LHAASO discovery of highest-energy photons

towards new physics

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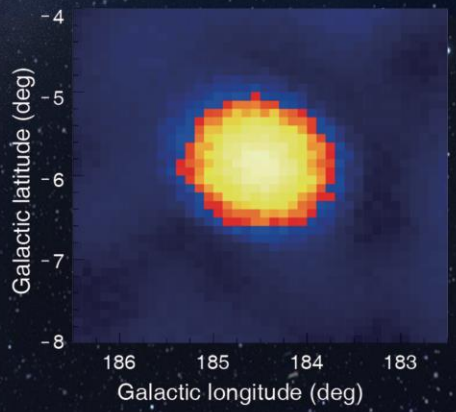
The Second LHAASO Collaboration Meeting in 2021

TD Lee Institute (SJTU), Shanghai, China

In collaboration with Zhi Xiao, Lijing Shao, Shimin Yang, Lingli Zhou, Haowei Xu, Yunqi Xu, Nan Qin, Shu Zhang, Yue Liu, Yanqi Huang, Xinyi Zhang, Hao Li, Yingtian Chen, Chengyi Li, Jie Zhu, ……

LHAASO discovery of PeV photons



LHAASO J2226+6057

LHAASO J2018+5157

LHAASO J2032+4102

LHAASO J2018+3651

LHAASO J1956+2845

LHAASO J1929+1745

LHAASO J1908+0621

LHAASO J1849−0003

LHAASO J1843−0338

LHAASO J1839−0545

LHAASO J1825−1326

Nature 594 (2021) 7861

C.Li and B.-Q.Ma, PRD 104 (2021) 063012, arXiv:2105.07967

LHAASO Observation of Cosmic Photons

versus

Lorentz Violation

- **Highest energy photon (E=1.4 PeV) observed by human being**
- **Strong constraint on superluminal Lorentz violation**
- **Permission for subluminal Lorentz violation**
- **Towards a string theory model for space-time foam**

Model independent LV photon dispersion relation

$$\mathcal{E}^2 = \mathbf{p}^2\left[1 - s_n\left(\frac{|\mathbf{p}|}{E_{\mathrm{LV},n}}\right)^n\right]$$

$$v = 1 - s_n\frac{n+1}{2}\left(\frac{\mathcal{E}}{E_{\mathrm{LV},n}}\right)^n$$

$n = 1$ or 2 ➡ linear and quadratic energy dependenc

s=1 subluminal case; s=-1 superluminal case

L.Shao and B.-Q.Ma, MPLA 25 (2010) 3251

See also, e.g.,

H.Xu, B.-Q.Ma, APP 82 (2016) 72, arXiv: 1607.03203
H.Xu, B.-Q.Ma, PLB 760 (2016) 602, arXiv: :1607.08043
H.Xu, B.-Q.Ma, JCAP 1801 (2018) 050, arXiv: 1801.08084

C.Li and B.-Q.Ma, PRD 104 (2021) 063012, arXiv:2105.07967

Strong Constraint on Superluminal Lorentz Violation

- **Photon decay due to superluminal LV**

$$\gamma \to e^+ + e^-$$

- **Constraint from LHAASO discovery of E=1.42 PeV photon**

$$E_{\rm LV}^{(\rm sup)} \gtrsim 9.57 \times 10^{32}\ {\rm eV} \left(\frac{E_\gamma}{\rm PeV}\right)^3$$

$$E_{\rm LV}^{(\rm sup)} \gtrsim 2.74 \times 10^{24}\ {\rm GeV}$$

- **Stringent constraints on certain LV theories**

- **Support for the space-time foam prediction: no photon decay**

C.Li and B.-Q.Ma, PRD 104 (2021) 063012, arXiv:2105.07967

Strong Constraint on Superluminal Lorentz Violation

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- **More detailed analysis of data by LHAASO Collaboration**

  LHAASO, arXiv:2106.12350

- **Similar analysis on LHAASO data by**

  Chen et al., arXiv: 2105:07927, CPC published

Energy limitation of cosmic photons

from standard special relativity

cosmic photon annihilation with CMB

$$\gamma + \gamma_{CMB} \rightarrow e^{+} + e^{-}$$

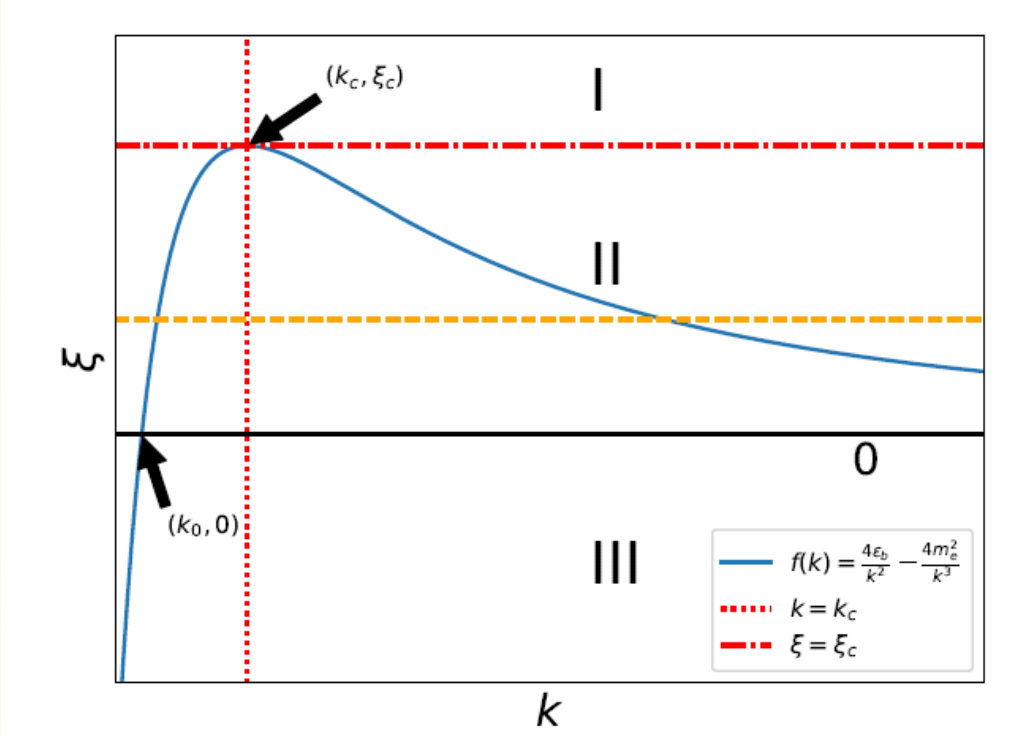
$$4E\varepsilon_{\gamma} \approx (2m_e)^2 \qquad E \sim 4\times10^{14}\ \text{eV}$$

Attenuation of above threshold E=411 TeV photons

H.Li and B.-Q.Ma, JHEAP 32(2021)1, arXiv:2105.06647

$\gamma + \gamma_{CMB} \rightarrow e^+ + e^-$ H.Li and B.-Q.Ma, JHEAP32 (2021)1, arXiv:2105.06647

Threshold Anomalies of Cosmic Photons due to Lorentz Violation



Case I Optical Transparency, $0 < \xi_c^{-1} = E_{LV} < 4.5 \times 10^{23}$ GeV

Case II Reappearance of UHE Photons, $\xi_c^{-1} = E_{LV} > 4.5 \times 10^{23}$ GeV

Case III Threshold Reduction, $\xi_c^{-1} = E_{LV} < 0$

H.Li and B.-Q.Ma, JHEAP32(2021)1, arXiv:2105.06647

Threshold Anomalies of Cosmic Photons due to Lorentz Violation

- **Photon annihilation is forbidden due to subluminal Lorentz violation.**

$$\gamma + \gamma_{CMB} \rightarrow e^+ + e^-$$

- **We predict optical transparency of cosmic photons for subluminal LV scale less than** $\xi_c^{-1} \simeq 4.5 \times 10^{23}\ \mathrm{GeV}$

- **Any observation of above threshold E=411 TeV photons from extragalactic sources can be considered as signals for new physics beyond special relativity.**

C.Li and B.-Q.Ma, PRD 104 (2021) 063012 & Science Bulletin 66 (2021) 2254

Breakthrough: LHAASO discovery of PeV photons

- **Observation of photons with energies above the threshold of photon annihilation process**
- **Permission for the subluminal Lorentz violation:**

  an upper bound with $E_{\rm LV}^{(\rm sub)} < \xi_c^{-1} \simeq 4.5 \times 10^{23}\ \rm GeV$

  are compatible with the observation of PeV photons
- **The sources for the above threshold photons:**

  galactic or extragalactic?
- **Further studies are necessary to identify sources for PeV photons**

C.Li, B.-Q.Ma, PLB (2021) 136443, arXiv:2105.06151

C.Li, B.-Q.Ma, PLB 819 (2021) 136443, arXiv:2105.06515

Predictions of LV features from space-time foam

- Linear energy dependence of light speed variation
- Subluminal Lorentz violation
- Photons are stable, no photon decay
- No birefringence for photon propagation in vacuum

Predictions are consistent with all current observations including a subluminal light speed variation

C.Li and B.-Q.Ma, PRD 104 (2021) 063012 & Science Bulletin 66 (2021) 2254

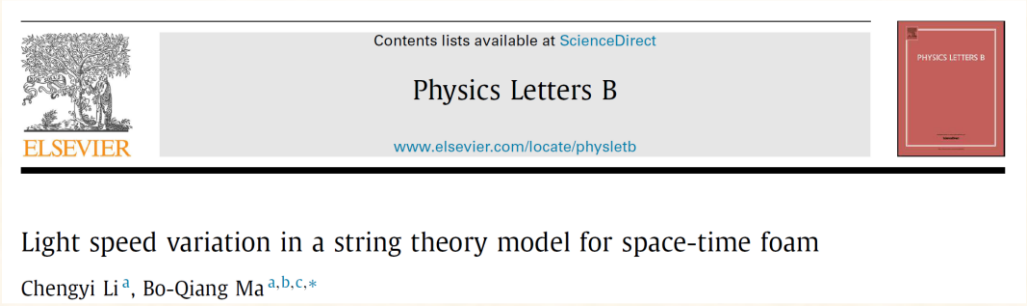
The string theory model of space-time foam

is consistent with current observations
including a subluminal light speed variation around Planck scale
and the LHAASO discovery of cosmic PeV photons

J.R. Ellis, N.E. Mavromatos, M. Westmuckett, Supersymmetric D-brane model of space-time foam, Phys. Rev. D 70 (2004) 044036, https://doi.org/10.1103/PhysRevD.70.044036, arXiv:gr-qc/0405066.

J.R. Ellis, N.E. Mavromatos, D.V. Nanopoulos, Derivation of a vacuum refractive index in a stringy space-time foam model, Phys. Lett. B 665 (2008) 412, https://doi.org/10.1016/j.physletb.2008.06.029, arXiv:0804.3566.

T. Li, N.E. Mavromatos, D.V. Nanopoulos, D. Xie, Time delays of strings in D-particle backgrounds and vacuum refractive indices, Phys. Lett. B 679 (2009) 407, https://doi.org/10.1016/j.physletb.2009.07.062, arXiv:0903.1303.



C.Li, B.-Q.Ma, PLB (2021) 136443, arXiv:2105.06151

Energy limitation of cosmic photons

from standard special relativity

cosmic photon annihilation with EBL (extragalactic background light)

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$$4E\varepsilon_{\gamma} \approx (2m_e)^2 \qquad E \sim 4\times10^{14}\ \mathrm{eV} \Leftarrow \text{CMB}$$

EBL: Attenuation of above threshold E=260 GeV photons

H.Li and B.-Q.Ma, JHEAP 32(2021)1, arXiv:2105.06647

LHAASO Internal Report: KM2A 数据和GRB与AGN的粗略关联

朱杰*, 李哲, 马伯强†

Abstract

我们尝试对从北京时间 2019 年 12 月31 日23:58:50到2020 年 11 月30日23:31:38的KM2A探测器的数据(10TeV-above 1PeV)与GRB、AGN进行关联。其中GRB的信息来自Swift GRB Table [1]，本报告中尝试关联的AGN的信息来自于TeVCat2 [2]。在这个粗略的关联里我们发现这些事例很难与GRB进行关联，在100 TeV以上的事例有可能与AGN进行关联，在10 – 100 TeV有若干AGN可能与事例有关联，这些可能关联的事例能量集中在10 TeV附近。

KM2A数据与GRB的关联

在389TeV以上，没有任何事例和其中一个GRB在1度之内。在100TeV到398TeV区间，存在若干事例和GRB在0.3度之内，但是这些事例与GRB观测到的时间差最少也有12天，根据上述结论在此能段范围内时间差应该在10天以内，因此在此能段没有事例能与GRB关联。

