INFN
Istituto Nazionale di Fisica Nucleare

Measurement of the $\bar{p}/p$ ratio in the few-TeV energy range with ARGO-YBJ

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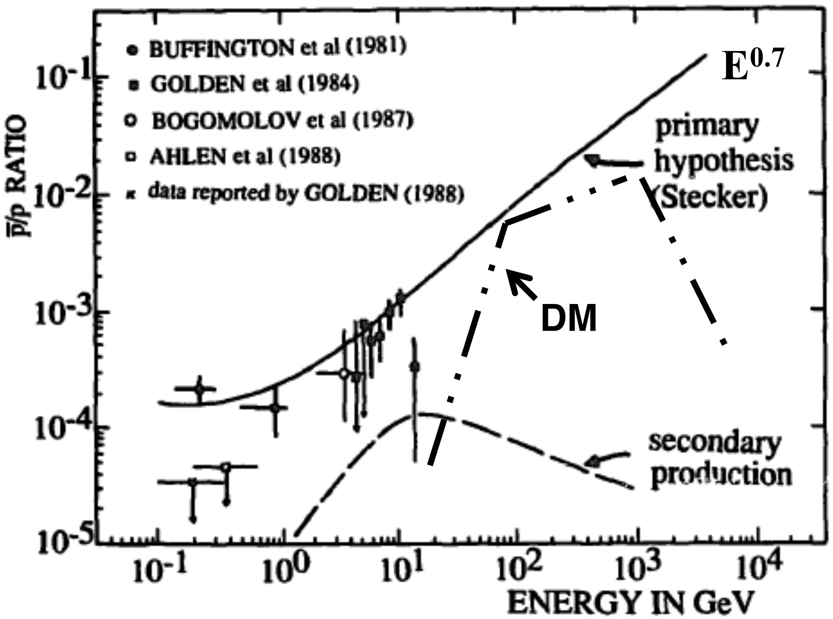
On behalf of the ARGO-YBJ Collaboration

Motivation for CR $\bar{p}$ search

The study of CR antiprotons provides an useful tool

- for the understanding of CR origin and propagation in the Galaxy.
- to investigate the matter/antimatter symmetry in the Universe
- to investigate the existence of Dark Matter.

Theoretical models



- ***Secondary production.*** **Most of the CR $\bar{p}$ observed near the Earth are secondaries produced in collisions of HE CRs with interstellar medium: $p + N \rightarrow \bar{p} + X$**

- ***Direct production by exotic sources***
  - Primordial Black Hole (PBH) evaporation
  - DM neutralino annihilation
  - Extragalactic sources in antimatter domains

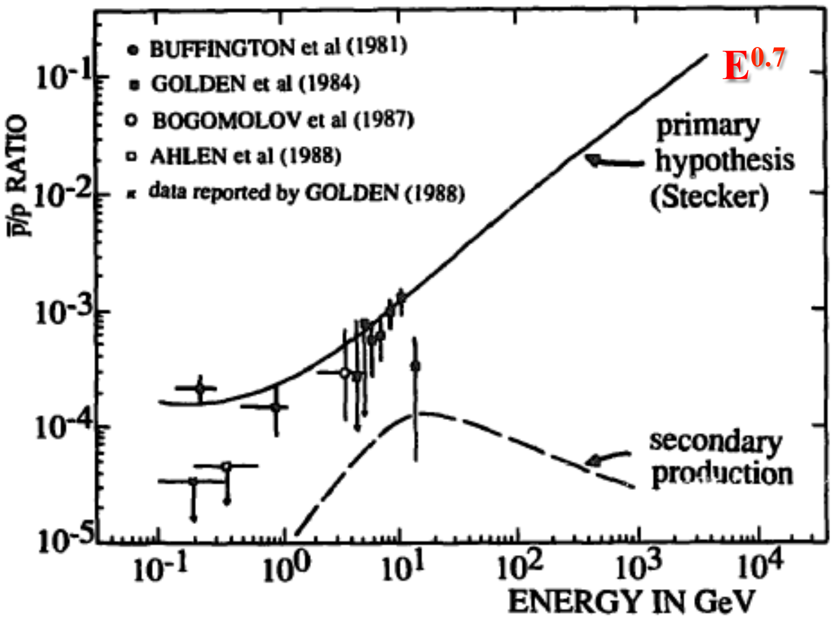
Antiprotons from anti-galaxies

In 1985 (19th ICRC) ***Wolfendale & Stecker*** **discussed the question:**

Does the antimatter play an equal role with matter in makeup of the galaxies ?

