

## **Bounds on Lorentz violation from observations of extensive air showers**

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Deutsche **DEG** Forschungsgemeinschaft

### **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)





### 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 loopquantum 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) The contraction of the term which breaks a single term which breaks a single term which breaks are single term which breaks a single term which breaks a single term which breaks a single term wh LORENTZ INVARIANCE ENTRE CONTROLLER INVARIANCE SIE ∙n sector  $\frac{1}{\sqrt{2}}$ LV in the  $\vert$



• Focus on **LV in the photon sector** within the SME: is and  $\overline{N}$  in the shoton coston within t • Focus on LV in the photon sector within the SME:

$$
\mathcal{L}(x) = \frac{1}{4} F^{\mu\nu}(x) F_{\mu\nu}(x)
$$

$$
+ \bar{\Psi}(x) (\gamma^{\mu} [i\partial_{\mu} - eA_{\mu}(x)] - m) \psi(x)
$$

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

- First two terms in the Lagrangian density correspond to **Conventional QED the last term gives CONVENTION QED**  $L$  -corresponding violation in the photon sector  $\mathcal{L}$  the corresponding violation sector  $\mathcal{L}$ erms in the cagrangian density correspond to the cagrangian of charge of correspond  $\overline{C}$  and  $\overline{C}$  and time reflection (P), and time reversion (P), and time reversal time r formation corresponds to the combined operation of charge • First two terms in the Lagrangian density correspond to conventional QED processes considered in this article.
- **Last term** introduces a dimension-four operator that gives LV While preserving CPT and gauge invariance [Chadha & Nielsen 1983] Lorentz violation in the photon sector [the CPT trans-• Last term introduces a dimension-four operator that gives LV  $\overline{a}$  **rideal CC** [Chadha & Nielsen 1983]<br> $\overline{a}$  *f* **(Kostelecký** & Mewes 2002]
- **Notes:** the Minkowski metric  $\eta_{\mu\nu} = [\text{diag}(+1,-1,-1,-1)]_{\mu\nu}$ and natural units  $\hbar = c = 1$  are used; the Maxwell field strength tensor is defined as usual:  $\overline{F}_{\mu\nu} \equiv \partial_\mu A_\nu - \partial_\nu A_\mu.$  $\mu$  is the spacetime indices. In the s  $[diag(+1, -1, -1, -1)]_{uv}$

4



- The constant tensor ( $k_F$ )<sub>μνρσ</sub> has 19 independent, dimensionless **components**   $\frac{1}{\sqrt{2}}$  $\frac{1}{\sqrt{2}}$  sufficiently high energy, then decay into an electron-positron pair, **[Carroll, Field, & Jackiw 1990]** 
	- 10 components lead to birefringence in the photon sector: constrained to high precision (~10<sup>-32</sup>) by cosmological observations Ca)<br>ICa انتخاب العربية المراد <br>ICa المراد المر ponents lead to birefringence in the photon seq<br>ined to high organism ( , 10-<sup>32)</sup> by correctorizal **[Carroll & Field 1997] [Kostelecký & Mewes 2001]**

(T)]. The Maxwell field strength tensor is defined as usual,

- 8 components lead to **direction-dependent modifications** of the photon-propagation properties: not discussed here propagation properties. The also assessed here  $w = \frac{1}{2}$
- **•** Remaining component leads to *isotropic modifications* of the photonpropagation properties and an unobservable double trace double trace double trace noton-
- **Isotropic, nonbirefringent LV** in the photon sector is then controlled by a **single dimensionless parameter** *κ*, which enters  $\left(k_{\rm F}\right)_{\mu\nu\rho\sigma}$  in the following way: nonbirefringent LV in the photon sector is the

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

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

where  $A$  ansatz (2a) gives non-birefringence and  $A$ 

## Isotropic, nonbirefringent LV



- Restriction on the **"deformation parameter"** <sup>κ</sup>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** 
	- $\kappa$  < 0: photon decay  $\tilde{\gamma} \rightarrow e^+ + e^-$

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

•  $\kappa$  > 0: vacuum Cherenkov radiation  $f^{\pm} \rightarrow f^{\pm} + \tilde{\gamma}$ 

