Shower formation constraints on cubic LIV parameters in quantum electrodynamics

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COST CA18108 Third Annual Conference, Napoli
15 July 2022

LIV: Dispersion relations and Effective Field Theory

- Kinematical approach – Dispersion relation

$$E^2 = m^2 + p^2\,(1 \pm \eta_0) \pm \frac{p^3}{E_{LIV,1}} \pm \frac{p^4}{E^2_{LIV,2}} \pm \ldots$$

  Kinematcal effects:
  - time delays
  - birefirgence
  - threshold modifications (decays..)
- Dynamical approach EFT Lagrangian - Dynamical effects
  - (Non-threshold) Modification of cross-sections
    Example: Bethe-Heitler process $\gamma N \to N e^+ e^-$
    (the 1st interaction in γ-induced air shower)

Current limits

Table with current limits from COST CA18108 Review 2111.05659 [hep-ph]

e^-/γ	Test of QG	Sub($-$) or super($+$) luminal	Limits $\lvert\xi_0\rvert(\lvert\eta_0\rvert)$	$E^{(1)}_{\rm LIV}$ (eV)	$E^{(2)}_{\rm LIV}$ (eV)	Source	Ref.
e^-	Synch.	both	2×10^{-20}	10^{33}	2×10^{25}	CRAB	[1316, 1317, 1336]
e^-	VC	$(+)$	10^{-20}	10^{31}	10^{23}	CRAB	[1314, 1320, 1366]
γ	PD	$(+)$	7.1×10^{-19}	1.7×10^{33}	1.4×10^{24}	LH. J2032+4102	[1147]
γ	PD	$(+)$	1.3×10^{-17}	2.2×10^{31}	8×10^{22}	MultiSrc	[1331]
γ	PD	$(+)$	1.8×10^{-17}	1.4×10^{31}	5.8×10^{22}	eHWCJ1825-134	[1331]
γ	PD	$(+)$	2.2×10^{-17}	9.9×10^{30}	4.7×10^{22}	eHWCJ1907+063	[1331]
γ	3γ	$(+)$	-	-	2.5×10^{25}	LH. J2032+4102	[1147]
γ	3γ	$(+)$	-	-	1.2×10^{24}	eHWC J1825-134	[1331]
γ	3γ	$(+)$	-	-	1.0×10^{24}	eHWC J1907+063	[1331]
γ	3γ	$(+)$	-	-	4.1×10^{23}	CRAB	[1330]
γ	AS	$(-)$	-	-	1.7×10^{22}	diffuse (Tibet)	[1148]
γ	AS	$(-)$	-	-	6.8×10^{21}	LH. J1908+0621	[1148]
γ	AS	$(-)$	-	-	1.4×10^{21}	CRAB	[1330]
γ	AS	$(-)$	-	-	9.7×10^{20}	CRAB	[1330]
γ	AS	$(-)$	-	-	2.1×10^{20}	CRAB	[1336]
γ	PP	$(-)$	-	1.2×10^{29}	2.4×10^{21}	MultiSrc (6)	[1367]
γ	PP	$(-)$	-	2.6×10^{28}	7.8×10^{20}	Mrk 501	[1368]
γ	PP	$(-)$	-	1.9×10^{28}	3.1×10^{20}	MultiSrc (32)	[1334]

Table 1: Strong and recent astrophysical bounds to LIV in the QED sector using synchrotron radiation (Synch.), vacuum Cherenkov radiation (VC), photon decay (PD), photon splitting (3γ), air shower suppression (AS), and pair production

Air shower (AS) limit for $n = 1$ is still not filled!