Hypothesys:

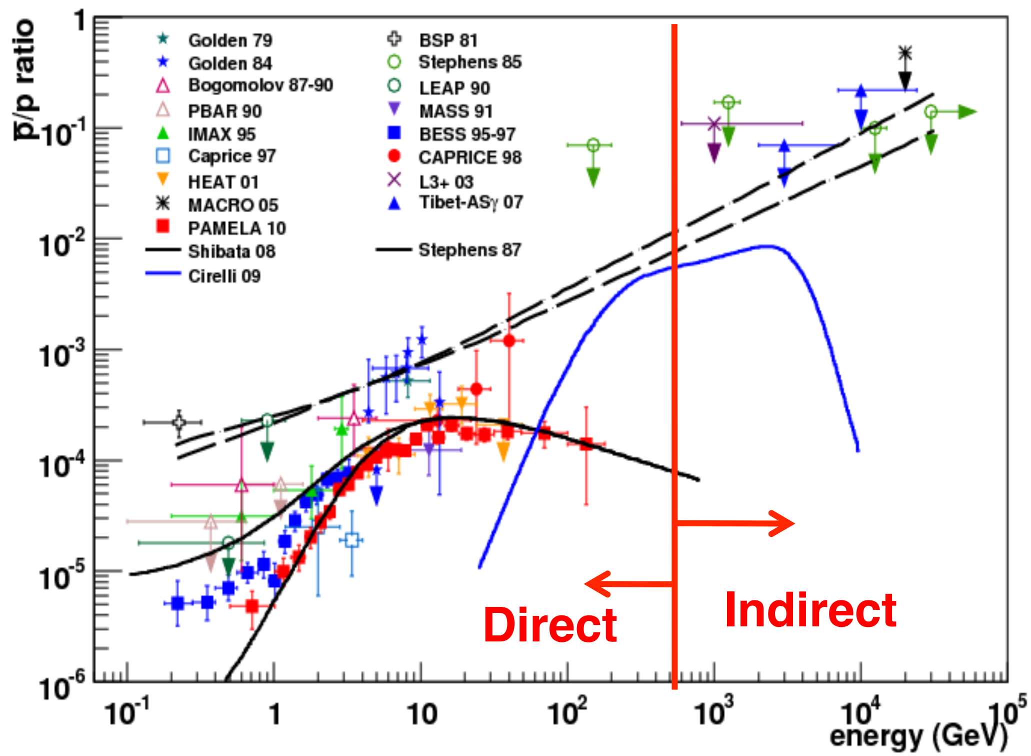
- **The mean lifetime of a CR in the galaxy falls with energy as $E^{-\delta}$ with δ = diffusion coefficient.**
- **Antip assumed to be primary and produced/ accelerated in an antimatter domain as the protons are in our galaxy.**
- **The antip/proton ratio, at high energies, would go $\sim E^{\delta}$, the antip being mainly extragalactic and the protons galactic.**
- **Taking δ = 0.7 antip could increase up ~1% of the CR flux at an energy of ~500 GeV and even ~50% at higher energies.**



Important observational implications

Experimental Measurement

- ***Direct measurement.*** **Balloon or satellite (so far < 200 GeV)**
- ***Indirect method (> 1 TeV)***
  - **Cosmic ray μ+/μ- ratio**
    (difficult, model dependent)
  - **Moon Shadow technique**

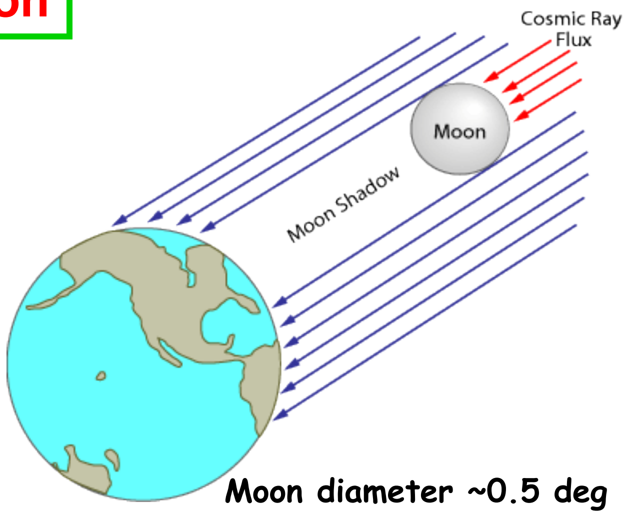


- **EAS arrays:** CYGNUS, EAS-TOP, HEGRA, CASA, TIBET ASγ, MILAGRO, GRAPES
- **Underground Muon detectors:** MACRO, SOUDAN, L3+C, BUST, MINOS

The Moon Shadow technique

Cosmic rays are blocked by the Moon → **Deficit of cosmic rays in the direction of the Moon**

- Size of the deficit → **Angular Resolution**
- Position of the deficit → **Pointing Error**



Geomagnetic Field: positively charged particles are deflected towards the West.

