Measurement of the Cosmic Ray all-particle and light-component energy spectra with ARGO-YBJ



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On behalf of the ARGO-YBJ Collaboration

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INFN

The ARGO-YBJ experiment



ARGO-YBJ

• Yangbajingzhen

Kaijiaquo

Image © 2013 DigitalGlobe © 2013 Cnes/Spot Image US Dept of State Geographer © 2013 Mapabc.com

ARGO YEJ

High Altitude Cosmic Ray Observatory @ YangBaJing, Tibet, China Site Altitude: 4,300 m a.s.l., ~ 600 g/cm²

Google earth

ARGO-YBJ physics

VHE *γ***-Ray Astronomy**:

(search for)/(study of) point-like (and diffuse) galactic and extra-galactic sources with few hundreds GeV energy threshold

Cosmic ray physics:

energy spectrum and composition

study of the shower space-time structure flux anisotropies at different angular scales p-Air cross section measurement hadronic interaction studies anti-p / p ratio at TeV energies, geomagnetic effects on EAS

Search for GRB's (full GeV / TeV energy range)

through the...

Observation of *Extensive Air Showers* produced in the atmosphere by primary γ 's and nuclei



. . .

The cosmic ray (nuclei) flux(es)

- Particle Data Gruop 2013 -

Direct measurements

- High precision
- fluxes of single components
- (acceptance) limited in energy

Indirect measurements

- Larger systematics
- Difficult composition measurements
- Can go to the highest energies











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The ARGO-YBJ detector





3-D view of a detected shower

Bruno Rossi conceptual EAS detector

The RPC analog readout



Real event

ARGO-YBJ (154 CL) - Event 242653 ARGO-YBJ (154 CL) - Event 242653 Big-Pad 4000 BigPads vn 4500 60 4000 3500 õ 3500 (analog) 50 G 3000 3000 Q 2500 2000 40 1500 2500 1000 500 30 2000 BigPads 20 1500 1000 (analog) 10 500 70 Big-Pad 10 20 30 40 50 60



- ✓ Extend the explored energy range
- Access the LDF down to the shower core
- ✓ Sensitivity to primary mass
- ✓ Info/checks on Hadronic Interactions

Eight different gain scales (G0, G1,,G7) ensure a good linearity up to about 2.10⁴ particles/m².

G7 data overlap the digital-mode linearity range, and have then been used for intercalibration and cross checks.

Three independent approaches

- Analysis of analog RPC data alone and energy determination on an event by event basis: all-particle and p+He spectra
- Analysis of analog RPC data alone and statistical measurement of the energy spectrum by using a bayesian approach: p+He spectrum
- Hybrid technique by using data from an imaging Cherenkov telescope in addition to analog RPC information : p+He spectrum

This talk

Next talk

This talk

The truncated size as (mass dependent) energy estimator

Np₈ (number of particles within 8m from the core):

- well correlated with primary energy
- not biased by finite detector size effects
- weakly affected by shower fluctuations

Only events with zenith angle less athn 15 degrees in this work

Look for information on the shower age in order to have a mass independent energy estimator

3.5

3

2.5

2

1.5

34

36

38

Log₁₀(E/TeV)

4.8

MC p

MC He

MC Fe

5.2

 $Log_{10}(N_{p8})$

5



LDF and shower age

With the analog data we can study the LDF without saturation near the core. It is well fitted by a modified NKG function





Mass independent Energy reconstruction



The measurement of Np8 and the (age correlated) LDF slope allows estimating the truncated size at the shower maximum.

This ensures a mass independent Energy determination.



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MC Energy distributions



Energy reconstruction: bias and resolution

The response function is gaussian in LogE. The spectra are then given in LogE bins, much larger than the estimated bias and well above the LogE resolution, in the considered energy range.



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Mean RMS

Trigger and event selection efficiencies for the all particle spectrum





Systematic uncertainty evaluations for the all-particle spectrum

For the flux:

- Geometrical Aperture : (5 % in/out contamination) \oplus (2.5% angular contamination) =5.6 %
- Efficiency: (5% from MC samples) \oplus (<10% efficiency estimation of the mixture) = 5.0-11.2 %
- Unfolding: 3%
- Hadronic interaction model < 5%
- TOTAL: 8.1% 13.8 %
- TOTAL: (conservative) = 14%

For the energy scale:

- Gain of the analog system: 3.7 %
- Energy calibration: 0.03 in LogE = 6.9%
- Hadronic interaction model: 5%
- TOTAL: 9.3 %

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- TOTAL: (conservative) = 10%

In the following plots an over -conservative +/- 14% shaded area has been temporarily drawn on the flux measurements. Error bars show the statistical uncertainties.





