High Energy Spectrum Measured by the Telescope Array Experiment

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Outline

- Telescope Array Experiment
- Surface Detector Spectrum
- Fluorescence Mono and Hybrid Spectra
- Comparison with HiRes and Auger
- Conclusions
Telescope Array
Hybrid detector
Millard County, UT
39.3° N, 112.9° W,
Alt. 1400m
~880g/cm²

507 Surface Detector (SD) counters, 1.2km apart, cover 680km²

3 Communication Towers (CT): BR, LR, SK
3 Fluorescence Detectors (FD): BR, LR, MD
TA FD
TA Surface Detector

- Powered by solar cells; radio readout.
- In operation since March, 2008.
- Self-calibration using single muons.
- Energy deposited by cosmic ray shower particles is measured in \textbf{VEM} units (Vertical Equivalent Muon = energy deposited by a vertical minimum ionizing muon)
Surface Detector Event

- **NORTH [1200m]**
- **EAST [1200m]**

**Array Edge**

**Time [4μS]**

**SD Time Fit**

**Time**

- Distance along shower axis on the ground, [1200m]

**SD LDF Fit**

**LDF (AGASA)**

**S800**

- Perpendicular distance from shower axis, [1200m]
A look-up table made from the Monte-Carlo

Event energy ($E_{TBL}$) = function of reconstructed S800 and sec(θ)

Energy reconstruction $\leftrightarrow$ interpolation between S800 vs sec(θ) contours of constant values of $E_{TBL}$

The overall energy scale locked to the fluorescence detector
SD Energy 2/2: Energy Scale Set to FD

- Energy scale locked to the FD to reduce the systematic due to the model
- Use events well reconstructed separately by SD and FD in hybrid mode:
  - SD ∩ [BR U LR U MD Hybrid]
  - $E_{\text{FINAL}} = \frac{E_{\text{TBL}}}{1.27}$
- TOP figure: $E_{\text{FINAL}}$ vs $E_{\text{FD}}$ scatter plot
- BOTTOM figure: histogram of $E_{\text{FINAL}} / E_{\text{FD}}$ ratio
- 2008/05/11-2013/05/04
Exposure from Monte Carlo

Zenith Angle

LDF $\chi^2$/DOF

Pulse Height

5400 km$^2$ sr yr

2008/05/11-2014/05/11
SD Resolution from Monte Carlo

- **35%** for $10^{18} - 10^{18.5}$ eV
- **30%** for $10^{18.5} - 10^{19.0}$ eV
- **20%** for $10^{19.0} - 10^{20.5}$ eV

Entries and Statistics:
- First section: Entries 84216, Mean 0.003649, RMS 0.3058, Underflow 0, Overflow 0
- Second section: Entries 62564, Mean -0.01182, RMS 0.255, Underflow 0, Overflow 0
- Third section: Entries 41223, Mean -0.01383, RMS 0.1765, Underflow 0, Overflow 0

Graphs showing distributions of $\ln(E_{\text{REC}} / E_{\text{GEN}})$ with percentage ranges for different energy intervals.
GZK Cutoff

$E_{1/2} = 10^{19.73 \pm 0.04} \text{ eV}$

$J_{\gamma}(E) \times 10^{12} \text{ [m}^{-2} \text{ s}^{-1} \text{ sr}^{-1}]$

$N_{\text{Events}} / \text{BIN}$

$N_{\text{Expect}} = 85.9$

$N_{\text{Observe}} = 32$

$(6.6 \sigma)$
Fit spectrum to energy-loss model

Inputs:
1. Pion photoproduction and e+e- pair production;
2. Hubble expansion.

Fitting parameters:
1. Power law at the source, $E^{-p}$
2. Evolution of the sources, $(1+z)^m$
Fluorescence Mono Analysis

Black Rock Mesa

Time fit

Profile fit
Combined Fluorescence Mono

Combined mono spectrum:
3 years of Middle Drum, APP 39 (2012) 109
3.5 years of Black Rock / Long Ridge, APP 48 (2013) 16
Use geometric mean of energies, account for the overlaps in the exposure
Hybrid analysis

EVENT: 2009/09/19 08:45:52

$\chi^2 / \text{ndf} = 52.86 / 45$

$T_\text{pp} = -98.72 \pm 0.31$

$R_\text{p} = 24.50 \times 10^3 \pm 0.03 \times 10^3$

$\psi = 61.26 \pm 0.21$

$\Delta R_\text{p} / R_\text{p}$

Entries 19631
Mean -0.060
Sigma 0.16

$\Delta R_\text{p} / R_\text{p}$

Entries 11628
Mean -0.0029
Sigma 0.0045
Combined Hybrid Spectrum

Combined hybrid spectrum:
4 years of Middle Drum Hybrid, submitted to APP
4 years of Black Rock / Long Ridge, APP 61 (2014) 93
Next

Compare with other experiments:
HiRes-II, HiRes-II (PRL-2008)
Pierre Auger combined (ICRC-2013)
TA SD and HiRes

- Different experiments using different techniques
- Looking at the same sky
- Agreement in overall shape
- Same energy scale
TA SD and Pierre Auger

- Similar experiments but looking at different parts of sky
- Auger flux 16% lower than TA in the flat ratio region
- Large differences at the highest energies
Auger energy scale increased by 8.5%

55% difference in the 2\textsuperscript{nd} break point measured by TA(10\textsuperscript{19.73} eV) and Auger (10\textsuperscript{19.54} eV)
TA SD, Pierre Auger, and HiRes

- Similar feature seen at the highest energies when Auger spectrum is compared to HiRes
Declination dependence of TA spectrum

- Auger and TA sensitive to different parts of the sky
  - TA: $\delta > -16^\circ$ (zenith angle $< 55$)
  - Auger: $\delta < 26^\circ$
- Hint for the declination dependence in TA data ($\sim 3\sigma$)
Conclusion

- SD Spectrum updated to 6 years of data, 2008/05/11-2014/05/11
- Energy scale result is unchanged after including more hybrid events into comparison
- TA Mono, Hybrid, and SD spectra all agree
- Fits the simple proton propagation model
- Agree with HiRes, discrepancy with Auger at the highest energies
- Hint of the declination dependence of the second break point
Thank You

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