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LHAASO Status and Physics Results

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Abstract. Status of the LHAASO experiment and its latest results in both γ-ray astronomic observations and charged cosmic ray (CR) measurements are reported in this paper. The discovery of photons around 1 PeV from the Crab, 12 PeVatrons in our galaxy and new sources with emissions above 100 TeV declare the onset of the utral-high-energy γ-ray astronomy. The capability of measurements of spectra of the individual species of CRs, e.g. protons and iron nuclei, starts the new era of the high precision measurement of CRs using the ground based extensive air shower technique. The detection of the highest energy photon at 1.4 PeV from the remote potential source in Cygnus region allows to test of the violation of fundamental physics rules, such as the Lorentz Invariance, and set the highest limits in the tests.

1 Introduction

Very High Energy (VHE) γ-ray astronomy has been making very important progresses with many historical discoveries in understanding the non-thermal universe, such as the discovery of the Crab as the first source in TeV band, Mrk421 as the first extragalactic source associated with the highly variable AGN, very difficult efforts on finding PeVatrons at the center of our galaxy and recent observation of TeV afterglow of GRBs by HESS and MAGIC. In last decode, extensive air shower detection technique has been developed at high altitudes to have sufficient sensitivity for TeV γ-ray sources and making discoveries, such as pulsar halos. However, the lack of observational data above 80 TeV due to the limited sensitivity at higher energies, start to constrain the development of the field. Not only in the γ-ray source search, the charged cosmic ray (CR) measurements and corresponding modeling/theory have also been stuck with low quality data in the very important range in which the knees of spectra of CR species, i.e. proton, helium and iron nuclei may exist. Comparing to the very precise measurements at energy below 100 TeV by many space borne detectors, the precision measurements of CRs in knee range, to release from the entanglement between the composition and interaction in shower development in particular, is more than necessary. To answer the challenges, the Large High Altitude Air Shower Observatory (LHAASO) was designed and started to construct in 2016. In July 2021, the whole complex of detector arrays as a specified instrument for the EAS detection was built completely. The operation with the partially finished arrays started in 2019 and with the full scale in last year are very stable

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with the duty cycle of 98% and detector failure rate <2%, thus maintains an unprecedented γ-ray detection sensitivity above 20 TeV and highest survey sensitivity of 10 mili-CrabUnit in VHE band. The capability of separation between proton from other CR species and iron from others light up hopes to improve our knowledge about the knee of CR spectrum, thus of the propagation properties of CRs in our galaxy and the mechanism of the knee. Data collected by LHAASO in last two years really tell us the difference in the new territory of the non-thermal universe from what we have learnt in last few decades. A new era, ultra-high-energy (UHE) astronomy, has been initiated. The status of the LHAASO experiment and the physics results in both γ-ray astronomy and CR measurements are reported in this paper.

2 LHAASO Experiment and the Status

LHAASO had been completely built on top of Mt. Haizi (4410 m above sea level) in Sichuan province, China by July 2021[1]. The vertical atmospheric depth is ~600 g/cm^2. Since then, the kilometer-square array of 5216 scintillator counters and 1188 μ-detectors (KM2A) and water Cherenkov detector array (WCDA) gaplessly covering 78,000 m^2 with 3120 detector cells are fully operated. The wide field of view (FoV) Cherenkov telescope array (WFCTA) composing of 18 telescopes with a 5 m^2 light collector for each is also operated in dry seasons for more than 1400 hours per year.

In KM2A, scintillator counters are deployed in a triangle grid with a space of 15 m between counters which is covered by a 5 mm thick lead plate, which converts secondary γ-rays into e^+e^- pairs in the counter, and measures the total deposited energy by all charged particles passing through the scintillator plates. The number of particles is measured according to the charge of single particle measured during the data taking. μ-detectors are also in the triangle grid with a distance of 30 m between detectors, and the total active area is 40,000 m^2. With the overburden of 2.5 m soil. The muon detection has nearly zero backgrounds of e^+s, e^-s or γ-rays in a shower, except for one or two detectors very closed to the shower core. The μ-content with the threshold energy of muons ~0.9 GeV is measured for each shower. The lateral distributions of both electromagnetic particles and muons in a shower are well measured using KM2A. μ-content is a very useful parameter for cutting CR background effectively in γ-ray astronomic observation. In the CR composition analysis, it is a sensitive parameter to the CR composition, as well.