KM2A数据与GRB的关联

在10-100TeV区间

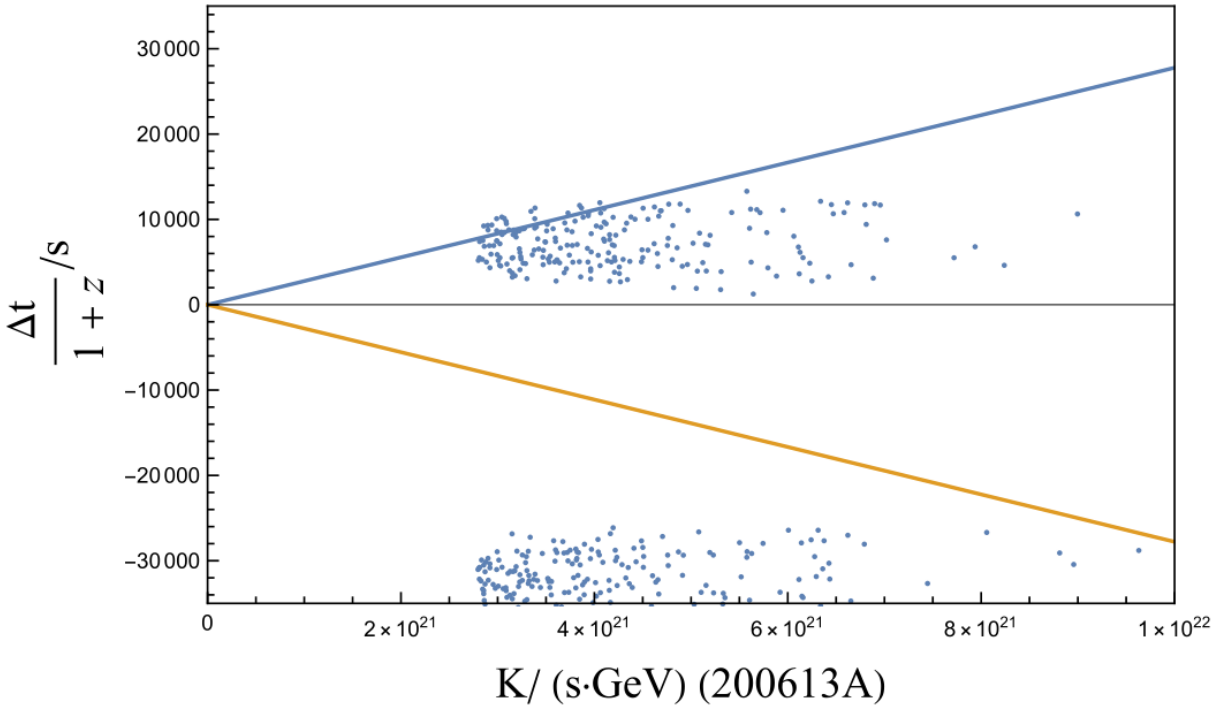


Figure 1: 200613A周围事例的$K-\tau$图

KM2A数据与AGN的关联

Table 1: 398TeV − 1PeV事件与AGN的关联

AGN name	RA1	DEC1	Event time	RA2	DEC2	E(TeV)	d
RGB J0136+391	24.1354	39.1	58949.37555302	25.33	38.93	454.97	0.94
HESS J1943+213	295.979	21.3022	59089.51884009	296.	21.12	568.38	0.18

398TeV − 1PeV事件与AGN的关联表格。前三列是关联的AGN的名称(AGN name)与位置(RA1, DEC1)，第四到第七列为事件的时间(Event time)、位置(RA2, DEC2)与能量(E)信息，最后一列(d)为事件与AGN的角度距离。其中位置与距离(RA1, DEC1, RA2, DEC2, d)的单位为度，事件的时间为MJD，事件能量单位为TeV。

KM2A数据与AGN的关联

Table 2: 100 – 398TeV事件与AGN的关联

AGN name	RA1	DEC1	Event time	RA2	DEC2	E(TeV)	d
1ES 0033+595	8.82	59.79	59155.76583021	9.2	59.59	155.57	0.28
1ES 1440+122	220.813	12.0031	59130.19028049	221.08	11.88	135.93	0.29
1ES 2344+514	356.767	51.7136	58991.00424211	357.04	51.74	129.78	0.17
H 1722+119	261.268	11.8708	59123.33355175	261.17	11.72	145.36	0.18
IC 310	49.1792	41.3247	59068.93742090	49.27	41.4	108.58	0.10
M 87	187.697	12.3975	58948.56822079	187.65	12.39	102.86	0.046
MAGIC J2001+435	300.315	43.879	58861.20711016	300.66	43.83	118.54	0.25
Markarian 501	253.468	39.7603	58882.90036784	253.85	39.73	105.53	0.30
NGC 1275	49.9504	41.5117	58904.50013662	50.15	41.68	105.56	0.22
OT 081	267.887	9.6502	58967.78222011	267.9	9.57	140.21	0.081
PGC 2402248	113.361	51.8983	58868.66202317	113.6	52.06	100.26	0.22
PGC 2402248	113.361	51.8983	59179.96747670	113.07	51.68	152.52	0.28
RBS 0413	49.9458	18.7617	59133.66266330	50.04	18.67	142.45	0.13
S3 1227+25	187.559	25.3019	58895.92179841	187.76	25.12	142.85	0.26
TON 0599	179.883	29.2456	58883.96276228	179.78	29.38	131.38	0.16
TON 0599	179.883	29.2456	59023.61919995	180.	29.01	120.88	0.26
W Comae	185.382	28.2331	59005.48300778	185.42	27.99	127.99	0.25

KM2A数据与AGN的关联

$10 - 100$ TeV

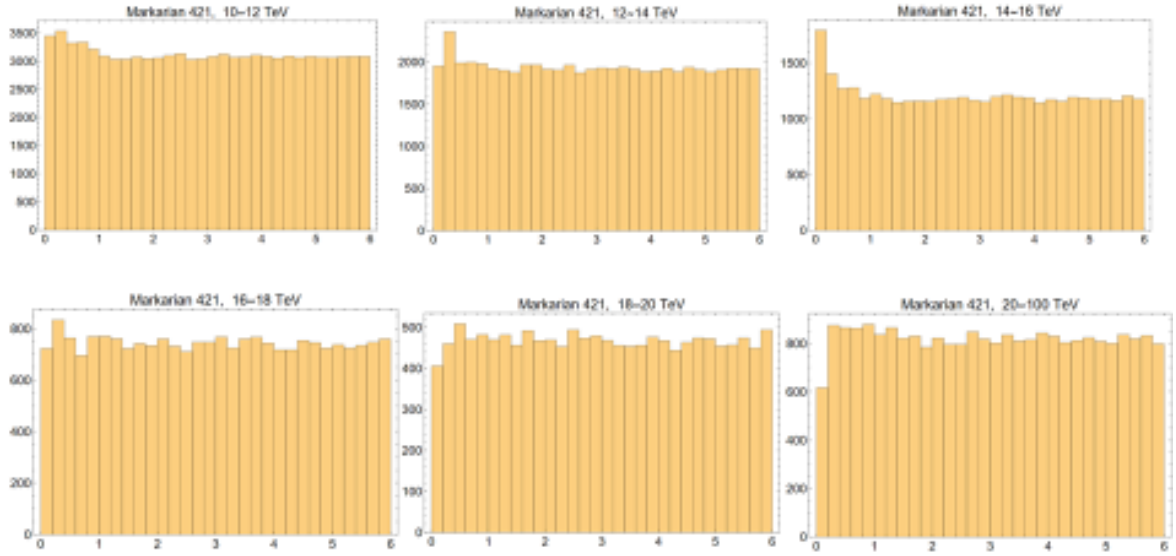
对TeVCat上面列举出的AGN进行上述判定操作，发现14个AGN可能与观测事例相关联，具体如下：

KM2A数据与AGN的关联

2.2.7 Markarian 421

Markarian 421，坐标为(166.079, 38.1947)(J2000)，红移0.031。得益于其极小的红移，此AGN在10-20TeV及其内部多能段超出特别明显，故认为有所关联。在20TeV以上可能有微弱超出(图8)。

Markarian 421, z=0.031

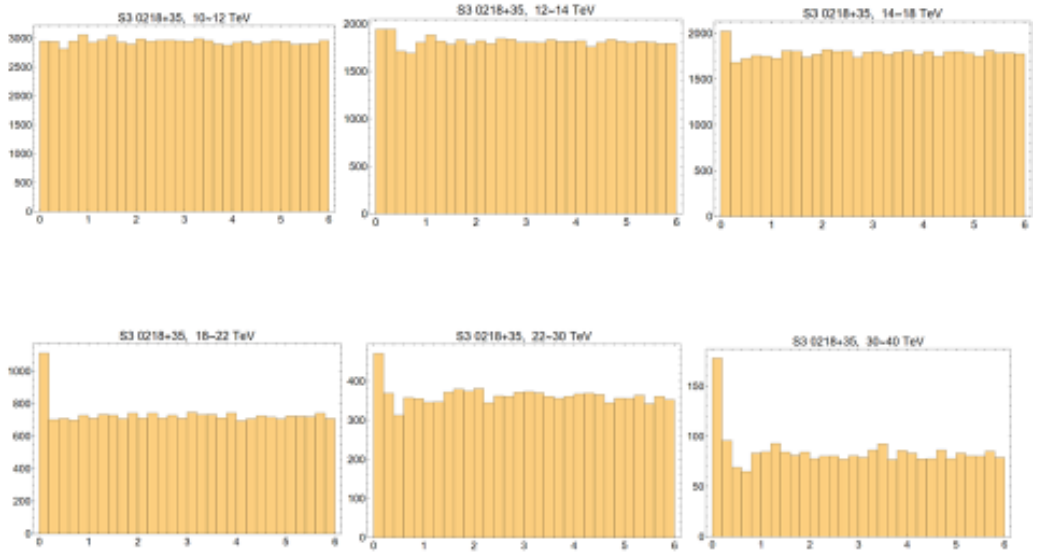


KM2A数据与AGN的关联

2.2.12 S3 0218+35

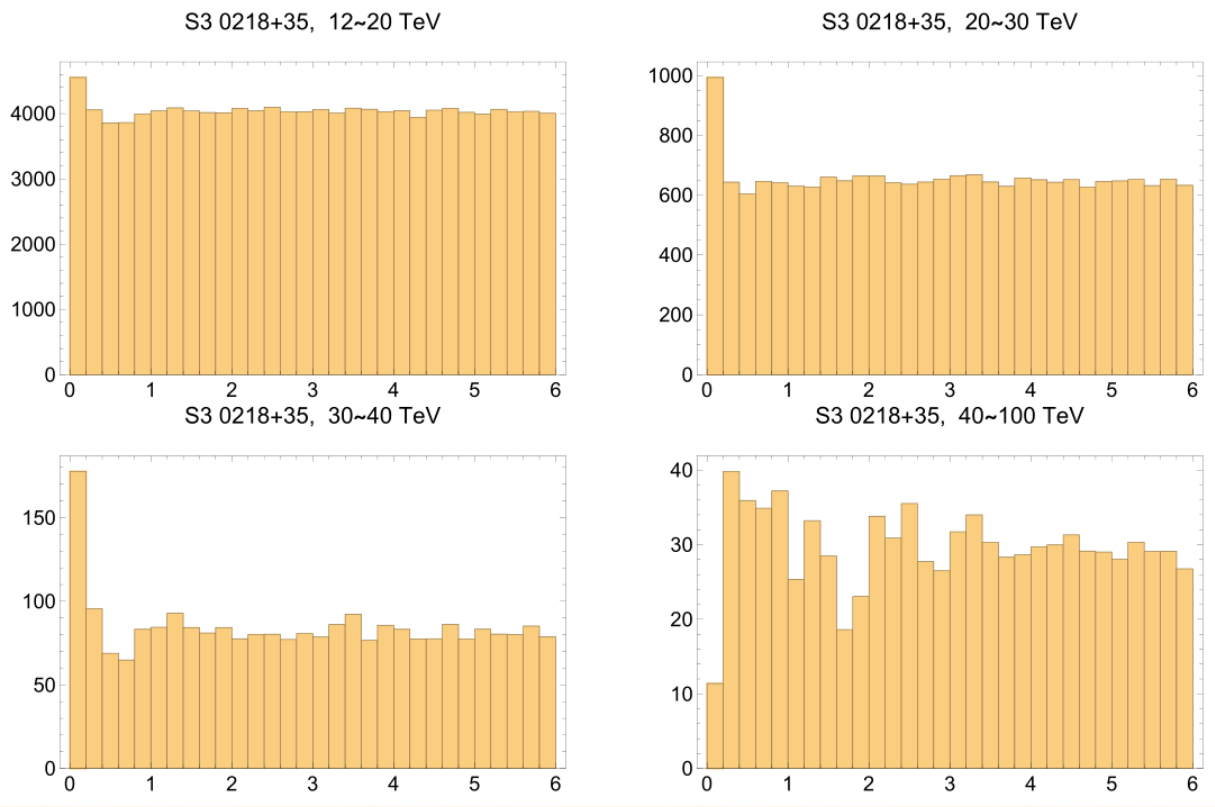
S3 0218+35，坐标为(35.2729, 35.9372)(J2000)，红移0.954。此AGN在12-20TeV、20-30TeV、30-40TeV均有超出，40TeV以上超出不明显(图13)。此超出均集中在0.2度内。注意到这个AGN红移如此之大，很有可能给出洛伦兹破缺的结果。

S3 0218+35 , z=0.954



KM2A数据与AGN的关联

S3 0218+35 , z=0.954



TeV J0218+359 SIMBAD

TeVCat Name:	TeV J0218+359
Common Name:	S3 0218+35
Other Names:	B2 0218+35, QSO B0218+357
Discovery Date:	2014-05-14
Source Tags:	XGal AGN Blzr FSRQ
Wavebands:	
Other Catalogs:	
TeVCat Subcatalog:	Default Catalog
Seen By:	MAGIC

Position Info:

RA (HH MM SS):	02 21 05.5	± No Data
Dec (DD MM SS):	+35 56 14	± No Data
Gal. Long. (deg):	142.6018	
Gal. Lat. (deg):	-23.4867	

Distance Info:

Redshift:	0.954	± No Data

[Show Comment] [Show Cite]

Morphology Info:

Source is extended?:	false

Flux Info:

Source is variable?:	false	
Flux (Crab %)	30.000	
Energy Thresh (GeV):	100	
Spectral Index:	3.8	± 0.61

Energy limitation of cosmic photons

from standard special relativity

cosmic photon annihilation with EBL (extragalactic background light)

$$\gamma\gamma_{\mathrm{b}} \rightarrow e^{+}e^{-}$$

$$4E\varepsilon_{\gamma} \approx (2m_e)^2 \qquad E \sim 4\times10^{14}\ \mathrm{eV} \Leftarrow \text{CMB}$$

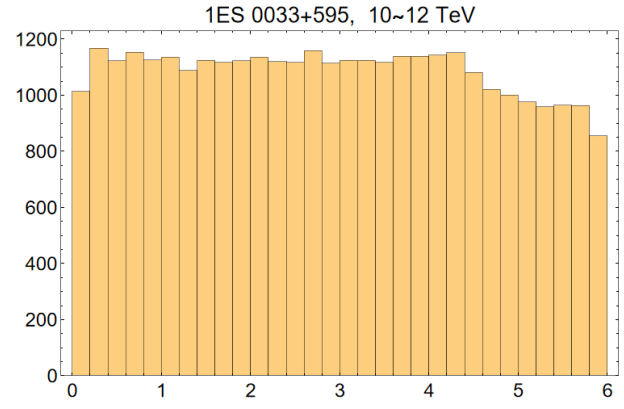
EBL: Attenuation of above threshold E=260 GeV photons

