THE COSMIC RAY SPECTRUM IN THE ENERGY REGION BETWEEN $10^{12}$ AND $10^{16}$ eV MEASURED BY ARGO-YBJ

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THE ARGO-YBJ EXPERIMENT

ASTROPHYSICAL RADIATION WITH GROUND BASED OBSERVATORY AT YANGBAJING

Istituto Nazionale di Fisica Nucleare (INFN) – Chinese Academy of Science (CAS)

- COSMIC RAY PHYSICS
- GAMMA RAY ASTRONOMY

- Longitude 90° 31’ 50” East
- Latitude 30° 06’ 38” North
- Altitude 4300 m a.s.l. (approx 600 g/cm²)

YANGBAJING COSMIC RAY OBSERVATORY
2.3.1 Le camere RPC

Le camere RPC sono largamente utilizzate negli esperimenti di fisica delle alte energie poiché sono rivelatori in grado di garantire prestazioni molto elevate, con un'efficienza di rivelazione pari a circa il 98% e una risoluzione temporale dell'ordine di 1 ns, ad un costo di produzione relativamente modesto. Gli RPC sono dei rivelatori a gas in grado di rivelare il passaggio di particelle cariche mediante processi di ionizzazione e moltiplicazione a cascata nella miscela di gas contenuta al loro interno.

Il principio di funzionamento alla base di questo tipo di rivelatori è il processo di ionizzazione. Quando una particella carica attraversa la miscela di gas, interagisce con le molecole del mezzo attraverso un certo numero di processi di natura...
THE ARGO-YBJ EXPERIMENT

- Full and stable data taking since Nov. 2007
- End of data taking in Feb. 2013
- Average duty cycle ~87%
- Trigger rate ~ 3.5 kHz @ 20 Pad threshold
- ~ 5 x 10^{11} events recorded
- ~ 100 TB/year data

Energy calibration

- Intrinsic Trigger Rate stability 0.5%
  (after corrections for T/p effects)

Intrinsic Trigger Rate stability 0.5%

Duty-cycle

Angular resolution

 Days

Event Rate

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

High space/time granularity
+ Full coverage
+ High altitude
detailed study
on the EAS

Energy scale uncertainty is estimated to be smaller than 13% in the energy range 1–30 (TeV/Z).?
**THE ARGO–YBJ EXPERIMENT**

**ANALOG READOUT**

- Extend the maximum energy range up to the PeV region
  - Access the LDF down to the shower core
  - Sensitivity to primary mass
  - Info/checks on Hadronic Interactions

Digital readout:
Showers up to \( \sim 23 \text{ particles/m}^2 \)

Analog Readout
Showers up to \( \sim 10^4 \text{ particles/m}^2 \)

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**Run 98175 Ev 6566476 (Pmax = 7110)**

- **Strips**
- Strips saturation

**G1**

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**Astropart Phys 67 (2015) 47**
**NIM A 783 (2015) 68**
THE ARGO-YBJ EXPERIMENT

ANALOG READOUT

- EXTEND THE MAXIMUM ENERGY RANGE UP TO THE PeV REGION
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8 Different gain scales: G0...G7

HERE WE USE G4 AND G1 SCALES TO COVER A LARGE ENERGY RANGE BETWEEN 10 TeV and 5 PeV

![Graph showing differential rate vs. log (particle maximum density/part/m²)]

- Linearity up to ≈ 2 • 10⁴ particle/m²

![Graph showing RPC signal (ADC count) vs. calorimeter signal (ADC count)]

TEST BEAM @ LNF

- 4 RPCs
- 60 x 60 cm²
- Beam pipe
- Calorimeter
- PMT

![Diagram of test beam setup]
MAIN GOALS IN CR PHYSICS

- COSMIC RAY ENERGY SPECTRUM
- ALL-PARTICLE
- PROTON + HELIUM
- COSMIC RAY ANISOTROPY
- SHOWER TIME STRUCTURE

![Graph showing the spectrum from below the knee to the ankle. The spectrum with the parameters of Table III is shown in comparison with data from various experiments.](image)
Learn information about the energy spectrum from the experimental data by using probability theory.

Analysis based on the $N^8$ parameter: the number of particles within 8 m from the shower core position.