In WCDA, all energy carried by e^+s, e^-s and γ-rays in a shower is deposited in water inside the detector. Cherenkov light generated in water is proportion to the deposited energy and sampled by the PMTs at the center of each cell and 4 m beneath the water surface. Muons in the shower could generate larger signals than electromagnetic particles since they have longer tracks in water. They could generate exceptionally large signals in cells that the muons pass through, particularly for those cells far from shower cores. In γ-ray detection, this can serve as a discriminator to suppress CR background. For showers with energy higher than 10 TeV in CR measurements, the lateral distribution of the energy flux is well measured as a rather smooth function. The extra fluctuation due to μ's is also useful in CR composition analysis.

Cherenkov telescopes are operated at higher threshold energy than those of WCDA and KM2A, so events recorded by the telescopes can find their counterparts either in WCDA or/and in KM2A. With the well reconstructed shower geometry by the arrays, the images recorded by the telescopes can be used to extract a couple of shower parameters. The shower energy can be reconstructed with the total number of photons in the image by knowing exact distance between the telescope and the shower axis. Simultaneously, the angular distance between the centroid of the image and the arrival direction measures the atmospheric depth of the shower maximum as well. The shape of image has a correlation with the shower composition at certain level.

All components of LHAASO are operated smoothly with very stable performance since July 2021 when all the detectors were deployed. KM2A and WCDA the two detector arrays for the γ-ray astronomy with a duty cycle more than 98%. Daily rate is 2×10^8 events above 10 TeV and 3×10^9 events above 300 GeV, respectively.

Up to now, 70 million CR events accumulated by WFCTA and matched with either WCDA or KM2A, thus forming a hybrid data set of CRs above 10 TeV. The shower geometry is reconstructed using the EAS arrays with very high resolutions, i.e. the shower arrival direction and the core location are measured with errors smaller than 0.2° and 3 m, respectively. Further analysis for CR composition and shower energy measurements are under development.

2.1 Scientific Results: Gamma Ray Astronomy Using KM2A and WCDA

As a γ-ray detector, LHAASO covers the very unique energy range from few hundred GeV to few PeV, the highest energy of photons expected from the universe. With a wide acceptance angle, which covers 1/6 of the sky at any moment and operates for 24 hours, LHAASO measures the diffuse γ-rays from the entire northern sky and surveys for sources. Obviously, such a detector is particularly good in monitoring for transient phenomena such as GRB and searching for spatially extended structure of γ-ray emission. Here in the γ-ray astronomy, we have a standard candle, the Crab, to be measured for calibration of the detector at energies it has been well measured by all other detectors in the whole world up to tens of TeV. Of course, as the very unique object, the Crab is discovered over again by LHAASO as a surprising PeVatron. Let us start with the Crab.

2.1.1 The Crab

At least three parameters, i.e. pointing error, angular resolution and photon flux at energies below 100 TeV are well measured in previous experiments by using different EAS detection techniques or in other band. WCDA and KM2A have measured the Crab with very high statistic significance, i.e. 300σ at E>1 TeV and 86σ at E>25 TeV, respectively. Therefore the direction of the Crab as a point-like source is measured with an error of 0.01°, thus the pointing direction of WCDA and KM2A is calibrated within at least 0.01°. The angular distribution of the significance of the Crab measures the resolution of WCDA and KM2A of 0.22° for E>1 TeV, 0.30° for E>25 TeV and 0.15° for E>100 TeV, respectively. The photon flux is measured from 0.5 to 100 TeV by WCDA and KM2A with an overlap at 12 TeV. The agreement between the two sub-arrays within the statistic error has realized a cross checking inside the collaboration and the overall Spectral Energy Distribution (SED) also agreed with other experiments, including experiments using IACT and EAS techniques, as shown in Figure 1. The exciting results from LHAASO is the measurement of the SED in UHE band, i.e. above 100 TeV marked in pink. Firstly it shows a power-law shape SED with the index of -3 up to 2 PeV. Secondly the highest energy photon detected from the Crab reaches 1.1 PeV. This gives a model-independent evidence of existence of an accelerator of either electrons or protons at energies at few PeV in the nebula. The electron accelerator seems more favored because the data could be successfully explained well enough up to 50 TeV even with a simple one-zone model that can produce photons up to few hundred TeV. This strongly implies the existence of so-called extreme accelerator that has an acceleration rate η higher than 15% which is 3 orders of magnitudes larger than the normal shock wave in SNRs. LHAASO data seems to favor a high energy proton component, with an improved fitting quality of the SED from 1 GeV to 2 PeV. In such a scenario, the protons with a spectrum of E^{-2} exponentially cut around tens of PeV are found to be mainly responsible to the photon emission at energies above 500 TeV. More PeV photons will be collected by LHAASO in following years for more conclusive selection between scenarios.