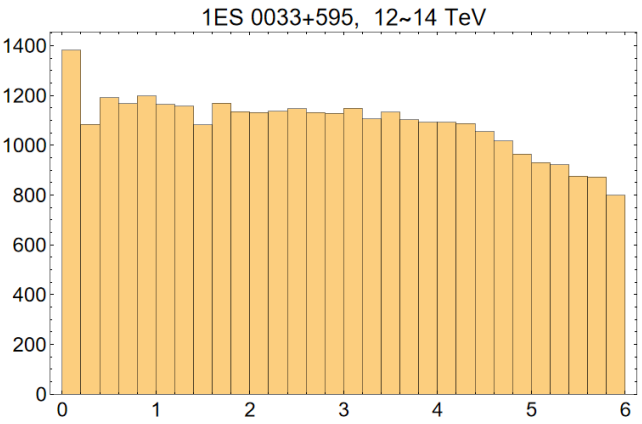
H.Li and B.-Q.Ma, JHEAP 32(2021)1, arXiv:2105.06647

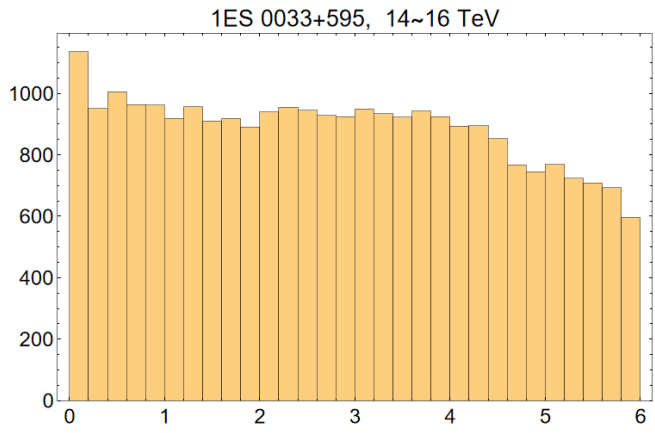
注释:

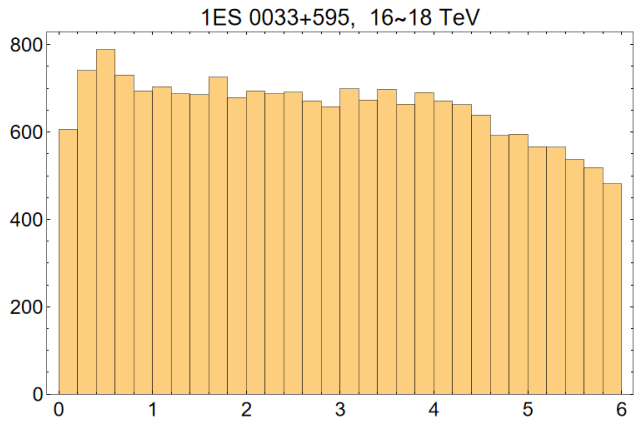
- 直方图的含义是把事例与AGN的距离按照 1/距离 的权重填充至直方图，横坐标为事例与AGN的距离，单位为度，纵坐标为填充数，单位 1/度；
- 在背景近似为空间均匀分布的情况下，在小角度若无信号，则直方图应该为平直的，当事例与AGN有关联时，原点附件会有超出；
- 在这种填充方式下，与AGN非常靠近的事例的贡献会很大，这种填充方式会放大与AGN特别靠近的事例的信号，但特别靠近AGN的背景可能会造成影响，这里筛选的AGN在各个能量范围都有超出以排除可能的背景影响
- 这种判别方式是一个快速而又粗糙的检验手段，有可能会误判，需要专业手段进一步检验。