→ Ion spectrometer

$$\Delta\alpha \approx \frac{1.6^0 \cdot Z}{E(TeV)}$$

The observation of the Moon shadow may provide a direct check of the relation between size and primary energy

- West displacement → **Energy calibration**

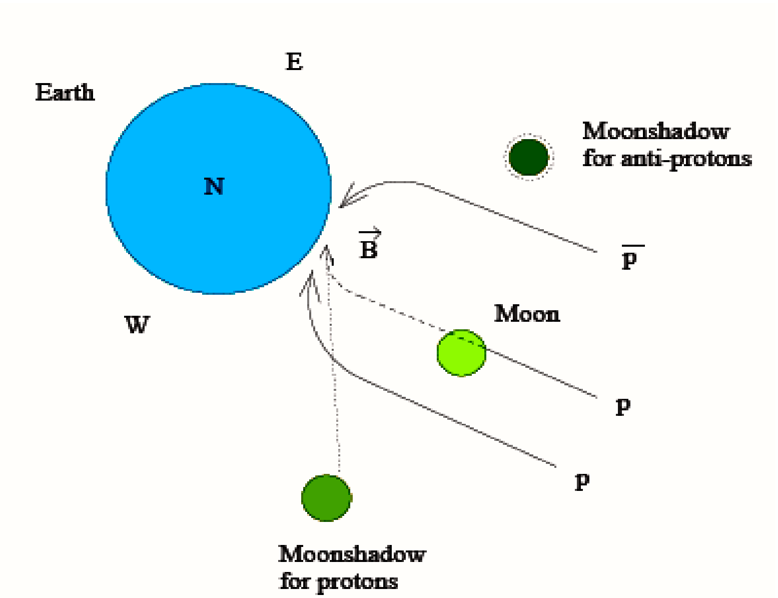
$\bar{p}/p$ ratio at TeV energies

Using data on Moon shadow, limits on antiparticle flux can be derived. Protons are deflected towards West, antiprotons are deflected towards East
➔ 2 symmetric shadows expected.

If the *displacement s(E)* is large and the *angular resolution σ(E)* small enough we can distinguish between the 2 shadows

$$\rho(E) \equiv \frac{\sigma(E)}{s(E)} \lesssim 1.$$

If no event deficit on the antimatter side is observed an upper limit on antiproton content can be calculated.

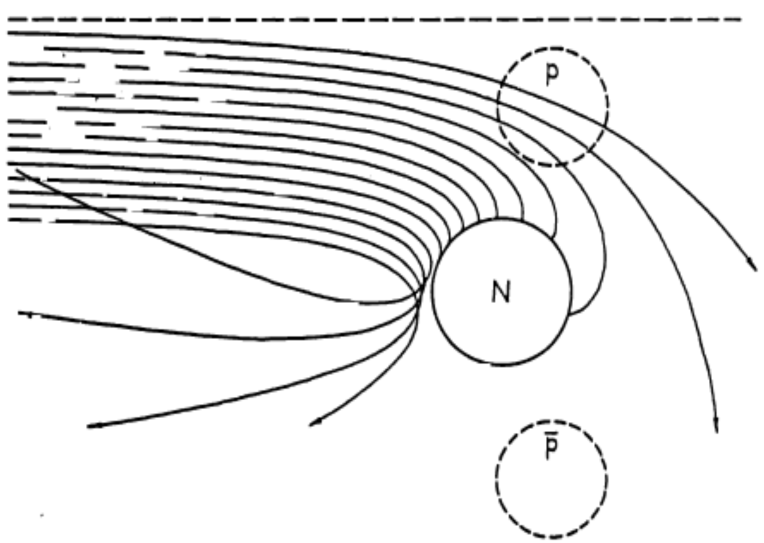


Moon Shadow History

- **G.W. Clark**, (Phys. Rev. 108 450, 1957): *"The Sun and Moon must cast a shadow in the flux of high energy primary CRs"*

- **J. Linsley** and **J. Lloyd-Evans** (ICRC1985), following a Watson's suggestion, independently *explored the possibility to use the Moon or Sun shadows as mass spectrometers* to measure the charge composition of CRs.

- In particular **J. Linsley** *first discussed the idea to measure the CR antiprotons abundance exploiting the separation of the p and antip shadows.*



- In **1990 Urban et al**. *carried out detailed calculation of this effect proposing this method as a way to search for antimatter in CRs at the TeV energies*.

- **CYGNUS** and **EASTOP 1991**: *first Moon shadow observations.*

Ground-based observations

The effect of Moon (Sun) on CRs was first noted by Clark in 1957. However the first observation of a shadowing effect had to wait for the results of CYGNUS in 1991.

