Cosmic Ray Energy Spectrum From 2 PeV to 2 EeV measured with the TALE Fluorescence Detector

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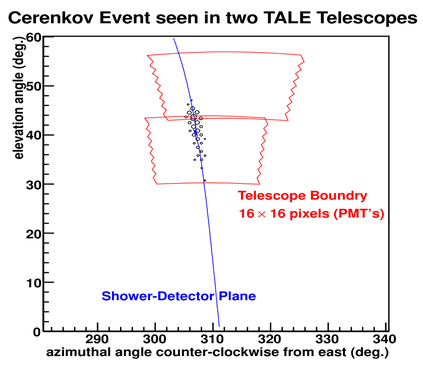
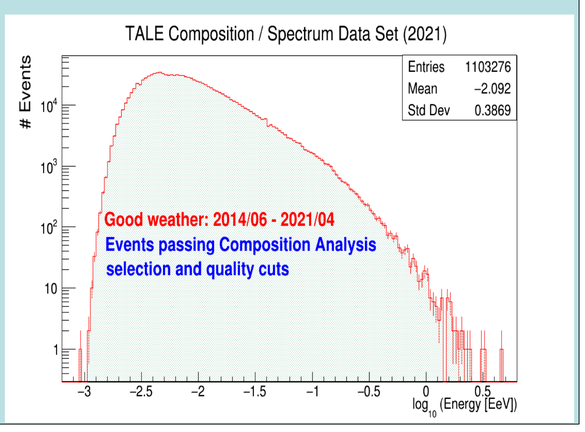
ABSTRACT:

The Telescope Array (TA) cosmic rays detector located in the State of Utah in the United States is the largest ultra high energy cosmic rays detector in the northern hemisphere. The Telescope Array Low Energy Extension (TALE) fluorescence detector (FD) was added to TA in order to lower the detector's energy threshold, and has succeeded in measuring the cosmic rays energy spectrum down to PeV energies, by making use of the direct Cherenkov light produced by air showers. In this contribution we present the results of a measurement of the cosmic-ray energy spectrum using TALE FD data collected over a period of ~7 years. The data set used for this measurement is the same one used for the mass composition measurement that is presented, as a separate contribution, at this conference. The energy spectrum shows features consistent with the "knee" and the "second knee"; a similar result to our previous energy spectrum publication. This time using a different hadronic model, and different event selection criteria as explained below.



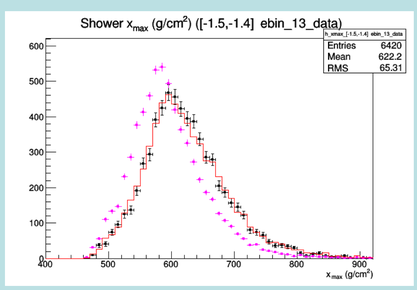
TALE Spectrum Data Set:

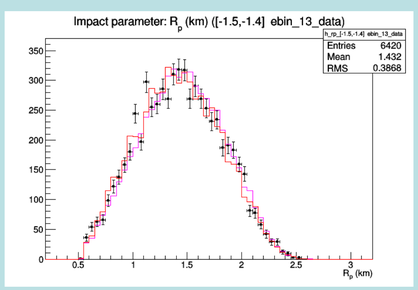
- The picture to the left shows the TALE building (with doors closed) sitting next to the Middle Drum (MD) detector building. MD FD has 14 telescopes covering elevation angles 3° - 31°,
- **TALE FD's 10 mirrors cover the elevation range 31°-59°.**
- The data used in this analysis was collected during the period of June 2014 through April 2021.
- After a "good weather" cut is applied to the collected data, a total of 3456.0 hours of observation is used to make the spectrum measurement.
- After event reconstruction and quality cuts, ~1.1E6 events comprise the final data set.
- Low energy events are Cherenkov events.
- however, at around 10^{17} eV and above mixed signal and fluorescence dominated events are present in TALE FD data.
- Only events with a 35% or more ***direct*** Cherenkov light contribution to the total observed signal are included in this data set.

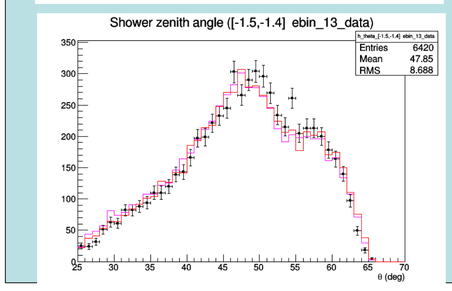


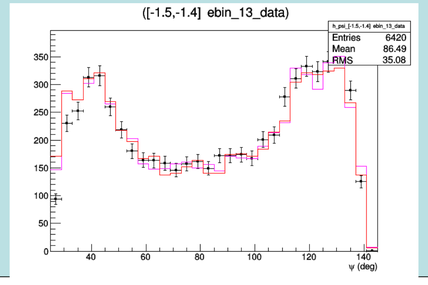
Data Analysis:

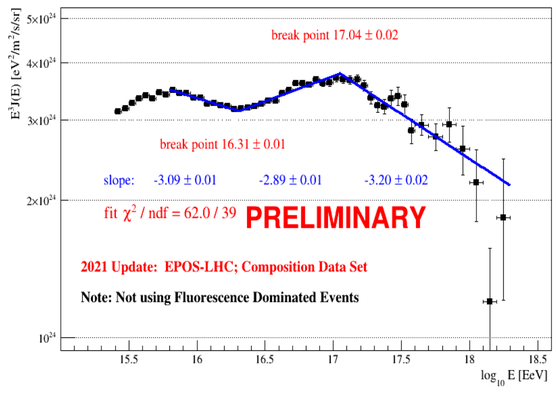
- The Cherenkov events included in this analysis have a PMT trigger pattern that is track-like.
- A feature of Cherenkov light produced in a shower is that it is not isotropic but rather highly directional, along the shower propagation direction. This allows for the accurate reconstruction of the shower geometry even when observed in monocular mode.
- It was found that as long as the direct Cherenkov contribution to the total light signal exceeded ~35%, the geometrical reconstruction was good.
- The energy resolution was ~15% - ~10% improving with shower energy.
- Monte Carlo simulations are used to determine the energy dependent aperture.
- Data-MC comparisons are used to verify that the simulation describes the detector response well enough. The figures below show results for one energy bin, as an example.
- In these plots the points are data while the two histograms represent MC with either an assumed composition (H4a model) or an adjusted primary fraction resulting from a fit to the data x_{max} distribution.





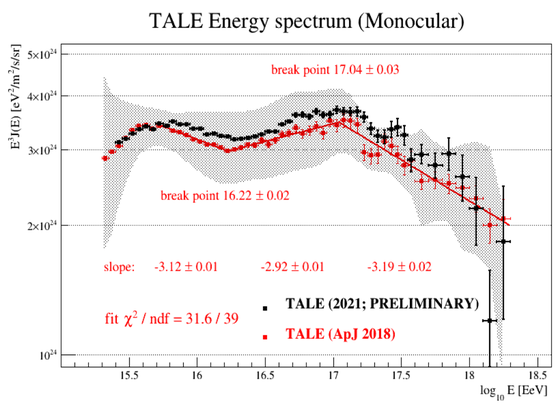






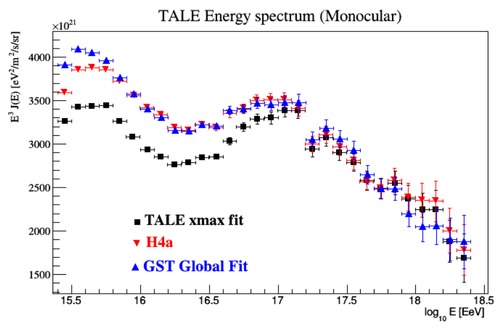
Updated cosmic-ray energy spectrum measured by TALE FD using the "mass composition" data set.

Broken power-law fit to the cosmic-ray energy spectrum gives similar results to the published results from 2018, as can be seen in the figure right below.



Changing the hadronic model changes the absolute normalization of the flux. Changing the composition assumption (updated Xmax fits) results a modified detector aperture value, Both these effects result in a change in the overall flux value.

Physics Assumptions:



- In a previous publication (ApJ 2018) we used the hadronic interaction model QGSJet II-3 to model the air showers in the detector MC and to make the correction for shower "missing energy". The composition analysis published in (ApJ 2021) moved to using EPOS-LHC as the main hadronic model. **The results shown here for the spectrum are also using EPOS-LHC.**
- The different model results in a slight change in the measured flux due to the slightly different missing energy correction, *and also due to a slight change in the reconstructed (predicted) CR primary-fractions*, which are obtained by comparing the data X_{max} distributions to model-dependent MC predictions. **This latter point is likely responsible for the shape of the updated energy spectrum at the lowest energies.**
- For the ApJ 2018 publication, we adopted a reference CR mass composition model (known as H4a) developed by T. Gaisser and used for the IceTop experiment flux measurement (2013). We also use another model (same physics, different parameters) as another check. The latter model is referred to as the GST global fit, with GST standing for Gaisser-Stanev-Tilav and published in 2013 by these authors.
- **The TALE Spectrum measurement is based on a mass composition assumption obtained by fitting the observed Xmax distributions to MC simulations of protons, Helium, Nitrogen, and Iron.**
- Changing the composition assumption results a modified detector aperture value, and it also implies a different mean shower missing energy correction. Both these effects result in a change in the overall flux value, as shown above.
- The shown figure (from a previous analysis) demonstrates the size of the effect of changing composition on the measured flux

Conclusion:

We reported on a measurement of the cosmic rays energy spectrum using an updated data set collected in about seven years of the TALE FD operation. The data set used here, is the one that is used for the CR composition analysis. We therefore have shown both flux and composition results based on a single data set and consistent event selection criteria.

Compared to our published energy spectrum from 2018, we see that the updated spectrum is consistent with that result: Keeping in mind the effects of the updated hadronic model. Those effects include a small shift in energy scale, but also have an effect on the inferred CR primary fractions; More protons at the lowest energies imply a slightly larger aperture and therefore a slightly lower flux normalization.

Acknowledgments:

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