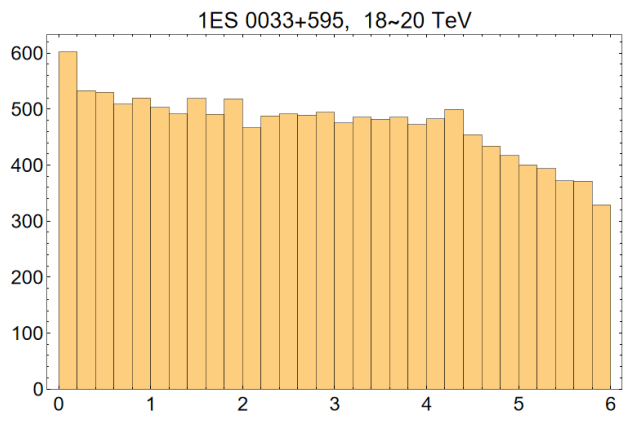
1ES 0033+595, z=0.467

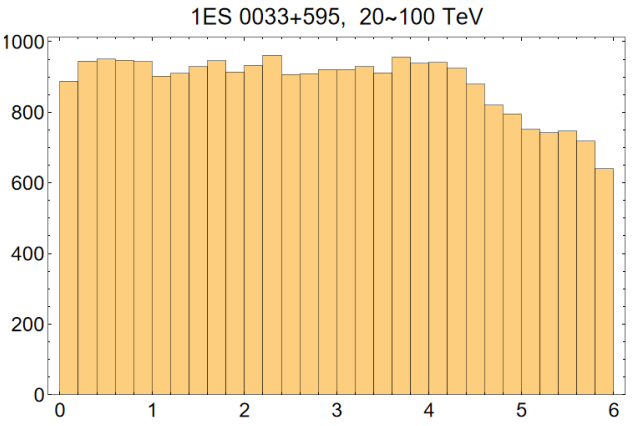




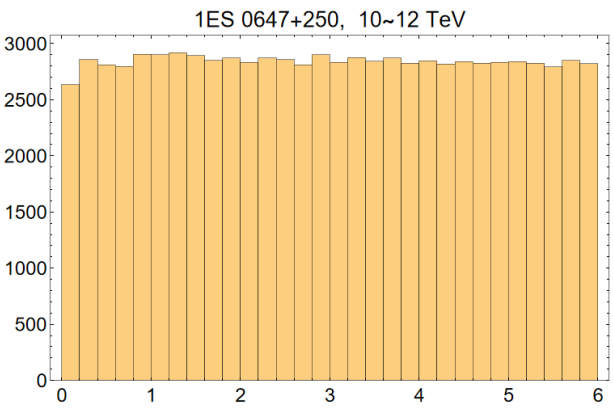


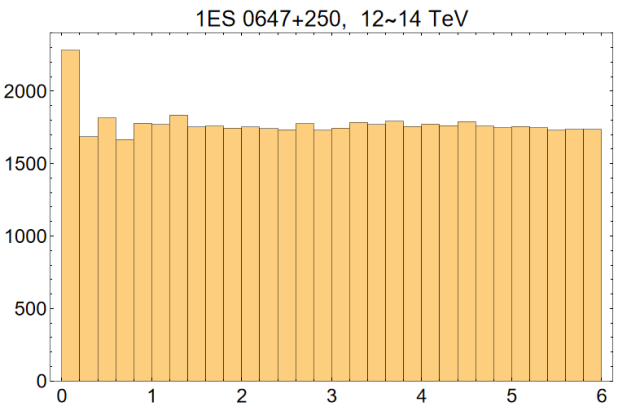


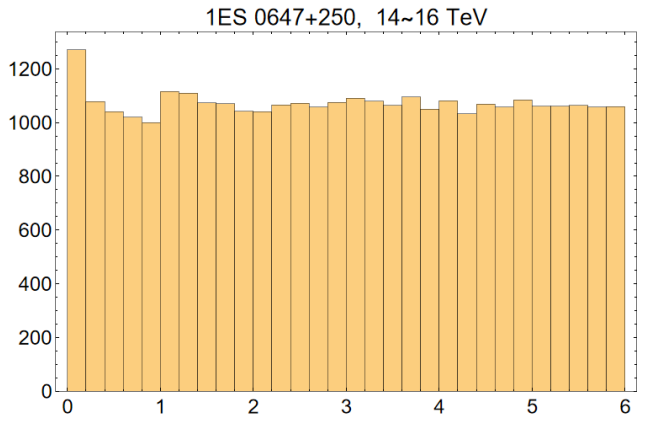


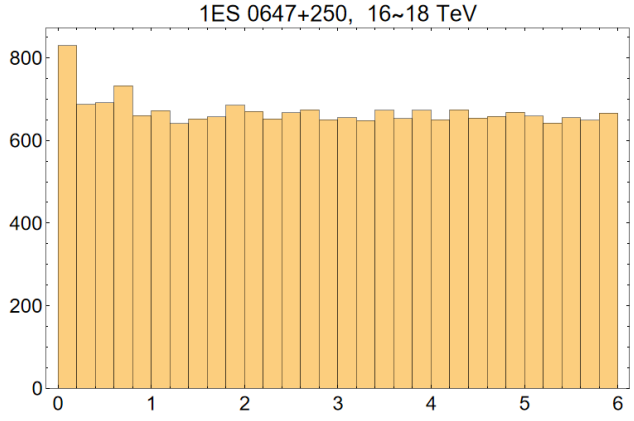


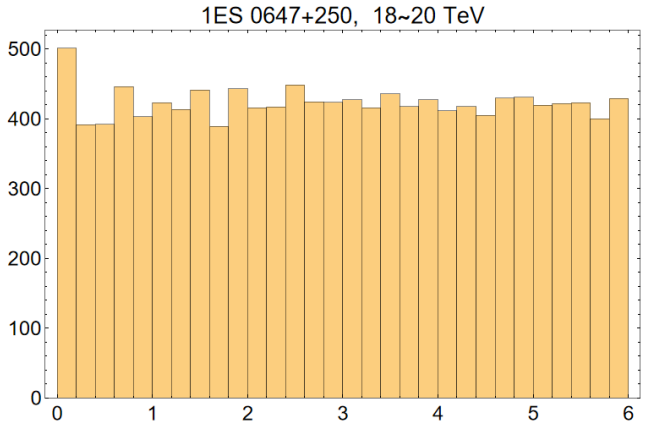
1ES 0647+250

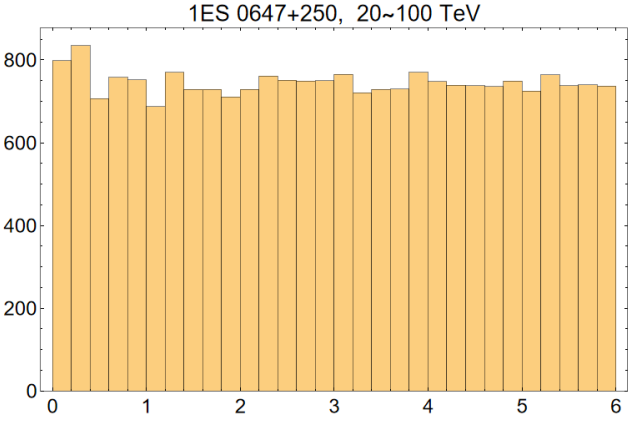

1ES 0647+250, 10~12 TeV
3000
2500
2000
1500
1000
500
0
0 1 2 3 4 5 6


1ES 0647+250, 12~14 TeV
2000
1500
1000
500
0
0 1 2 3 4 5 6

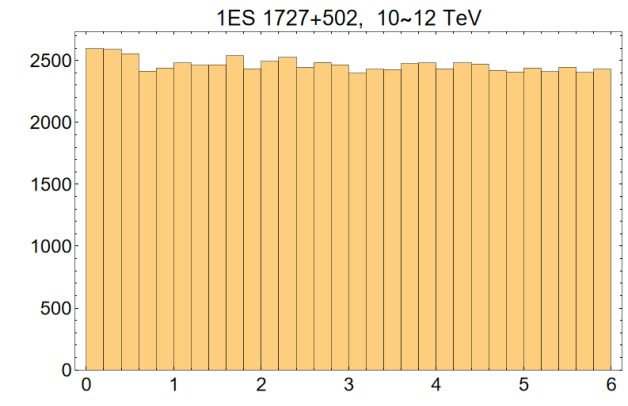

1ES 0647+250, 14~16 TeV
1200
1000
800
600
400
200
0
0 1 2 3 4 5 6

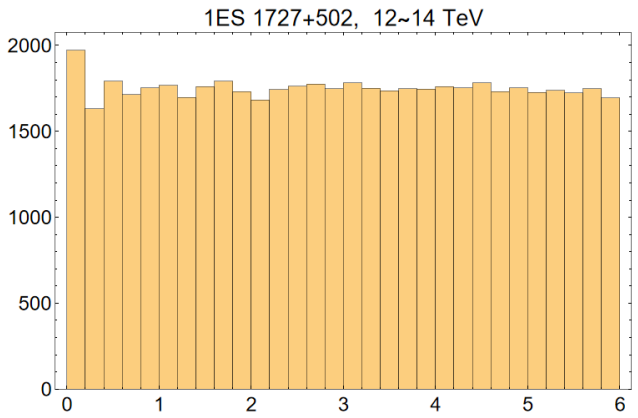

1ES 0647+250, 16~18 TeV
800
600
400
200
0
0 1 2 3 4 5 6

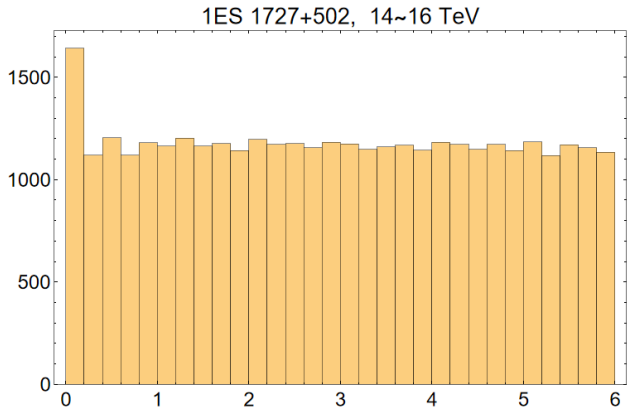

1ES 0647+250, 18~20 TeV
500
400
300
200
100
0
0 1 2 3 4 5 6

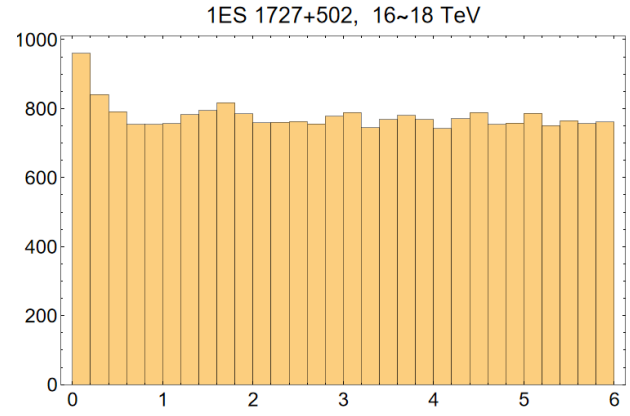

1ES 0647+250, 20~100 TeV
800
600
400
200
0
0 1 2 3 4 5 6

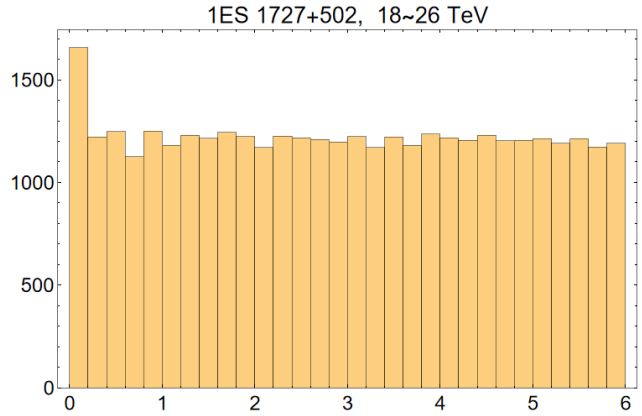
1ES 1727+502, z=0.055

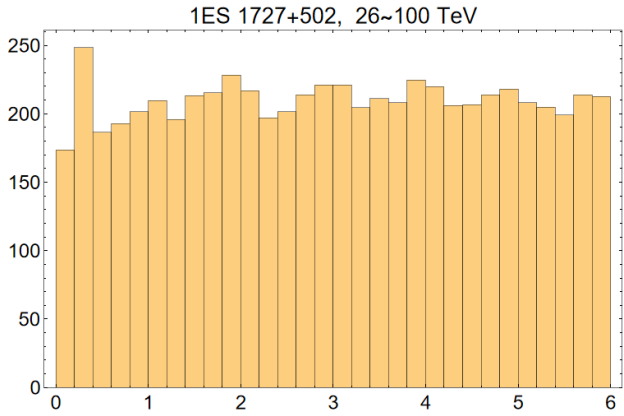




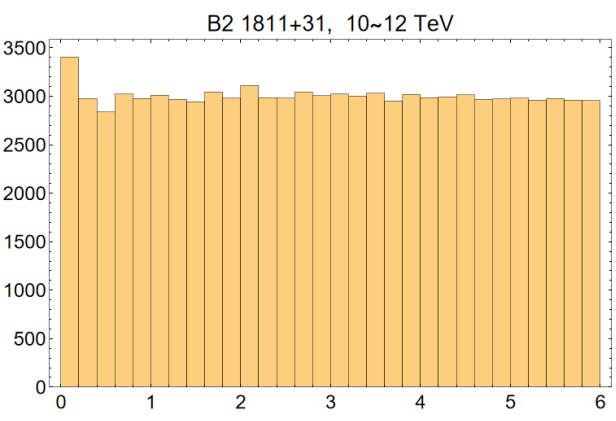


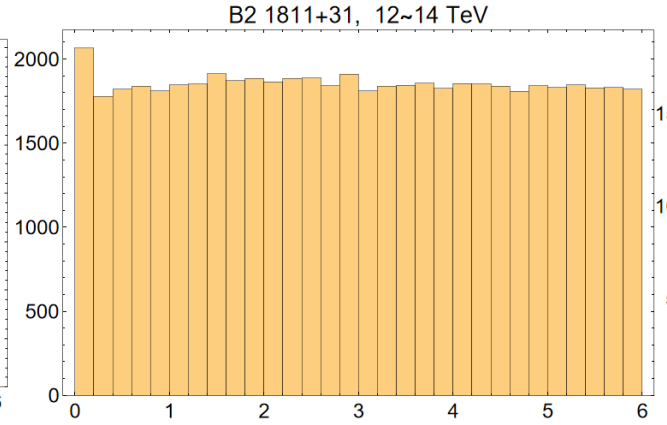


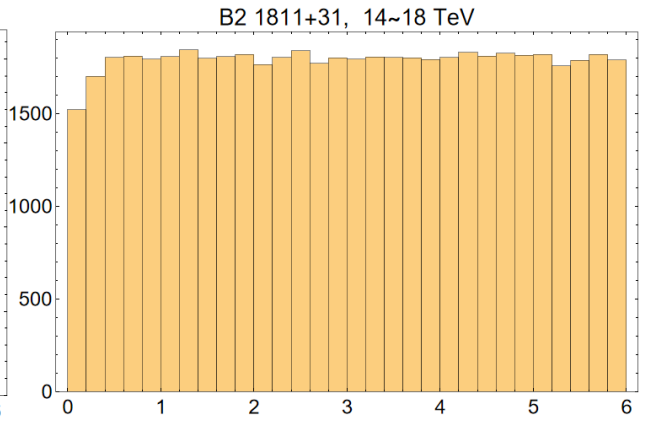


