Results from the ARGO-YBJ experiment
Outline

✓ Detector features and performance
✓ Cosmic rays and Moon shadow
✓ Gamma astronomy
✓ Search for Gamma Ray Bursts
The YangBaJing Cosmic Ray Observatory (Tibet, China)

Altitude  4300 m a.s.l.
Longitude  90° 31’ 50” East
Latitude   30° 06’ 38” North

Astrophysical Radiation with Ground-based Observatory at YangBaJing
Layer of Resistive Plate Chambers (RPC)

Active area:
- Central carpet: ~ 5600 m²
- Sampling guard-ring: ~ 1000 m²

Data taking:
- Since July 2006 with the central carpet
- Since November 2007 with the guard-ring

Installation of analog charge read-out in progress
- Dynamical range up to ~ 10⁴ TeV
Operation modes

**Shower mode**

Trigger: number of fired pads ($N_{pad}$) within 420 ns on the central carpet

for $N_{pad} \geq 20$, rate $\sim 3.6$ kHz ($\sim 220$ GBytes/day)

Detection of Extensive Air Showers (direction, size, core ...)

Aims: cosmic-ray physics (threshold $\sim 1$ TeV)
VHE $\gamma$-astronomy (threshold $\sim 300$ GeV)
gamma-ray bursts

**Scaler mode**

counting rates ($\geq 1, \geq 2, \geq 3, \geq 4$ coincidences) for each cluster

Aims: detector and environment monitor
flaring phenomena (gamma ray bursts, solar flares) with a threshold of few GeV
**Shower mode**

Space pixel: single strip (7×62 cm²)  

Time pixel: pad (56×62 cm²) is the OR of 8 strips, with a resolution of ~1.8 ns

The number of pixels, the time resolution and the full coverage of the central carpet allow to reconstruct the shower with unprecedented details.

The detailed shower topology is a possible tool for γ/h discrimination.
Cosmic rays
High space/time granularity allows unprecedented studies on the EAS phenomenology (different topologies and time structures)

Conical shape in small shower

High energy

Same trigger: two showers

Conical shape in small shower
Studies in progress on the shower time structure

**shower curvature**

**shower thickness**

<table>
<thead>
<tr>
<th>Data</th>
<th>N_{hit} = (200 - 400)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MC</td>
<td>N_{hit} = (200 - 400)</td>
</tr>
</tbody>
</table>

| N_{hit} = (400 - 800) |
| N_{hit} = (800 - 1000) |
| N_{hit} = (1000 - 1200) |

Distance to core (m)

RMS of residuals (conical fit) ns

Time residuals (planar fit) ns
Measurement of attenuation length ($\Lambda$) and p-Air cross section

\[ I(\theta) = I_0 \exp \left[ -\frac{h_0}{\Lambda} (\sec \theta - 1) \right] \]

\[ \Lambda = k \lambda_{\text{INT}} \]

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

submitted to Phys. Rev. D
The shadow of the Moon
The shadow of the Moon

A deficit in the cosmic ray flux is expected from the Moon direction. Many items are connected:

- **angular resolution** (width of the deficit)

- **pointing accuracy** (position of the deficit)

- **energy calibration** (the westward deflection due to the geomagnetic field depends on the energy of cosmic rays)

- **proton/antiproton ratio** (antiprotons are deflected eastward)

\[ \Delta \theta \approx \frac{Z \times 1.6^\circ}{E \,[\text{TeV}]} \]
2006-2008 data, with the cut $N_{\text{STRIP}} > 60$

Until November 2007: installation and debug operations, low duty-cycle
Since December 2007: stable data taking with high duty-cycle

The deficit surface is the convolution of the Point Spread Function of the detector and the widespread Moon disc

$$RMS \simeq \sigma \sqrt{1 + \left( \frac{R}{2\sigma} \right)^2}$$
**Selected sample (1-year data)**

December 2007 – December 2008
$N_{\text{STRIP}} > 40$ and $\theta < 50^\circ$

130 x $10^9$ analyzed events

Observation time 1350 hrs
Source visibility time 1500 hrs
On-source duty-cycle 90%

Signal statistical significance 32 s.d.

$$n_\sigma \approx 0.88 \sqrt{t [\text{hrs}]}$$

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**Angular resolution**

- **MC expectation**
- **Data**

**EW displacement**

- **equi-zenith**
- **MC expectation**
- **time-swapping**
Looking for an antiproton signal (East deficit)

Deficit on the East-West axis

A likelihood method is applied to estimate the upper limit of the antiproton flux