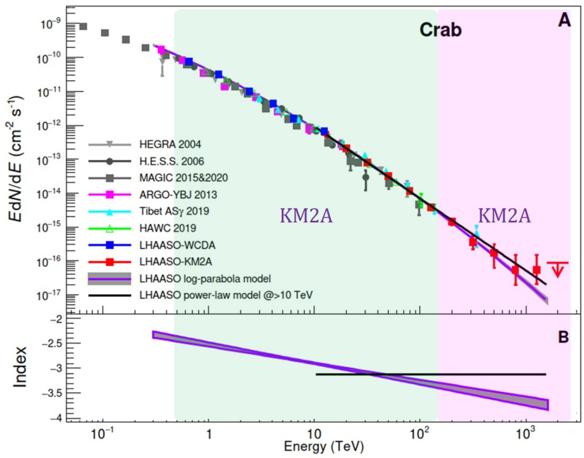

Figure 1. The SED of the Crab Nebula measured by LHAASO-WCDA from 0.5 to 12 TeV and LHAASO-KM2A from 12 TeV to 3 PeV together with other 7 experiments (upper panel). The figure is quoted from reference [2]. The energy range marked in green has been covered by the previous experiments, see the references in [2]. 7 of them are shown here with good agreement with LHAASO measurements. In the lower panel, the spectral index as function of energy is shown with gradual softening and the SED could also be fitted well enough with a power-law in UHE band above 100 TeV with the index around -3.

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2.1.2 The Pevatrons

12 new γ-ray sources discovered by LHAASO with emission in UHE band, including the sole identified Crab as a nearly isolated pulsar wind nebula. This reveals the existence of PeVatrons as the central engines boosting particles at energies higher than 1 PeV and emitting the observed photons in interactions with ambient materials. The PeVatrons are lining up along the Galactic plane and 11 out of the 12 have their counterparts found in VHE band i.e. above 100 GeV. Similar to the Crab, the SEDs of the bright ones among the 12 do not show significant cut-off around 100 TeV. This implies that 1. PeVatrons are widely existing in our galaxy and 2. the limit on the particle acceleration capability around 1 PeV for the Galactic accelerators is not real. Amazingly, those discoveries are realized only by the partially finished LHAASO-KM2A (1/2 of designed size) with the observation in first 11 months. The μ-detector array played the key role in γ-ray selection with a CR background rejection power of 10^{-4} at 100 TeV and 10^{-5} above 500 TeV. The large collection area of KM2A enables a collection of 530 UHE photons distributing spatially in 12 clusters with significance greater than 7σ for each. Except for the number of the PeVatrons, which is a surprise to the community that has hunted the PeVatrons for years, the divergence of types of potential counterparts of those UHE γ-ray sources conveys very important information about the origin of the particles that emit the UHE photons. It can be read from Table 1[3] and the references in [3]. No

Table 1. The PeVatrons discovered by LHAASO-KM2A in the operation with the partially finished array in the first 11 months. This is the Version-0 LHAASO UHE γ-ray sources with their name, possible origin, type of the celestial body of the origin, distance, age and spin-down luminosity for pulsars are listed for each source.