#### Photon decay  $(\kappa < 0)$  $\mathsf{\textcolor{red}{\mathsf{P}}{noton~decay~(}}{}$  and  $\mathsf{\textcolor{red}{\mathsf{K}}{<<}\mathsf{U}{\textcolor{red}{})}}$  $\frac{1}{\sqrt{2}}$  with  $\frac{1}{\sqrt{2}}$  with  $\frac{1}{\sqrt{2}}$ . Specifically, the specifica  $\sum_{k=1}^{\infty}$ ndia Enotoni  $\overline{\phantom{a}}$  and the dimensionless parameter  $\overline{\phantom{a}}$  $(0)$



**•** Decay of photons above the **threshold** the photon propagation and an unobservable double trace photons above the threshold fixed tensor  $\bullet$ photons above the till eshota

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

• Decay rate for the decay into an e<sup>+</sup>/e<sup>-</sup> pair at tree level: ion the occur nico and  $\gamma$  pair at tree to  $V = 2K$   $\sqrt{-2}K$ <br>**For the desay inte an ot/o-pair at tree lovel:** [Klinkhamer & Schreck 2008] **[Díaz & Klinkhamer 2015]** 

$$
\Gamma_{\rm PhD}(E_{\gamma}) = \frac{\alpha}{3} \frac{-\kappa}{1 - \kappa^2} \sqrt{(E_{\gamma})^2 - (E_{\gamma}^{\rm thresh})^2}
$$

$$
\times (2 + (E_{\gamma}^{\rm thresh}/E_{\gamma})^2)
$$

• **Decay length** drops to cm-scales right at the threshold: essentially instantaneous decay • Decay length drops to cm-scales right at the<br>escontially instantaneous decay. <sub>9</sub> + ogene de ern<br>∫  $\mathbf{e}$ is extended micro $f(x) = \cos(x)$ the photon theory is the photon theory in the set of th with the fine-states in grit at the threshot In this appendix, we present some further details on the Light at the threshold:



modifications of the photon propagation. The remaining

 $p_{\rm{max}}$ 

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



- Exploit the quasi-instantaneous decay to derive a **bound on** <sup>κ</sup> 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  $\kappa$  can be derived  $\frac{\text{[Beall 2005]}}{\text{[Coleman & Glashow 1997]}}$  $\epsilon$ e is measured at Earth the LV threshold must be higher than  $F$  and  $\epsilon$ size of camera images at 300 photo-electrons was applied. The background estimate in this case is derived with the *ON*/*OFF* analysis. For 2004 **[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]  $2.5.$  measurements of the supernova remnant 2006 111 009 01 011 011 020 031 032 04 04 05 04 05 04 05 04 05 04 05 05 07 07 07 07 07 07 07 07 07 07 07 07 07  $27.2046$  (dictance  $1\text{ln}0$ ) **[H.E.S.S. Collab. 2008]**



• With  $E_{\gamma}$ =30TeV (±15%):  $\kappa$ >-9×10<sup>-16</sup> (at 98% C.L.) [Klinkhamer & Schreck 2008  $N$  ( $\pm$ 15 %) $\cdot$   $\kappa$   $\sim$   $-$  0  $\sim$  10 $^{-16}$  (st 0.9 %  $C$  )  $\cdot$  1 left-hand *PSF*, **In** and **PSF** in the same Gaussian, the corner as Schreck 2008 linear colour scale is in units of excess counts per smoothing radius. Note that for the 2005 data, only data recorded at zenith angles less than 60◦  $\overline{a}$ =30 TeV (± 15 %): K > -9 X TO \* absolute energy scale. This shift can be corrected using mea-**(at 98 % C.L.)** [Klinkhamer & Schreck 2008]

sured images of local muons, for which the light yield is pre-

are taken into account. On the *left-hand side*, the overlaid light-gray contours illustrate the significance of the different features. The levels are at 8,

