Vacuum Cherenkov radiation in UHE air showers: a way of probing Lorentz violation

Fabian Duenkel, Marcus Niechciol, Markus Risse
University of Siegen

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What is Lorentz Violation

- Lorentz symmetry is a fundamental pillar of the Standard Model of Particle Physics
- The Standard Model does not give a complete description of the universe
- Current approaches to establish a more comprehensive theory allow for deviations from exact Lorentz symmetry
- Consequences of LV can only be observed at the highest possible energies
- Ultra-high-energy cosmic rays and air showers can be used to test Lorentz symmetry

LV through EFT

- We work in the framework of the Standard Model Extensions (SME)
- Lorentz Violation (LV) in the photon sector is achieved by adding a single term which preserves CPT and gauge invariance to the standard QED Lagrangian:

[Colladay and Kostelecky, PRD 58:116002, 1998]

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

- Focusing on the specific case of isotropic nonbirefringent LV in the photon sector, k_F is controlled by a single parameter κ

Lorentz Violation (κ < 0)

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- Consequence of LV:
  modified photon phase velocity

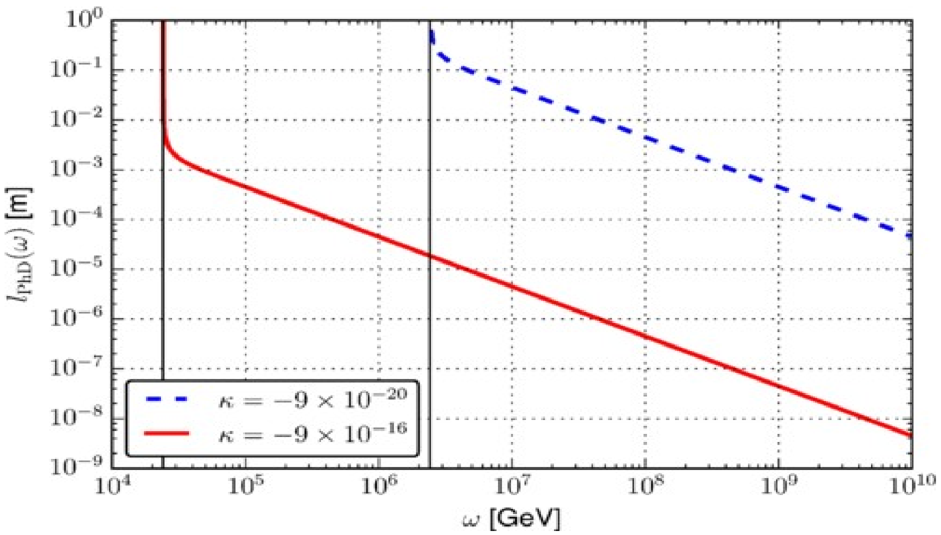
$$v_{ph} = \frac{\omega}{|\vec{k}|} = \sqrt{\frac{1-\kappa}{1+\kappa}}c$$

$$\kappa = \frac{c^2 - (v_{ph})^2}{c^2 + (v_{ph})^2} \approx 1 - \frac{v_{ph}}{c}$$

- Restricted to -1 < $\kappa \leq 1$
- Previously: Focus on negative κ (“fast” photon)
- Consequence: Photon decay $\tilde{\gamma} \to e^- + e^+$

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

- Photon decay length drops to practically zero right above energy threshold



[Diaz, Klinkhamer, Risse, PRD 94:085025, 2016]

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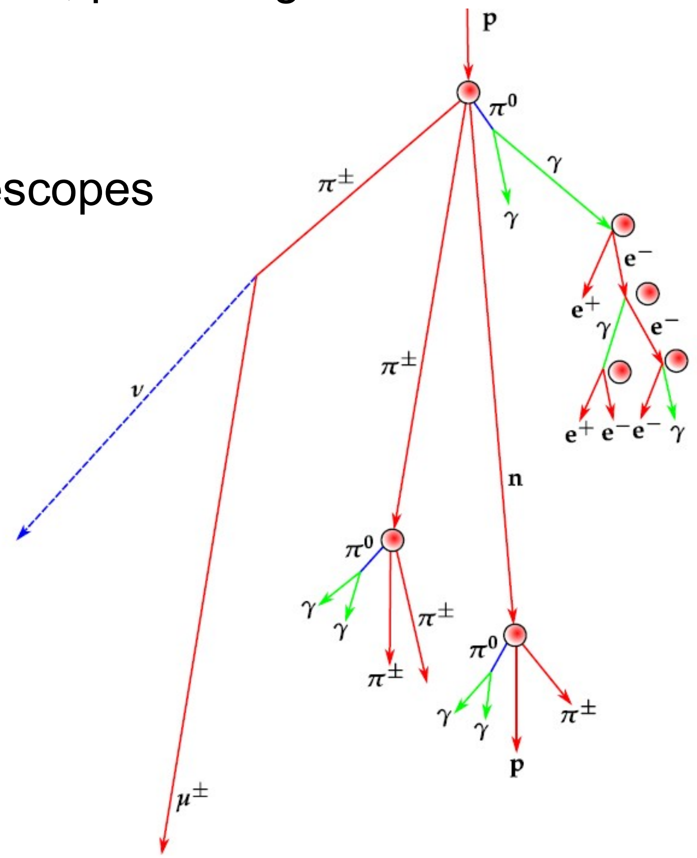
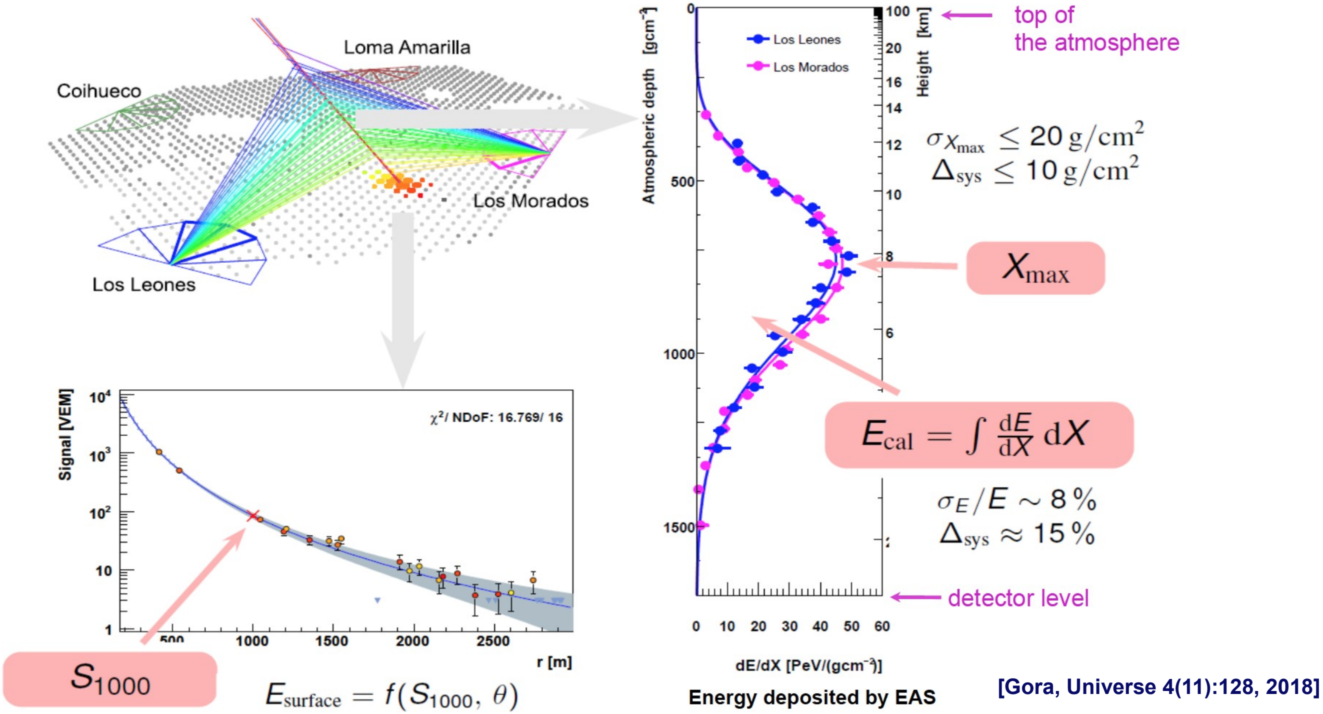
- Cosmic rays interact with the earth's atmosphere, producing a cascade of secondary particles
- Secondary particles can be measured using ground-based detectors and fluorescence telescopes
  - Reconstruction of primary parameters, e.g. direction, energy, particle type