LHAASO Source	Possible Origin	Type	Distance (kpc)	Age (kyr)	L_s (erg/s)
LHAASO J0534+2202	PSR J0534+2200	PSR	2.0	1.26	4.5×10^{38}
LHAASO J1825-1326	PSR J1826-1334	PSR	3.1 ± 0.2	21.4	2.8×10^{36}
	PSR J1826-1256	PSR	1.6	14.4	3.6×10^{36}
LHAASO J1839-0545	PSR J1837-0604	PSR	4.8	33.8	2.0×10^{36}
	PSR J1838-0537	PSR	1.3	4.9	6.0×10^{36}
LHAASO J1843-0338	SNR G28.6-0.1	SNR	9.6 ± 0.3	$\lesssim 2$	—
LHAASO J1849-0003	PSR J1849-0001	PSR	7	43.1	9.8×10^{36}
	W43	YMC	5.5	—	—
LHAASO J1908+0621	SNR G40.5-0.5	SNR	3.4	$\sim 10-20$	—
	PSR 1907+0602	PSR	2.4	19.5	2.8×10^{36}
	PSR 1907+0631	PSR	3.4	11.3	5.3×10^{35}
LHAASO J1929+1745	PSR J1928+1746	PSR	4.6	82.6	1.6×10^{36}
	PSR J1930+1852	PSR	6.2	2.9	1.2×10^{37}
	SNR G54.1+0.3	SNR	$6.3^{+0.8}_{-0.7}$	$1.8-3.3$	—
LHAASO J1956+2845	PSR J1958+2846	PSR	2.0	21.7	3.4×10^{35}
	SNR G66.0-0.0	SNR	2.3 ± 0.2	—	
LHAASO J2018+3651	PSR J2021+3651	PSR	$1.8^{+1.7}_{-1.4}$	17.2	3.4×10^{36}
	Sh 2-104	H II/YMC	$3.3 \pm 0.3/4.0 \pm 0.5$	—	—
LHAASO J2032+4102	Cygnus OB2	YMC	1.40 ± 0.08	—	—
	PSR 2032+4127	PSR	1.40 ± 0.08	201	1.5×10^{35}
	SNR G79.8+1.2	SNR candidate	—	—	—
LHAASO J2108+5157	—	—	—	—	—
LHAASO J2226+6057	SNR G106.3+2.7	SNR	0.8	~ 10	—
	PSR J2229+6114	PSR	0.8	~ 10	2.2×10^{37}

doubt, this initiates a new era of the γ-ray astronomy in the new band of γ-ray energy greater than 100 TeV, the highest energy band for electromagnetic waves in the universe.

2.1.3 New VHE/UHE γ-ray Source Catalog

As mentioned above, one of the PeVatrons does not have its counterpart found in TeV catalog. Actually in lower energy range several new source have been discovered already. LHAASO J0341+5258, J2108+5157 and J0622+3794 are three newly discovered VHE sources have published with detailed analyses about their morphology and SEDs[4–6]. The last has been found a candidate of the pulsar halo. Many more new sources have been discovered in the LHAASO observation in last two years. As discussed in the beginning of this section, LHAASO has capability of finding sources with large spatial extension which is a common feature of the new sources. The new catalog as LHAASO-Ver-1 will be published very soon.

2.2 Scientific Results: Cosmic Ray Measurements Using Hybrid detection Technique

Identification of primary particle of EAS is a very challenging task. Measuring as many independent parameters of showers as possible is a promising way to approach. LHAASO, which is equipped with at least four types of detector sub-arrays, offers the opportunity to identify the primary particle species fore individual detected shower at energies from 100 TeV to 100 PeV. This is a very interesting energy range in which the knees of spectra of proton, helium and iron nuclei may appear. The flux around the knee of the proton spectrum is approximately 5 orders of magnitudes higher than the iron flux around its knee which might be at energies higher than the proton knee by a factor of 26 or 56. Obviously, different configurations of the hybrid detector arrays will be used for the proton and iron spectrum measurements. The experiment is naturally divided into two phases according to the schedule of construction of the detector arrays.

