Cosmic Ray Physics with ARGO-YBJ

Ivan De Mitri

University of Salento and
Istituto Nazionale di Fisica Nucleare
Lecce, Italy

On behalf of the ARGO-YBJ Collaboration
The ARGO-YBJ experiment

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

- **VHE $\gamma$-Ray Astronomy:** (see S. Vernetto’s talk)
  (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 ($E_{th}$ few TeV),
  - study of the shower space-time structure,
  - flux anisotropies at different angular scales
  - p-Air cross section measurement and hadronic interaction studies
  - anti-p / p ratio at TeV energies,
  - geomagnetic effects

- **Search for GRB’s** (full GeV / TeV energy range)

- …

through the…

Observation of *Extensive Air Showers* produced in the atmosphere by primary $\gamma$’s and nuclei
The ARGO-YBJ detector

Strip counting
Pad = space-time pixel
Time resolution ~1.7 ns

1 CLUSTER = 12 RPC
(~43 m²)

10 Pads (56 x 62 cm²) for each RPC

8 Strips (6.5 x 62 cm²) for each Pad

+ Analog charge read-out on “Big Pads”
**RPC performance**

ARGO-YBJ coll., NIM A (2009) 246

C$_2$H$_2$F$_4$ / Ar / i-C$_4$H$_{10}$
75 / 15 / 10 %
7.2kV applied to 2mm gas gap
Streamer mode

Continuous RPC monitoring.
Small efficiency and time resolution drifts with temperature:
- 0.03% / °C
- 0.04 ns / °C
Angular resolution substantially unaffected

\[ \text{Gain} \propto \frac{HV}{\rho} \propto HV \cdot \frac{T}{P} \]

**Graphs:**
- Efficiency vs. Temperature (°C)
- Time resolution vs. Temperature (°C)
- Angular Resolution vs. Time Resolution (ns)

**Equation:**

\[ \frac{\text{Efficiency}}{\text{Temperature}} = \frac{HV}{\rho} \cdot \frac{T}{P} \]
EAS reconstruction

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 space/time structure
with unique capabilities

3-D view of a detected shower

Top view of the same shower
Shower front time structure

**Curvature:**

time residuals $\Delta t(R)$ with respect to a **planar fit**

**Thickness:**

the RMS of time residuals $\sigma(R)$ with respect to a **conical fit**

Conicity parameter $\alpha$:
Give useful information on shower age and/or primary mass
The Moon Shadow and the antip/p ratio

ARGO-YBJ coll., PRD 84 (2011) 022003

- Size of the deficit ⇒ angular resolution
- Position ⇒ pointing accuracy
- West displacement ⇒ Energy calibration (Geomagnetic bending ≈ 1.57° / E (TeV))
- Antiprotons should give a shadow on the opposite side ⇒ Upper limit

ARGO-YBJ coll., PRD 85 (2012) 022003

N_{pad} > 100, 71 s.d.
The Sun Shadow and the Interplanetary Magnetic Field

ARGO-YBJ coll., APJ 729 (2011) 113

Sun shadow data are useful for an indirect measurement of the IMF carried by the solar wind near the Earth. In agreement with the OMNI spacecraft data repository (NASA).
Large scale anisotropy (LSA)

Structures appear to dissolve to smaller angular scale at high energy.

First measurement with an EAS array in an energy region so far investigated only by underground muon detectors

\[ 1 + A_1 \cos\left(\frac{2\pi(x - \phi_1)}{360}\right) + A_2 \cos\left(\frac{2\pi(x - \phi_2)}{180}\right) \]
LSA First harmonic amplitude and phase

Measurement covering either the rise and the fall of the signal

Uniform phase decrease
The Compton-Getting effect (in solar time)

Expected CR anisotropy due to Earth’s orbital motion around the Sun

2008 – 2009

Nhit $\geq$ 500 $\rightarrow$ $\approx$ 8 TeV

to avoid solar effects on low energy CRs
Medium Scale Anisotropy (MSA)

Map *smoothed with the detector PSF for CRs*

Proton median energy $\approx 1$ TeV

Cosmic rays excess $\approx 0.06\%$

$\Delta t = 3$ hr $= 45^\circ$

Equatorial coordinates: projection of the earth longitude and latitude

Galactic Plane

Cygnus region

New-structures

Sub-structures

Crab

Harder spectra than isotropic CR

No evidence for time dependence
Light-component spectrum of CRs

Measurement of the *light-component* \((p + \text{He})\) spectrum of primary CRs in the energy region \((5 - 250)\) TeV via a Bayesian unfolding procedure.


The contribution of heavier nuclei to the trigger is a few %

ARGO data agree with CREAM results

*For the first time direct and ground-based measurements overlap for a wide energy range thus making possible the cross-calibration of the experiments.*
Light-component spectrum of CRs

Extract the primary energy spectrum starting from the measured particle multiplicity spectrum at ground

Choose an initial value for $P(E)$

\[ P_0(E) \]

Use the Bayes theorem

\[ P(E \mid M) = \frac{P(M \mid E)P(E)}{P(M)} \]

$P(M \mid E)$ eval. from Monte Carlo events

\[ P(E) = \frac{N(E)}{N_{tot}} \]

\[ N(E) = N(M)P(E \mid M) \]

Iterate this procedure until variations on $P(E)$ are negligible
Light-component spectrum of CRs


Two new approaches in order to extend the energy region up to few PeV, by using:
- The RPC analog readout
- Hybrid approach using the atmospheric Cerenkov detectors installed at YangBaJing

Both analysis are now in progress.