#### Vacuum Cherenkov radiation  $(k>0)$ i Cherenkov radiation (k > 0)<br>2 <u>b M2 p and quadron (k + 0)</u>



- Charged particles above the **threshold** *E***th** emit vacuum Cherenkov radiation:  $\sqrt{1 + \kappa}$ III. VACUUM CHERENKOV RADIATION  $\Gamma$  positive Lorentz-violating parameter  $\Gamma$ M has an energy above the threshold  $E_{\text{th}} = M$  $\frac{1}{1 + \kappa}$ defined by  $\mathcal{L}(\mathcal{L})$  . From now on, the 'hat' on  $\mathcal{L}(\mathcal{L})$  on  $\mathcal{L}(\mathcal{L})$  on  $\mathcal{L}(\mathcal{L})$ ticles above the threshold  $E_{\text{\tiny th}}$  emit vacuum quation:  $F = M_1 \frac{\left(1 + K\right)}{2}$
- **•** Assuming a structureless proton, the **radiated Cherenkov power** is given by  $\hat{P}(E) = \frac{\alpha}{\sqrt{E^2 - M^2}} \left(\sqrt{E^2 - M^2} - E/n\right)^2$  $\bullet$  Ass  $\overline{\phantom{a}}$  is e  $\mathcal{L}$  $\times$  [2E<sup>2</sup>(2κ<sup>2</sup> + 4κ + 3)  $-3M^2(1 + \kappa)(1 + 2\kappa)$  $f(x) = \sqrt{x^2 + t^2/4}$  $-2nE\sqrt{E^2-M^2(1-\kappa)(4\kappa+3)}$ energy E,  $\hat{P}(E) = \frac{\alpha}{12\kappa^3 E \sqrt{I}}$  $12\kappa^3 E\sqrt{E^2 - M^2}$  $\left(\sqrt{E^2 - M^2} - E/n\right)^2$  $\sqrt{E^2 - M^2}$  $(1 - \kappa)(4\kappa + 3)$ **[Díaz & Klinkhamer 2015]**

 $2<sub>k</sub>$ 

 $t_{\text{th}} = M \sqrt{2\kappa}$ 

**• Radiation length** below cm-scales to  $\frac{1}{100}$ right at the threshold:  $\begin{array}{cc} \mathsf{right} & \mathsf{in} \mathsf{in} \ \$ particles above the threshold lose  $\frac{15}{9}$  for  $\frac{1}{10^{3}}$ their energy quickly, dropping almost immediately below the proton momentum takes the following form at tree level: composite particle, the Cherenkov photon can be taken threshold ; proton with  $\frac{1}{2}$   $\frac{1}{2}$  $\sum_{i=1}^{\infty}$  quickly, a opping  $\sum_{i=1}^{\infty}$   $\sum_{i=1}^{\infty}$   $\sum_{i=1}^{\infty}$  structurele PARTON-MODEL CALCULATION OF A NONSTANDARD … PHYSICAL REVIEW D 92, 025007 (2015)  $\frac{1}{\sqrt{2}}$  is the case for proton pro  $\frac{10}{\epsilon}$  encry, aropping  $\frac{10}{\epsilon}$   $\frac{10}{\epsilon}$   $\frac{10}{\epsilon}$   $\frac{10}{\epsilon}$   $\frac{10}{\epsilon}$   $\frac{10}{\epsilon}$   $\frac{10}{\epsilon}$   $\frac{10}{\epsilon}$ 



## Previous bounds on LV  $(\overline{\kappa} > 0)$



- 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]



With  $E \sim 200$  EeV (± 25%) and conservatively assuming an iron nucleus as the primary particle (*M*=52GeV): <sup>κ</sup> **< 6×10-20** (at 98% C.L.)**[Klinkhamer & Risse 2008] [Klinkhamer & Schreck 2008]** 

### LV and extensive air showers

- 
- Significantly improving the bound on κ < 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<sup>18</sup> 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  $\gamma \rightarrow e^+ + e^$ and bremsstrahlung  $e^{\pm} \rightarrow e^{\pm} + \gamma$
	- **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***<sup>c</sup>**
	- **Maximum number of particles** for a cascade initiated by a photon of energy  $E_0$  is reached at the atmospheric depth

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



 $E/E_0$ 

*N* 

0  $\frac{1}{2}$  2  $\frac{1}{2}$ 

 $n = X / X_0$ 

1 2×3 1 /2×<sup>1</sup> /3

2 | 2×9 |  $1/2 \times 1/9$ 

3 ||  $2 \times 9 \times 2$  ||  $1/2 \times 1/9 \times 1/2$ 



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

**[Díaz, Klinkhamer & Risse 2016]** 

- **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 *E*γ **thresh**
	- If the energy per particle falls **below the threshold**, the cascade continues according to the conventional Heitler model

