Recent Highlights from ARGO-YBJ

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Fifth Workshop on Air Shower Detection at High Altitude
26-28 May 2014 Paris (France)
Outline

★Gamma-Ray Astronomy

● First Northern sky survey (-10° < δ < 70°) at 0.25 Crab Units
● Study of extended sources

★Cosmic Ray Physics

● CR Light component (p+He) Energy Spectrum (3 TeV - 5 PeV)
● Elemental composition approaching the knee: the ‘proton' knee
The ARGO-YBJ experiment

Longitude 90° 31’ 50” East
Latitude 30° 06’ 38” North
90 Km North from Lhasa (Tibet)

4300 m above the sea level ~ 600 g/cm²
The basic concepts

…for an unconventional air shower detector

❖ HIGH ALTITUDE SITE
   (YBJ - Tibet 4300 m asl - 600 g/cm2)

❖ FULL COVERAGE
   (RPC technology, 92% covering factor)

❖ HIGH SEGMENTATION OF THE READOUT
   (small space-time pixels)
   
   Space pixels: 146,880 strips (7×62 cm²)
   Time pixels: 18,360 pads (56×62 cm²)

… in order to

• image the shower front with unprecedented details

• get an energy threshold of a few hundreds of GeV
The RPC analog readout

...extending the dynamical range up to PeV

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

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

- Extend the covered energy range
- Access the LDF in the shower core
- Sensitivity to primary mass
- Info/checks on Hadronic Interactions

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Single layer of Resistive Plate Chambers (RPCs) with a full coverage (92% active surface) of a large area (5600 m$^2$) + sampling guard ring (6700 m$^2$ in total)
The ARGO-YBJ Collaboration

Collaboration Institutions:
Chinese Academy of Sciences (CAS)
Istituto Nazionale di Fisica Nucleare (INFN)

INAF/IASE, Palermo and INFN, Catania
INFN and Dpt. di Fisica Università, Lecce
INFN and Dpt. di Fisica Università, Napoli
INFN and Dpt. di Fisica Università, Pavia
INFN and Dpt di Fisica Università “Roma Tre”, Roma
INFN and Dpt. di Fisica Università “Tor Vergata”, Roma
INAF/IFSI and INFN, Torino

IHEP, Beijing
Shandong University, Jinan
South West Jiaotong University, Chengdu
Tibet University, Lhasa
Yunnan University, Kunming
Hebei Normal University, Shijiazhuang
The birth of an idea

Detection of small size air showers at high altitude: the expected performances of an RPC’s carpet

B. D’Ettorre Piazzoli(1), G. Di Sciascio(1), E. Pompei(2), A. Surdo(3)

Experimental set-up

An RPC’s carpet of $120 \times 120 \text{ m}^2$ has been considered with a 95% active area. Moreover a 95% efficiency has been take into account. Each RPC ($1 \times 2 \text{ m}^2$) is equipped with a read-out system of 3 cm wide, 50 cm long strips. Signals from the strips are OR-ed in order to get the time of the first particle hitting each $50 \times 50 \text{ cm}^2$ ‘pad’. This time is smeared out with the detector response and assigned

Conclusions

Preliminary calculations indicate that an RPC’s carpet operating at high altitude could achieve excellent performances in detecting air showers initiated by photons of energy $\geq 300 \text{ GeV}$. At this energy the minimum detectable integral flux at 4$\sigma$ level in 1 yr of data taking is expected to be about $6 \times 10^{-11} \cdot \left(\frac{\text{flux}}{0.6\text{ eV}}\right) \cdot \frac{1}{Q} \text{ cm}^{-2} \text{s}^{-1}$, comparable to fluxes expected from extragalactic sources. Here $Q$ is a rejection factor resulting

