Exploring Lorentz Invariance Violation With Sources of LHAASO

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Motivation

- Lorentz invariance is one of the founding principles of the Special Relativity theory

- Unify theory such as Quantum Gravity or String Theory, can lead to deviations from Lorentz symmetry

- Lorentz invariance violations (LIV) could lead to modifications of the dispersion relation. This will lead to some effect:

  1. speed of light changed
  2. Vacuum dispersion
  3. Vacuum birefringence
  4. vacuum Cherenkov radiation at superluminal for charge paritcles.
  5. Photon decay or splitting at superluminal speed

  ....

- Due to long distance, astrophysical searches provide sensitive probes of LIV

LIV

Dispersion relation

$$E_\gamma^2 - p_\gamma^2 = \pm|\alpha_n|p_\gamma^{n+2},$$
$$E_{LIV}^{(n)} = \alpha_n^{-1/n}.(n > 0)$$

superluminal case

Process: $\gamma \rightarrow e^+e^-$

$$E_\gamma^2 - p_\gamma^2 = |\alpha_n|p_\gamma^{n+2} = m_{\gamma,eff}^2,$$
$$E_{LIV}^{(n)} = \alpha_n^{-1/n}, (n > 0)$$
$$m_{\gamma,eff} < 2m_e.$$

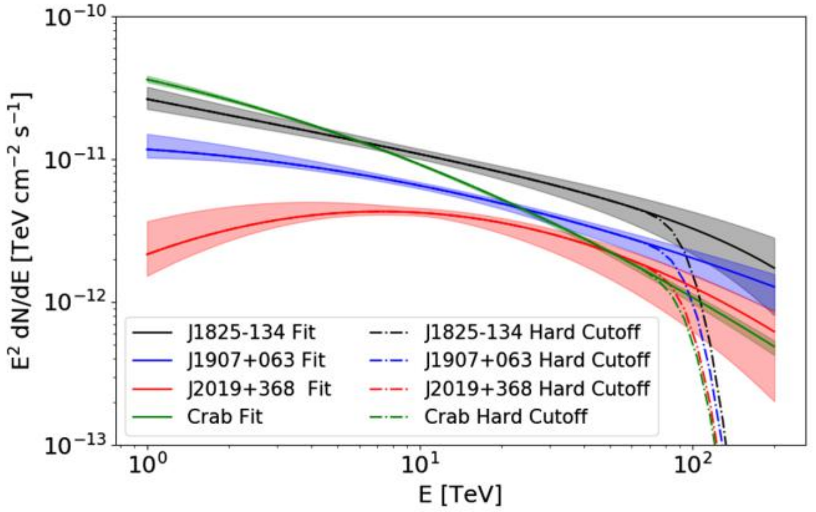
$$\alpha_0 \leq \frac{4m_e^2}{E_\gamma^2 - 4m_e^2},$$
$$E_{LIV}^{(1)} \geq 9.57 \times 10^{23}\mathrm{eV}\left(\frac{E_\gamma}{\mathrm{TeV}}\right)^3,$$
$$E_{LIV}^{(2)} \geq 9.78 \times 10^{17}\mathrm{eV}\left(\frac{E_\gamma}{\mathrm{TeV}}\right)^2.$$

Process: $\gamma \rightarrow 3\gamma$

$$\Gamma_{\gamma\rightarrow 3\gamma} = 5 \times 10^{-14}\frac{E_\gamma^{19}}{m_e^8 E_{LIV}^{(2)10}},$$
$$E_{LIV}^{(2)} > 3.33 \times 10^{19}\mathrm{eV}\left(\frac{L}{\mathrm{kpc}}\right)^{0.1}\left(\frac{E_\gamma}{\mathrm{TeV}}\right)^{1.9}.$$

1. **Hard cutoff** in SED
2. we need find is cut energy Eγ

HAWC results



	E_c	L	α_0	$E_{\rm LIV}^{(1)}$	$E_{\rm LIV}^{(2)}$	$E_{\rm LIV}^{(2)}$ (3γ)
Source	TeV	kpc	10^{-17}	10^{31} eV	10^{23} eV	10^{23} eV
J1825 – 134	244	1.55	1.75	1.39	0.58	12
J1907 + 063	218	2.37	2.2	0.99	0.47	10.1
J0534 + 220	152	2	4.52	0.34	0.23	4.99
J2019 + 368	120	1.8	7.25	0.17	0.14	3.15
Combined	285	...	1.29	2.22	0.8	...

