Recent measurement of the Telescope Array energy spectrum and observation of the shoulder feature in the Northern Hemisphere

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The Telescope Array (TA) is a hybrid cosmic ray detector deployed in 2007 in Millard County, Utah, USA, which consists of a surface detector of 507 plastic scintillation counters spanning a 700 km^2 area on the ground that is overlooked by three fluorescence detector stations. The High Resolution Fly's Eye (HiRes) experiment is a predecessor of TA, which consisted of two fluorescence detector stations operating from 1997 until 2006 from Dugway Proving Ground, Utah, USA, and which was the the first cosmic ray experiment with sufficient resolution and exposure to successfully observe the Greisen–Zatsepin–Kuzmin (GZK) suppression at $10^{19.75}$ eV. In this work, we present an updated TA energy spectrum result and a joint fit of independent spectrum measurements by the TA surface detector, TA fluorescence detector, and HiRes fluorescence detector to a broken power law function, which exhibits the ankle, GZK suppression, and the new shoulder feature initially seen by the Pierre Auger Observatory in the Southern Hemisphere. HiRes and TA observe the shoulder feature in the Northern Hemisphere at $10^{19.25}$ eV, with a statistical significance of 5.3 standard deviations.

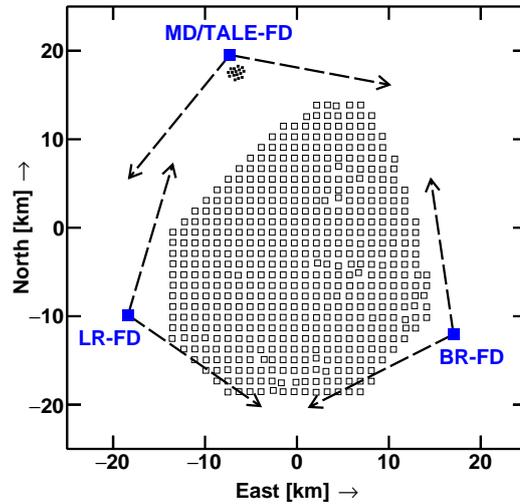*Presenter

https://pos.sissa.it/

Figure 1: Layout of the Telescope Array (TA) detector. Open squares are the main TA surface detector (SD) counters, small filled squares are the TA Low Energy Extension (TALE) SD counters, and the large boxes show the TA fluorescence detector (FD) stations Black Rock Mesa (BR), Long Ridge (LR), and Middle Drum (MD). Arrows show the FD viewing ranges.

1. Introduction

The Telescope Array (TA) is a hybrid detector that measures cosmic rays mostly in the Northern Hemisphere. TA is located in Millard County, UT, USA and it is collecting data since March 2007. The main TA consists of a ~700 km^2 surface detector (SD) of 507 plastic scintillation counters [1] that is overlooked by three fluorescence detector (FD) stations [2, 3], as depicted in Figure 1.

The Telescope Array Black Rock (BR) and Long Ridge (LR) fluorescence detectors (FD) consist of 10 telescopes each, which are viewing 3 to 33º elevations and a 2 x 108º azimuth range. The TA Middle Drum (MD) site consists of 14 telescopes that are covering 3 to 31º elevations and an azimuth range of 112º. The Telescope Array Low Energy Extension (TALE) is an additional hybrid detector that extends the TA energy range down to $10^{15.4}$ eV. TALE consist of 10 HiRes II - type [4] fluorescence telescopes added at the TA MD site to cover 31º to 57º elevations and to overlook an infill array of 103 plastic scintillation counters.

The High Resolution Fly's Eye (HiRes) experiment, [4], was built on Dugway Proving Ground, UT, and was collecting data from 1997 to 2006. HiRes had two fluorescence detectors, HiRes I and HiRes II, separated by 13 km. HiRes experiment viewed 3 to 31º in elevation and about 360 º in azimuth.