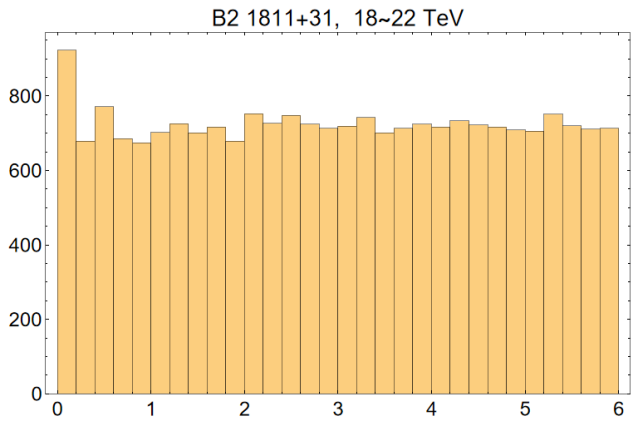


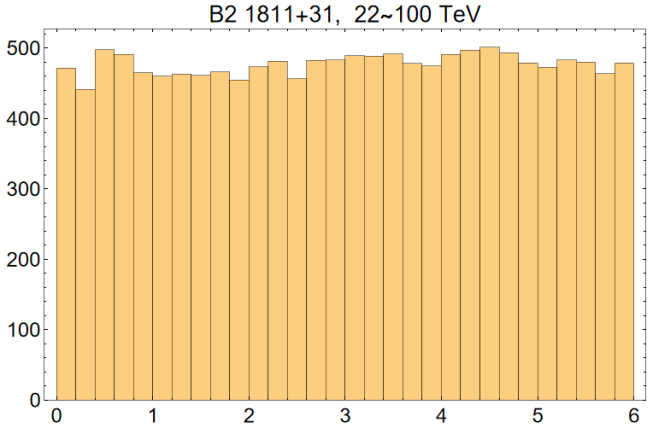
B2 1811+31, z=0.117



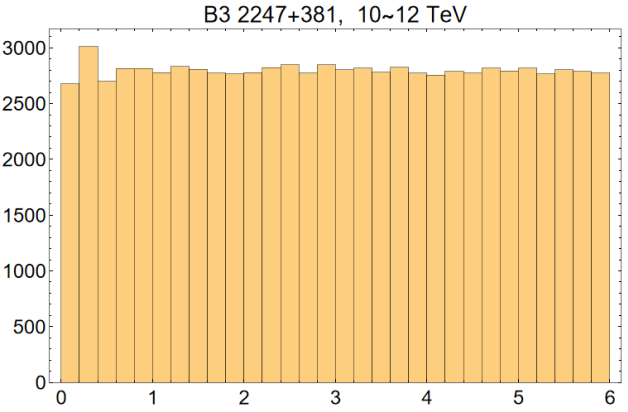


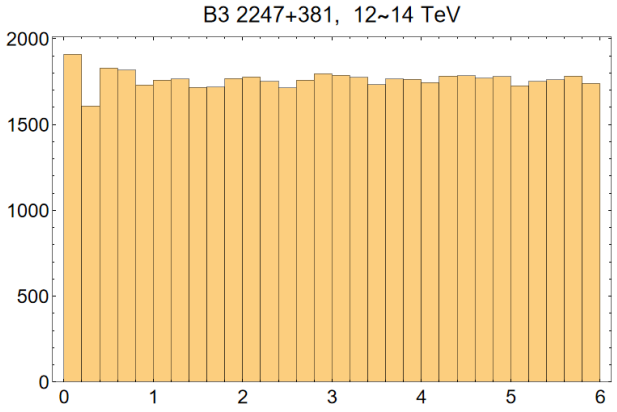


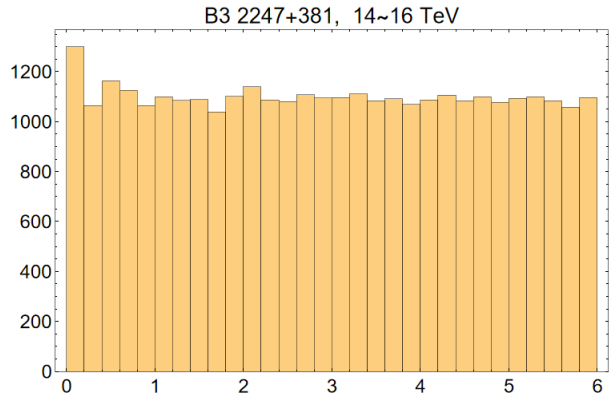


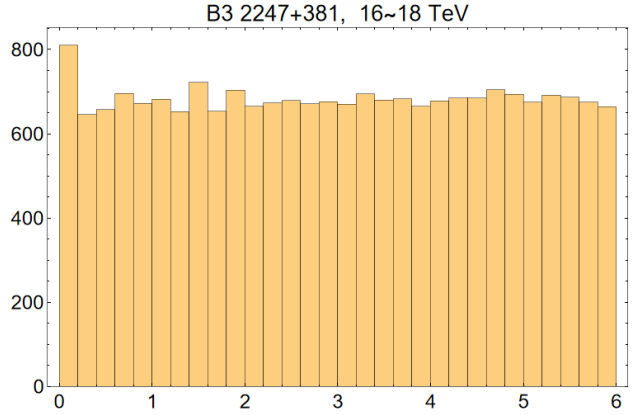


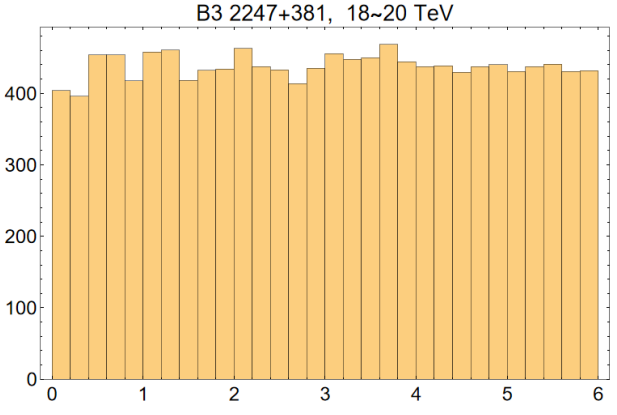
B3 2247+381, z=0.1187

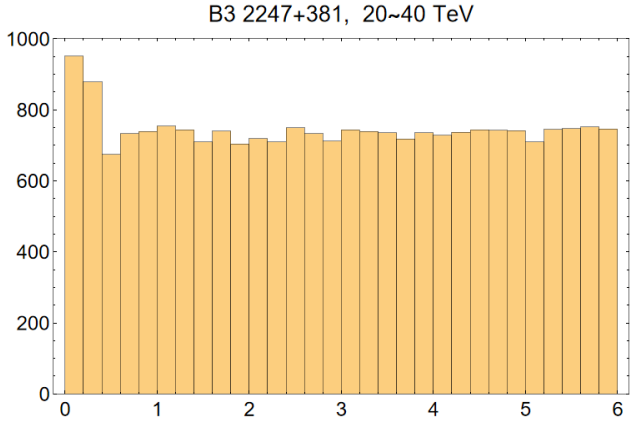




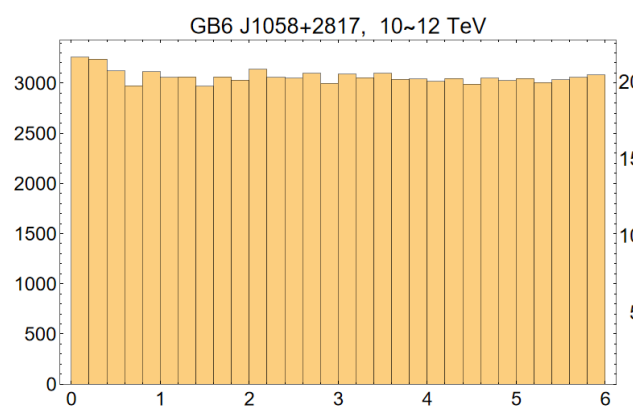


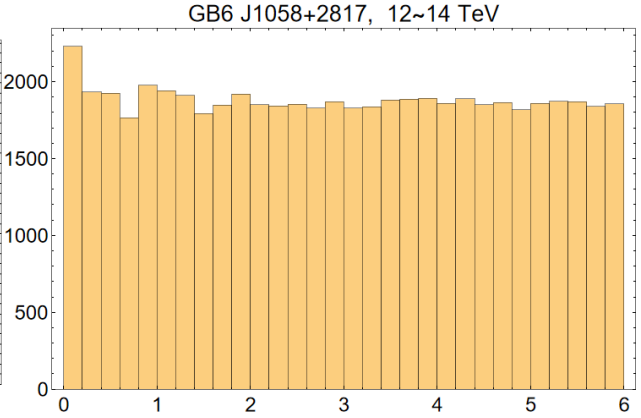


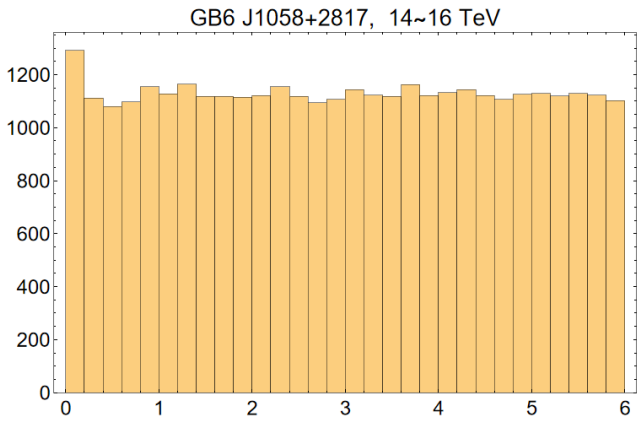


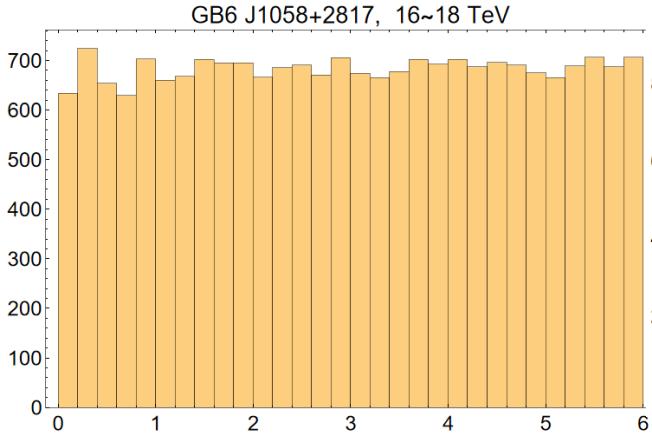


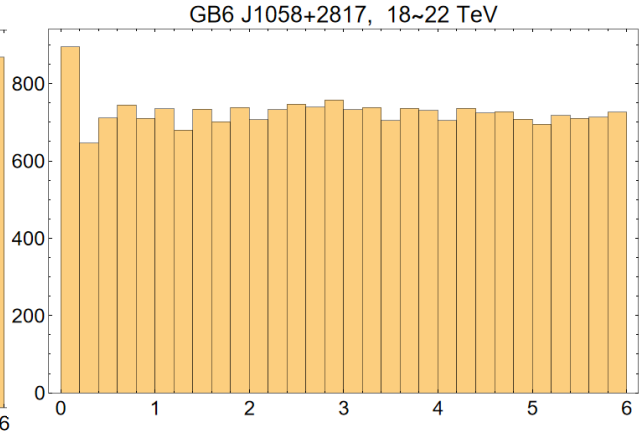
GB6 J1058+2817

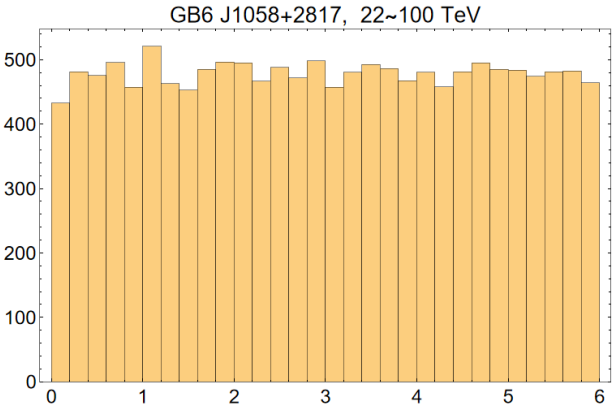




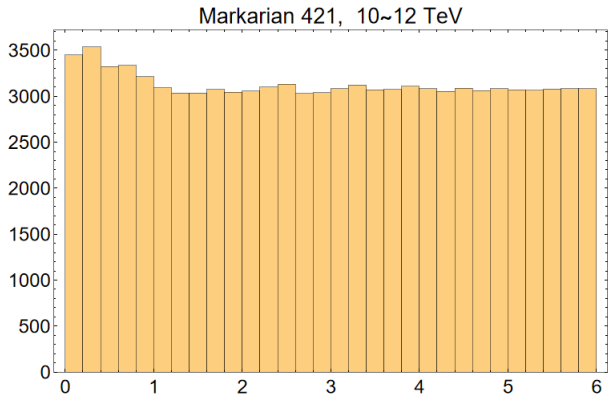


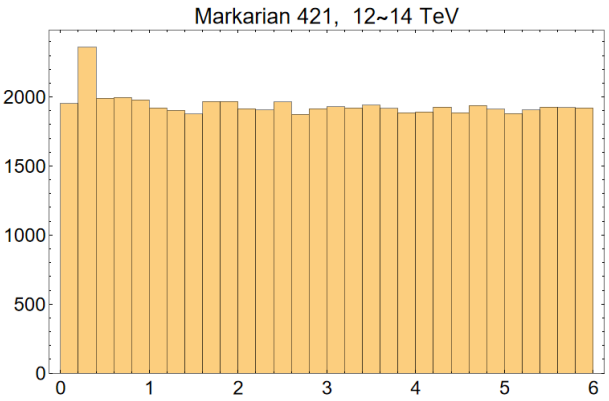


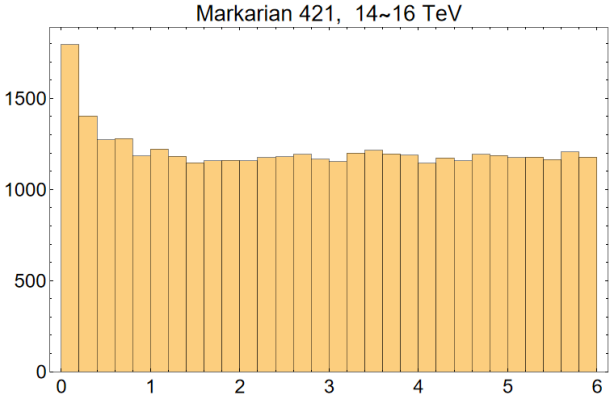


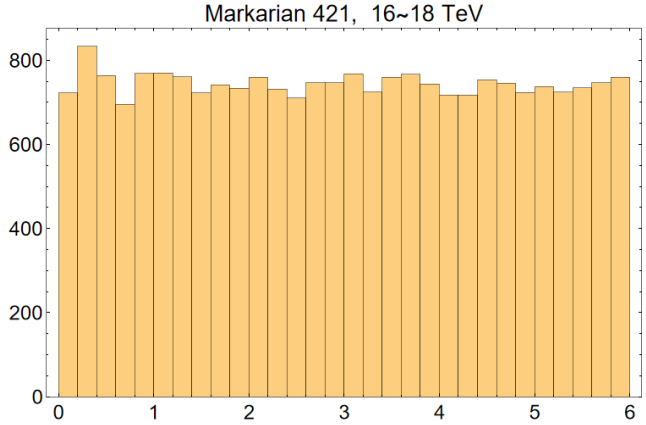


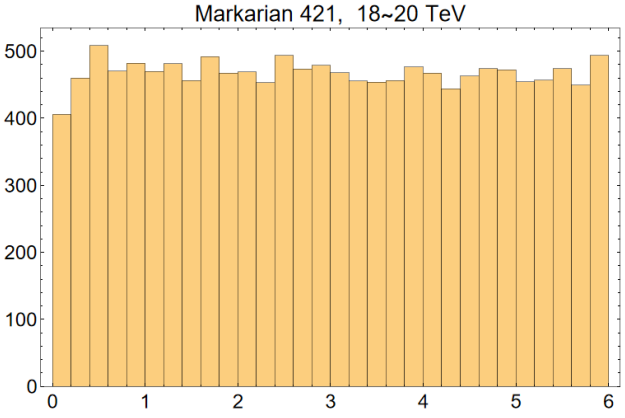
Markarian 421, z=0.031

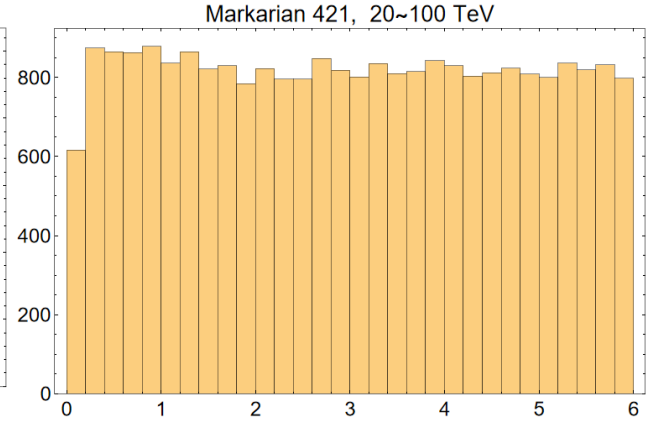




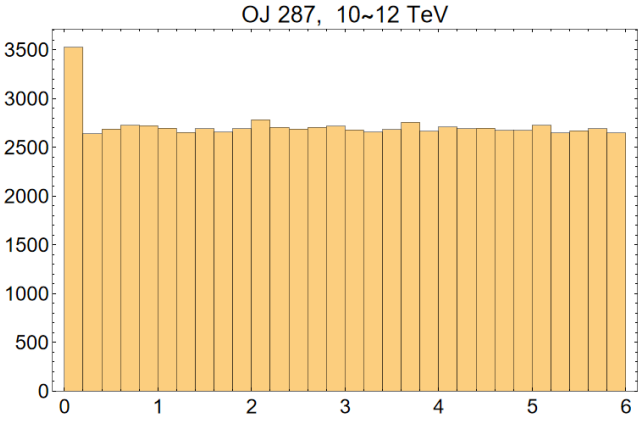


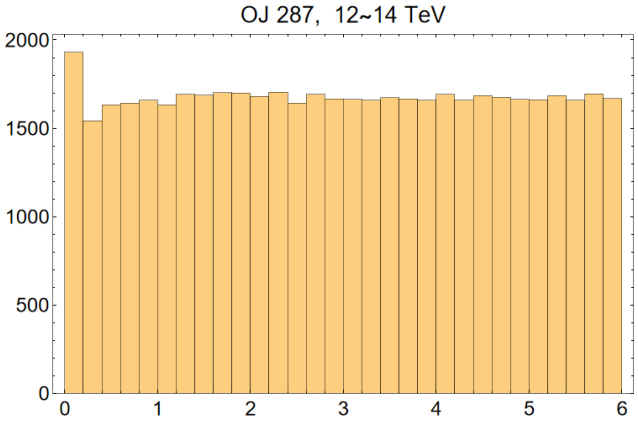


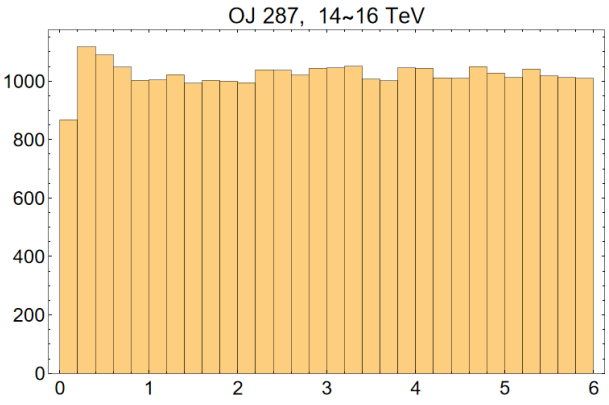


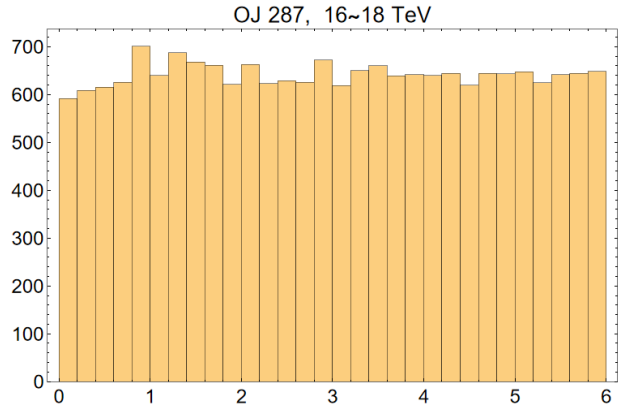


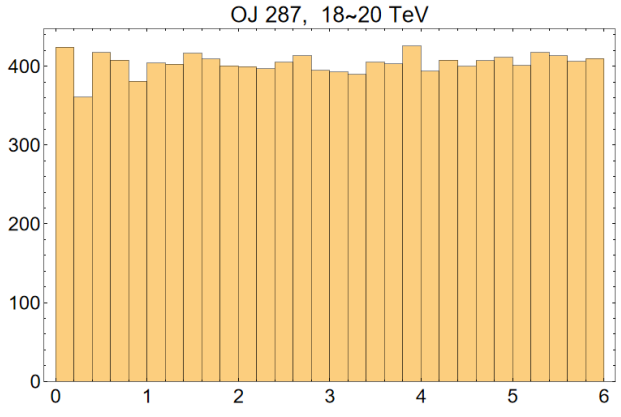
OJ 287, z=0.3056