Pierre Auger Observatory

- Pierre Auger Observatory uses a combination of surface detector stations and fluorescence telescopes
- We will use X_{max} measurements from the Pierre Auger Observatory
  - Good precision due to FD measurements



[Gora, Universe 4(11):128, 2018]

Modified Air Shower Simulation

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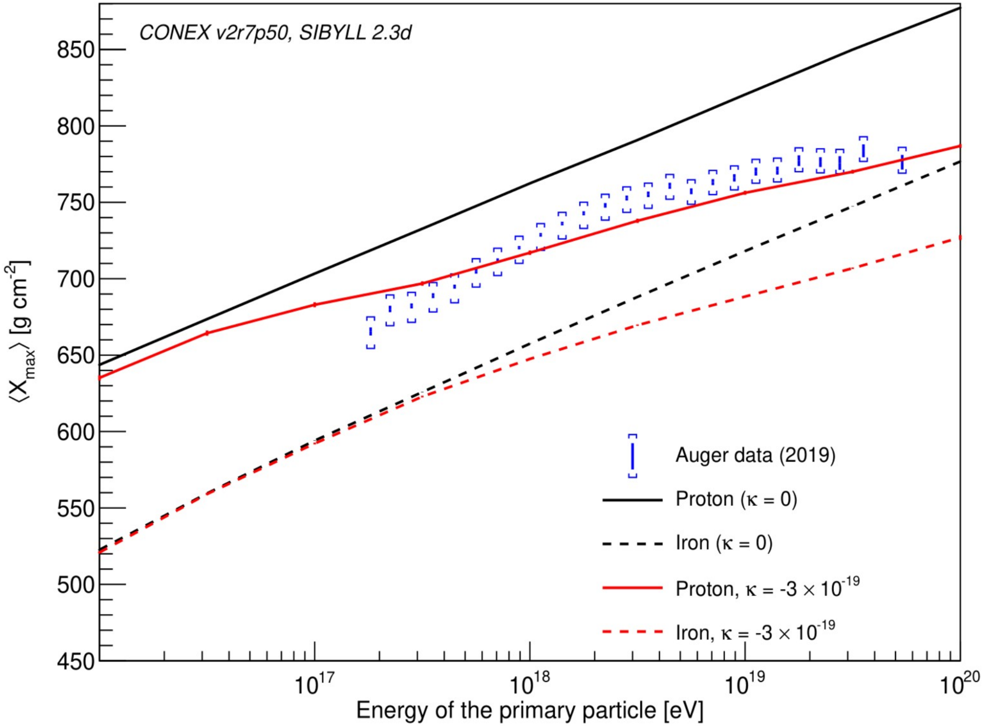
- Simulation of the modified air showers are generally done using MC simulations
- We are using the hybrid simulation code CONEX v2r7p50 [Bergmann et al., Astropart. Phys.26, 420 ,2007]
  - CONEX is a combination of a MC simulation of high-energy interactions and fast numerical solutions of the cascade equations for secondary particles below a given energy threshold
  - The MC part of the simulation code can easily be modified to include additional LV processes

Lorentz Violation (κ < 0)

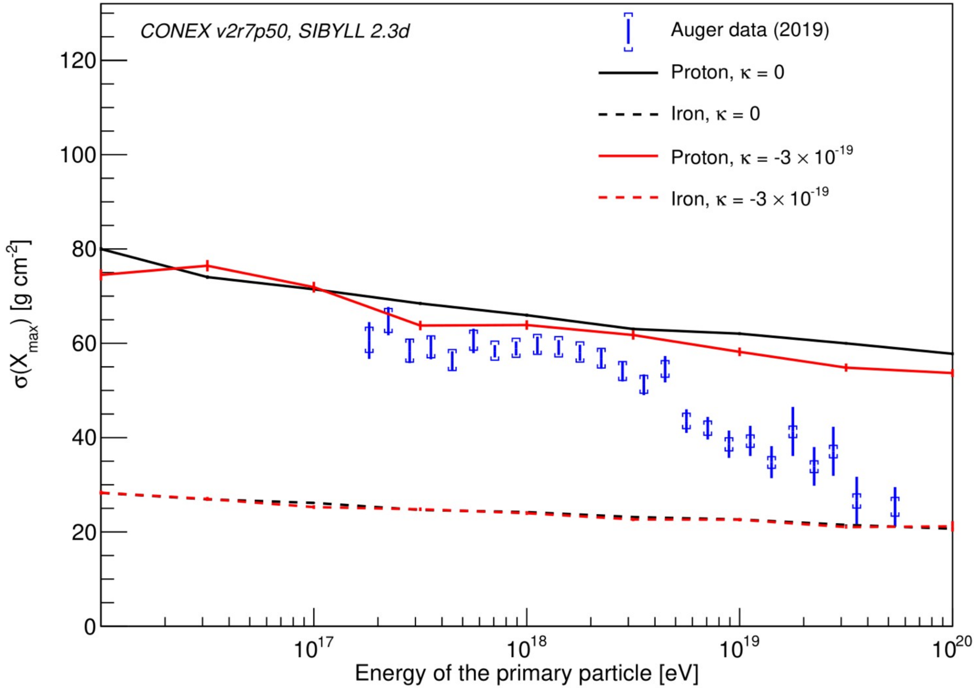
- Implementing these modifications into shower simulations reveals significant change in $\langle X_{max} \rangle$
- Comparison with shower data has been used to set stringent bound on κ
  - Most conservative approach: Assume pure proton composition
  - Limit of $\kappa = -3 \times 10^{-19}$



[Duenkel, Niechciol, Risse, PRD 104:015010, 2021]

Improving the bounds on LV

- Use $\sigma(X_{max})$ as a second parameter to increase sensitivity
  - $\sigma(X_{max})$ has only minor dependence on κ
  - Pure-proton composition does not match all Auger data in any simulation with or without LV



[Duenkel, Niechciol, Risse, PRD 104:015010, 2021]