2 reasons for this long delay:

- ***Poor angular resolution of EAS-arrays*. The performance of the detector has to cope with the angular radius of the Moon or Sun (≈0.26 deg) and only at the beginning of the 90s the angular resolutions of EAS-arrays reached the 1 deg level.**
- ***High energy threshold* (>100 TeV) of detectors ➔ poor statistics.**

↳ No sensitivity to GMF ➔ no shadow displacement

Advantage of ARGO-YBJ

- **Good angular resolution and pointing**
- **Low energy threshold**
- **Long-term detector stability**
- **Real sensitivity on the Earth magnetic field**

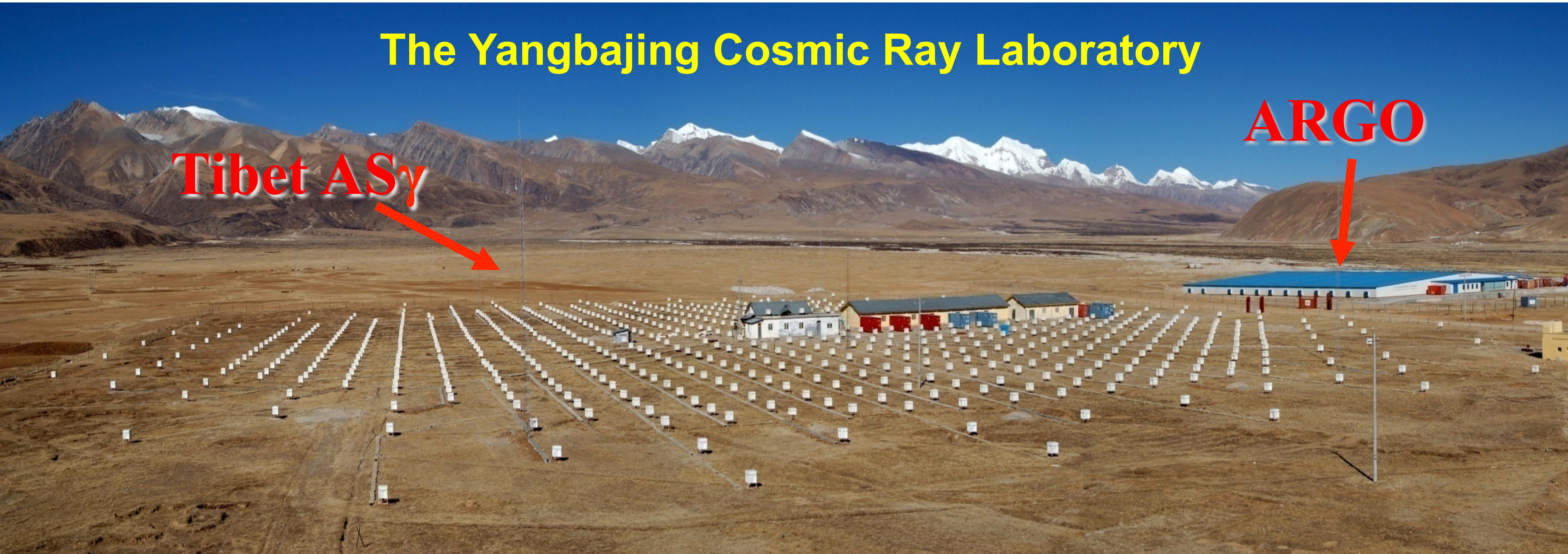
The ARGO-YBJ experiment

An unconventional EAS-array exploiting the full coverage approach at very high altitude to detect small air showers at an energy threshold of a few hundreds of GeV.

Longitude 90° 31’ 50” East
Latitude 30° 06’ 38” North

90 Km North from Lhasa (Tibet)

4300 m above the sea level
~ 600 g/cm^2



The basic concepts

…for an unconventional air shower detector

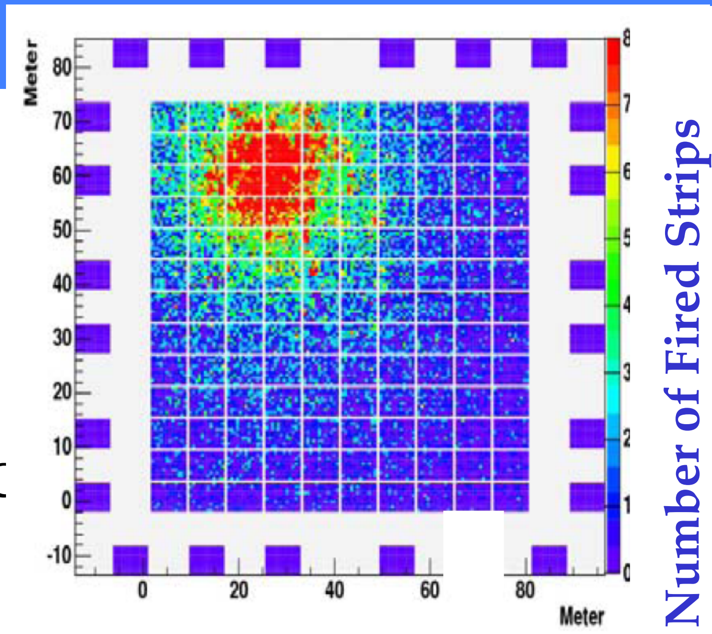
- ***HIGH ALTITUDE SITE***
  (YBJ - Tibet, 4300 m a.s.l, ~ 600 g/cm^2)