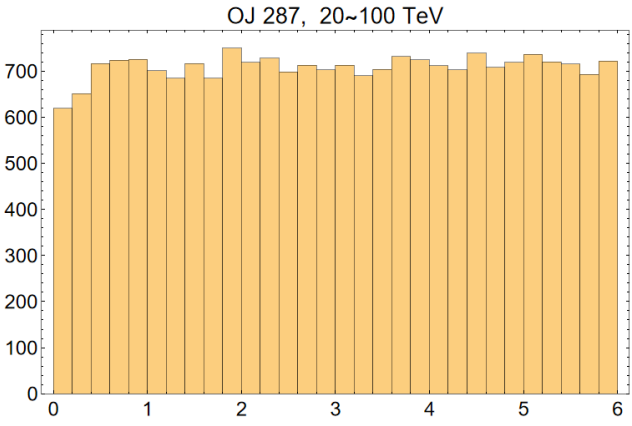




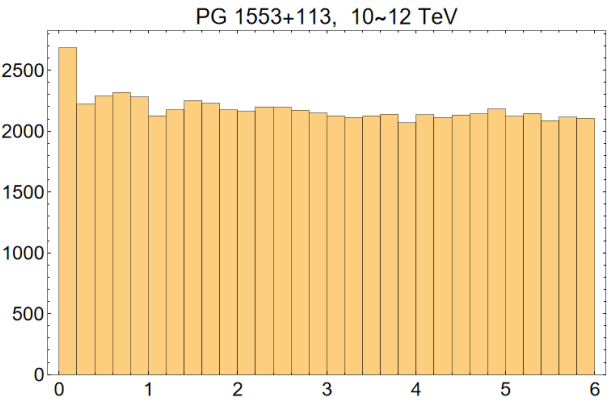


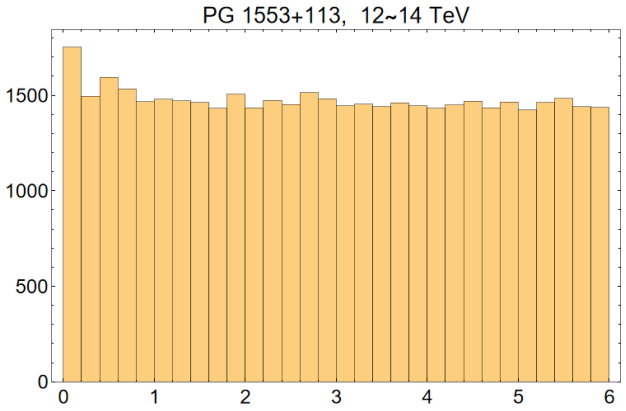


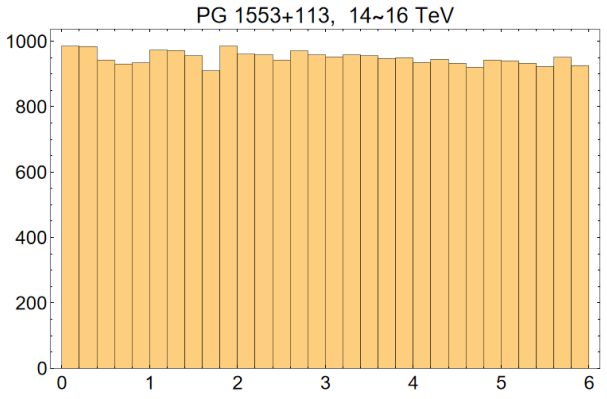


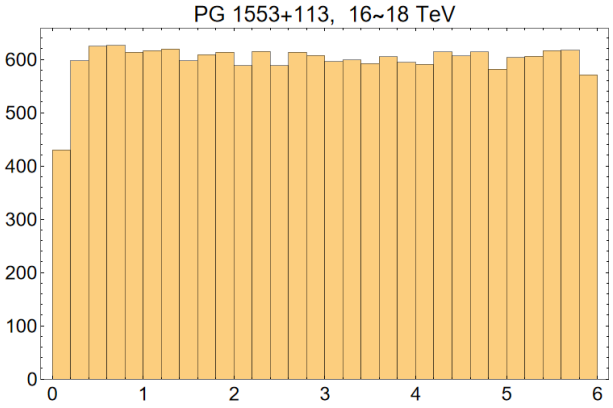


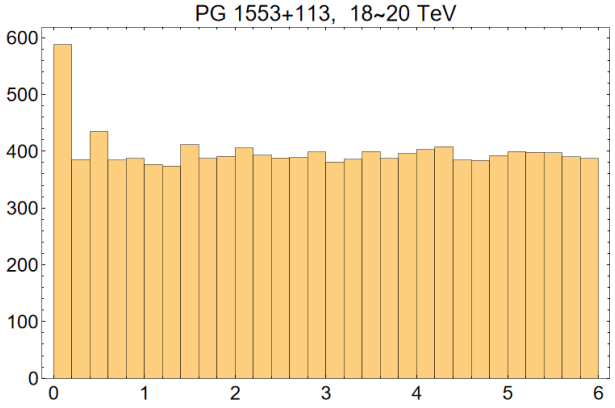
PG 1553+113, z=0.5

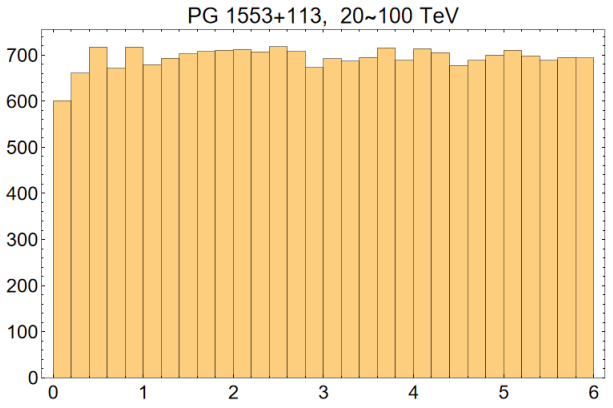




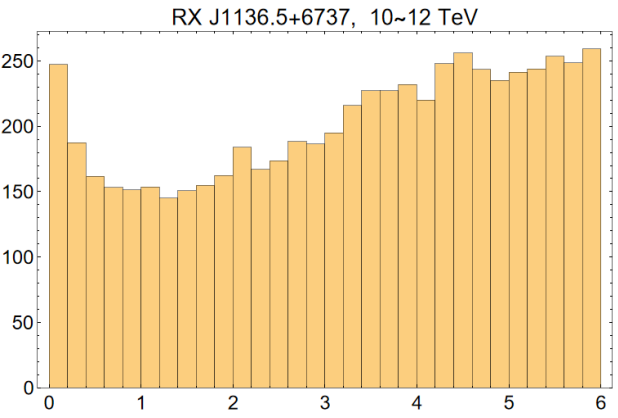


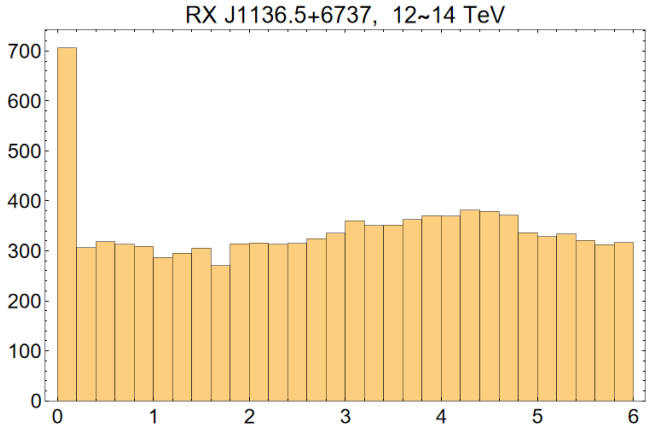


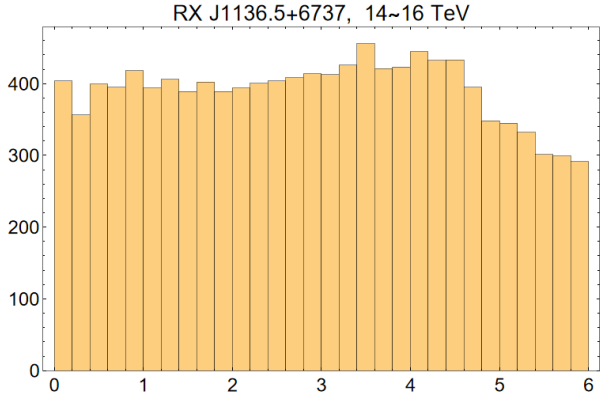


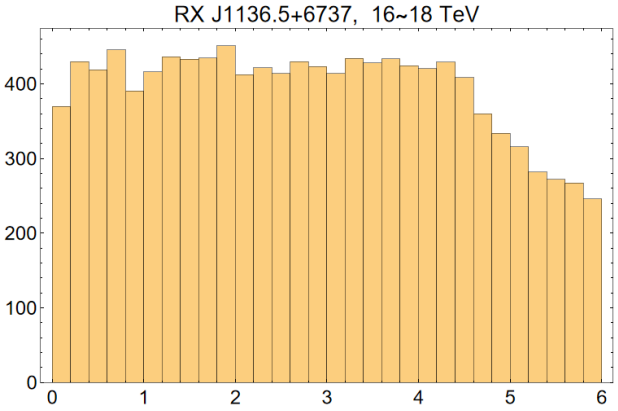


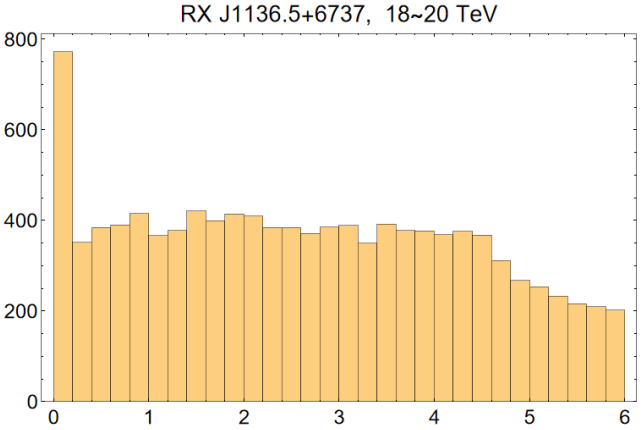
RX J1136.5+6737, z=0.1342

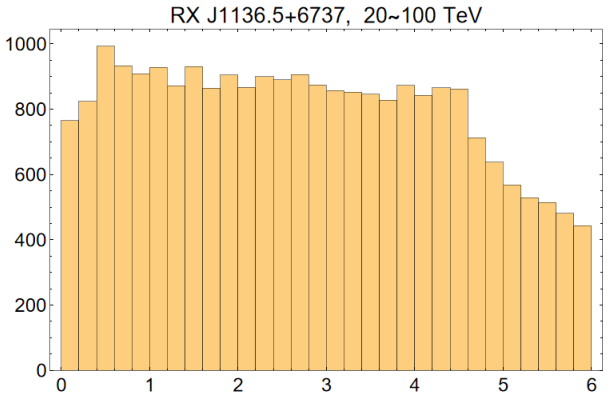




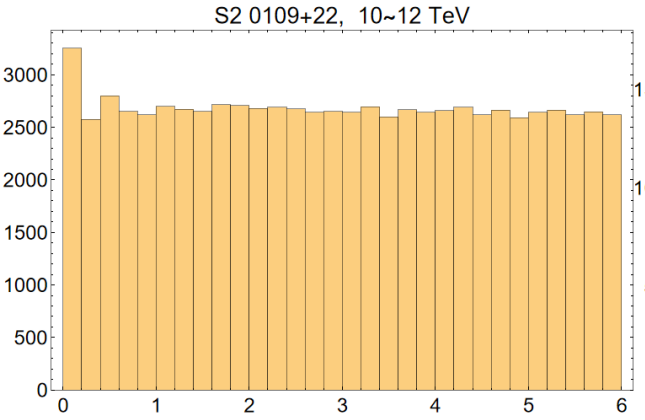


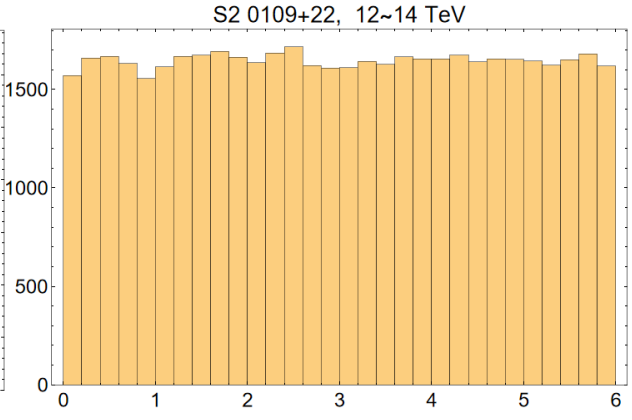


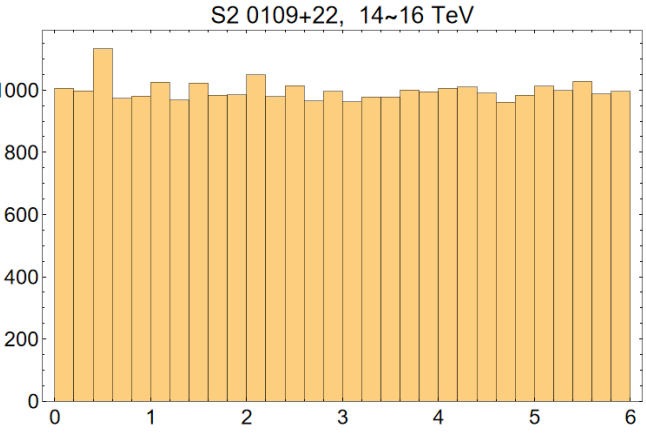


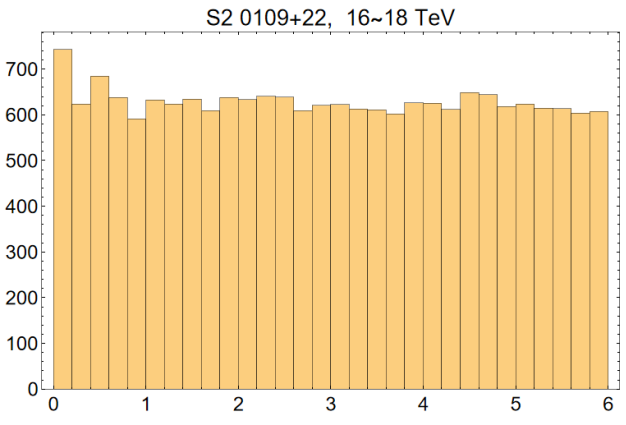


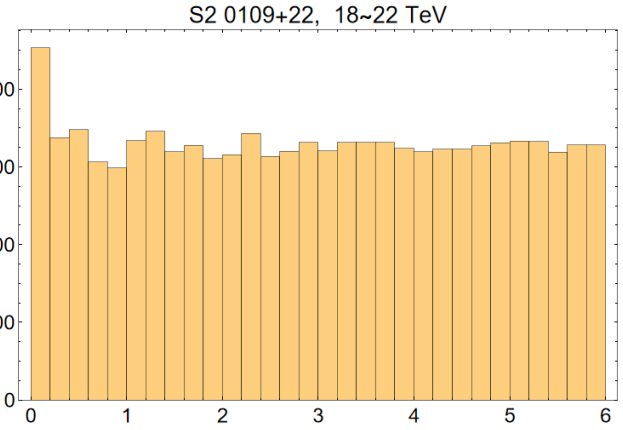
S2 0109+22

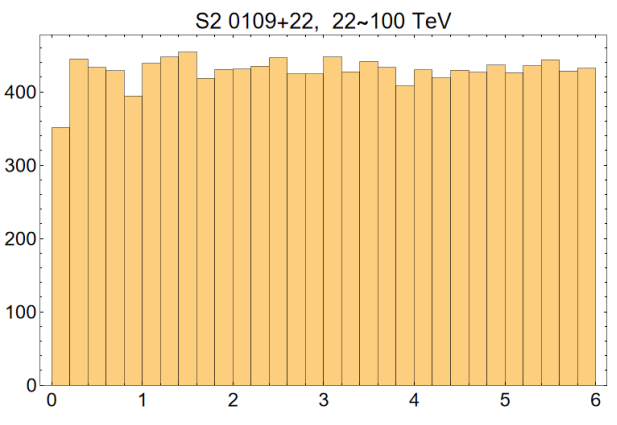

S2 0109+22, 10~12 TeV
3000
2500
2000
1500
1000
500
0
0 1 2 3 4 5 6


S2 0109+22, 12~14 TeV
1500
1000
500
0
0 1 2 3 4 5 6

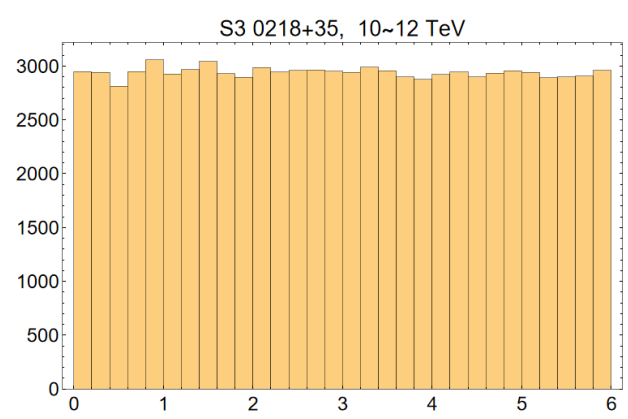

S2 0109+22, 14~16 TeV
1000
800
600
400
200
0
0 1 2 3 4 5 6

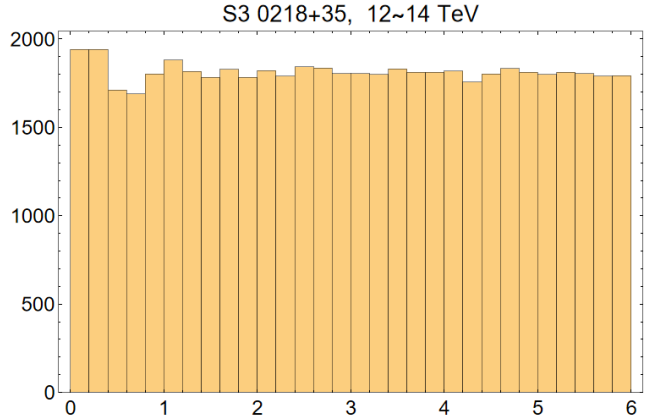

S2 0109+22, 16~18 TeV
