Observation of a knee in the p+He energy spectrum below 1 PeV

by measuring particle densities very close to the EAS core
with the ARGO-YBJ experiment

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Site Altitude: 4,300 m a.s.l., ~ 600 g/cm²
The ARGO-YBJ detector

Strip counting
Pad = space-time pixel
Time resolution ~1.8 ns

+ Analog charge read-out on “Big Pads”

Data taking in full configuration for 5 years up to February 2013
The RPC analog readout

- 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 $10^4$ particles/m$^2$

G7 data overlap the digital-mode linearity range, and have then been used for intercalibration and cross checks.
The truncated size as (mass dependent) energy estimator

$N_{p8}$ (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 than 15 degrees in this work

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

\[ \rho_{NKG}' = A \cdot \left( \frac{r}{r_0} \right)^{s'-2} \cdot \left( 1 + \frac{r}{r_0} \right)^{s'-4.5} \]

The LDF slope \( s' \) is related to the shower age independently on the primary mass.

Assume an exponential absorption after the shower maximum. Get the correct signal at maximum \( (Np8_{max}) \) by using \( Np8 \) and \( s' \) measurements for each event.

\[ N_{p8_{max}} \approx N_{p8} \cdot e^{-\lambda_{abs} h_0 \sec \theta - X_{max} (s')} \]

Also checks with Gaisser-Hillas, Greisen, and Gaussian-in-age profiles.
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.
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.

Bin size chosen for the energy spectrum

Measurement energy range
Apertures for the all-particle spectrum

No dependence on mass composition above 250 TeV

Below 200 TeV dependence at the level of 5%
The all particle spectrum

- Consistent picture with models and previous measurements
- Cross check with another ARGO-YBJ analysis (see poster #993)
- Nice overlap with the two gain scales (different data set,...)
- Suggest spectral index of -2.6 below 1 PeV and smaller at larger energies

![Graph showing energy spectrum with data points and error bars.](image.png)
p and He selection
(MC Hoerandel spectra and normalizations)

- Protons
- He
- CNO
- Fe
Apertures for the p+He spectrum

CNO (and Fe) contamination below 15% (assuming Hoerandel / GST fluxes). Included in the sistematics.
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 independent analyses
- Consistent with previous hints (MACRO, CASA-MIA, Chacaltaya, EAS-TOP, YAC-Tibet…)
- Overlap with direct measurements at low energy
- Flux systematics as for the all particle spectrum \( \Theta < 15\% \) mainly for the CNO contamination \( \Rightarrow \) Overall \(< 20\% \)

![Graph showing the p+He spectrum with error bars and shaded area for systematic uncertainty.](image-url)

Error bars: statistical uncertainty
Shaded area: systematic uncertainty
10% on energy scale not included
This work vs previous measurements

A factor 26
Summary

- Measurement of the all-particle spectrum from 80 TeV to 20 PeV consistent with both direct and indirect experiments
- Measurement of the p+He component from 30 TeV to 3 PeV
- Evidence for a bending in the p+He spectrum 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 some further improvements on the way
- Complete analysis of systematic uncertainties in progress
More Stuff
Analog data: Four 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

- Analysis of analog RPC data alone and energy determination on an event by event basis (second analysis): all-particle spectrum
Comparison with other p+He measurements

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

Error bars: statistical uncertainty
Shaded area: systematic uncertainty
10% on energy scale not included
Cover a wide region between direct and indirect measurements.
High space/time granularity
+ Full coverage
+ High altitude

detailed study on the EAS space/time structure with unique capabilities

Event Rate ~ 3.5 kHz for $N_{\text{hit}} > 20$ - Duty cycle ~ 86% - $10^{11}$ evts/yr – 100TB/yr

Data taking with full configuration: November 2007 - February 2013

3-D view of a detected shower

Bruno Rossi conceptual EAS detector
On the analog readout system

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

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 – 20 PeV energy range.
Finding the best $\lambda_{\text{abs}}$ parameter

1 $\sigma$ of Log($E_{\text{rec}}/E_{\text{true}}$)

LogE resolution at 270 TeV vs $\lambda_{\text{abs}}$

$\lambda=100$ g/cm²

LogE bias at 270 TeV vs $\lambda_{\text{abs}}$

Correction with $\lambda=100$ g/cm²

Small residual shift with LogA as foreseen by theory

No correction ($\lambda\to\infty$)

See poster #1029
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.
Systematic uncertainty evaluations for the all-particle spectrum

For the flux:
- Geometrical Aperture: (5% in/out contamination) + (2.5% angular contamination) = 5.6%
- Efficiency: (5% from MC samples) + (<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%
- TOTAL: (conservative) = 10%

Preliminary