95% limit cut energy is 285 TeV

HAWC: PHYSICAL REVIEW LETTERS 124, 131101 (2020)

Sources with high significance above 100 TeV in LHAASO-KM2A

source name	R.A. (°)	dec (°)	Significance (σ) above 100 TeV	E_{Max} (PeV)	Flux ($\pm$ error) (CU) at 100 TeV
LHAASO J0534+2202	83.55	22.05	17.8	0.88 $\pm$0.11	1.00(0.14)
LHAASO J1825-1326	276.45	-13.45	16.4	0.42 $\pm$0.16	3.57(0.52)
LHAASO J1839-0545	279.95	-5.75	7.7	0.21 $\pm$0.05	0.70(0.18)
LHAASO J1843-0338	280.75	-3.65	8.5	$0.26^{+0.16}_{-0.10}$	0.73(0.17)
LHAASO J1849-0003	282.35	-0.05	10.4	0.35 $\pm$0.07	0.74(0.15)
LHAASO J1908+0621	287.05	6.35	17.2	0.44 $\pm$0.05	1.36(0.18)
LHAASO J1929+1745	292.25	17.75	7.4	$0.71^{+0.16}_{-0.07}$	0.38(0.09)
LHAASO J1956+2845	299.05	28.75	7.4	0.42 $\pm$0.03	0.41(0.09)
LHAASO J2018+3651	304.75	36.85	10.4	0.27 $\pm$0.02	0.50(0.10)
LHAASO J2032+4102	308.05	41.05	10.5	1.42 $\pm$0.13	0.54(0.10)
LHAASO J2108+5157	317.15	51.95	8.3	0.43 $\pm$0.05	0.38(0.09)
LHAASO J2226+6057	336.75	60.95	13.6	0.57 $\pm$0.19	1.05(0.16)

a

Data:

KM2A Half Array
Data: 2019.12.27-2020.11.30 V1
Live time: 312.6 days

Energy Spectrum:

Almost same as Crab (1). Main difference:

- Energy bin width: logE 0.1
- Estimate the background with “Equal zenith angle method”

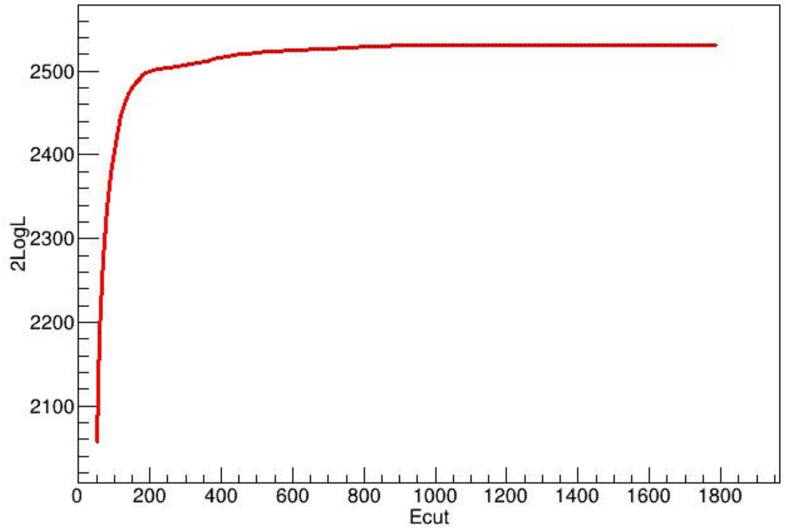
CPC crab: Chinese Physics C Vol. 45, No. 2 (2021) 025002

LHAASO J0534+2202 (E_{max} = 0.88 PeV)

if cut exists?