- Well correlated with primary energy
- Not biased by finite detector size
- Weakly affected by shower fluctuations

$$N(E, ID) = P(E, A|N^8, LDF) \cdot N(N^8, LDF)$$

**Light/Heavy discrimination based on the analysis of the LDF**

![ARGO-YBJ: Cosmic Ray Energy Spectrum](image)

**Consistency check with simulations**

- Proton GST generated spectrum
- Proton GST reconstructed spectrum
- Helium GST generated spectrum
- Helium GST reconstructed spectrum
- Light GST generated spectrum
- Light GST reconstructed spectrum

**MC + Bayes**
Shower Core Pos.

Rec. Zenith Angle

N_{\text{Max}}, N_{8}

Good consistency between Data & MC

<table>
<thead>
<tr>
<th>Cut</th>
<th>Data Surviving fraction (%)</th>
<th>Data Cumulative (%)</th>
<th>Monte Carlo Surviving fraction (%)</th>
<th>Monte Carlo Cumulative (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direction</td>
<td>70.2</td>
<td>70.2</td>
<td>68.7</td>
<td>68.7</td>
</tr>
<tr>
<td>Containment</td>
<td>40.3</td>
<td>28.3</td>
<td>43.3</td>
<td>29.7</td>
</tr>
<tr>
<td>Size</td>
<td>61.8</td>
<td>17.5</td>
<td>62.0</td>
<td>18.4</td>
</tr>
<tr>
<td>Maximum</td>
<td>91.7</td>
<td>16.0</td>
<td>89.0</td>
<td>16.4</td>
</tr>
</tbody>
</table>

FIG. 1. Core position resolution obtained from Monte Carlo simulations.

FIG. 2. Reconstructed shower size spectra of the two datasets.

\text{ANALOG DATA: ALL-PARTICLE & P+HE ENERGY SPECTRA}
ALL-PARTICLE SPECTRUM

→ CONSISTENT PICTURE WITH MODELS AND OTHER EXPERIMENTS

➡

PRELIMINARY WORK IN PROGRESS...

Flux $\times E^{2.6}$ [m$^{-2}$ s$^{-1}$ sr$^{-1}$ GeV$^{1.6}$]

- ARGO-YBJ all-particle (unfolding)
- Horandel 2003 - ALL
- Gaisser-Stanev-Tilav 2013 - ALL
- Horandel 2003 - P+He
- Gaisser-Stanev-Tilav 2013 - P+He

Energy [GeV]
**L I G H T / H E A V Y  D I S C R I M I N A T I O N**

- High segmentation
- Access the LDF down to the shower core
- Precision measurement of the LDF at several distance from the core

\[ \beta_5 = \rho_5 / \rho_0 \]

\[ \beta_{10} = \rho_{10} / \rho_0 \]

**CORE POSITION RESOLUTION**

\[ \sigma(R - R_0) [m] \]

\[ \log(E/\text{GeV}) \]

\[ \rho_5 / \rho_0 \]

\[ 4.5 \leq N_\theta \leq 5.0 \]

\[ E \approx 550 \text{ TeV} \]
\[ N(E_l, A_m) = \sum_{i,j,k} P(E_l, A_m | N_{8,i}, \beta_{5,j}, \beta_{10,k}) \cdot N(N_{8,i}, \beta_{5,j}, \beta_{10,k}). \]

- Find a range of mass group estimators that correspond to light primaries
- In these bins a large fraction of events is produced by light primaries
P+HE ENERGY SPECTRUM

UNCERTAINTIES

SYSTEMATIC

- **SELECTION CRITERIA**
  - ± 2.5% over the whole energy range

- **HADRONIC INTERACTION MODEL**
  - Check with SIBYLL hadr, interaction model
    - + (4 - 10)%

- **RESPONSE MATRIX**
  - ~10% @ E < 300 TeV
  - ~5% @ 300 TeV < E < 500 TeV
  - Gradually increase up to ~20% @ PeV energies

- **UNFOLDING**
  - < 1%

- **FLUX MODEL IN SIMULATIONS**
  - < 1%

STATISTICAL ERRORS

1% @ E ~ 10 TeV Up to
18% @ E ~ 1 PEV

TOTAL SYSTEMATIC:

-5.8% + 7% @ E < 600 TeV
-20.2% + 22.5% @ E > 1 PEV
Gradual change of the spectral index at $E \sim 1$ PeV

Consistent with the Digital Readout data (different data set)

Hybrid measurement gives consistent results

Shaded Area: Sys. Uncertainties
Error Bars: Stat. Uncertainties
SUMMARY OF ALL ARGO RESULTS