EFT: QED with cubic LIV - Myers-Pospelov model

Myers, Pospelov hep-ph/0301124 (PRL) 2003

LI is broken by external fixed timelike vector $n_\mu = (1, 0, 0, 0)$

EFT (CPT-odd!!): The only LIV dim 5 operators to the Lagrangian

$$\mathcal{L} = \mathcal{L}_{\text{QED}} + \mathcal{L}_\gamma + \mathcal{L}_e,$$

$$\mathcal{L}_{\text{QED}} = \bar{\psi}(i\gamma^\mu D_\mu - m)\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu},$$

$$\mathcal{L}_\gamma = \frac{\xi}{M_{\text{Pl}}} n^\mu F_{\mu\nu} n \cdot \partial \left(n_\sigma \tilde{F}^{\sigma\nu} \right),$$

$$\mathcal{L}_e = \frac{1}{M_{Pl}} \bar{\psi}(n \cdot \gamma) \left(\eta_L (1 - \gamma_5) + \eta_R (1 + \gamma_5) \right) (n \cdot \partial)^2 \psi.$$

Myers-Pospelov model - Dispersion relations

Left- and Right- polarized photons:

$$\varepsilon^{\mu}_{(L)} = \frac{1}{\sqrt{2}}(0, 1, -i, 0), \qquad \varepsilon^{\mu}_{(R)} = \frac{1}{\sqrt{2}}(0, 1, i, 0)$$

Differents signs in the dispersion relation for different polarizations

$$E^2_{(L)} = k^2_{(L)} + \frac{2\xi}{M_{Pl}} k^3_{(L)} \qquad \text{Superluminal}$$

$$E^2_{(R)} = k^2_{(R)} - \frac{2\xi}{M_{Pl}} k^3_{(R)} \qquad \text{Subluminal}$$

Left- and Right- chiral electrons:

$$E^2_{(.)} = m^2 + p^2_{(.)} + 2\eta_{(.)} \frac{p^3_{(.)}}{M_{Pl}}, \qquad (.) = (L) \text{ or } (R)$$

Myers-Pospelov model: Kinematical constraints on $E_{LIV,1}$ for photons

refs from COST CA18108 Review 2111.05659 [hep-ph]

Time delays

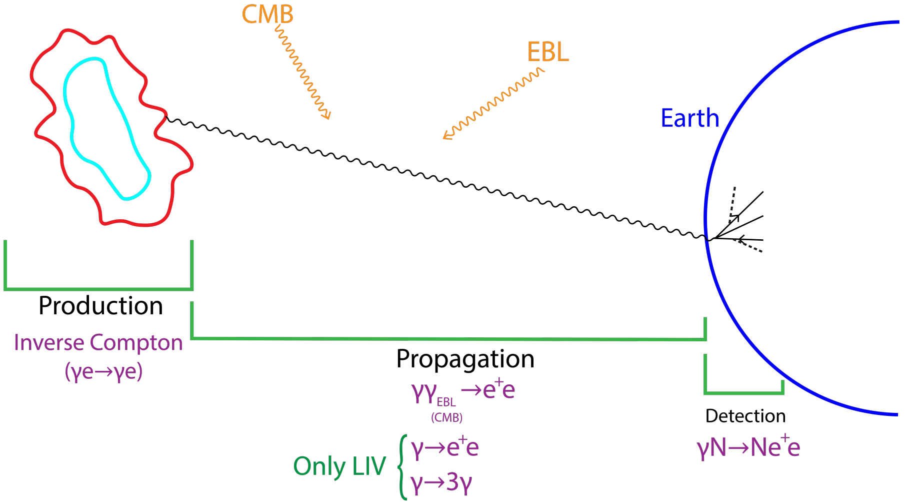
AGN:	$E_{LIV,1} > 2 \cdot 10^{18}$ GeV	*H.E.S.S. 2011*
GRB:	$E_{LIV,1} > 1.5 \cdot 10^{19}$ GeV	*Fermi 2009*

Birefirgence (n=1 only)

GRBs:	$\xi < 3.4 \cdot 10^{-16}$	$\leftrightarrow$	$E_{LIV,1} > 1.8 \cdot 10^{34}$ GeV	*Gotz et al, 2013*
combined:	$\xi < 8.6 \cdot 10^{-17}$	$\leftrightarrow$	$E_{LIV,1} > 7.1 \cdot 10^{34}$ GeV	*Galaverni et al, 2015*