2.2.1 Multi Parameter Measurement of EAS

A typical hybrid shower event with the core inside WCDA-1 recorded in Phase-I is shown in Figure 2. In the right-upper panel, WCDA-1 measures the shower core with a huge dynamic range up to 0.2 million photoelectrons recorded in a cell as indicated by the color scale in the figure. This allows a measurement of the fine structure of the lateral distribution of the energy flux in the core. Here, shower particles have not experienced much scattering in the air so that they represent the fresh population generated not far above the surface, in other words, the hadronic components of the shower before them hit the surface. The energy flux weighted average lateral distance r_i of detector cells $< ER >= \Sigma Q_i r_i / \Sigma Q_i$, where Q_i is the charge measured by the *i*-th cell, is chosen as a parameter sensitive to the primary species, denoted as p_F after normalized by the preliminarily determined shower energy. The right-lower panel in Figure 2, the detection of the muon lateral distribution is shown as the number of muons in each MD. It is noticed that only handful muons recorded by each MD at distance more than 100 m from the core. Summing over all MDs between 30m and 380 m from the core for the total measured number of muons. It is a rather traditional parameter for species selection in EAS observation due to the relation $ln\mathrm{N}_\mu \sim 0.1 ln\mathrm{A}$, where N_μ is the muon content of the shower induced by a primary particle with the atomic number A. Normalized by using the total muon content in the shower, the parameter P_μ is selected as a sensitive variable for primary species identification. In the left-upper panel of Figure 2, a typical image of the shower is recorded in the camera of WFCTA. It is well known that the shower elongates longer for proton initiated shower than that by heavier nuclei. However, the length of the image depends the distance of the the shower to the telescope, R_p, due to a pure geometrical effect. Corrected by R_p and the preliminarily reconstructed shower energy, the parameter defined as the ratio of the length and the width of the image, denoted as P_C, is found sensitive to the composition of the primary species.

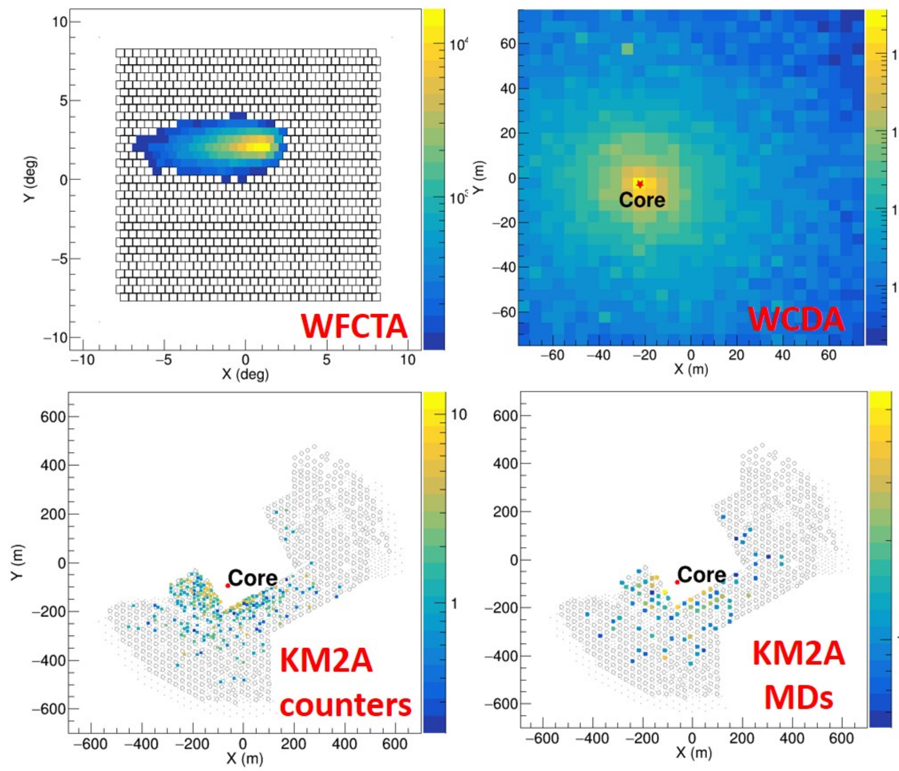

Figure 2. A typical hybrid event recorded in Phase-1.