HAWC: $\approx 140 \times 140 \text{ m}^2$
The main stages

- ARGO proposal (1996)
- Approval of a successful test in Tibet (ARGO-TEST, 1997-1998)
- Approval of the ARGO-YBJ experiment (1999)
- Inauguration of the ARGO-YBJ laboratory (June 2001)
- Central carpet in data taking (2006)
- Full layout in stable data taking (2007)

- End/Stop data taking: January 2013
Status and performance

- In observation since July 2006 (commissioning phase)
- Stable data taking since November 2007
- End/Stop data taking: January 2013
- Average duty cycle ~87%
- Trigger rate ~3.5 kHz @ 20 pad threshold
- N. recorded events: \( \approx 5 \times 10^{11} \) from 100 GeV to 10 PeV
- 100 TB/year data

Intrinsic Trigger Rate stability 0.5%
(after corrections for T/p effects)
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● Elemental composition approaching the knee:
Cosmic Rays and $\gamma$-Ray Astronomy connection

★ Hadro-production (CR sources)

\[ p + p/\gamma \Rightarrow n \ (\pi^+ + \pi^- + \pi^0) + h \]

\[ \gamma \ \text{Gamma-Ray Astronomy} \]

\[ \nu \ \text{Neutrino Astronomy} \]

CRs, photons and neutrinos strongly correlated

ONLY charged CRs observed at $E > 10^{14}$ eV so far!
Recent observations of PeV neutrinos by Icecube

★ Electro-production (Inverse Compton)

\[ e + \gamma \Rightarrow e' + \gamma' \]

SSC model: photons radiated by high energy ($10^{15}$ eV) electrons boosted by the same electrons

Gammas (and neutrinos) point back to their sources (SNR, PWN, BS, AGN ..)
Gamma-Ray Astronomy with ARGO-YBJ

- Energy threshold: few hundreds of GeV → Overlaps with Cherenkov detectors
- Large duty cycle: 86%
- Large field of view: ~2 sr
- Declination band from -10° to 70°
- Integrated sensitivity in 5 y at ~1 TeV: 0.25 Crab for dec 15° - 45°

Crab Nebula 5 years data

\[
\frac{dN}{dE} = (2.94 \pm 0.20_{\text{stat}}) \times 10^{-11} \left( \frac{E}{1 \text{ TeV}} \right)^{-2.67 \pm 0.06_{\text{stat}}} \text{ cm}^{-2} \text{ s}^{-1} \text{ TeV}^{-1} \]

(0.5 – 10) TeV
Sensitivity to gamma point sources

EAS-array: 5 s.d. in 1 year

Cherenkov: 5 s.d. in 50 h on source
ARGO-YBJ Sky Survey at 1 TeV

- Integrated sensitivity in 5 y at ~1 TeV: 0.25 Crab for dec 15° - 45°
ARGO-YBJ 5-years Survey of Inner Galactic Plane