2. TA Spectrum and the shoulder feature

Figure 2 shows the Telescope Array (TA) combined energy spectrum produced using the 22 months TA Low Energy Extension (TALE) [5] measurement below $10^{18.2}$ eV and an 11 year TA surface detector spectrum (SD) [7] above $10^{18.2}$ eV.
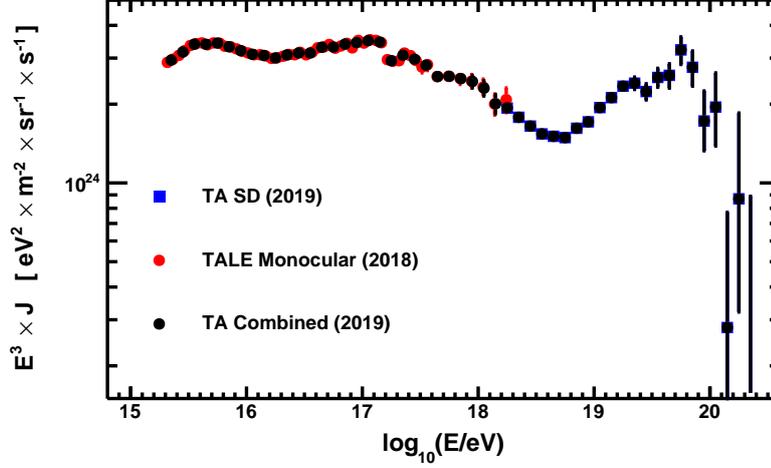
Figure 2: The Telescope Array (TA) energy spectrum (black points) composed of 11 years of the main TA surface detector (SD) data (blue squares) and 22 months of TA Low Energy Extension (TALE) monocular data (red circles). The combined TA spectrum exhibits the *knee* feature at about $10^{15.5}$ eV, the *low energy ankle* feature at $10^{16.22\pm0.02}$ eV, the *second knee* at $10^{17.04\pm0.04}$ eV, the *ankle* at $10^{18.69\pm0.01}$ eV, and the *cutoff* at $10^{19.81\pm0.03}$ eV.

A new feature, which we call here the *shoulder*, was initially seen by the Pierre Auger Observatory (Auger) in 2020 [8]. Auger field of view is concentrated mostly in the Southern Hemisphere. It is now interesting to ask whether this new feature also exists in the Northern Hemisphere.

Following the Auger report [8], we have conducted a search for the new *shoulder* feature in the Northern Hemisphere by combining HiRes I monocular [4], TA Black Rock – Long Ridge monocular [6], and TA SD [7] spectrum measurements to obtain the best statistical power for the Northern Hemisphere. All HiRes and TA detectors employ the same spectrum analysis technique that consists of using detailed Monte Carlo simulations in aperture calculations. To ensure statistical independence of the three measurements, we have additionally removed the TA Black Rock - Long Ridge observation period from the TA SD 11 year spectrum measurement.

Figure 3 shows a joint fit of HiRes I, TA Black Rock – Long Ridge, and TA surface detector spectra into a thrice broken power law. The fit finds the *shoulder* feature at $10^{19.25\pm0.03}$ eV. The statistical significance of the feature is estimated by the procedure described in Figure 3 to be 5.3 standard deviations.