$\Phi(\bar{p}) < 0.03 \Phi(p)$ at 2.0 TeV (90% c.l.)
γ-astronomy
The technique of EAS detection allows a duty-cycle limited only by maintenance:

\[ \text{Duty-cycle} \rightarrow 100\% \]

The field of view is limited only by the atmosphere thickness. Requiring zenith angle \(< 40^\circ\) :

\[ \text{Field of View} \sim 2 \text{ sr} \]

Continuous monitoring of the sky in the declination band

\[ -10^\circ < \delta < 70^\circ \]

Presently ARGO-YBJ is the only wide-field-of-view \(\gamma\)-telescope able to detect AGN TeV flares on a few days
CR excesses in the sky map

Smoothing radius 5°

$N_{PAD} > 40 \rightarrow$ Proton median energy $\approx 2$ TeV

Data collected in 424 days

$\approx 0.06\%$

$\approx 0.1\%$
Sky map after correction

Data collected in 424 days

Smoothing radius 1.3°

Mrk 421 (8 σ)

Crab (7 σ)

$N_{PAD} > 40 \quad \rightarrow \quad \text{Gamma median energy} \approx 0.6-2 \text{ TeV}$
Crab Nebula energy spectrum

\[
dN/dE = (3.73 \pm 0.80) \times 10^{-11} E^{-2.67 \pm 0.25} \gamma \text{ cm}^{-2} \text{ s}^{-1} \text{ TeV}^{-1}
\]

<table>
<thead>
<tr>
<th>( N_{\text{PAD}} )</th>
<th>Events /day</th>
<th>( E_{\text{med}} ) (TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40 - 99</td>
<td>128 \pm 24</td>
<td>0.85</td>
</tr>
<tr>
<td>100 - 299</td>
<td>17.9 \pm 6.3</td>
<td>1.8</td>
</tr>
<tr>
<td>( \geq 300 )</td>
<td>9.2 \pm 2.3</td>
<td>5.2</td>
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Mrk 421 X-ray data by ASM/RXTE

**Mrk 421 - July-August 2006**

ARGO-YBJ test data collected during the x-ray flare

**Observation time** ≈ 109 hours

**Flux** ≈ 4 Crab units
Mrk 421
2008 activity

ARGO-YBJ
$N_{PAD} > 100$

ASM/RXTE

γ-x correlation coefficient
$\rho = 0.64$
The June 2008 flare observed from optical to TeV energies (12 decades)

-- optical R-band (GASP-WEBT)
-- UV band (UVOT)
-- soft x-rays (ASM/RXTE and SWIFT)
-- hard x-rays (SWIFT and AGILE)
-- gamma rays (AGILE)
-- VHE gamma-rays (Veritas and Magic)

No VHE Cerenkov data after June 8
SEDs for June 2008 flares

SEDs for June 2008 flares

ARGO-YBJ measurements in agreement with the model by Donnarumma et al.
Search for Gamma Ray Burst
Scaler mode: the counting rates (≥1, ≥2, ≥3, ≥4 counts on each cluster) are measured each 0.5 s

Search for sudden increases of the counting rate in coincidence with GRBs observed by satellites

Energy range of the scaler mode search: 1 - 100 GeV

December 2004 – April 2009

66 GRBs in the ARGO-YBJ Field of View (θ < 40°)

11 with known redshift

59 long duration GRBs (> 2s)
7 short duration GRBs (≤ 2s)

Look for coincidences:
1) in coincidence within ΔT_{90}
2) in different time intervals around the GRB time

Also the analysis of the stacked GRBs has been performed
No signal detected (1-100 GeV)

Fluence Upper Limits of the order of $10^{-5} - 10^{-4}$ erg cm$^{-2}$

Upper Limits on the GRB cutoff energy
Intersection of the fluence upper limit with the extrapolation of the fluence measured by the satellites

These limits are a significant test for competing GRB models
Conclusions

- ARGO-YBJ detector (central carpet + guard ring) is taking data since November 2007 (duty-cycle > 90%)

- Studies on Cosmic Rays are going on (p-p cross section, anisotropies, shower profile, limit on antiproton flux ...)

- First results on γ-astronomy (mainly 1-year data)
  - angular resolution as expected (Moon shadow)
  - limits on 1-100 GeV fluence from GRBs
  - Crab Nebula γ-spectrum in agreement with other measurements
  - continuous monitor of all sky

- Studies to increase the sensitivity are in progress (data quality, γ-hadron separation)

- VHE γ-sky survey is going on