$$f(E) = \phi_0 \left(\frac{E}{E0}\right)^{(-\alpha-\beta log(E/E0))} \theta(E_{cut}, E) \qquad E_0 = 20\ \text{TeV}$$

$$L(\phi_0, \alpha, \beta, E_{cut}) = \prod_{i=1}^{n} Possion(Nobs_i, Nsig_i(\phi_0, \alpha, \beta, E_{cut}) + Nbkg_i)$$



SED: Ecut->Infinity

Φ_0: $1.06 \times 10^{-14} \pm 3.55 \times 10^{-16}$

α: -2.978 ± 0.068

β: -0.018 ± 0.046

2LogL: 2531.4

95% constraints on cut energy

$$TS(E_{cut}) = -\sum_{bin} 2\log\left(\frac{L_1(\alpha_1, \beta_1, \gamma_1, E_{cut})}{L_0(\alpha_2, \beta_2, \gamma_2, E_{cut} \to \infty)}\right)$$

$$L(\phi_0, \alpha, \beta, E_{cut}) = \prod_{i=1}^{n} Possion(Nobs_i, Nsig_i(\phi_0, \alpha, \beta, E_{cut}) + Nbkg_i)$$

In high energy bins, the number of events is small, Wilks theorem does not apply

TS(Ecut) distribution is not a chi2(1) distribution, MC is needed

For a Ecut model

- we produce MC data
- Get distribution of pseudo data.
- Calculate exlusion limit.

A group of Ecut are chosen, get distribution and find
Ecut corrsponding to 95% exlusion.

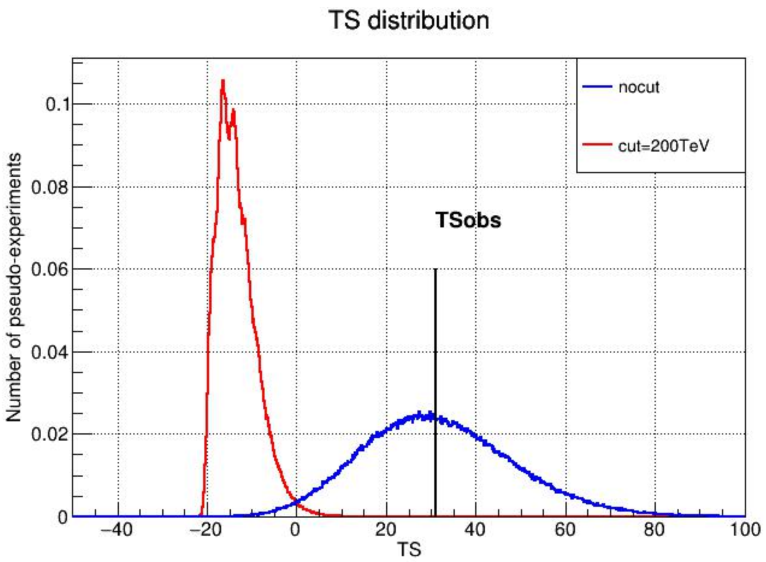
TS distribution of pseudo data

As an example, we get exlusion for cut=200 TeV SED.

$$TS(E_{cut}=200TeV) = -\sum_{bin} 2\log\left(\frac{L_1(\alpha_1,\beta_1,\gamma_1,E_{cut}=200TeV)}{L_0(\alpha_2,\beta_2,\gamma_2,E_{cut}\to\infty)}\right)$$

$$L(\phi_0,\alpha,\beta,E_{cut}) = \prod_{i=1}^{n} Possion(Nobs_i, Nsig_i(\phi_0,\alpha,\beta,E_{cut}) + Nbkg_i)$$