Improving the bounds on LV

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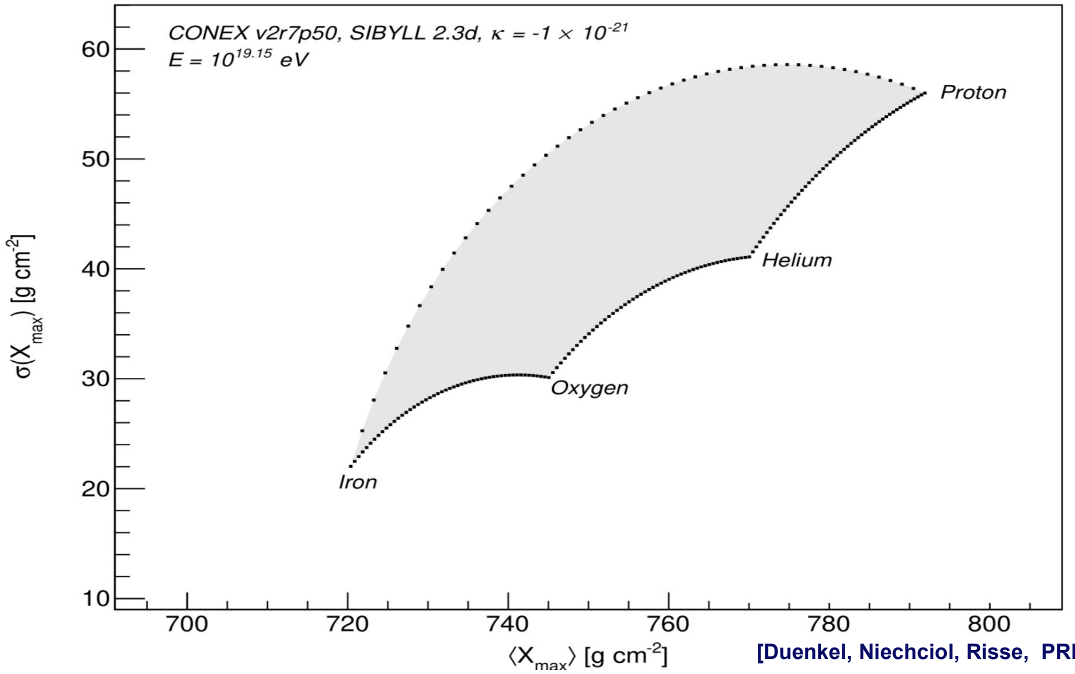
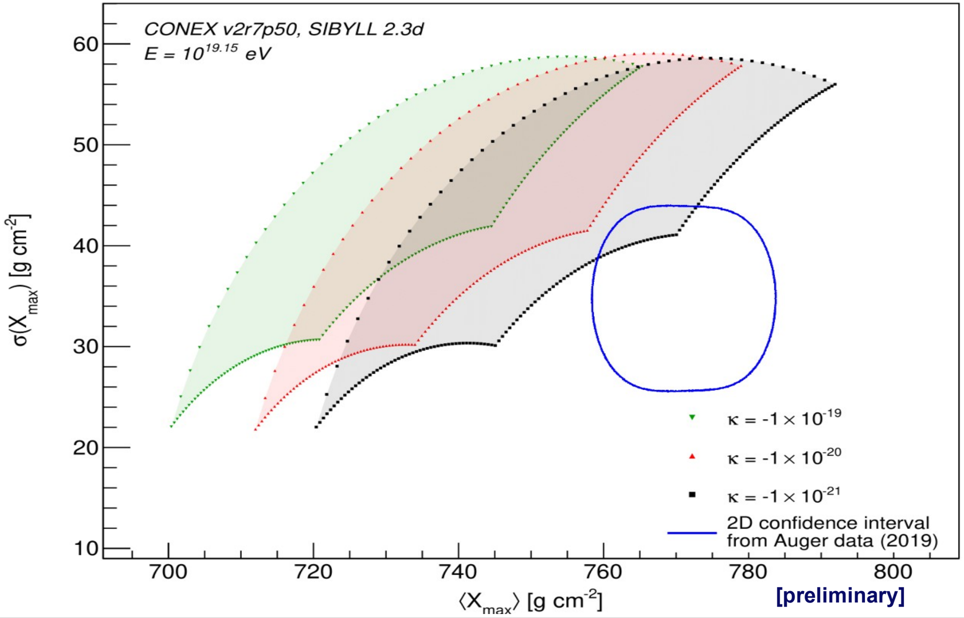
- Extend the analysis: allow for combinations of four primary particle types: protons, helium, oxygen and iron
- A range of possible $\langle X_{max} \rangle$ and $\sigma(X_{max})$ can be established for every κ and particle energy



[Duenkel, Niechciol, Risse, PRD 104:015010, 2021]

Improving the bounds on LV

- Compare showers simulated with different κ to confidence interval given by X_{max} measurements from the Pierre Auger Observatory [PoS(ICRC2019)482]
- κ is “rejected” if there is no overlap between the simulated possible combinations and Auger data for the entire energy spectrum
- Highest excluded value:
  $\kappa = -6 \times 10^{-21}$ (98 % C.L.)



[preliminary]

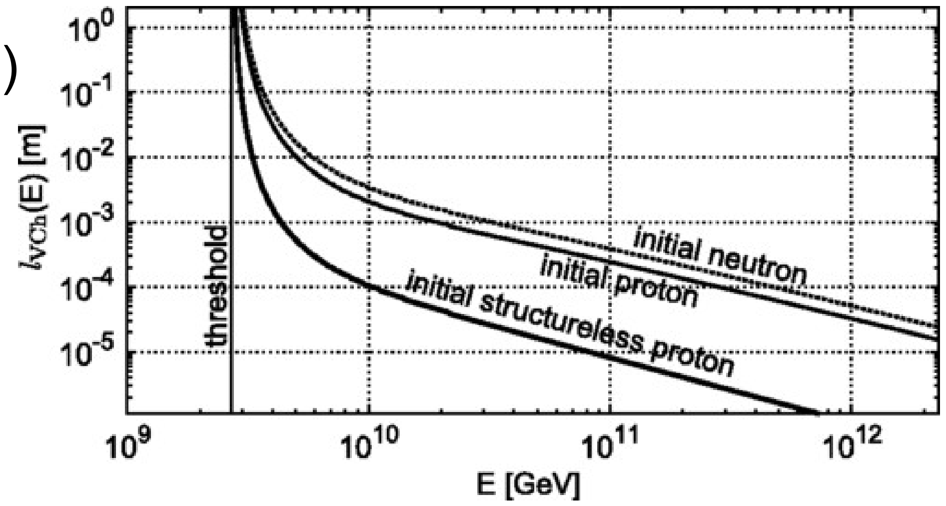
Lorentz Violation ($\kappa > 0$)

- Now: Focus on positive κ (“slow” photon)
- Consequence: Vacuum Cherenkov radiation

$$e^{\pm} \to e^{\pm} + \gamma$$

$$E_e^{thresh}(\kappa) = m \cdot \sqrt{\frac{1+\kappa}{2 \cdot \kappa}}$$

[Kaufhold, Klinkhamer, PRD 76:025024, 2007]

