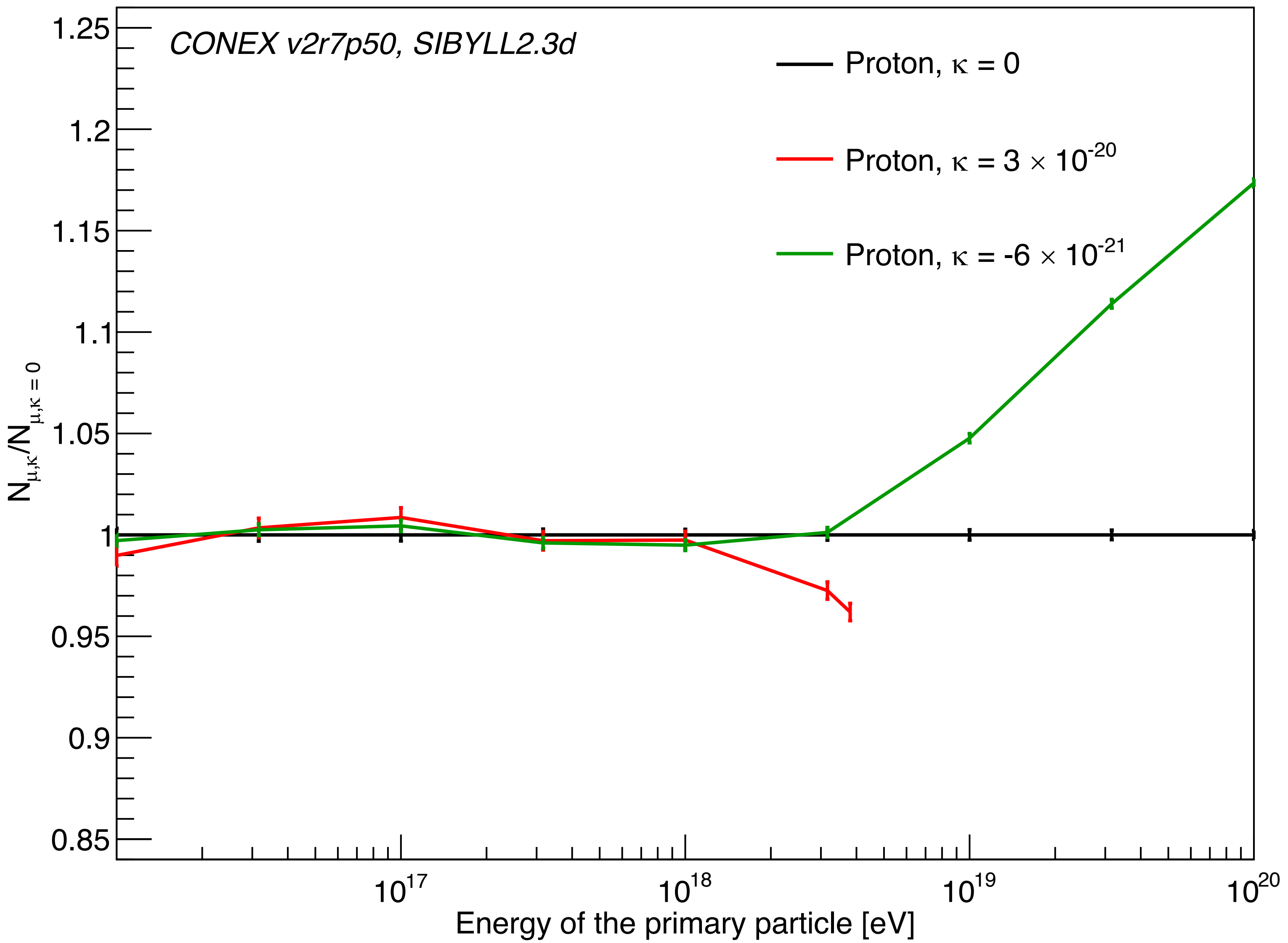
Umbrellas get smaller as more primaries drop out

Result after comparison with Auger data:

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

What about muons?

[Duenkel, MN, Risse; PoS (ICRC 2023) 217]



The number of muons at ground level N_μ **increases with energy for $\kappa < 0$ and decreases for $\kappa > 0$**

Correlation between $X_{\max}$ and N_μ can be an additional observable to look at