SED(Ec=200TeV) —bestfit data→ expected sig —sampling→ MC data → TS 红线

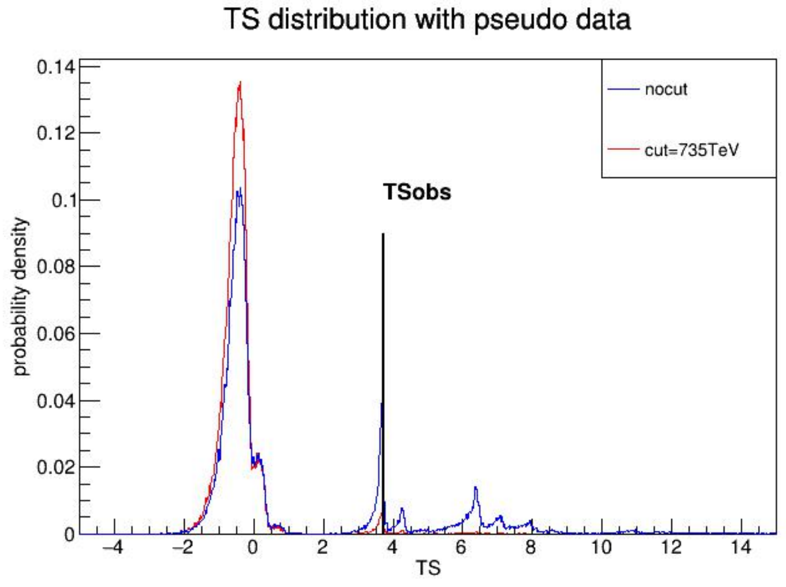


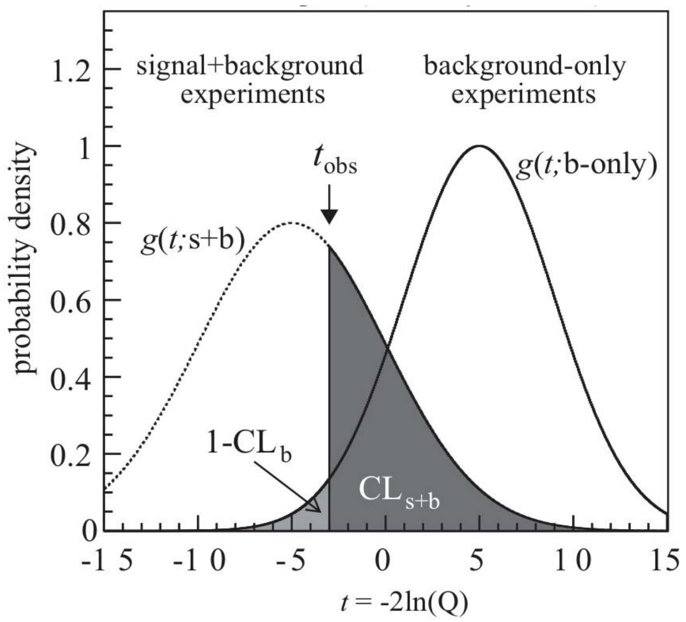
TSobs = 31
CLs+b: 0.00001%

95% correspond to higher Ecut

95% exclude Ecut

Ecut=735TeV





TSobs = 3.72
CL_{s+b}: 0.8%
CL_b: 15.8%
CL_s: 5%

CLs method: $CL_s = CL_{s+b}/CL_b$

CLs method: J. Phys. G: Nucl. Part. Phys. 28 (2002) 2693–2704

LHAASO J2032+4102 & J1929+1745

LHAASO J2032+4102 (1.42 PeV)

0.3° extension

Φ_0: $5.22 \times 10^{-15} \pm 3.33 \times 10^{-16}$

$\alpha: -3.095 \pm 0.115$

$\beta: -0.021 \pm 0.063$

2LogL: 515.6

95% CLs limit:
Ecut = **1103 TeV**

J1929+1745 (0.71PeV)