## Modified Heitler model: X<sub>max</sub>



Change in  $X_{\text{max}}$  due to the different shower development:



**Large difference** in  $X_{\text{max}}$ , above the typical  $X_{\text{max}}$  resolution of current UHECR experiments (e.g. Auger: 26 g cm<sup>-2</sup> 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) SINEX. PHOLOH-HIQUCCU SHOWCIS (1)





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#### CONEX: photon-induced showers (II) SINEX. PHOLOH-HIQUCCU SHOWCIS (II)





#### CONEX: photon-induced showers (III) SINEX. PHOLOH-HIQUCCU SHOWCIS (III)





#### Neutral pion decay Since we intend to study and the study study and the shower showers in the shower shower showers in Noutral nion docay of other processes and the to LV, which may also have an

we have to take into account possible relationship of the count possible relationship of the count possible re

influence on the development of the air shower. The



• Next step: extend the study to air showers initiated by hadrons rcis<br>.  $\epsilon$  Novt stop: oxtond the study to give **TYCAL SECP.** CALCTIO LITE SLUOY LO UN SHOWEIS INILIALED BY HUOLONS

code.

- 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 influence on the development of the air shower. The • But before: need to look at other processes involving photons, Ince they may be changed in the 3 that those is replaced hy first consider the constant of principles of principles  $\mathcal{L}$
- Most important process here: <mark>neutral pion decay</mark>  $\pi^0 \rightarrow \tilde{\gamma} + \tilde{\gamma}$  $\begin{array}{ccc} \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \end{array}$ from decay  $\pi \rightarrow \gamma + \gamma$ depending on the energy En <u>Latin parameter κ</u> is shown as a function of the primary energy for  $\alpha$ l pion decay  $\pi^* \to \gamma + \gamma$
- "Straightforward but tedious calculation": the **decay time of** the neutral pion is modified in the following way [Klinkhamer 2018] depending on the energy **Lives** parameter κ  $\cdots$  shown as a function of the primary energy for different  $\cdots$  $JWII12$  Wdy [Klinkhamer 2018]  $\frac{1}{n}$  is m  $\mathbf{r}$  and the previous by the previous bound (8). Jon . the decay time of  $\mathsf{allowing}$  way [Klinkhamer 2018]



## **IMPROVED BOUND CONNOTS:**  $\langle X_{\text{max}} \rangle$  (I) **2018** SIEGEN





# **IMPROVED BOUND CONNOTS:**  $\langle X_{\text{max}} \rangle$  (II) **2018** SIEGEN





# **Hadron-induced showers:**  $\langle X_{\text{max}} \rangle$  **(III) Let universität**





# **IMPROVED BOUND CONDUCTS:**  $\langle X_{\text{max}} \rangle$  (IV) **2018** SIEGEN





## **IMPROVED BOUND CONDUCTS:**  $\langle X_{\text{max}} \rangle$  (V) **Example 11** U 966 116011 SIEGEN





## in the first induced showers: σ( $X_{\text{max}}$ ) (I) and the single showers in the single showers: σ( $X_{\text{max}}$ ) (I) and the single showers in the shower showers in the shower showers in the shower shower showers in the shower s





hXmaxi by the Pierre Auger Observatory [18]. The gray boxes

## in the first induced showers: σ( $X_{\text{max}}$ ) (II) and the singlet



as the shower fluctuations are dominated by fluctuations are dominated by fluctuations are dominated by fluctuations  $\mathcal{L}_\text{max}$ 

hXmaxi by the Pierre Auger Observatory [18]. The gray boxes

## **IMPROVED BOUND ON ISOTROPIC LORENT ENDINEER PHYSICAL REVIEW DELT CONVERSITÄT**





# **IMPROVED BOUND CONNOTS:**  $\langle N_\mu \rangle$  (II) **Example 1160 NUNIVERSITÄT**





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# **IMPROVED BOUND CONNOTS:**  $\langle N_\mu \rangle$  (III) **CONNOTES 1966** IN 1965 IN 1976 IN 1976 IN 1976 IN 1976 IN 1976 IN 1977