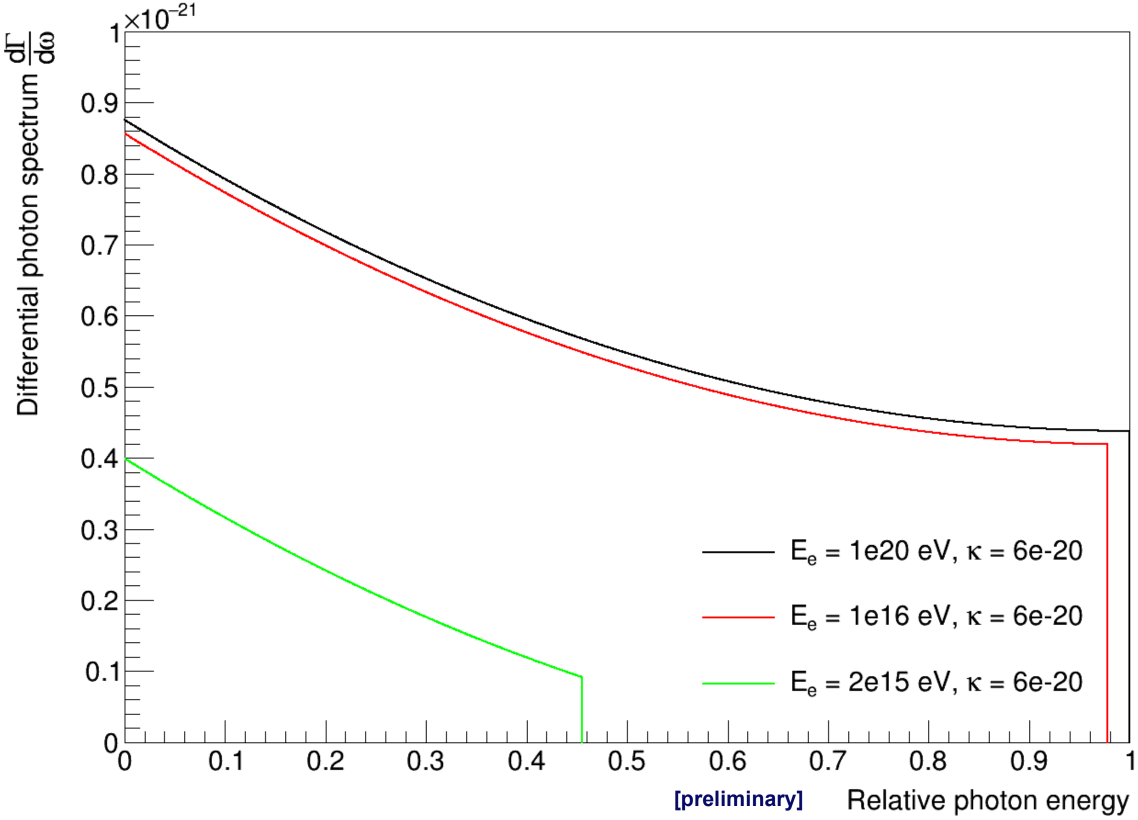


[Diaz, Klinkhamer, PRD 92:025007, 2015]

- Cherenkov radiation length drops to practically zero right above the energy threshold
- Current bound set by mere existence of UHECR with energies > 100 EeV: $\kappa < 6 \times 10^{-20}$

[Klinkhamer, Schreck PRD 78:085026, 2008] [Klinkhamer, Risse PRD 77:016002, 2008]

- Photon spectrum radiated by electrons depends on electron energy
- Radiated photons can inherit a significant share of the electron energy
- Differential photon spectrum shape changes only on electron Energies E_e near threshold energy ($E_{thresh} = 1.475 \times 10^{15}$ eV)



Changes in the shower development

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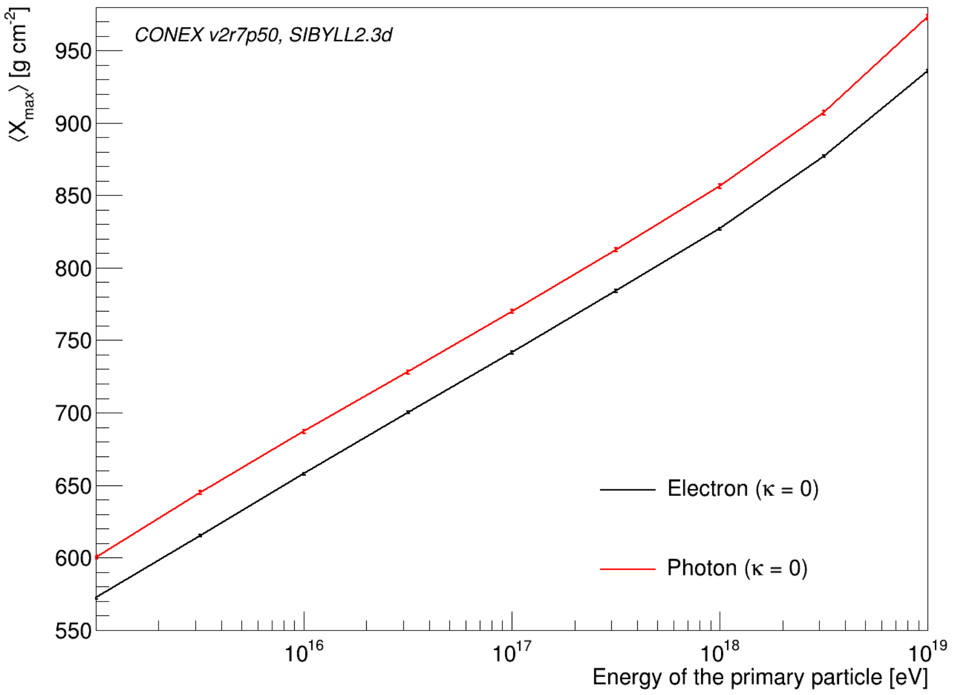
- Electrons above E_{thresh} effectively are replaced by multiple lower energy photons and an electron below E_{thresh}
  - Subshowers induced by lower energy particles are shorter
  - Subshowers induced by photons are longer than those induced by electrons of the same energy
  - Both effects are counteracting each other