Extremely strong limits from birefirgence.
However, independent constraints from other processes may be also interesting

The fate of VHE (TeV-PeV) photon & crucial reactions



QED processes crucial for super- and subluminal photons

Appear in case of superluminal LIV ($E^2 = k^2 + \frac{k^{n+2}}{E^n_{LIV,n}}$):

- Photon decay $\gamma \to e^+ e^-$
- Photon splitting $\gamma \to 3\gamma$

Both processes supress the photon flux

Modified in case of subluminal LIV ($E^2 = k^2 - \frac{k^{n+2}}{E^n_{LIV,n}}$):

- Pair production on background photons, $\gamma\gamma_b \to e^+ e^-$
  responsible for suppression of the extragalactic photon flux in LI case
  in subluminal LIV the process suppressed $\to$ the photon flux may be enhanced
- Pair production in Coulomb field of a nuclei $\gamma N \to N\, e^+ e^-$ (Bethe-Heitler process)
  in subluminal LIV the process suppressed $\to$ the observed photon flux suppressed

VHE (TeV - PeV energies) photons

Assumption: both polarizations produced in the source (additional analysis is needed!)

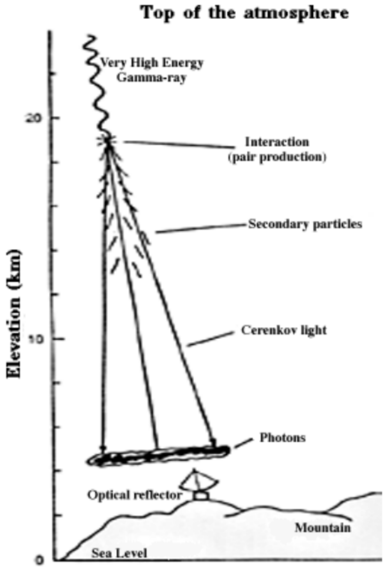
$$E_{(L)}^2 = k_{(L)}^2 + \frac{2\xi}{M_{Pl}} k_{(L)}^3 \qquad \text{Superluminal}$$

$$E_{(R)}^2 = k_{(R)}^2 - \frac{2\xi}{M_{Pl}} k_{(R)}^3 \qquad \text{Subluminal}$$

If some photon-like events detected (polarization is uknown):

- No decay/splitting at these energies
- No observational suppression of shower formation

Atmosphere shower formation: sensitivity to LIV



- First interaction in the atmosphere — pair production in the Coulomb field of a nuclei *Bethe, Heitler, 1934*
- The most energetic interaction $\rightarrow$ the most sensitive to LIV. Suppressed in case of subluminal LV (see the next slide).
- Subsequent interactions — less energetic, no change in LIV case in the leading order

Bethe-Heitler process and sensitivity to LIV

Cross-section in LI case (with screening): *Bethe, Heitler, 1934*

$$\sigma_{\mathrm{BH}}^{\mathrm{LI}} = \frac{28 Z^2 \alpha^3}{9 m_e^2}\left(\log\frac{183}{Z^{1/3}} - \frac{1}{42}\right)$$

In case of **subluminal** LIV Bethe-Heitler cross-section gets suppressed

idea: Vankov, Stanev, 2002

Calculation for $(n=2)$ LIV — *Rubtsov, P.S., Sibiryakov 2012*

(n=1, R-polarization) In the limit $E_\gamma^3 \gg m_e E_{LIV,1}^2$ Bethe-Hetler cross-section reads,

this work

$$\sigma_{\mathrm{BH}}^{\mathrm{LV}} \simeq \sigma_{\mathrm{BH}}^{\mathrm{LI}} \cdot 1.7 \frac{m_e^2 E_{LIV,1}}{E_\gamma^3} \cdot \log\frac{E_\gamma^3}{2 m_e^2 E_{LIV,1}}$$