Systematics from the hadronic interaction models



The dependence on the adopted hadronic interaction model is small.[|] The differences among the QGSJET-II.03 and Sibyll-2.1 are within few percent in the explored energy range (no bias due to muon number). All further results shown here were obtained with QGSJET-II.03.



The all particle spectrum

- Consistent picture with models and previous measurements
- Nice overlap with the two gain scales (different data,...)
- Suggest spectral index of -2.6 below 1 PeV and smaller at larger energes
- Ongoing extension to about 10 PeV thanks to more statistics and G0 and inclined data





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The p+He spectrum

- Same considerations as for the all-particle spectrum
- Gradual change of the slope starting around 700 TeV
- Agreement with other two ARGO-YBJ independet analyses (see next two slides)
- Consistent with previous hints (MACRO, CASA-MIA, Chacaltaya, EAS-TOP,...) and YAC-Tibet spectrum
- Overlap with direct measurements at low energy
- Flux systematics as for the all particle spectrum \oplus < 14% mainly for the CNO contamination \rightarrow Overall < 20 % CREAM







Preliminary

p+He spectrum: measurement of Cerenkov light



Wide Field of View Cerenkov Telescope (Array): (WFCTA)

> 5m² spherical mirror 16×16 PMT array 14° ×16° Field Of View Elevation angle: 60°

Energy easurement by using the Cerenkov signal and the shower geometry as reconstructed with the ARGO-YBJ analog data.

Light elements are selected by using information of particle desity near the core (ARGO-YBJ) and the shape of the Cerenkov image **Chin. Phys. C 38 (2014) 045001**









Hybrid approach: The light component selection



- Contamination of heavier component < 5 %
- Energy resolution: ~25%
- Uncertainty : ~25% on flux
- $p_L = N_{\text{max}} 1.44 \log_{10}(E_{\text{rec}}/1TeV)$
- $p_c = L/W 0.091 \times (R_p/10m) 0.14/og_{10}(E_{rec}/1TeV)$





p+He spectrum: measurement of Cerenkov light



Results are consistent with other analyses. May be different shape.

Different data/detector, different fiducial cuts, inclined events,...



The ARGO-YBJ measurements of the p+He spectrum



Results also consistent with measurement at lower energies, done with the strip data. Consistent picture within systematics. Further cross-checking still ongoing.



Comparison with other p+He measurements



Consistent results with direct measurements (i.e. below 200 TeV) and YAC-Tibet



(Some of the) Previous hints





The overall picture



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Summary

- Measurement of the all-particle spectrum from 50TeV to 5 PeV consistent with both direct and indirect experiments
- Measurement of the p+He component from 3 TeV to 3 PeV
- Evidence for a bending in the p+He spectrum (just) below 1 PeV
- Two different (p+He) analyses of ARGO-YBJ data in agreement within quoted uncertainties. A third independent (hybrid) analysis, using also the Cerenkov light signal, gives consistent results.
- Many cross check made and improvements on the way (e.g. different hadronic interaction models, no big differences expected).
- Now extending data set and MC statistics for the final results





More Stuff

On the analog readout system

Eight different gain scales (G0, G1,,G7) ensure a good linearity up to about $2 \cdot 10^4$ particles/m².

G7 data overlap the digital-mode linearity range, and have then been used for intercalibration and cross checks.

In this study we used data taken with G4 and G1 scales that allow covering the 50TeV – 5 PeV energy range with high efficiency and no saturation.



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p+He spectrum: bayesian analysis of analog data



Direct link between observables and primary energy and mass

- Causes: {E_i,.....E_n; ID_i,.....ID_n}
- Effects: {Np8_i,...,Np8_n; D_i,...,D_n}



p+He spectrum: bayesian analysis of analog data



Results are consistent with previous analysis.

Different fiducial cuts, also inclined events, fully bayesian approach,...