2.2.2 Measuring the pure proton spectrum

The first phase started with 6 telescopes deployed at the southwest corner of WCDA-1, i.e. the first built pool of 150m×150m for the 900 cells of the LHAASO-WCDA, from 2019-2020 observational season. All telescopes have the elevation angle of 60°, i.e. the zenith angle range from 22° to 38° is covered, so that there is at least 647 g/cm^2 for showers to develop in the air. Before April 2021, the hybrid operation with this configuration, had accumulated more than 70 million events with the cores inside WCDA-1 for 720 hours during which 1/2 of KM2A were operated.

Examing the capability of the parameters individually in the primary particle identification with a simulation toolkit that takes all detector effects into account for all four type of detectors in LHAASO, it seems very challenging if a high purity of the proton sample, e.g. 90%, is the demand, the event selection efficiency is only ~20%. On the other hand, correlations between those parameters are found not negligible. Further efforts to find more independent parameters is still on going. Moreover, for cores falling in KM2A, P_μ and P_C are available. Selection efficiency using P_μ is even improved due to better muon content is measured than those in WCDA. Large statistics provided by the huge KM2A, makes this measurement very useful, particularly serves as cross checking.

2.2.3 Measuring the Fe spectrum

In phase II starting from September 2021, all 18 telescopes are deployed to the sites near the southeast corner of WCDA-1, and form a ring-shaped FoV covering all azimuthal direction between zenith angle range from 37° to 53°. Such a setup is aiming at the detection of CRs at higher energies around the possible knee of iron spectrum, i.e. >10 PeV, so that more atmospheric depth, >751 g/cm^2, allows better developments of showers. To collect sufficient statistics,the entire KM2A needs to be used to achieve the hybrid measurements. The geometrical factor enhancement of a factor of 3 due to the total field-of-view (FoV) of telescopes and a factor of 44 due to the acceptance of the ground array are expected from the re-configuration of the experiment. In the operation for 6 years, a sample of pure iron induced showers with a smaller statistics, roughly estimated to be 20 times smaller than the proton sample, would be expected.

2.2.4 Energy Reconstruction

For pure proton or iron samples, the shower energy reconstruction is rather straightforward by using the total charge measured in the Cherenkov image of a shower at the impact parameter R_p from the telescope. Given the well determined shower geometry by using the EAS arrays, the shower energy uncertainty is dominated by the fluctuation of shower longitudinal development. In case of proton showers, quite symmetric resolution functions are found to be fitted with a Gaussian form with the σ to be 20% around 0.1 PeV and 15% above 1 PeV. The systematic shift of the Gaussian central expectations are less than 2% over the energy range from 0.1 to 10 PeV. The energy response function for showers at impact parameters of 120-130 m from the telescope, resolution and systematic shift as functions of shower energy and a resolution distribution at 1 PeV are shown in Figure 3. Some non-Gaussian tails are found beyond 2σ region due to the deeply developed showers were favored in the proton selection procedure. Further modification of the energy reconstruction by taking into account the EAS parameters is underdevelopment to improve the resolution.

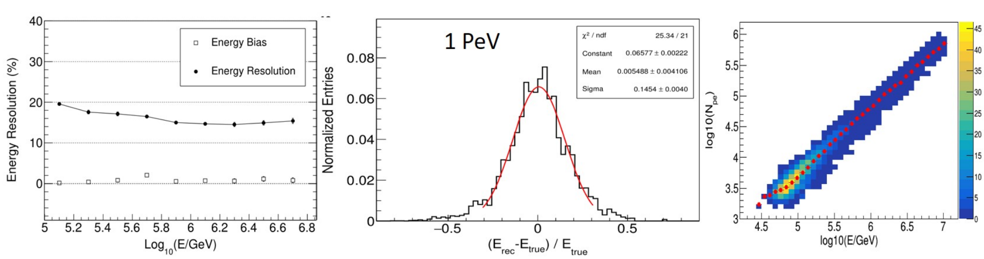

Figure 3. Energy reconstruction for pure proton samples. In the left panel, the shower energy resolution and systematic shift are shown over the energy from 100 Te V to 5 PeV. In the middle panel, the energy resolution function, i.e. the distribution of relative deviation between the reconstructed energy E_{rec} and input energy E_{true}, at 1 PeV. In the right panel, the energy response function for showers at impact parameters from 120 to 130 m from the telescope. The energy estimator is the total charge measured in the shower image in unit of number photo-electrons (N_{pe}).