$20^\circ < l < 90^\circ$, $|b| < 10^\circ$

$E_{50} \approx 0.7$ TeV

$E_{50} \approx 1.8$ TeV
Detected Sources

Table 2. Location of the excess regions

<table>
<thead>
<tr>
<th>ARGO-YBJ Name</th>
<th>Ra (deg)</th>
<th>Dec (deg)</th>
<th>l (deg)</th>
<th>b (deg)</th>
<th>S (s.d.)</th>
<th>Associated TeV Source</th>
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<tr>
<td>ARGO J0409–0627</td>
<td>62.35</td>
<td>-6.45</td>
<td>198.51</td>
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<td>4.8</td>
<td>Crab Nebula</td>
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<td>ARGO J0535+2203</td>
<td>83.75</td>
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<td>-5.67</td>
<td>20.8</td>
<td>Mrk 421</td>
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<td>ARGO J1105+3821</td>
<td>166.25</td>
<td>38.35</td>
<td>179.43</td>
<td>65.09</td>
<td>14.1</td>
<td>Mrk 501</td>
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<tr>
<td>ARGO J1654+3945</td>
<td>253.55</td>
<td>39.75</td>
<td>63.59</td>
<td>38.80</td>
<td>9.4</td>
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<tr>
<td>ARGO J1839–0627</td>
<td>279.95</td>
<td>-6.45</td>
<td>25.87</td>
<td>-0.36</td>
<td>6.0</td>
<td>HESS J1841–055</td>
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<tr>
<td>ARGO J1907+0627</td>
<td>286.95</td>
<td>6.45</td>
<td>40.53</td>
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<td>ARGO J1910+0720</td>
<td>287.65</td>
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<td>41.65</td>
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<td>ARGO J1912+1026</td>
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<td>10.45</td>
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<td>0.20</td>
<td>4.2</td>
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<tr>
<td>ARGO J2021+4038</td>
<td>305.25</td>
<td>40.65</td>
<td>78.34</td>
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<td>4.3</td>
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<tr>
<td>ARGO J2031+4157</td>
<td>307.95</td>
<td>41.95</td>
<td>80.58</td>
<td>1.38</td>
<td>6.1</td>
<td>MGRO J2031+41</td>
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<tr>
<td>ARGO J1841-0332</td>
<td>280.25</td>
<td>-3.55</td>
<td>28.58</td>
<td>0.70</td>
<td>4.2</td>
<td>HESS J1843–033</td>
</tr>
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</table>

Fig. 4: Average 95% C.L. flux upper limit at energy above
500 GeV, averaged on the right ascension direction, as a
function of declinations. Different curves indicate sources
with different power-law spectral indices −2.0, −2.6 and
−3.0. The Crab unit is 5.77×10^{−11} cm^{−2} s^{−1}.

G. Di Sciascio, 5th Workshop of EAS detection at high altitude, Paris (France), 26-28 May 2014
Why gamma-ray extended sources?

- TeV gamma-ray extended sources are an important tool to investigate the sources of cosmic rays.
- The observed degree-scale extended emission could be produced by high-energy cosmic rays escaping from the source and diffusing in the interstellar medium. The gamma-ray emission should result from the interaction of these cosmic rays with the ISM particles.
- 80% of TeV galactic gamma ray sources are extended.
- Many of them are still unidentified.
- To study degree-scale sources we need instruments with a large field of view and able to correctly evaluate the cosmic ray background over a large solid angle.
- Sensitivity to an extended source is relatively better for an EAS than an IACT because angular resolution is not as important.

\[ S_{\text{extended}} \approx S_{\text{point}} \frac{\sigma_{\text{source}}}{\sigma_{\text{detector}}} \]
The Cygnus Region

Very important region populated by many unidentified strong sources

- The brightest diffuse γ-rays source in the northern hemisphere
- 9 supernova remnants
- >20 Wolf-Rayet starts
- 6 OB associations
- shocked gas

Natural site for cosmic-ray acceleration

★ Fermi data (1-100 GeV):
  A cocoon of freshly accelerated CRs?

★ Milagro detected 2 sources at 20 TeV
  ✔ MGRO J2019+37 (12.4 σ)
  ✔ MGRO J2031+41 (7.6 σ)
Both consistent with Fermi source locations

★ Complex emission observed by VERITAS
  consistent with location of MGRO J2019+37

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The Cygnus Region by ARGO-YBJ


The Cygnus Region by ARGO-YBJ

A cocoon of freshly accelerated cosmic rays by hadronic mechanism?

NO signal from the MGRO J2019+37 below 10 TeV

✓ Insufficient exposure above 5 TeV?
✓ Variability?