ARGO-YBJ:
\[ \gamma_{(p+He)} = 2.61 \pm 0.04 \]
Measurement of p-air cross section

Use the shower frequency vs (sec$\theta$ - 1)

\[ I(\theta) = I(0) \cdot e^{-\frac{h_0}{\Lambda}(\text{sec} \theta - 1)} \]

for fixed energy and shower age.

The length $\Lambda$ is connected to the p interaction length by the relation $\Lambda = k \lambda_{\text{int}}$

where $k$ is determined by simulations and depends on:

- hadronic interactions
- detector features and location (atm. depth)
- actual set of experimental observables
- analysis cuts
- energy, ...

Then:

\[ \sigma_{\text{p-Air}} \text{ (mb)} = 2.4 \times 10^4 / \lambda_{\text{int}} \text{ (g/cm}^2) \]

\[ ARGO-YBJ \text{ Coll., Phys. Rev D 80, 092004 (2009)} \]
### The total p-p cross section

- Energy interval scarcely explored by p-p (and pbar-p) accelerator experiments
- The $\log^2(s)$ asymptotic behaviour is favoured

![Graph showing p-p cross section vs. energy](image)

**ARGO-YBJ Coll.**


Extending the energy range above 100 TeV with the analog readout
The total p-p cross section

...ARGO-YBJ data in the Review of Particle Properties 2012
The RPC analog readout

Readout of the charge signal on $1.39 \times 1.23 \text{ m}^2$ “big pads” (two / RPC)

Different gain scales used to cover a wide range in particle density:

\[ \rho_{\text{max–strip}} \approx 20 \text{particles/m}^2 \]
\[ \rho_{\text{max–analog}} \approx 10^4 \text{particles/m}^2 \]

Intrinsic limit at about one particle per cm$^2$, due to space charge effects of the streamer discharge: the so called *dead zone*.

Calibration procedure

Correction for Pressure and Temperature effects
The RPC analog readout

- Strips (digital)
- BigPads (analog)

- Extend the covered energy range
- Access the LDF down to the shower core
- Sensitivity to primary mass
- Info/checks on Hadronic Interactions
The truncated size as 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

QGSJET-II based MC samples

Vertical error bars: RMS(Energy)
Lateral Distribution Function

With the analog data we can study the LDF without saturation near the core

Tests are in progress in order to have:

- Better resolution on $X_{dm}$ and then lower systematics on the cross section measurement
- Better energy determination / shower reconstruction
- Sensitivity to the hadronic interaction model
- Sensitivity to shower age (primary mass)
Lateral Distribution Function

Several function used to fit the LDF shape in the range 0.5 m < R < 15.5 m from the core.

A NKG-like function found to reasonably reproduce the LDF shape in the above distance interval

\[ r_M' = r_M^{(YBJ)}/4 = 30.3m: \text{fixed} \]

Normalization factor \( A \) and \( s' \): free parameters

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

**Remarks:**

- \( s' \): ‘lateral shower age’, describing the slope of the radial distribution of charged particles
- In principle, \( s' \) differs from the ‘longitudinal age’ \( s \) (reflecting the longitudinal shower development)
- In practice \( s' \) and \( s \) are highly correlated...
Shower age vs truncated size

The $s'$ parameter is correlated to the $X_{\text{max}}$ position, **whatever the primary is.**

⇒ **Possibility to get hints on (a) shower age and (b) primary mass**
The ARGO-YBJ data lie between the expectations from extreme pure compositions (p and Fe)

A trend towards a heavier composition for increasing energy can be envisaged. Cross checks are in progress.
Multicore events with analog data

Preliminary results show the feasibility of these studies.

Hadronic physics, $p_t$ distributions,..
Horizontal Air Showers

- High energy muon induced events
- Energy spectra

θ > 70° → 1248 g/cm²
θ > 80° → 2458 g/cm²

Theta Rec
82.65°

Theta Rec
85.34°

Theta Rec
88.42°

Theta Rec
83.6°
The HAS flux is anticorrelated with nearby mountain profile.

The spectral index of the multiplicity distribution shows a sharp transition at large zenith angle (muon signature).
Summary and Outlook (not including gammas)

- Full detector in stable data taking since Nov. 2007 (first data in 2006)
- Trigger Rate ~3.5 kHz - Dead time 4%
- 220 GB/day transferred to IHEP (China) / CNAF (Italy) data centers
- End of data taking: February 2013
- Detailed analysis of the Moon shadowing effect (pointing, energy scale)
- Measurement of CR light component energy spectrum below 100TeV
- Study of the CR anisotropy at different angular scales
- Measurement of the CR antip/p flux ratio in TeV energy range
- Monitoring of the IMF by the Sun shadow displacement
- Measurement of the p-air and p-p cross sections up to 100TeV
- Geomagnetic effects on particle distributions at ground
- Extending the energy range to the PeV region by the RPC charge readout
- LDF near the shower core and shower age estimation
- Time structure of the shower front
- Hadronic interactions and primary mass sensitivity
- .....several new analysis in progress: final results within the next two years