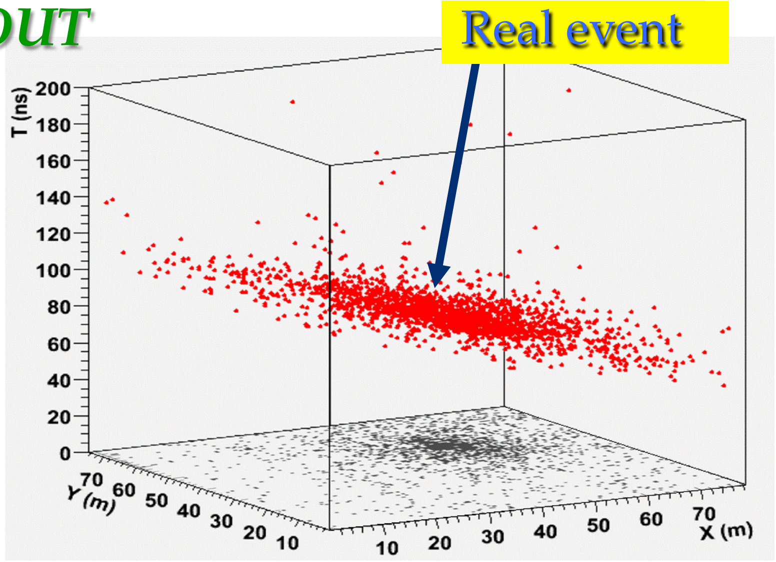
- ***FULL COVERAGE*** (RPC
  technology, 92% covering factor)

- ***HIGH SEGMENTATION OF THE READOUT***
  (small space-time pixels)
  Space pixels: 146,880 strips (7×62 cm^2)
  Time pixels: 18,360 pads (56×62 cm^2)

… in order to:

- image the shower front
- get a energy threshold of a few hundreds of GeV



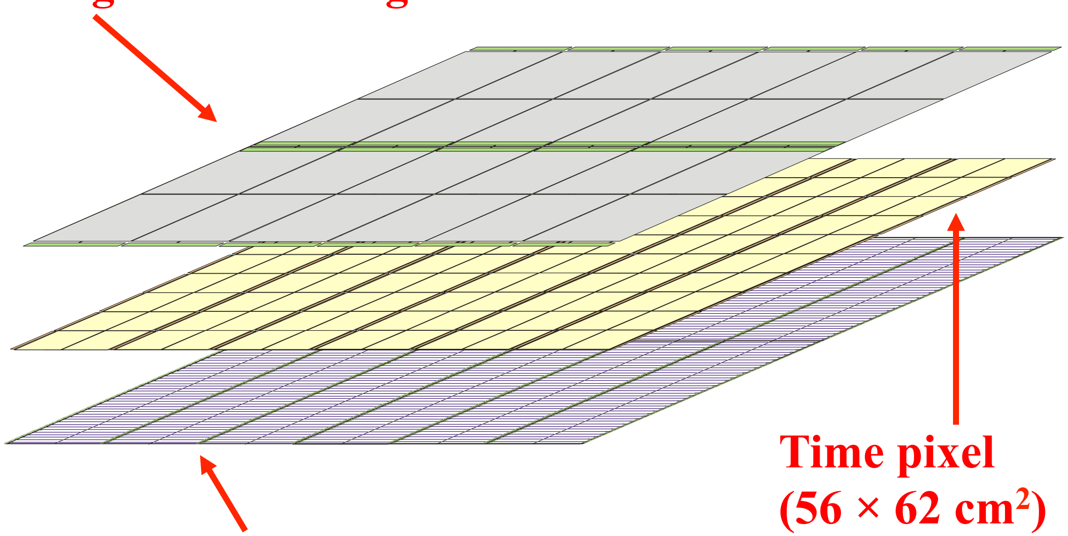


The basic concepts

…extending the dynamical range

- *ANALOG READ-OUT → PeV*
  (3672 1.40 × 1.25 m² "big pads")