The Fermi Cocoon

The TeV counterpart of the Fermi Cocoon

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Observation of extended sources with ARGO-YBJ

**HESS J1841-055**

**MGRO J2031+41**

**The Fermi Cocoon**


**MGRO J1908+06**


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Comments on extended sources

- CRAB point source flux agrees with IACTs
- MGRO J2031+41 extended flux $\sim 10 \times$ IACTs
- MGRO J1908+06 extended flux $\sim 4 \times$ IACTs
- HESS J1841-055 extended flux $\sim 3 \times$ IACTs

Systematic disagreement for extended sources! ARGO-YBJ (and MILAGRO) measure higher fluxes

Possible systematics in ARGO-YBJ

- CR background evaluation: checked with the distribution of the excesses (Gauss with $s=1$)
- Pointing accuracy (at 0.1° level checked with the Moon Shadow)
- Error in energy scale < 13%
- Contribution from the diffuse emission of the Galactic plane < 15%

Overall systematics on the flux < 30%

★The discrepancy could origin from the different techniques used in the background estimation for extended sources.
★Maybe the extended excess is due to the contribution of different sources

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- CR Light component (p+He) Energy Spectrum (3 TeV - 5 PeV)
- Elemental composition approaching the knee: the ‘proton’ knee
Galactic Cosmic Rays

- CRs below $10^{17}$ eV are predominantly galactic.
- The bulk of CR is produced by shock acceleration in SN explosions.
- Diffusion of accelerated CRs through non-uniform, non-homogeneous ISM.
- Galactic CRs are scrambled by galactic magnetic field over very long time.

The main feature: the ‘knee’ in the all-particle spectrum

Different models to explain the ‘knee’ and different signature…

- **Acceleration in SNRs:**
  - finite lifetime of shock $E_{\text{max}} \approx Z \cdot 10^{15}$ eV
  - $E_{\text{knee}} \propto Z$
  - No anisotropy change

- **Diffusion process:**
  - probability of escape from Galaxy $= f(Z)$
  - $E_{\text{knee}} \propto Z$
  - Anisotropy $\propto E^5$

- **Interaction with bckg particles:**
  - Photo-disintegration - interaction with in galactic halo etc.
  - $E_{\text{knee}} \propto A$

Key elements: mass composition and anisotropy
Approaching the knee

How well do we know the structure of the primary spectrum around the knee ($10^{14} - 10^{16}$ eV)?

The standard model:

- Knee attributed to light (proton) component
- Rigidity-dependent structure (Peters cycle): cut-offs at energies proportional to the nuclear charge $E_Z = Z \cdot 4.5$ PeV
- The sum of the flux of all elements with their individual cut-offs makes up the all-particle spectrum.
- Not only does the spectrum become steeper due to such a cutoff but also heavier.

Experimental results conflicting.
Measurement of the CR spectrum

- Measurement of the CR energy spectrum (all-particle and light component) in the energy range few TeV - 5 PeV by ARGO-YBJ with different ‘eyes’
  - ‘Digital readout’ (based on strip multiplicity) below 200 TeV
  - ‘Analog readout’ (based on the shower core density) up to 10 PeV
  - Hybrid measurement with a Wide Field of view Cherenkov Telescope 200 TeV - PeV
    → talk by Cao Zhen

- Working at high altitude (4000 m asl):
  1. p and Fe produce showers with similar size
  2. Small fluctuations: shower maximum
  3. Low energy threshold: overposition with direct measurements
(p+He) spectrum below 300 TeV: data selection

Digital readout: strip multiplicity

Data collected between Jan. 2008 and Dec. 2012 $\approx 8 \times 10^{10}$ high quality events

- $M \leq 50,000$
- Zenith Angle $\leq 35^\circ$
- Highest density cluster in $40 \times 40 \text{m}^2$

Shower size distribution on the central carpet, $M$ (strip multiplicity)

Light Component (p+He) selection:

$\rho_{A20} > \rho_{A42}$

$A20 = 20$ innermost clusters
$A42 = 42$ outermost clusters

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Light component spectrum

Year | spectral index
--- | ---
2008 | -2.61 ± 0.02
2009 | -2.61 ± 0.02
2010 | -2.61 ± 0.02
2011 | -2.62 ± 0.02

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The light-component spectrum (3 - 300 TeV)

Measurement of the light-component (p+He) CR spectrum in the energy region (3 – 300) TeV via a Bayesian unfolding procedure.