700
600
500
400
300
200
100
0
0 1 2 3 4 5 6

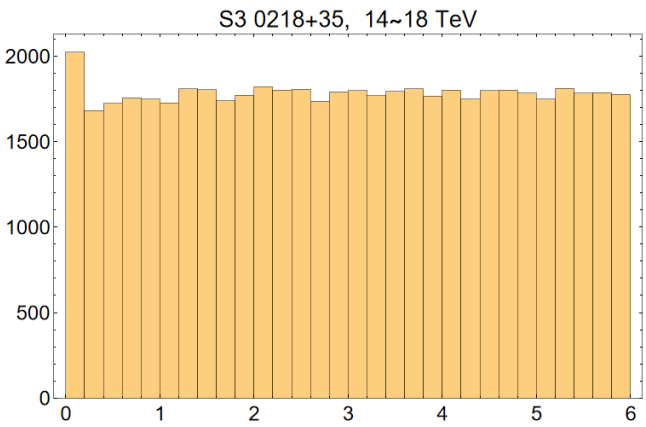

S2 0109+22, 18~22 TeV
800
600
400
200
0
0 1 2 3 4 5 6

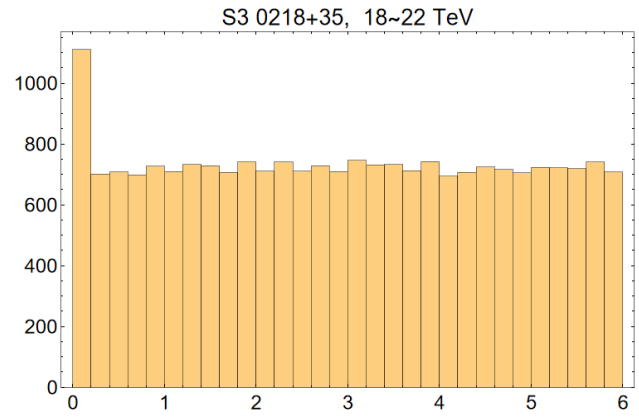

S2 0109+22, 22~100 TeV
400
300
200
100
0
0 1 2 3 4 5 6

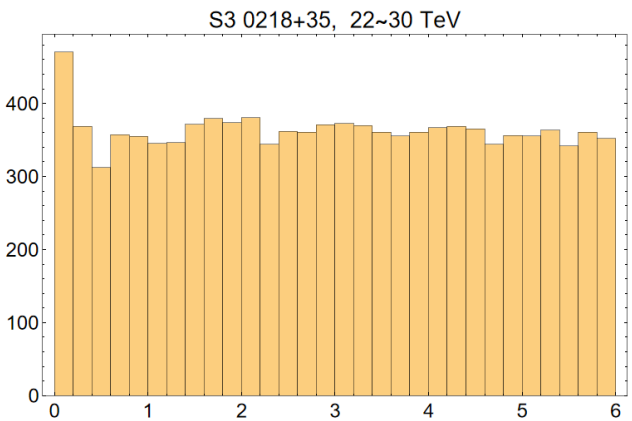
S3 0218+35 , z=0.954

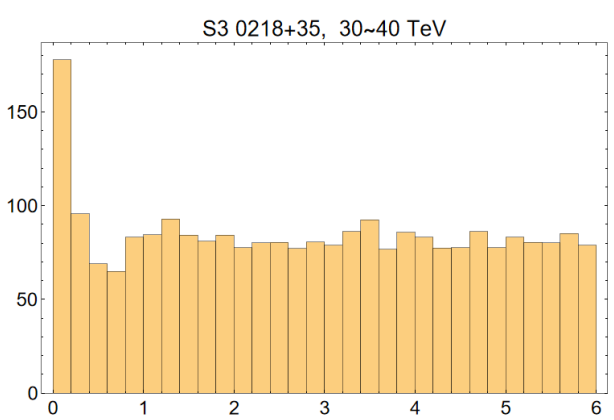




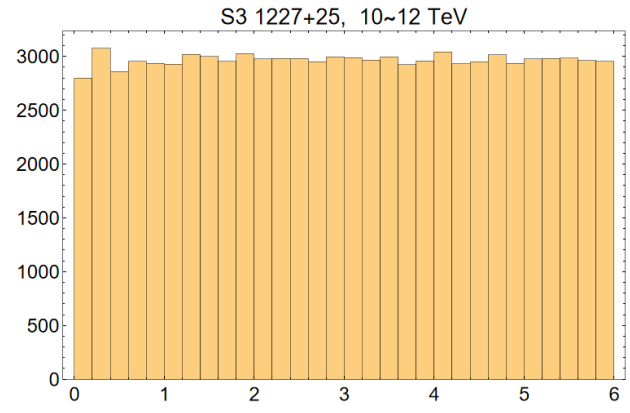


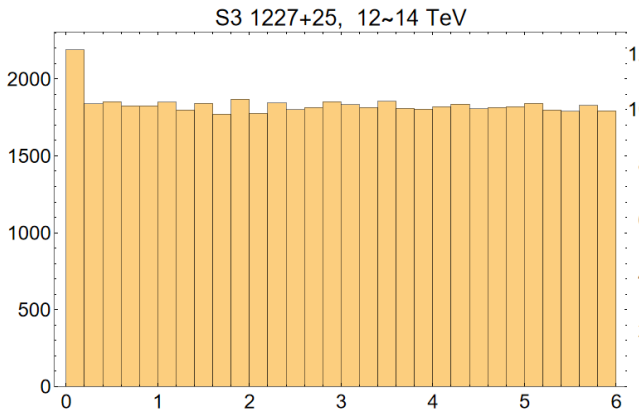


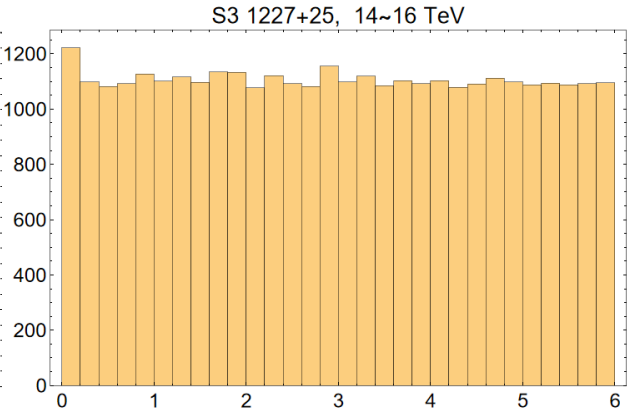


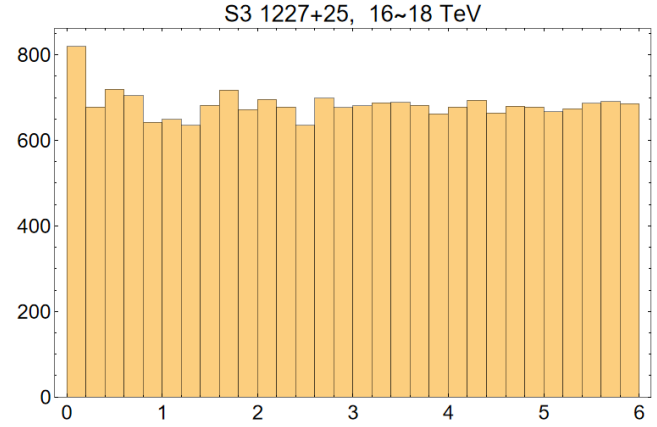


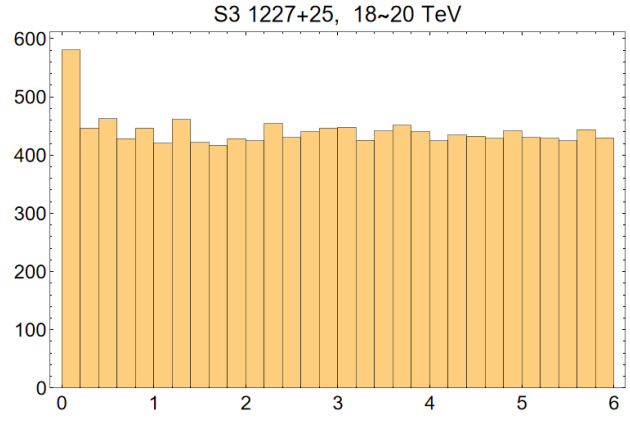
S3 1227+25, z=0.135

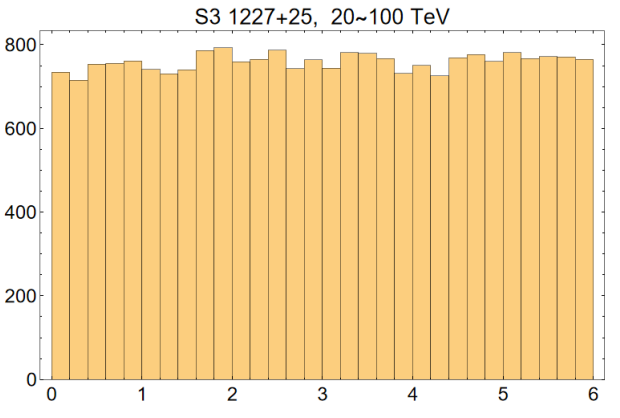




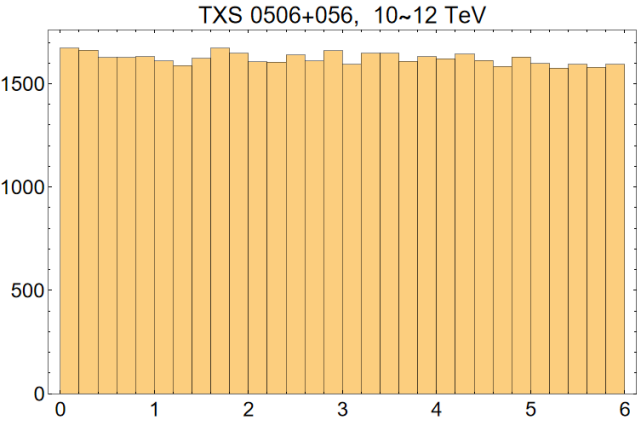


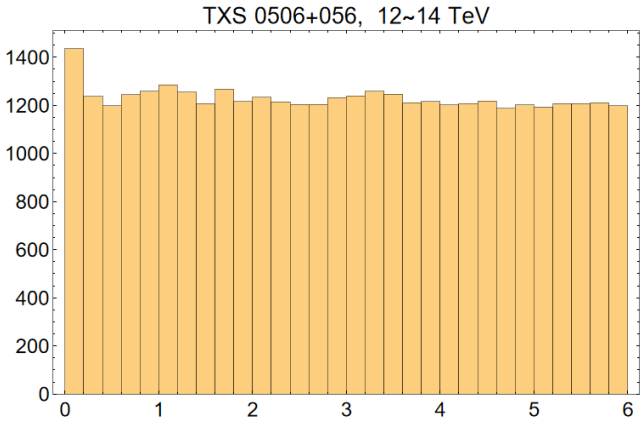


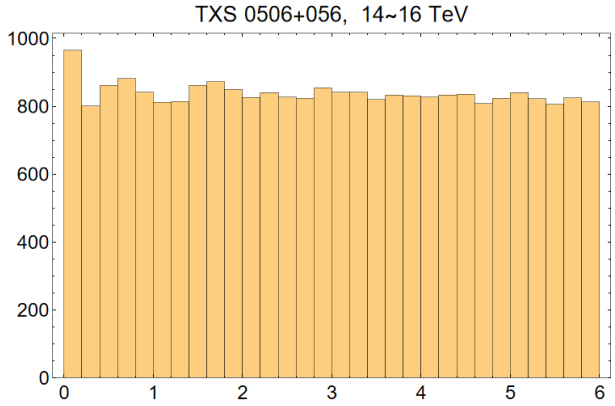


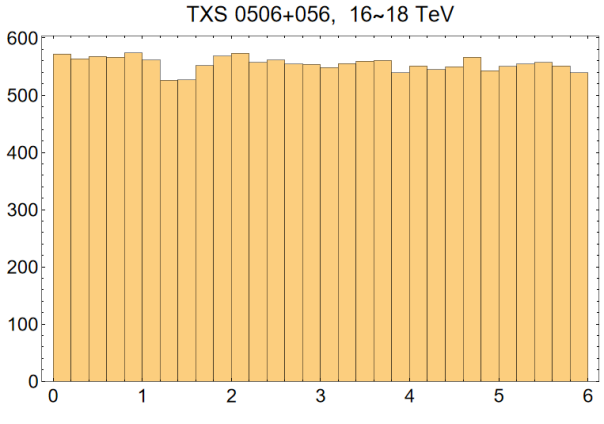


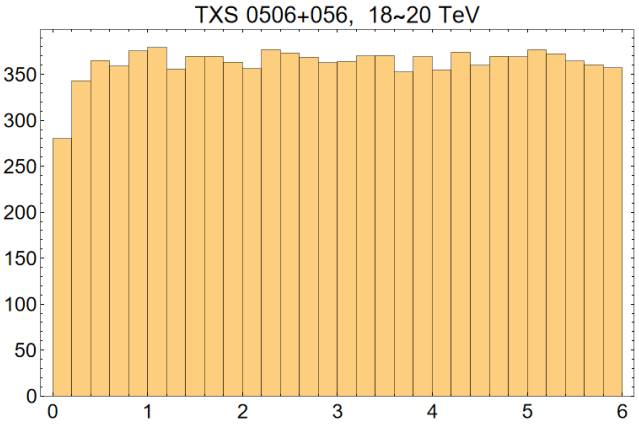
TXS 0506+056, z=0.3365

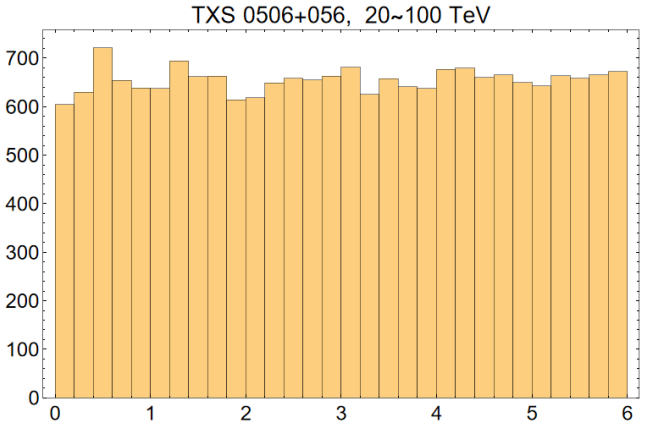






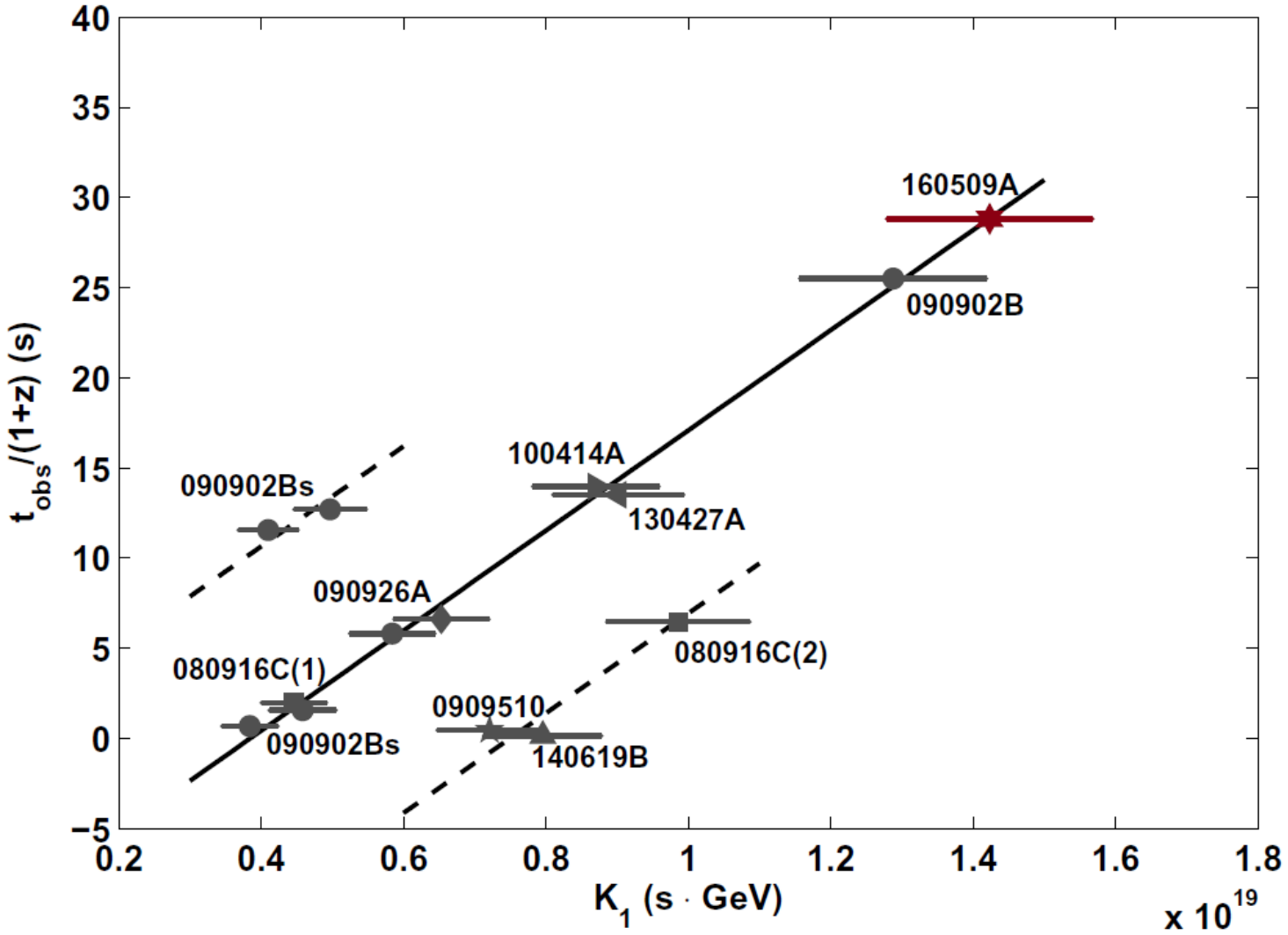






- H.Xu, B.-Q.Ma, Phys.Lett.B 760 (2016) 602

New GRB: 160509A



- H.Xu, B.-Q.Ma, Phys.Lett.B 760 (2016) 602

New GRB: 160509A

we find evidence

to support the prediction for a linear form modification of light speed