0.3° extension

Φ_0: $3.38 \times 10^{-15} \pm 3.37 \times 10^{-16}$

$\alpha: -2.941 \pm 0.185$

$\beta: -0.058 \pm 0.097$

2LogL: 244.2

95% CLs limit:
Ecut = **520 TeV**

95% LIV scale constraints

$\gamma \to$

$\gamma \to 3\gamma$

Source	Emax (PeV)	$\text{Ecut}_{95\%}$ (PeV)	α_0 $\times 10^{-18}$	$E_{LIV}^{(1)}$ (eV) $\times 10^{32}$	$E_{LIV}^{(2)}$ (eV) $\times 10^{23}$	L kpc	$E_{LIV}^{(2)}$ (3γ) (eV) $\times 10^{24}$
J0534+2202	0.88	0.735	1.92	3.79	5.28	2	9.9
J2032+4102	1.42	1.1	0.86	12.7	11.8	1.4	20.7
J1929+1745	0.71	0.52	3.84	1.34	2.64	6.3	5.61
combine	-	1.1	0.86	12.7	11.8	-	-
eHWC 2020 (HAWC)	-	-	13	0.22	0.58	-	1.2
Crab 2017 (HEGRA)	-	-	-	0.0015	0.028	-	-
Crab 2013 (HEGRA)	-	-	400	-	-	-	-
Crab 2001 (CANGAROO)	-	-	400	-	-	-	-
Crab 2019 (Tibet)	-	-	-	-	-	-	0.41
GRB 090510 (Fermi-LAT)	-	-	-	0.0013	0.0009	-	-

$$E_{LIV}^{(1)} \sim 10^5 E_{Planck} \qquad E_{LIV}^{(2)} \sim 0.0017 E_{Planck}$$

Error analysis on 95% Ecut

Simulation

flux: 7%
spectral index: 0.02

Spectrum fit

spectrum: Ecut->Infinity

Φ_0: $1.06 \times 10^{-14} \pm 3.55 \times 10^{-16}$

α: -2.978 ± 0.068

β: -0.018 ± 0.046

2LogL: 2531.4

Check

Effect of bkg

bkg	Ecut(TeV)
bkg*10	570
bkg*2	695
bkg	735
bkg/2	757
bkg/10	773
0	775

Spectrum choice

$$f(E) = \phi_0 \left(\frac{E}{E_0}\right)^{-\alpha} e^{-\frac{E}{E_\beta}}$$

Ecut: 620 TeV

Summary

- LIV superluminal case : $\gamma \rightarrow e^+e^-$, $\gamma \rightarrow 3\gamma$
- Three source
  LHAASO J0534+2202
  LHAASO J1929+1745
  LHAASO J2032+4102
- 95% constraints using CLs method

$$E_{LIV}^{(1)} \sim 10^5 E_{Planck} \qquad E_{LIV}^{(2)} \sim 0.0017 E_{Planck}$$

- One order better comparing to HAWC results

Summary

- LIV superluminal case : $\gamma \rightarrow e^+e^-$, $\gamma \rightarrow 3\gamma$

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THANK YOU

看谱指数的影响

logE > 2.0

phi0 : (1.730e-14 +- 1.481e-14)
alpha : (-3.484 +- 0.374)

index	95% Ecut (TeV)
-3.48	735
-3.3	737
-3.6	724

1

LHAASO J0534+2202 (0.88 PeV)

$$f(E) = \phi_0 \left(\frac{E}{E0}\right)^{(-\alpha-\beta log(E/E0))} \theta(E_{cut}, E) \qquad E_0 = 20 \text{ TeV}$$

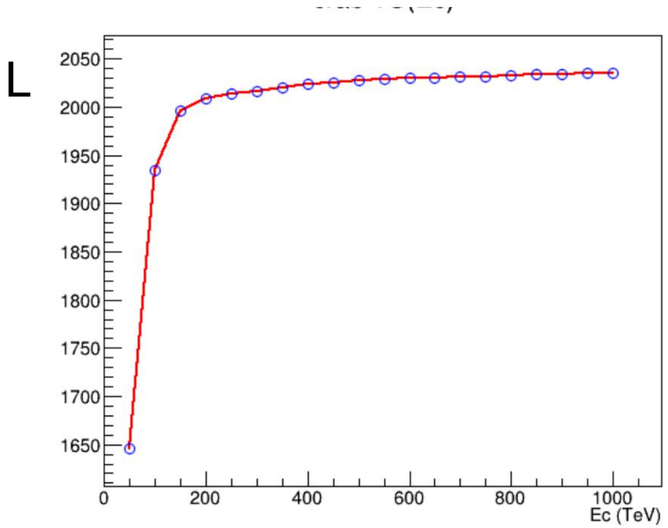
90% events around source

on: 13955, 8838, 3501, 1880, 353, 275, 127, 75, 74, 38,
23, 14, 8, 3, 1, 1, 2, 1, 0, 1, 0, 0, 0