PRD 85, 092005 (2012)
ARGO-YBJ and AMS-02 (ICRC13)

Flux $\times E^{2.7}$ [m$^2$ s$^{-1}$ sr$^{-1}$ GeV$^{-1}$]

- AMS-02 (p+He)
- PAMELA (Light)
- MACRO+EAS-TOP
- CREAM (Light)
- ARGO-YBJ (2012)
- ARGO-YBJ (2013)

extrapolation
Extending the energy range

To extend the energy range up to 10 PeV we use **different eyes**: 

- **ARGO-YBJ Analog Readout**

- **Wide Field of view Cherenkov Telescope (WFCTA)**
  - 5 m² spherical mirror
  - 16 × 16 PMT array
  - pixel size 1°
  - FOV: 14° × 14°
  - Elevation angle: 60°

...to performe 2 different analysis:

- **ARGO-YBJ Analog Readout alone**

- **Hybrid measurement ARGO-YBJ/WFCTA**

Talk by Zhen Cao
Intrinsic linearity: test at the BTF facility

**Linearity of the RPC @ BTF in INFN Frascati Lab:**

- electrons (or positrons)
- $E = 25-750$ MeV (0.5% resolution)
- $<N>=1\div10^8$ particles/pulse
- 10 ns pulses, 1-49 Hz
- beam spot uniform on $3\times5$ cm

$\Rightarrow$ Linearity up to $\approx 2 \cdot 10^4$ particle/m$^2$

Calorimeter: lead glass block from OPAL, PMT a Hamamatsu R2238.

The RPC signal vs the calorimeter signal

![Graph showing the relationship between RPC signal and calorimeter signal with a straight line fit and residual values normalized to the fit.](image)

$\chi^2$/d.o.f. for the fitted values of the gaussian parameters, indicating a good agreement with local deviations contained within a few per cent (r.m.s) and an integral deviation (mean) below 1%.

Linearity up to $\approx 2 \cdot 10^4$ particle/m$^2$
Performance evaluation

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

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

4 data sample:
\[ \rho: 10 \rightarrow 10^4 \text{ part/m}^2 \]

Event selection:
- Core reconstructed in a fiducial area of 2400 m\(^2\)
- Zenith angle < 15°

Good overlap between 4 scales with the maximum density of the showers spanning over three decades

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Absolute comparison Data - MonteCarlo

Differential rate of \( P_{\text{max}} \), shower core density, for 2 gain scales

Excellent agreement with MonteCarlo

Event selection:
- ★ Core reconstructed in a fiducial area of 2400 m\(^2\)
- ★ Zenith angle < 15°

\( P_{\text{max}} \) spans over two and half decades, while the event frequency runs over five decades.

ARGO-YBJ + WFCTA

- **ARGO-YBJ**: lateral distribution
  In the core region → mass sensitive

- **Cherenkov telescope**: longitudinal information
  Hillas parameters → mass sensitive
  Better energy resolution
  - angular resolution: 0.2°
  - shower core position resolution: 2 m
Hybrid observation data set

- **Period**
  - Good wheater: 728,000 sec

- **Criteria for reconstruction**
  - Shower cores well inside the ARGO-YBJ central carpet
  - Cherenkov images well contained in the telescope, i.e. space angle with respect to the telescope axis < 6°
  - Number of fired PMTs ≥ 6

- **Cherenkov image cleaning**
  - Single channel threshold: S/N>3.5.
  - Arrival time: all triggered pixels in a window of Δt = 240 ns.
  - Isolated pixels rejected

8218 events well reconstructed above 100 TeV
Light-component (p+He) selection

- Contamination of heavier component < 5 %
- Energy resolution: ~25%
- Uncertainty: ~25% on flux