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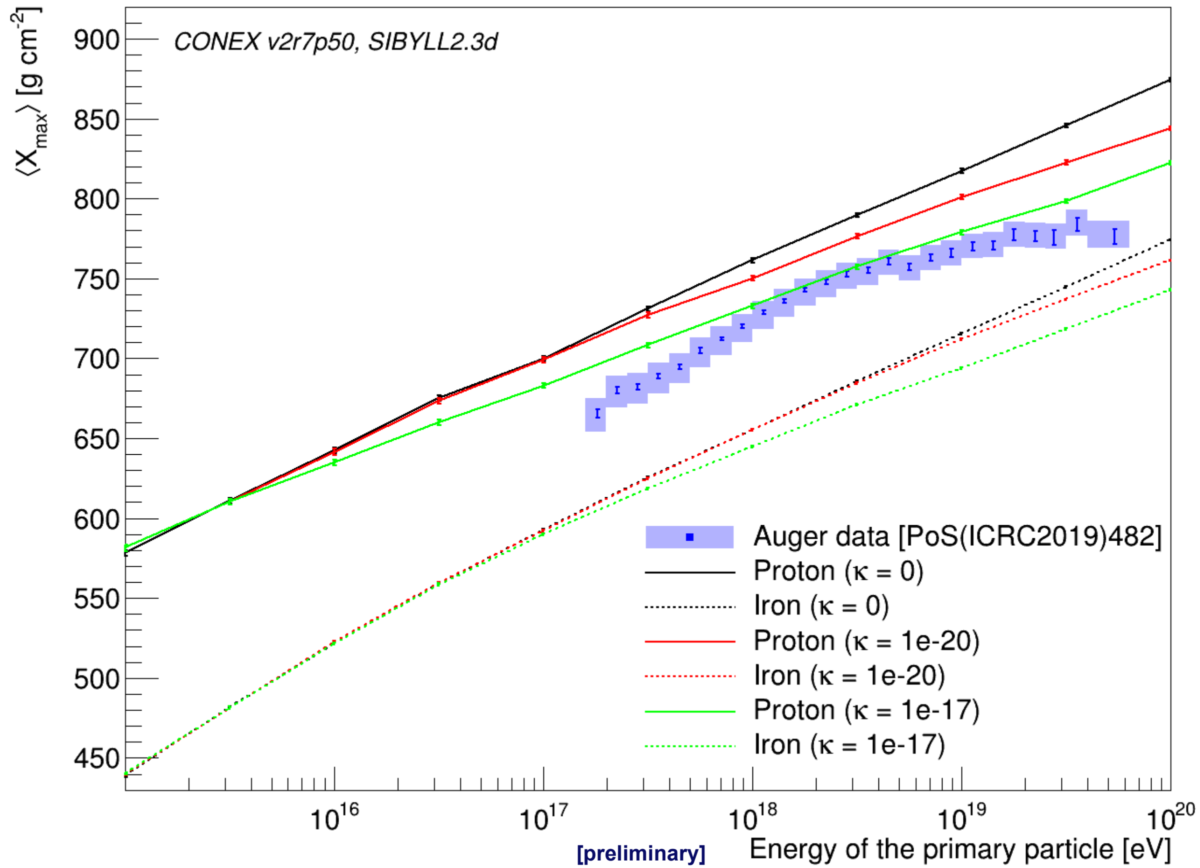
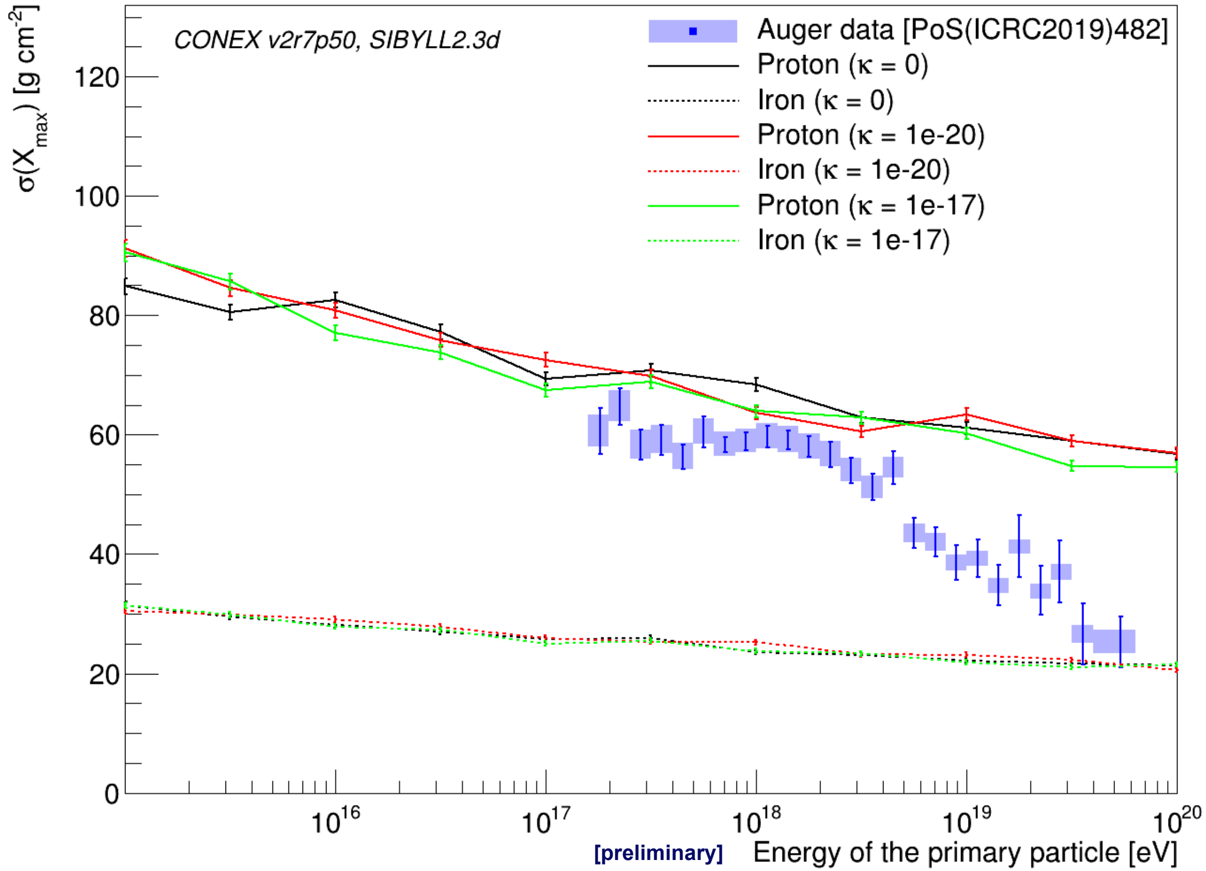
Changes in the shower development

- Lower values of $\langle X_{max} \rangle$ compared to the SM are obtained at higher energies, yielding differences in the order of 20 g/cm^2 for primary protons simulated with E = 10^{19} eV and $\kappa = 10^{-20}$
- Use this change to establish bounds on LV



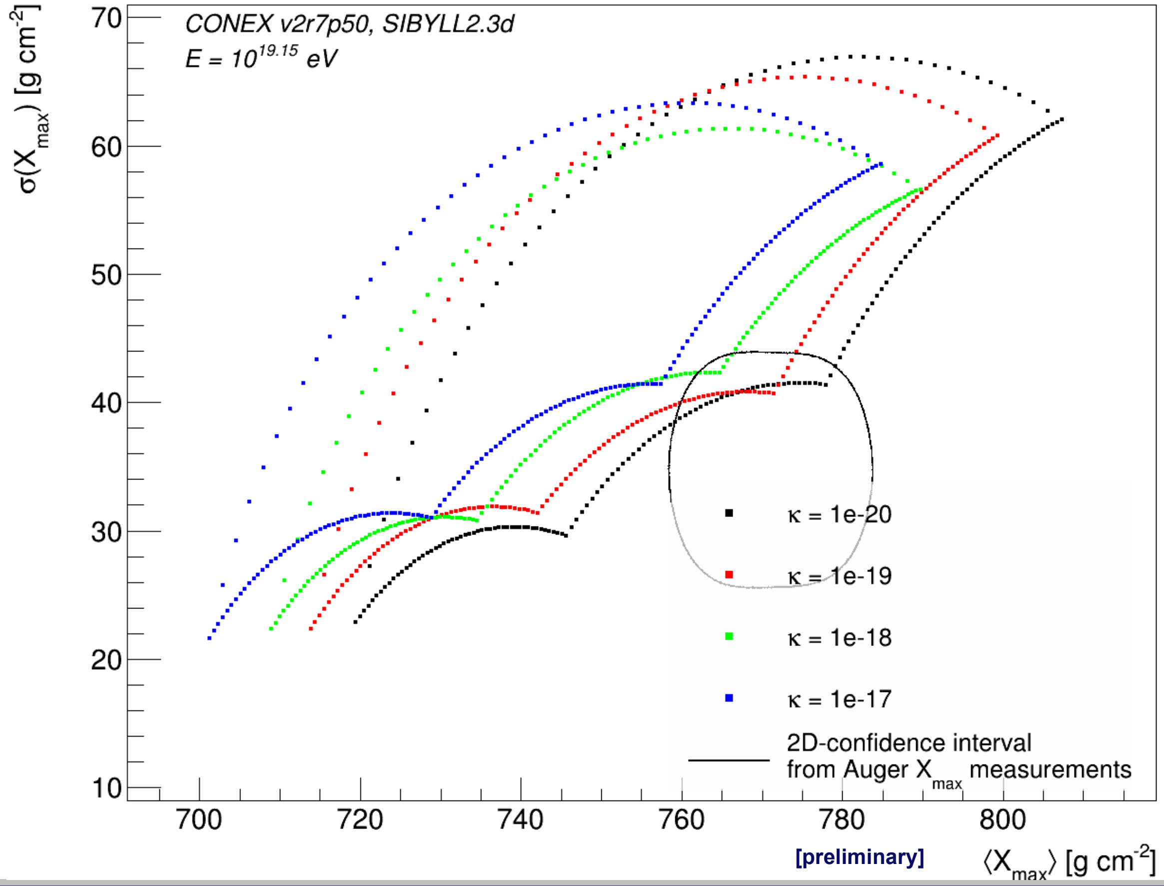
Changes in the shower development

- No significant change of $\sigma(X_{max})$ compared to the SM
- Exact composition of arriving CRs is unknown
- Use combination of both observables to constrain allowed CR-composition