3. Conclusion

We conclude that the shoulder feature of the cosmic ray spectrum has been also observed in the Northern Hemisphere by the High Resolution Fly's Eye and the Telescope Array experiments.
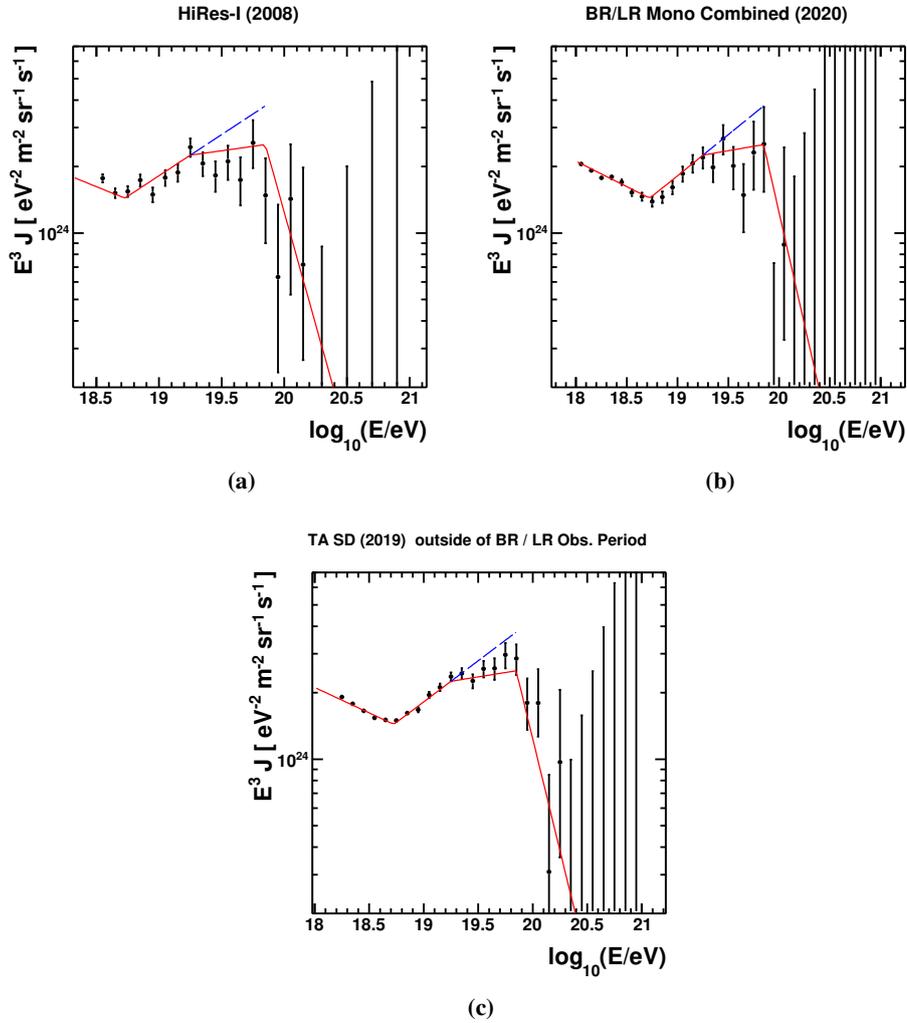
(a)

(b)

(c)

Figure 3: Joint fit (red line) to the HiRes and TA spectra, which are measured mostly in the Northern Hemisphere. The spectrum shoulder feature is seen at $10^{19.25}$ eV in (a) HiRes I monocular, (b) TA Black Rock (BR) – Long Ridge (LR) monocular, and (c) TA surface detector (SD) spectra. The significance of the shoulder is found by comparing the number of events expected in the absence of the feature (blue line) and the number of events reported by the experiments. The number of events between $10^{19.25}$ and $10^{19.85}$ eV, expected in the absence of the shoulder, is 1269.3, and the number of events measured by HiRes and TA in that energy range is 1086. The chance probability of this being a Poisson fluctuation is 7.4×10^{-8}, or, equivalently, 5.3 standard deviations.

References

[1] T. Abu-Zayyad *et al.*, Nucl. Instrum. Meth. A **689** (2012) 87

[2] T. Abu-Zayyad *et al.*, Nucl. Instrum. Meth. A **609** (2009) 227

[3] T. Abu-Zayyad *et al.*, Astropart. Phys. **39-40** (2012) 109

[4] R. U. Abbasi *et al.*, Phys. Rev. Lett. A **100** (2008) 101101

[5] R. U. Abbasi *et al.* [Telescope Array Collaboration] Astrophys. J. **865**, 74 (2018)

[6] D. R. Bergman *et al.*, This conference **2019**, 800 (2021).

[7] D. Ivanov, for the Telescope Array Collaboration, PoS ICRC **2019**, 298 (2019).

[8] A. Aab *et al.* [Pierre Auger], Phys. Rev. Lett. **125** (2020) no.12, 121106

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