- Independent measurements
- Different Analysis technique
- Results are quite consistent within systematic errors

**HYBRID**

![Graph of Flux vs. Energy](image)

**UNFOLDING**

![Graph of Flux vs. Energy](image)

**EVENT BY EVENT ENERGY RECONSTRUCTION**

![Graph of Flux vs. Energy](image)
CONCLUSIONS

• ARGO-YBJ has been taken data for more than 5 years
  • Excellent stability of the detector
  • 2 Independent readout systems
  • Covers a very wide energy range: TeV ➞ PeV

• P+He spectrum
  • 10-100 TeV energy range
    • Good agreement with previous analysis
  • 100-3000 TeV energy range
    • Evidence of a gradual change of the spectral index at energies around 1 PeV
    • Good agreement between independent analyses within systematic errors

• All–particle spectrum
  • Good agreement with other experiments
MORE STUFF...
**P+HE ENERGY SPECTRUM: DIGITAL READOUT**

**3 - 300 TeV energy range**

- Excellent stability over a long period
- Overlap with direct measurements in a wide energy region
- Total systematic uncertainty ~ 5%

**Bayesian Approach**

<table>
<thead>
<tr>
<th>YEAR</th>
<th>Flux x 10^{-9} ± tot. err</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td>4.53 ± 0.28</td>
</tr>
<tr>
<td>2009</td>
<td>4.54 ± 0.28</td>
</tr>
<tr>
<td>2010</td>
<td>4.54 ± 0.28</td>
</tr>
<tr>
<td>2011</td>
<td>4.50 ± 0.27</td>
</tr>
<tr>
<td>2012</td>
<td>4.36 ± 0.27</td>
</tr>
</tbody>
</table>

**FLUX @ 50 TeV**

**YEAR** | **Gamma**
---|---
2008 | 2.63 ± 0.01
2009 | 2.63 ± 0.01
2010 | 2.63 ± 0.01
2011 | 2.64 ± 0.01
2012 | 2.65 ± 0.01

Extension of the previous ARGO-YBJ light component spectrum measurement in the low energy region

**Full sample** \( \gamma = 2.64 ± 0.01 \)

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**Phys. Rev. D 85 092005 (2012)**

**Phys. Rev. D 91 112017 (2015)**

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**ARGO-YBJ - P+He**

**ARGO-YBJ - P+He (2012)**

**CREAM - P+He**

**Pamela - P**

**Pamela - He**

**Horandel - P+He**

**Gaisser-Stanev-Tilav - P+He**

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**P. MONTINI**

CR SPECTRUM WITH ARGO-YBJ

RICAP 2016
Hybrid Analysis

\( N_0^{pe} \) is the total number of photo-electrons normalized to \( R_p = 0 \) and \( \alpha = 0^\circ \)

\( R_p \): the impact parameter;

\( \alpha \): the space angle between shower direction and Cherenkov telescope main axis.

\[
p_c = \frac{L}{W} - \frac{R_p}{109.9 m} - 0.1 \log_{10} N_0^{pe}
\]

\[
p_L = \log_{10} N_{max} - 1.44 \log_{10} N_0^{pe}
\]

H&He selection criteria: \( p_L > -4.53 \) & \( p_c > 0.78 \)

Energy reconstruction based on \( \sum N_{pe} \) in the Cerenkov image

- The purity of H&He showers: ~93% below 700 TeV;
- The contamination of heavy nuclei increases with energy: 13% @ 1 PeV, gradually increases to 27% @ 3 PeV
The P+He Spectrum

100-2500 TeV energy range

- The knee of H&He spectrum at (700±230) TeV is clearly measured
- Broken power law fits data well with indices
- -2.56 ± 0.05 and -3.24 ± 0.36 below and above the knee
- Consistent with other two independent analyses
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

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

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

Assume an exponential absorption after the shower maximum. Get the correct signal at maximum (\( N_{p8\text{max}} \)) by using \( N_{p8} \) and \( s' \) measurements for each event.

\[ N_{p8\text{max}} \approx N_{p8} \cdot e^{\frac{h_0 \sec \vartheta - X_{\text{max}}(s')}{\chi_{\text{abs}}}} \]
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.
ALL—PARTICLE & P+HE SPECTRA

ALL-PARTICLE SPECTRUM

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

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
• Overlap with direct measurements at low energy
• Flux systematics as for the all particle spectrum ⊕ < 15% mainly for the CNO contamination ➔ Overall < 20 %