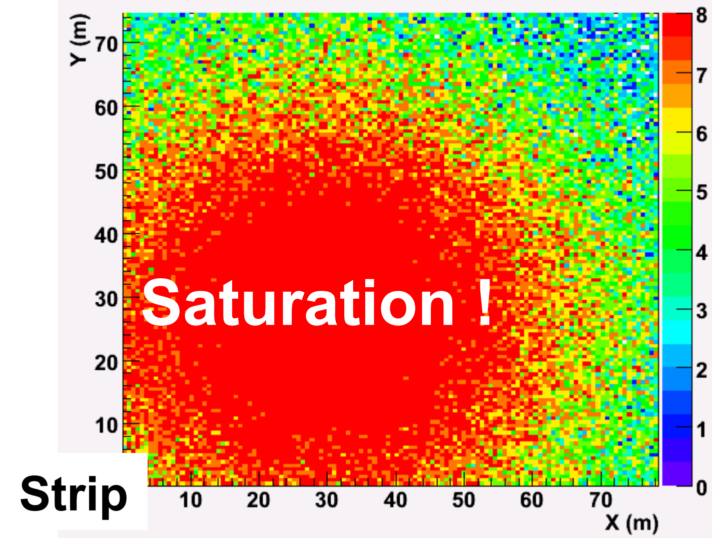
Big Pad for charge read-out

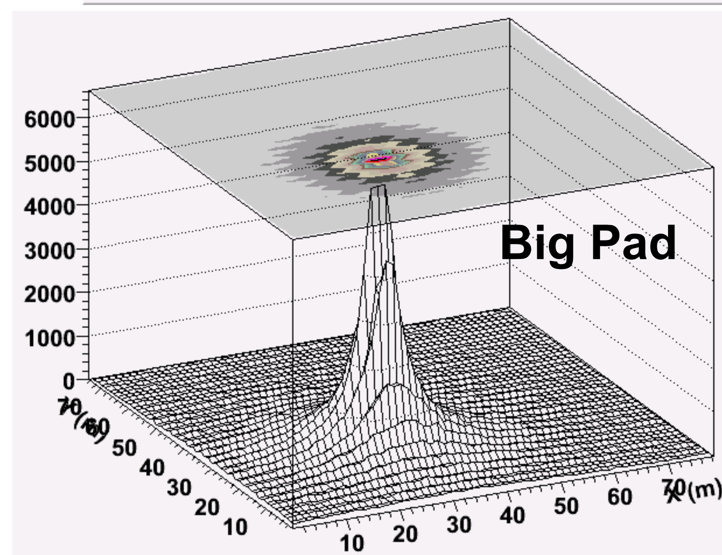


Time pixel
(56 × 62 cm²)
#18360

Space (digital) pixel
(6.7 × 62 cm²)
#146880

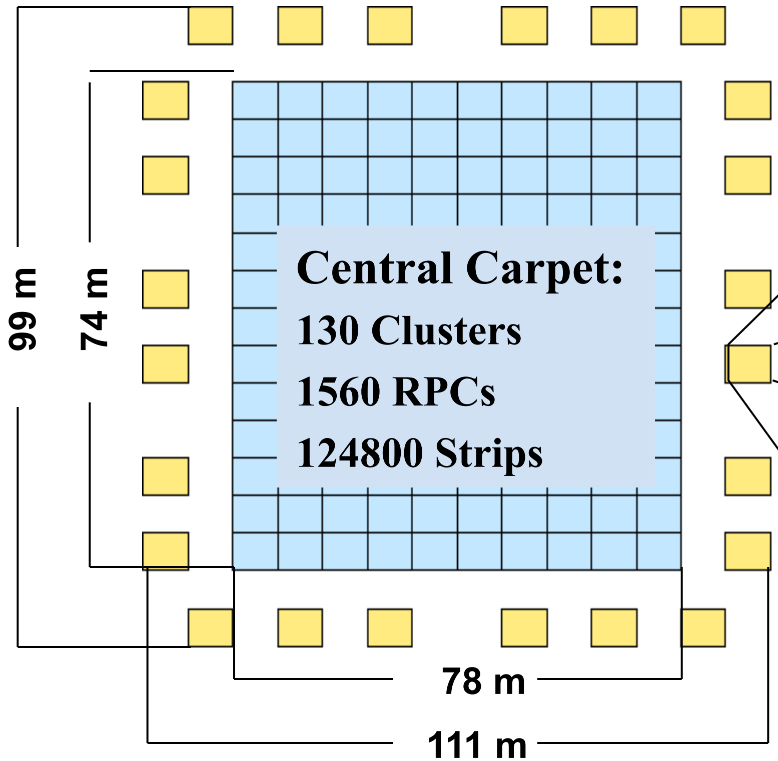
E ~ 1000 TeV

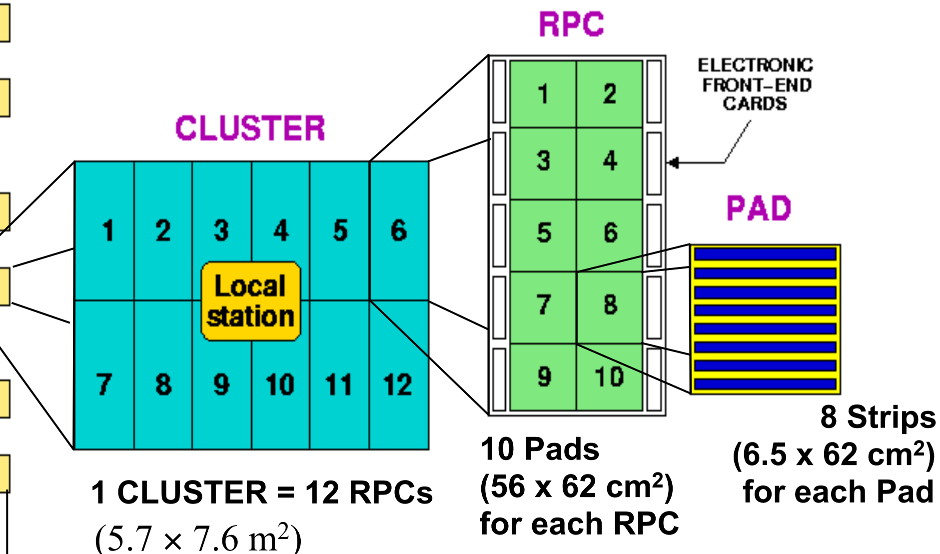




Experimental Hall & Detector Layout

time resolution ~1-2 ns (pad)
space resolution = strip