<table>
<thead>
<tr>
<th></th>
<th>Proton</th>
<th>Helium</th>
<th>CNO</th>
<th>MgAlSi</th>
<th>Iron</th>
<th>SUM</th>
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<tr>
<td>The initial fractions</td>
<td>20%</td>
<td>20%</td>
<td>20%</td>
<td>20%</td>
<td>20%</td>
<td>100%</td>
</tr>
<tr>
<td>The fractions after composition selection</td>
<td>69.1%</td>
<td>25.8%</td>
<td>3.8%</td>
<td>1.1%</td>
<td>0.2%</td>
<td>100%</td>
</tr>
<tr>
<td>The selection efficiency</td>
<td>51.0%</td>
<td>19.1%</td>
<td>2.7%</td>
<td>0.8%</td>
<td>0.1%</td>
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</tr>
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</table>

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The light-component (p+He) spectrum (2 - 700) TeV

- CREAM: $1.09 \times 1.95 \times 10^{-11} \text{(E/400 TeV)}^{-2.62}$
- ARGO-YBJ: $1.95 \times 10^{-11} \text{(E/400 TeV)}^{-2.61}$
- Hybrid: $0.92 \times 1.95 \times 10^{-11} \text{(E/400 TeV)}^{-2.63}$

Flux at 400 TeV:
$1.95 \times 10^{-11} \pm 9\% \ (\text{GeV}^{-1} \text{ m}^{-2} \text{ sr}^{-1} \text{ s}^{-1})$

The 9% difference in flux corresponds to a difference of ± 3.5% in energy scale between different experiments.

Bartoli et al., Chin. Phys. C 38, 045001 (2014)
HE-CR: ICRC2013 Spectra

Many thanks to the groups for providing the (prelim.) data points!
Approaching the all-particle knee

We modified the selection criteria to increase the statistics above 700 TeV with tolerable contamination from heavier nuclei.

The aperture increases by a factor of 2.4 and the number of (p+He) events increases from 490 to 1162 above 200 TeV.

The contamination increases from 3% to 7% below 700 TeV and the purity worsens from 98% to 93%.
Analysis with ARGO-YBJ analog data

Analysis based on the $N_p^{8\text{m}}$ parameter: the number of particle within 8 m from the shower core position.

This truncated size is

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

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

$$\rho'_{\text{NKG}} = A \cdot \left( \frac{r}{r_0} \right)^{s'-2} \cdot \left( 1 + \frac{r}{r_0} \right)^{s'-4.5}$$

$R_0 = 30 \text{ m}$

$s'$ is NOT the shower age. It is correlated to it.

Assume an exponential absorption after the shower maximum. Get the correct signal at maximum (Np8max) by using Np8 and $s'$ measurements for each event.

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

Also checks with Gaisser-Hillas profile

The LDF slope $s'$ is $<X_{\text{max}}>$ estimator mass-independent.
Finding the best $\lambda_{\text{abs}}$ parameter

Results from the ARGO-YBJ test experiment
Astroparticle Physics 17 (2002) 151–165

According to numerous measurements from sea level to an altitude of about 4 km, $\lambda_{\text{att}}$ lies between 120 g/cm$^2$ and 150 g/cm$^2$ for showers with moderate size [15,19]. Thus the exponent of the angular (sec $\theta - 1$) law. The parameter $\alpha$ is found to be 4.88 $\pm$ 0.45, so that $\lambda_{\text{att}} = (124 \pm 11)$ g/cm$^2$, in excellent agreement with previous results. For comparison, the value provided by Monte Carlo simulations is 4.11 $\pm$ 0.37. For angles greater than

- $p$
- He
- CNO
- Fe

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

Correction with $\lambda = 120$ g/cm$^2$

Small residual shift with LogA as foreseen by theory

Further improvements in progress
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.