The cross-section decreases with energy as $E_\gamma^{-3}\log E_\gamma$ (fixed $E_{LIV,1}$)

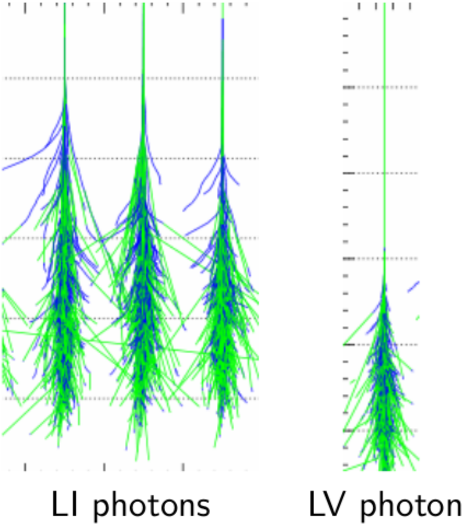
Photon-induced shower formation: LI vs. LIV cases

- LI:
  First interaction
  $\langle X_0 \rangle = m_{at}/\sigma_{BH} \approx 57\ \mathrm{g\,cm^{-2}}$
- Shower maximum
  $X_{max} = X_0 + \Delta X$.
  $\langle X_{max} \rangle \approx 320\ \mathrm{g\,cm^{-2}}$.

LIV:

- X_0 increases
- ΔX does not change
  (in the leading order)

Photon-induced showers become deeper and may avoid detection!



Shower formation

$$\langle X_0 \rangle_{LIV} = m_{at}/\sigma_{BH}^{LIV}$$

The probability for a photon to produce pair in the atmosphere reads,

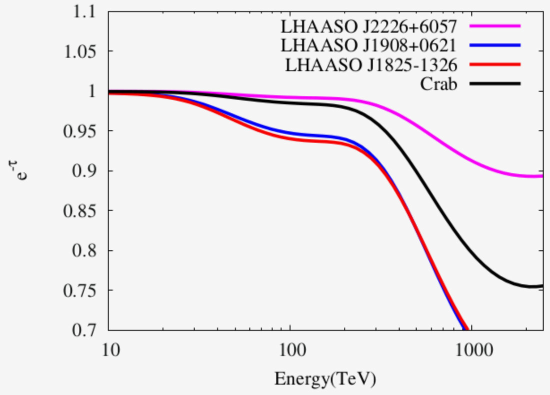
$$P = \int_0^{X_{\rm atm}} dX_0 \, \frac{\mathrm{e}^{-X_0/\langle X_0 \rangle_{LIV}}}{\langle X_0 \rangle_{LIV}} = 1 - \mathrm{e}^{-X_{\rm atm}/\langle X_0 \rangle_{LIV}}$$

The detected photon flux gets reduced,

$$\left(\frac{d\Phi}{dE}\right)_{LIV} = P \times \left.\frac{d\Phi}{dE}\right|_{source}$$

Attenuation of galactic γ-ray flux due to pair production on CMB

M.f.p. for 1 PeV photon is $\sim$ 10 kpc — galactic scales! *LHAASO coll. Nature, 2021*



| **γ-ray opacity of LHAASO J2226+6057, J1908+0621, J1825-1326 and Crab Nebula.** The absorption due to both ISRFs and CMB

$$\left(\frac{d\Phi}{dE}\right)_{LI} = e^{-\tau} \times \left.\frac{d\Phi}{dE}\right|_{source}$$

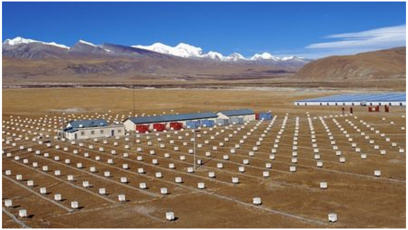
Sub-PeV γ-ray flux: Shower formation vs pair production on CMB