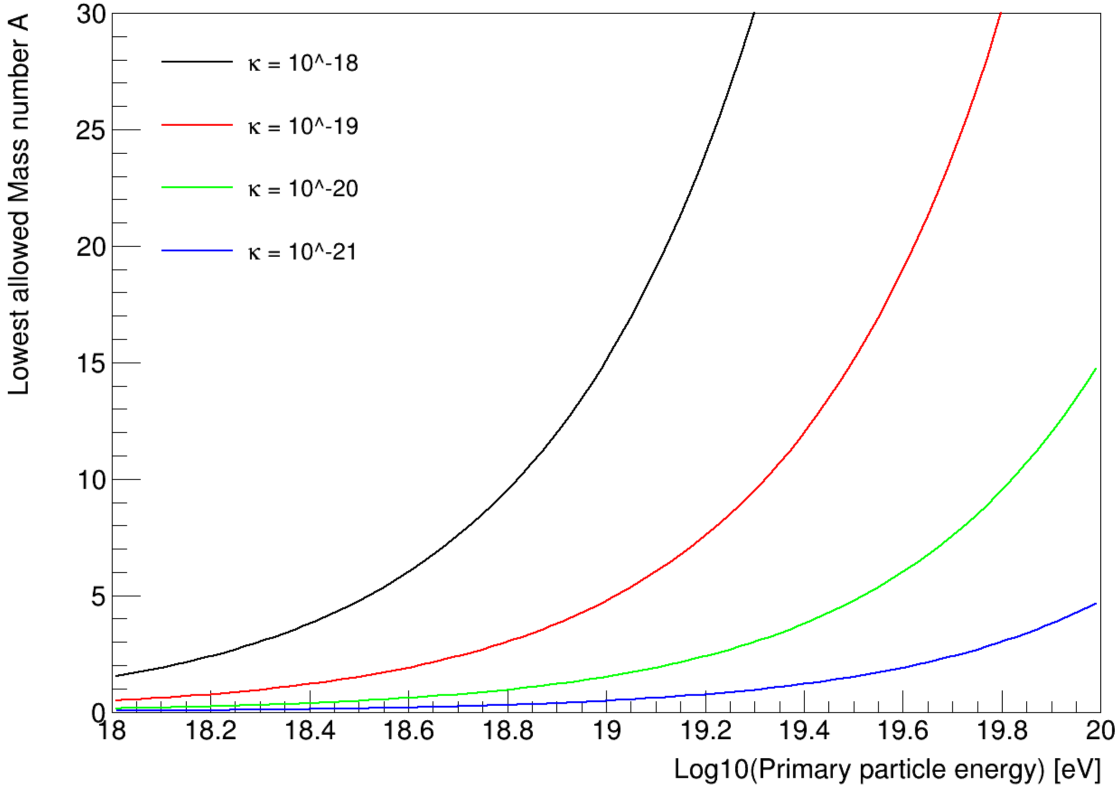
Comparison to air shower data

- Shower observables of simulated and measured showers can be compared
- No overlap between simulation and measurements excludes κ-value
- A priori restriction on primary energy due to κ further restricts possible compositions



Restriction on primary particle masses

- Arriving primary CR particles must have an energy below their respective threshold
- For higher energies, only higher mass primary particles are allowed



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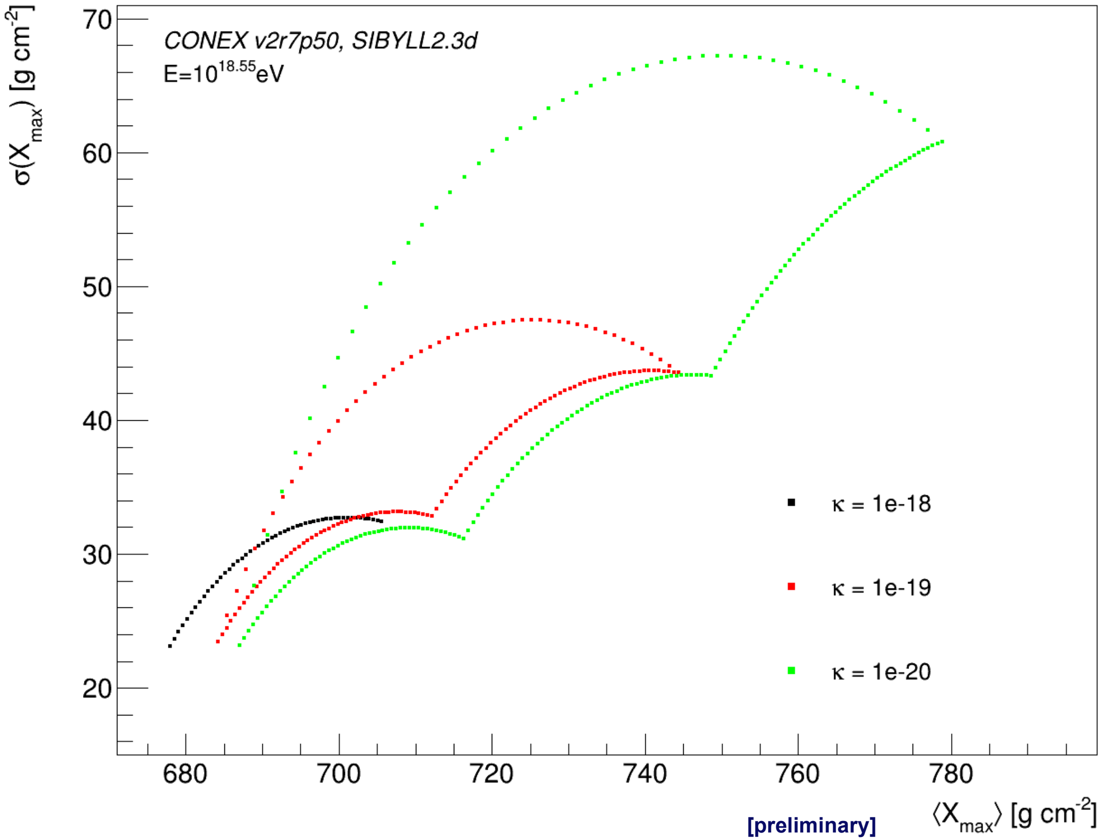
Comparison to air shower data