off: 12531.7, 7745.85, 2719.33, 1307.66, 120.06, 67.7357, 14.5503, 6.89506, 6.50599, 2.94018,
0.904979, 0.524104, 0.200803, 0.193915, 0.0491451, 0.0244675, 0.0152723, 0.0308566, 0.0036518,
0.00125205, 0.00103157, 0.000687712, 0.00128946

$$L(\phi_0, \alpha, \beta, E_{cut}) = \prod_{i=1}^{n} Possion(Nobs_i, Nsig_i(\phi_0, \alpha, \beta, E_{cut}) + Nbkg_i)$$

spectrum: Ecut->Infinity
alpha:(1.059e-14 +- 3.545e-16)
beta:(-2.978 +- 0.068)
beta2:(-0.118 +- 0.046)
TS 2531.373



2 LHAASO J2032+4102 (1.42 PeV)

(源1.5°范围内, est<-2.36)

Energy bin (logE)	logE	E (TeV)	mjd	angle (°)	ra (°)	dec (°)	est	theta (°)	phi (°)
2.8-3.0									
2.6-2.8	2.65296	449.738	58855.1881067448	1.0016	306.73	41.1698			
3.0-3.2	3.07639	1192.31	58990.0322822316	0.529082	307.45	41.329	-2.5966	36.8268	239.63
	3.16924	1476.52	59101.6096527316	0.189554	307.92	40.8876	-2.4275	11.6103	182.87
	3.15269	1421.31	59101.6259100342	0.113385	308.072	40.9379	-2.9745	12.7345	202.74

core_x	core_y	NfiltE	NfiltM	NuM4	NpE3
230.068	-102.153	219	6	7.4161	2929.374
-193.1925	-227.7205	284	14	23.7453	6355.3320
-205.8047	389.0966	312	6	6.6367	6258.6689

est=log10((NuM4+0.0001)/NpE3)

0.3°拓展

on: 18378, 11907, 4929, 2577, 387, 230, 112, 41, 57, 31, 15, 10, 2, 6, 3, 1, 0, 0, 0, 0, 1, 1, 0

off: 17631.1, 11276.7, 4546.26, 2237.79, 241.556, 142.478, 37.9953, 18.3223, 20.2199, 9.06783,3.28855, 1.63565, 0.829864, 0.590427, 0.408925, 0.238034, 0.118758, 0.0570179, 0.0319564,0.0140984, 0.00733407, 0.00550056, 0.00733407

alpha:(5.221e-15 +- 3.326e-16)
beta:(-3.095 +- 0.115)
beta2:(-0.021 +- 0.063)
TS 515.594

Ecut 1103.5 TS_nocut_ratio 0.027743, TS_cut_ratio 0.001347, ratio 0.0485528
Ecut 1103.6 TS_nocut_ratio 0.031008, TS_cut_ratio 0.001602, ratio 0.0516641

3 LHAASO J1929+1745 (0.71PeV)

on: 15747, 10127, 4186, 2038, 290, 212, 76, 36, 30, 19, 8, 11, 5, 2, 0, 1, 1, 1, 1, 0, 0, 0, 0

off: 15397.9, 9789.64, 3925.18, 1911.34, 214.137, 121.776, 31.6733, 15.3863, 17.8276, 6.92699, 3.16392, 1.75766, 0.941066, 0.482397, 0.224137, 0.132253, 0.141542, 0.029024, 0.0269757, 0.0142372, 0.0116941, 0.00730881, 0.00803969

alpha:(3.383e-15 +- 3.371e-16)
beta:(-2.941 +- 0.185)
beta2:(-0.058 +- 0.097)
TS 244.164

Ecut 520TeV
TS_nocut_ratio 0.135093, TS_cut_ratio 0.006777, ratio 0.0501654415846861