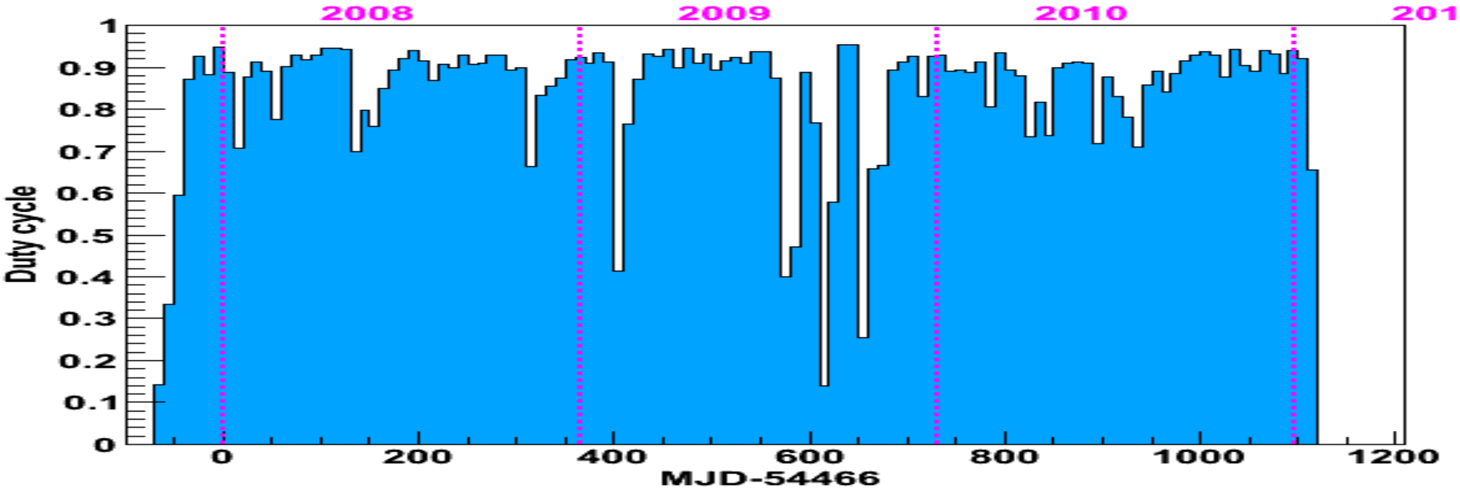
Gas Mixture: **Ar/ Iso/TFE = 15/10/75**

HV = 7200 V

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)

Current Status

- In observation since July 2006 (commissioning phase)
- Stable data taking since November 2007
- The **average duty cycle ~ 85%**
- **Trigger rate ~3.5 kHz** @ 20 pad threshold
- Dead time 4%
- 220 GB/day transferred to IHEP/CNAF data centers