## **IMPROVED BOUND CONDUCTS:**  $\langle N_\mu \rangle$  (IV) **Example 1160 UNIVERSITÄT**





## $\langle X_{\text{max}} \rangle$ -dependence on *κ* and *A* (I) **11 (2018)** sieg





 $F = \frac{1}{2}$  simulated values of  $\frac{1}{2}$  function of  $\frac{1}{2}$  function of  $\frac{1}{2}$  for  $\frac{1}{2}$  for  $\frac{1}{2}$  for  $\frac{1}{2}$ 13.12.2018 M. Niechciol | Seminar at Fyzikální ústav AV ČR (FZÚ), Prague 33 / 42

## $\langle X_{\text{max}} \rangle$ -dependence on *κ* and *A* (I) **11 (2018)** sieg





#### $\langle X_{\text{max}} \rangle$ -dependence on *κ* and *A* (II) **And according to the onset of the estimate from (12). The onset of neutral to the estimate from (12). The onset of neutral to the estimate from (12). The onset of neutral to t** perioence on  $K$  and  $A$   $\{II\}$  as a minor effect only as a minor effect on  $R$





 $F = \frac{1}{2}$  simulated values of  $\frac{1}{2}$  function of  $\frac{1}{2}$  function of  $\frac{1}{2}$  for  $\frac{1}{2}$  for  $\frac{1}{2}$  for  $\frac{1}{2}$ obtained from a fit to the distribution of the distribution from a fit to the distribution of the distribution

## **Differences between the models (I) Hadronic interaction models (I) Heading Computer**





parameter κ, the primary energy E, and the primary mass A.

improved bound on k (to be discussed in Sec. III)

## **Differences between the models (II) Hadronic interaction models (II)**





parameter κ, the primary energy E, and the primary mass A.

improved bound on k (to be discussed in Sec. III)

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#### $\sum_{i=1}^{n}$ Comparison to Auger  $\langle X_{\text{max}}\rangle$  data (I)





#### $\sum_{i=1}^{n}$ Comparison to Auger  $\langle X_{\text{max}}\rangle$  data (II)





#### New bound on κ<0



- **Ingredients** to calculate an improved bound on  $\kappa < 0$ :
	- Focus on the energy bin around **2.8×1018 eV**
	- Conservatively assume a **pure proton composition**
	- Add a (conservative) systematic uncertainty of  $20$  g cm<sup>-2</sup> due to the **choice of the hadronic interaction model** (here: EPOS LHC)

**New bound:** κ**>-3×10-19 (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 2PeV** 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  $K < 0$  are possible:
	- **Additional**  $\langle X_{\text{max}}\rangle$  **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 3×1018 eV) **[Auger Collab. 2016]**
- Extend the study to **additional shower observables**, e.g.  $\sigma(X_{\text{max}})$  or the correlation between  $X_{\text{max}}$  and the ground signal
	- NB: the latter observable would require full MC simulations (CORSIKA)
- Use a **similar approach** to explore the range <sup>κ</sup>**>0** 
	- Vacuum-Cherenkov emission from secondary electrons in the shower could lead to similar modifications of  $\langle X_{\text{max}} \rangle$



- 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**  $\langle X_{\text{max}}\rangle$  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  $(X_{max})$  data, an *improved bound on*  $K < 0$  *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**

#### Lorentz-violating photon decay process, based on the positron pair and Fig. 9 shows the energy fraction of Expected shift in  $\langle X_{\rm max} \rangle$ 15 g cm−<sup>2</sup> (instead of approximately 25 g cm−<sup>2</sup> just above 400 γ mod. Heitler model, κ = -9e-20  $γ = 9e-16$  $max/$ IN  $\langle X_{\rm max} \rangle$ γ mod. Heitler model, κ = -9e-20 μ σιστικ  $\mathcal{F}(\mathcal{F}) = \mathcal{F}(\mathcal{F})$  model,  $\mathcal{F}(\mathcal{F}) = \mathcal{F}(\mathcal{F})$



 $\overline{\phantom{a}}$ 



```
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
              rate of approximately 85 g cm−2 per decade for electro-
```