In excellent agreement with total-size vs E theoretical plot. The shift is simply due to the fact that we are using the truncated size.
All particle spectrum: trigger and selection efficiencies

- **Energy range for the spectrum measurement**
  - **G4**
  - **G1**

- **G4 ⊕ G1** in full efficiency for all species from 300 TeV to 5 PeV


Preliminary!
Systematic uncertainty evaluations

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%**

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%**

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 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.

LDF -p- $\Delta \log N_{p^5} = (3.7-4.0)\cdot \Theta_{zen} = (0-15)^{\circ}$

LDF - SIBYLL vs QGSjet $\Delta \log Np8 = (3.7-4.0)$

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<th>QRatio1P_2</th>
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</tbody>
</table>

G. Di Sciascio, 5th Workshop of EAS detection at high altitude, Paris (France), 26-28 May 2014
The “all-particle” spectrum by ARGO-YBJ

Preliminary!
The “all-particle” spectrum by ARGO-YBJ

- Consistent picture with models and previous measurements
- Overlap with the two gain scales (different data,…)
- Suggest spectral index -2.6 below 1 PeV and -2.8 from 1 to 5 PeV

Preliminary!
The light component spectrum by ARGO-YBJ (1)

The Bayesian unfolding method used for the analysis of data below 200 TeV is adapted to the ARGO-YBJ analog data.

- \( \text{NPmax} > 500 \)
- \( 10^4 < \text{Np8} < 10^6 \)
- \( \theta \leq 35^\circ \)
- Reconstructed shower core position in a fiducial area 40 \( \times \) 40 \( m^2 \) centered on the central carpet

Selection of the light component: shower topology

**Light Component \((p+\text{He})\) selection:**

\[ \rho_{A20} > \rho_{A42} \]

A20 = 20 innermost clusters
A42 = 42 outermost clusters
The light component spectrum by ARGO-YBJ (1)

The Bayesian unfolding method used for the analysis of data below 200 TeV is adapted to the ARGO-YBJ analog data.

Observation of gradual change of the slope starting around 650 TeV

Contamination $\geq$ CNO: $\approx 15\%$

Preliminary!
p and He selection

A simple cut in the plane s’ vs Np8

Contamination ≥ CNO: ≈ 15%

MC Horandel spectra and normalizations
p+He: trigger and selection efficiencies

On the efficiency plateau above 200 TeV

Energy range for p+He measurement with

Energy range for p+He measurement with G1
Observation of gradual change of the slope starting around 650 TeV
Light component spectrum (3 TeV - 5 PeV) by ARGO-YBJ

Good overposition with the digital readout < 300 TeV
Observation of gradual change of the slope starting around 650 TeV

Preliminary!
Light component spectrum (3 TeV - 5 PeV) by ARGO-YBJ

Comparison with direct measurements and with Tibet ASgamma (SYBILL)

Preliminary!
Other results

The cosmic ray composition between $10^{14}$ and $10^{16}$ eV

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The overall picture

Preliminary!
Conclusions

The ARGO-YBJ detector exploiting the full coverage approach and the high segmentation of the readout is imaging the front of atmospheric showers with unprecedented resolution and detail.

The digital and analog readout are allowing a deep study of the CR physics in the wide TeV - PeV energy range.

A number of interesting results have been obtained

- First Northern sky survey (-10° < δ < 70°) at 0.25 Crab Units.
- Observed TeV gamma-ray emission from 6 sources above 5 s.d.
- Detailed study of flaring and extended TeV gamma-ray sources

- Measurement of CR energy spectrum (all-particle and light component) up to 5 PeV
- Study of EAS phenomenology up to PeV
- Study of the CR anisotropy at different angular scales
- Measurement of the CR antip/p flux ratio in TeV energy range
- Measurement of the p-air and p-p cross sections up to 100 TeV

- Detailed study of the Sun shadow in correlation with the solar activity
Backup slides
ARGO-YBJ + WFCTA: p+He