- Depending on κ, different particle compositions are possible



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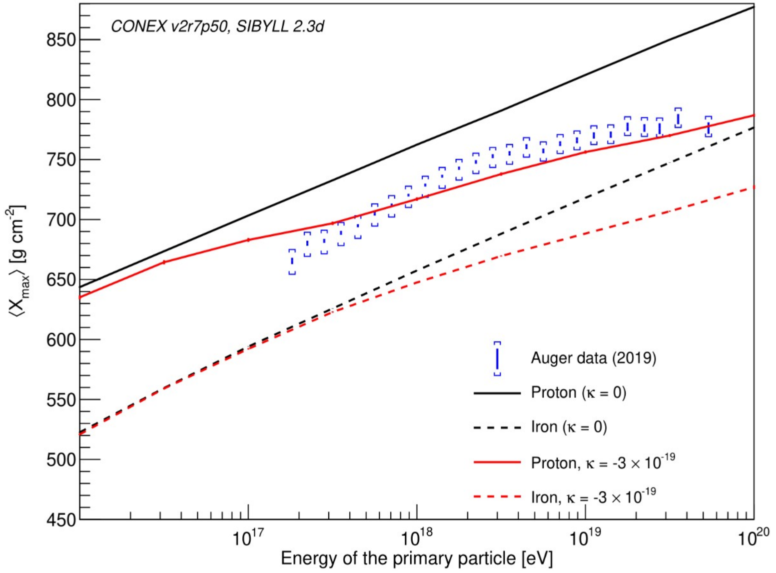
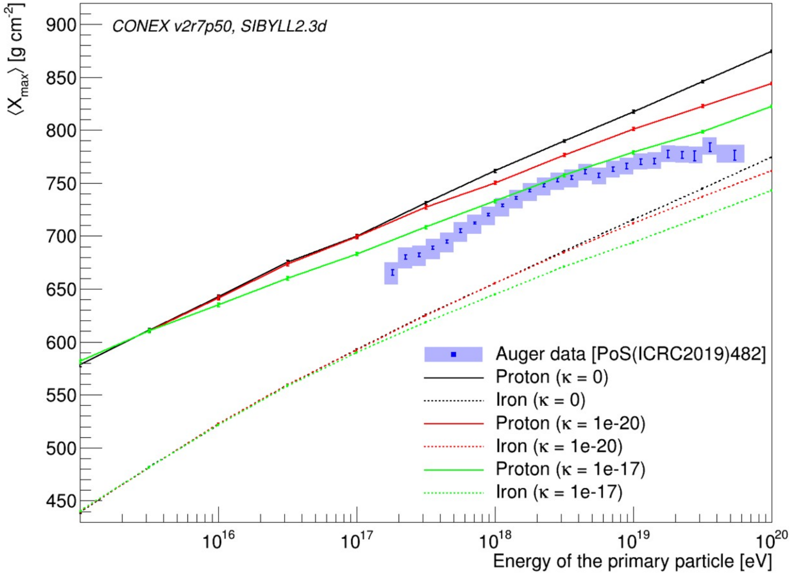
Summary

- Strong constraints on LV have already been determined using simulations of extensive air showers and comparing these simulations with air shower data for $\kappa < 0$
- Similar effects on $\langle X_{max} \rangle$ are observed for negative and positive κ
- Combination of parameters $\langle X_{max} \rangle$ and $\sigma(X_{\mathrm{max}})$ can also be used to set constraints in the case of $\kappa > 0$
- Consistent application of VC leads to additional restrictions of possible primary particle masses

- Implementing Lorentz violation into shower simulations reveals similar changes in $\langle X_{max} \rangle$ for positive and negative κ
- Comparison with shower data can be used in both cases to set stringent bounds on κ



[Duenkel, Niechciol, Risse, PRD 104:015010, 2021]



[preliminary]

Backup: LV Tensor components

- Fixed tensor k_F has 20 independent components
  - 10 produce birefringence (constrained through cosmological observations)
  - 8 lead to direction-dependent modifications of the photon propagation
  - 1 corresponds to an unobservable double trace
  - 1 corresponds to an isotropic modification of the photon propagation
- Focusing on the specific case of isotropic nonbirefringent LV in the photon sector, k_F is controlled by a single parameter κ

$$
\begin{aligned}
(k_F)_{\mu\nu\rho\sigma} &= \frac{1}{2}(\eta_{\mu\rho}\tilde{\kappa}_{\nu\sigma} - \eta_{\mu\sigma}\tilde{\kappa}_{\nu\rho} + \eta_{\nu\sigma}\tilde{\kappa}_{\mu\rho} - \eta_{\nu\rho}\tilde{\kappa}_{\mu\sigma}) \\
\kappa_{\mu\nu} &= \frac{\kappa}{2}[diag(3,1,1,1)]_{\mu\nu}
\end{aligned}
$$

[Klinkhamer and Schreck, Nucl. Phys. B848, 90, 2011]

Backup: Lorentz Violation ($\kappa < 0$)

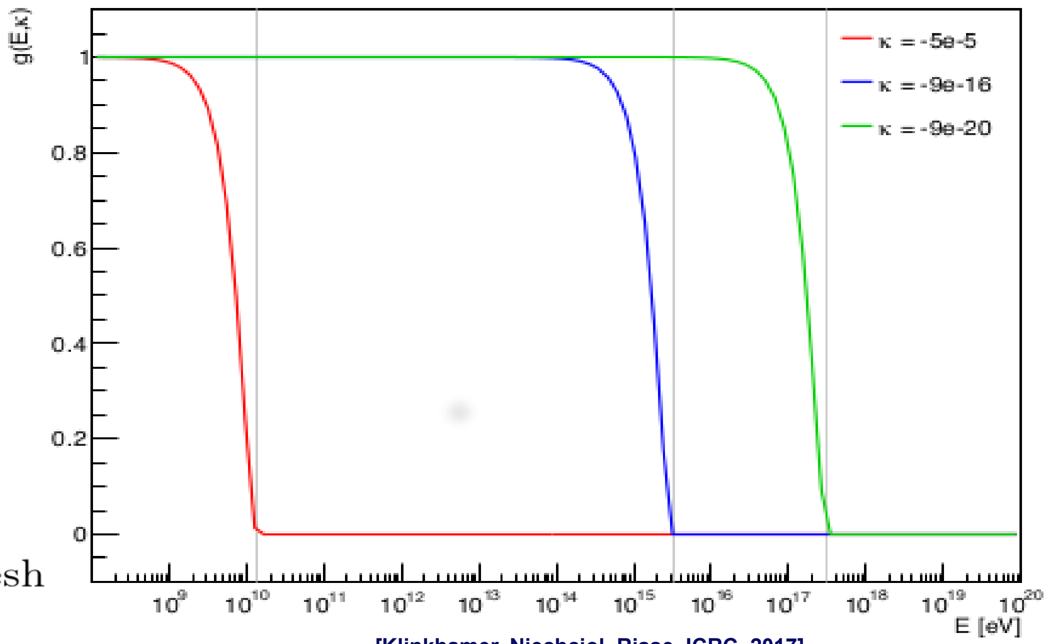
- Modified neutral pion decay

$$\pi^0 \rightarrow \tilde{\gamma} + \tilde{\gamma}$$

- Decay time is modified:

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

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



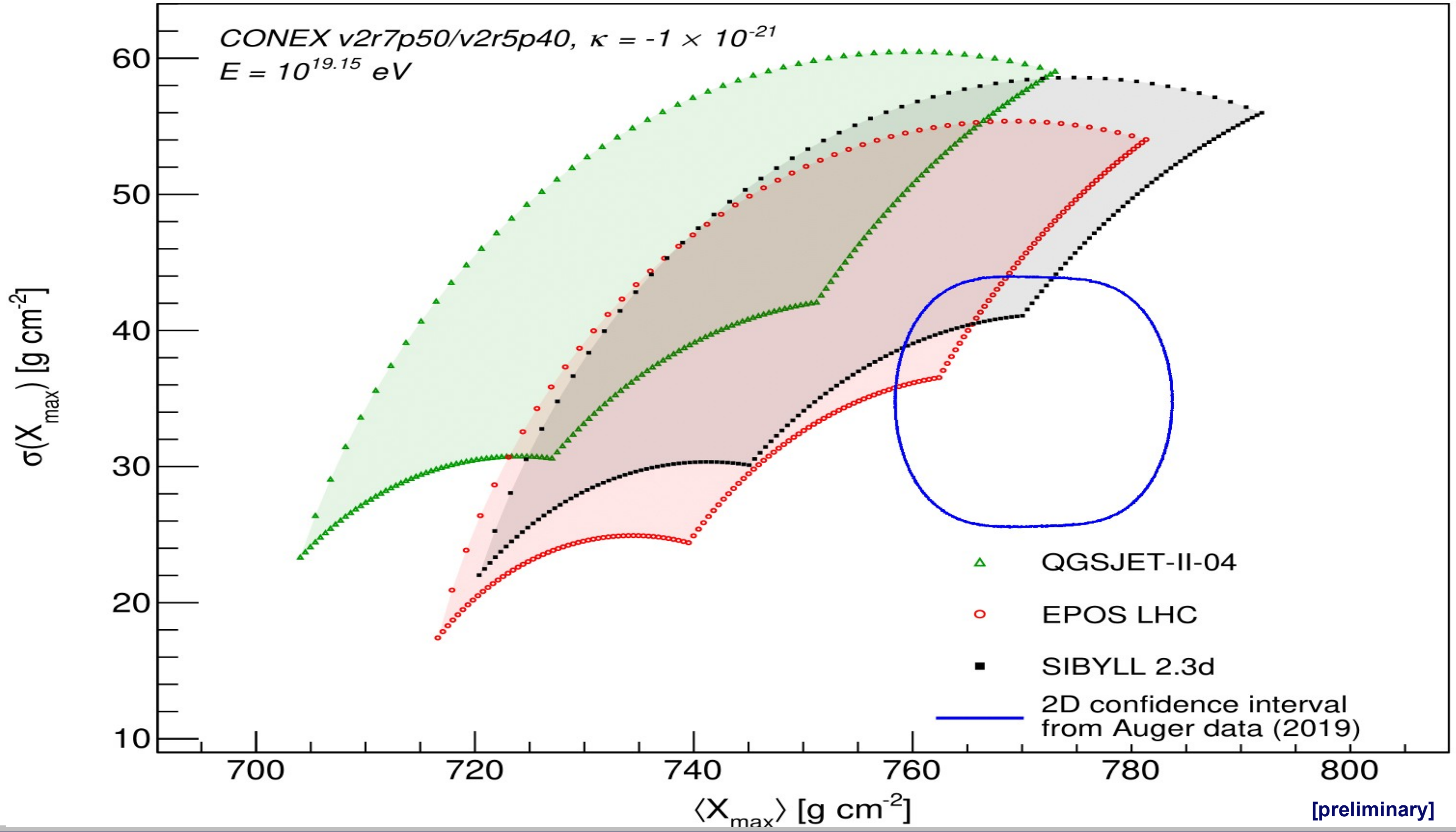
[Klinkhamer, Niechciol, Risse, ICRC, 2017]

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

[Klinkhamer, Mod. Phys. Lett. A Vol. 33, 1850104, 2018]

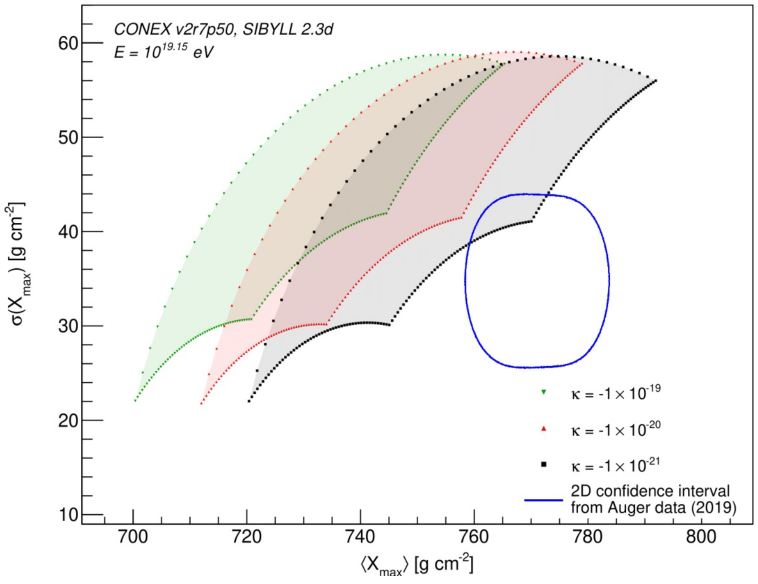
Backup: Different Models

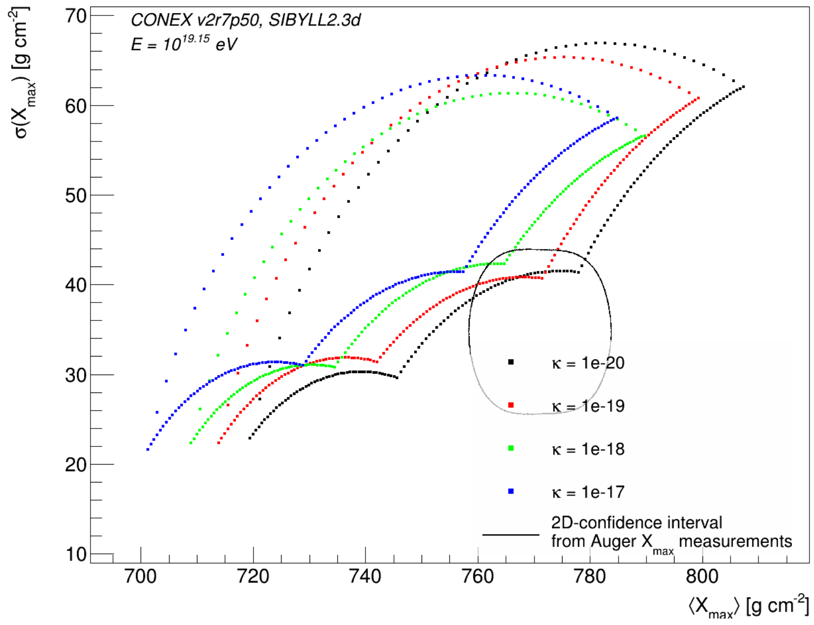
- Using SIBYLL 2.3d results in the most conservative limit.



[preliminary]

- Shower observables of simulated and measured showers can be compared
- No overlap between simulation and measurements excludes *κ*-value
- For *κ<0*: Improves bound from $\kappa = -3 \times 10^{-19}$ to $\kappa = -6 \times 10^{-21}$
- For *κ>0*: Work in progress





Backup: Improving the bounds on LV

- If for any energy there is no combination of simulated showers matching Auger data, the corresponding κ is excluded
- Highest excluded value: $\kappa = -6 \times 10^{-21}$ (98 % C.L.)