Subluminal LIV shifts the threshold of p.p. from CMB peak to EBL where it is almost negligible

$$\left(\frac{d\Phi}{dE}\right)_{LIV} = \frac{P_{sh.form}(E_\gamma, E_{LIV,1})}{\mathrm{e}^{-\tau(L_{source}, E_\gamma)}} \times \left.\frac{d\Phi}{dE}\right|_{source}$$

More details in application to (n=2) case *P.S. EPJC 2021*

Experimental data



- Tibet ASγ — diffuse γ-rays from the Galactic Disk.
  Maximal photon energy 0.8 PeV *Tibet ASγ, PRL 2021*
- LHAASO — observation of 12 galactic sources in > 100 TeV
  Maximal photon energy 1.4 PeV *LHAASO, Nature, 2021*
- LHAASO — Crab Nebula spectrum up to PeV
  Maximal photon energy 1.1 PeV *LHAASO, Science, 2021*

Tibet ASγ: observation of diffuse γ-ray flux from the galactic disk — more than predicted by theoretical models *Lipari, Verneto '08*

Model consistent with Tibet-ASγ — *Koldobskiy, Neronov, Semikoz '21*

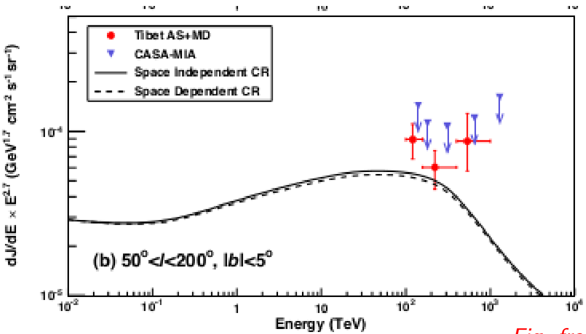
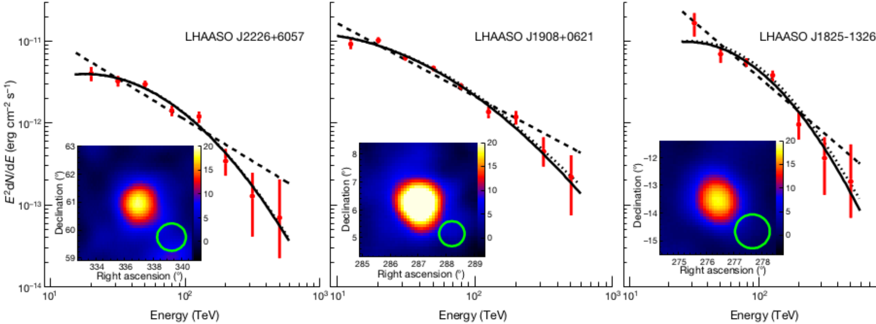


Fig. from Tibet-ASγ '21

Distance to the outer disk $L \sim 1 - 5$ kpc,
the absorption coeff. due to p.p. on CMB $e^{-\tau} = 0.73$ ($L_{max} \sim 5$ kpc)

LHAASO

- 12 sources (Pevatrons) with energy 100+ TeV discovered.
- Energy spectra for 3 sources:



- We test the hypothesys of LIV shower suppression assuming the most conservative power-law flux with experimental data points.

Shower formation limits on subluminal $E_{LIV,1}$

Source	L, kpc	Bound $E_{LIV,1}$, 10^{20} GeV
Tibet diffuse	1-5	8.2
LHAASO		
Crab Nebula	2	0.5
J2226+6057	0.8	1.5
J1908+0621	2.37	2.1

Table: The 95% CL constraints on LIV mass scale from 3 sub-PeV sources observed by LHAASO.

Conclusions

- EFT impies birefirgent photons for $n = 1$ LIV
- Obtained shower formation constraints are many orders of magnitude weaker than the birefirgence limits but independent and comparable with other limits
- Shower formation with LIV in electrons – work in progress

Thank you for your attention!

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[1] This work is supported by RSF foundation under contract 22-12-00253.