$$v(E) = c(1 - E/E_{\mathrm{LV}})$$

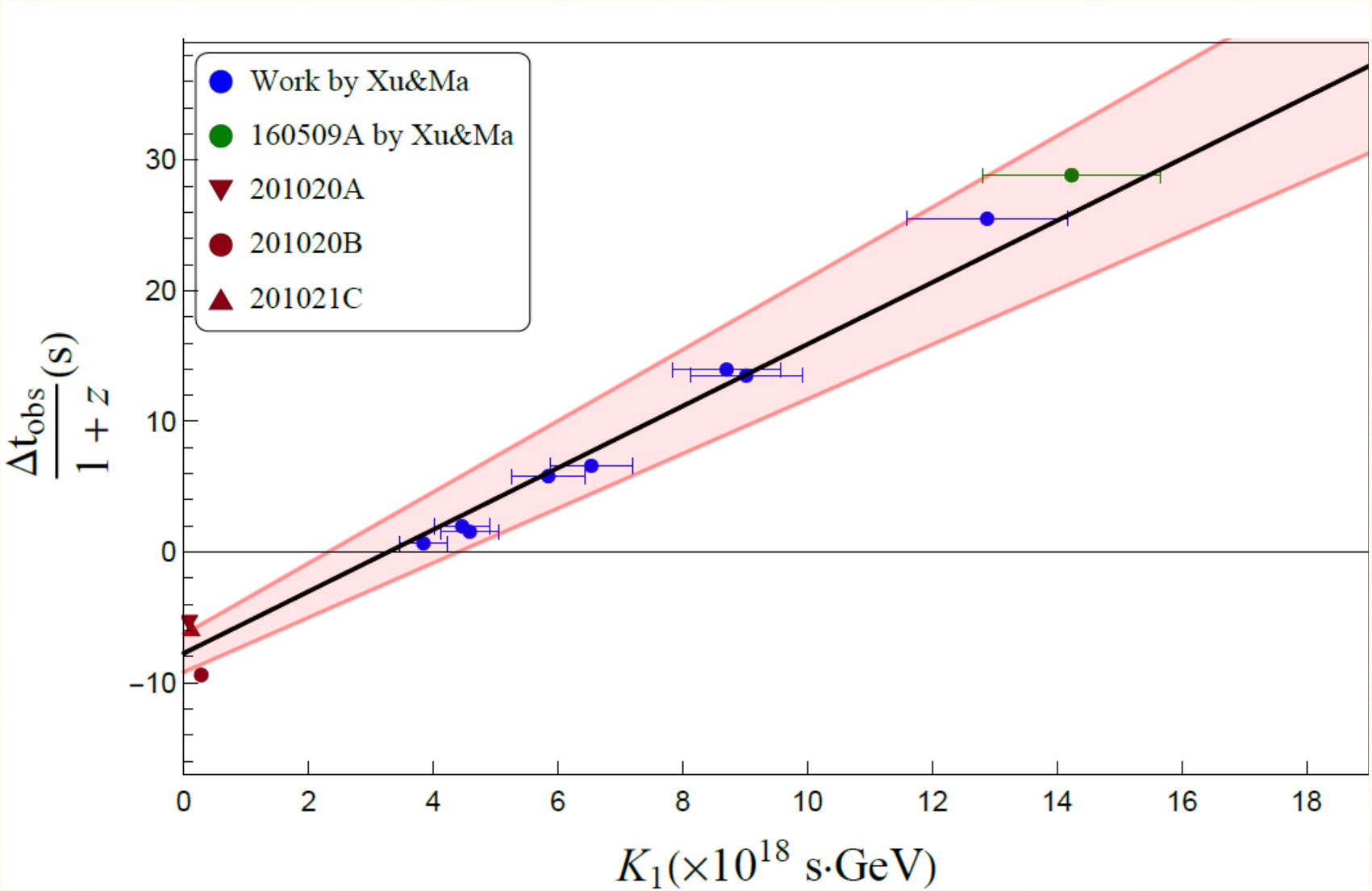
$$E_{\mathrm{LV}} = 3.60 \times 10^{17}\ \mathrm{GeV}$$

A B S T R A C T

It is postulated in Einstein's relativity that the speed of light in vacuum is a constant for all observers. However, the effect of quantum gravity could bring an energy dependence of light speed. Even a tiny speed variation, when amplified by the cosmological distance, may be revealed by the observed time lags between photons with different energies from astrophysical sources. From the newly detected long gamma ray burst GRB 160509A, we find evidence to support the prediction for a linear form modification of light speed in cosmological space.

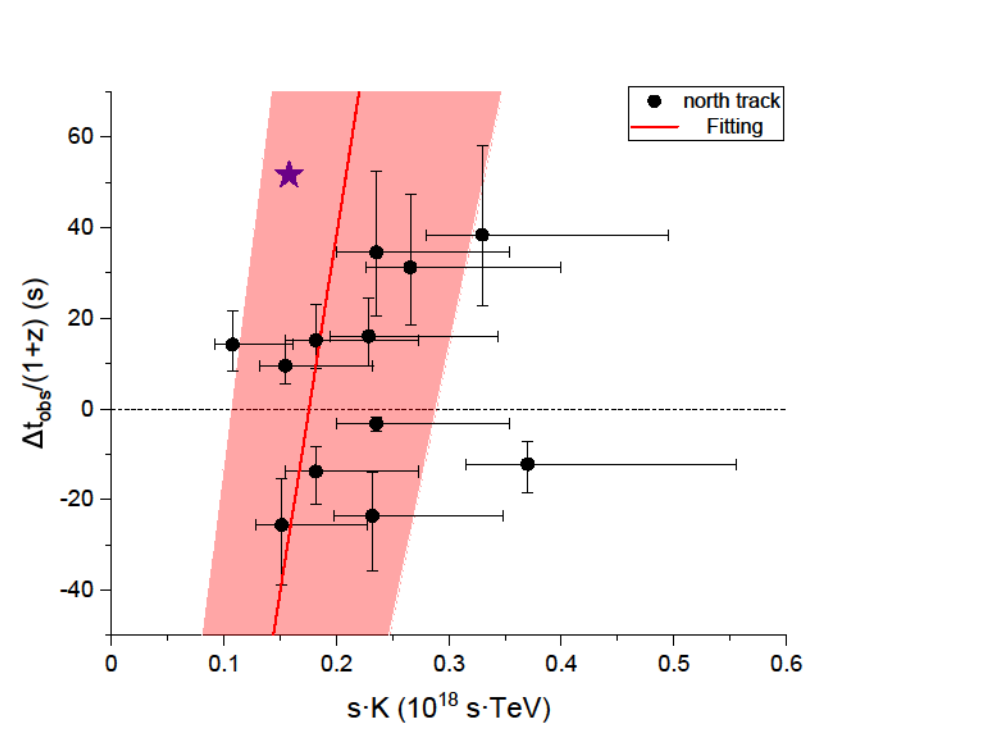
- J.Zhu, B.-Q.Ma, Phys.Lett.B 820 (2021) 136518

New GRBs: 201020A, 201020B, 201021C



Correlation of MAGIC TeV event with IceCube near-TeV events

Y. Huang, H.Li, B.-Q. Ma, PRD 99 (2019) 123018



★ MAGIC event: E=1.07 TeV, z=0.4245, t=T0+73.6 s

GRB190114C, PRL125 (2020) 021301

J.Zhu, B.-Q.Ma, Phys.Lett.B 820 (2021) 136546

MAGIC event accompanied by pre-burst photon and neutrino events