2.3 New Physics Search: LIV Tests

If Lorentz invariance was violated (LIV), photon is no longer a stable particle and could decay on the journey from the source to LHAASO at the Earth. Two possible channels of decay are into either electron/positron pair or 3 γs. The former does not depend how far the source is and the first order violation had been ruled out by previous observations. The second order effect still needs to be tested. The later channel has stronger effect at the second order effect (there is no contribution to the first order expansion) and depends on the length of the path that the original γ-ray traveled. Taking the fact that the SED of the Cygnus region does not show any cut off at the highest energy detected at 1.4 PeV, the violation would not happen to cause the decay of photons below a conservatively selected E_{cut} = 1.14 PeV over the distance of the possible source at L ~1.4 kpc from the Earth. This results in an lower limit for the second order LIV effect of $3.33\times10^{19}L^{0.1}E_{cut}^{1.9} = 2.25\times10^{25}$ eV. This is the highest lower limit for the second order LIV effect[7] and still about 3 order of magnitudes below the Planck scale. The limits set by recent experiments and different methods are summarised in Figure 4.

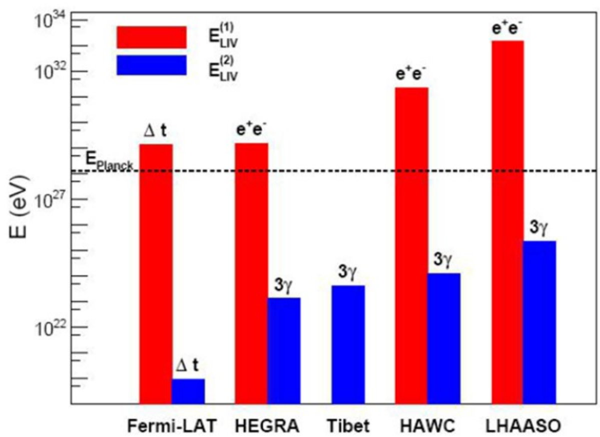

Figure 4. Limits, above which LIV could happen, set by various experiments by measuring the time lag between photons at different energies (LAT) and the photon decay through electron/positron pair or 3 γs (others). The first order expansion of LIV effect has been found a limit much higher limit than Planck scale, indicated by the dotted line. LHAASO which measures the SED of a source in Cygnus region up to 1.4 PeV, pushes the limit to > 10^{33} eV. Giving the distance ~1.4 kpc of the source, the limit for the second order LIV effect has been raised by more than 1 order of magnitude than previous experiments, see [7] and references in it for more detailed discussion.

3 Summary and Prospects

LHAASO as a dual-purpose large scale γ-ray/CR observatory has been built in July 2021 and operated with a very stable high duty cycle since then. By measuring photons around 1 PeV from the Crab, the highest energy photon at 1.4 PeV from the Cygnus region and discovering 12 PeVatrons in the Milky Way, LHAASO has started the era of UHE γ-ray astronomy. As the sole identified origin of the UHE photons, the Crab is accelerating electron/positron pairs to energies at least 2.3 PeV, thus posing challenge to the particle acceleration theories. The SED that extends to 1.4 PeV of a remote source at ~1.4 kpc offers opportunity to test on LIV and set highest limits on the effect.

Multiple EAS parameters are measured with unprecedented precision and statistics in LHAASO, thus opens an opportunity to measure the knees of spectra of individual CR species, such as the protons and iron nuclei at first time. In the first phase of operation of the hybrid observation, 70 million events have been collected for the proton spectrum measurement. The analysis is undergoing. The second phase operation with the full scale LHAASO array started in the dry season of 2021. To accumulate sufficient statistics for the iron spectrum measurement above 10 PeV, a stable operation for 5 or 6 years is necessary.

The CR propagation through the Milky Way will be investigated through the diffuse γ-ray measurement by LHAASO. Some UHE γ-ray sources are investigated in depth to find their CR origin and the potential accelerator, such as the Cygnus region. A much larger catalog of VHE/UHE sources found by LHAASO will be published soon. Among the sources, many CR origin related investigations will be carried out afterwards.

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