ARGO-YBJ: a multi-purpose experiment

- Sky survey $-20^{\circ} \le \delta \le 80^{\circ}$ above 300 GeV (γ-sources)
- High exposure for flaring activity (γ-sources, GRBs, solar flares)
- CR physics 1 TeV → 10^4 TeV
  - (p + He) spectrum at low energies
  - Knee region
  - p-air and p-p cross sections
  - Anisotropies
  - Multicore events
- CR $\bar{p}$/p flux ratio at TeV energies
- Solar and heliospheric physics

by 2 independent operational modes:

- **scaler mode** (counting rate, > 1 GeV)
- **shower mode** (full reconstruction, > 300 GeV)

The observed Moon Shadow

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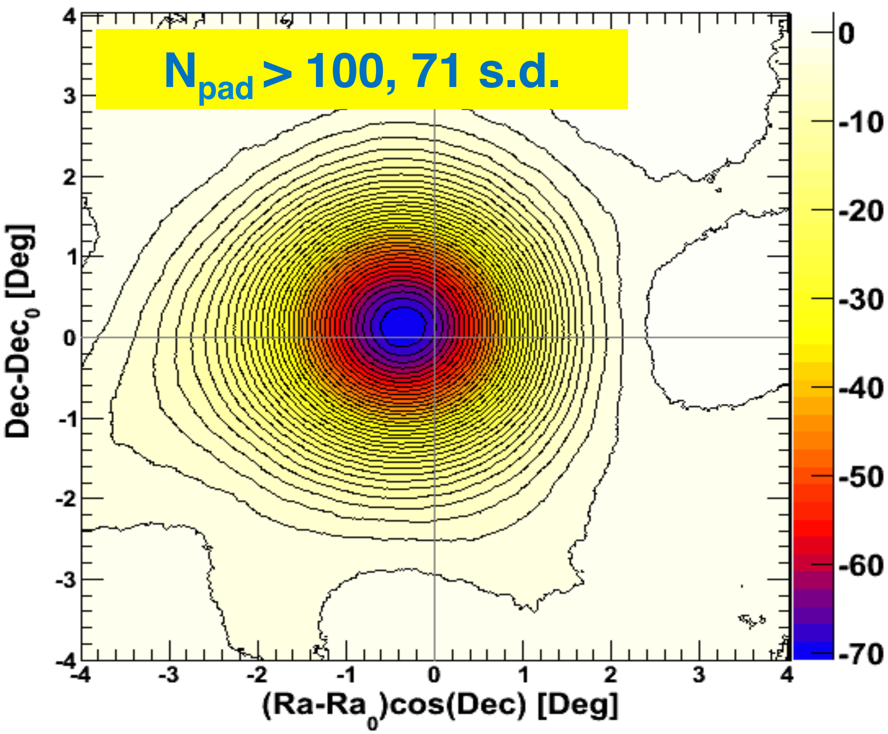
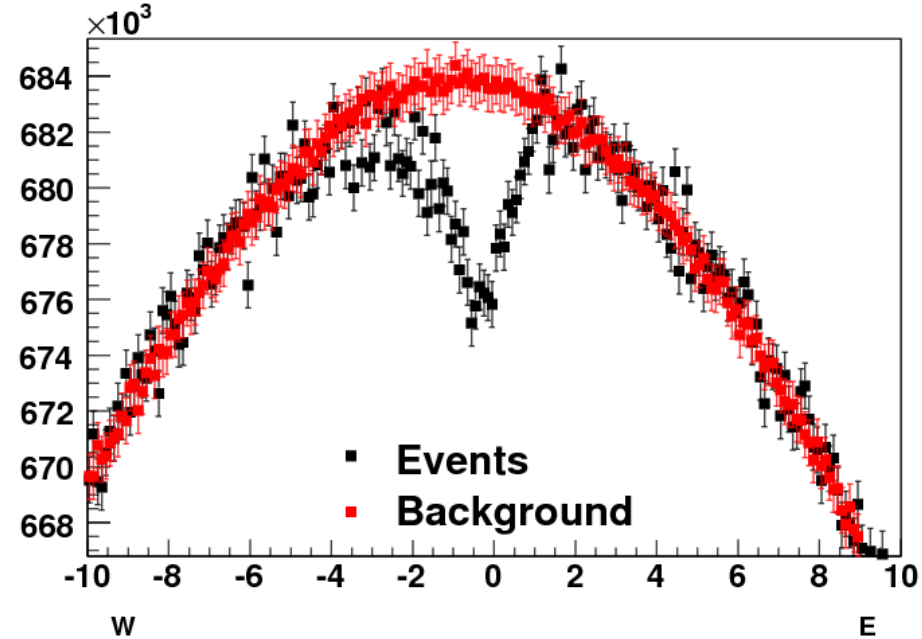
All data: 2006 → 2010

N > 100   θ < 50°



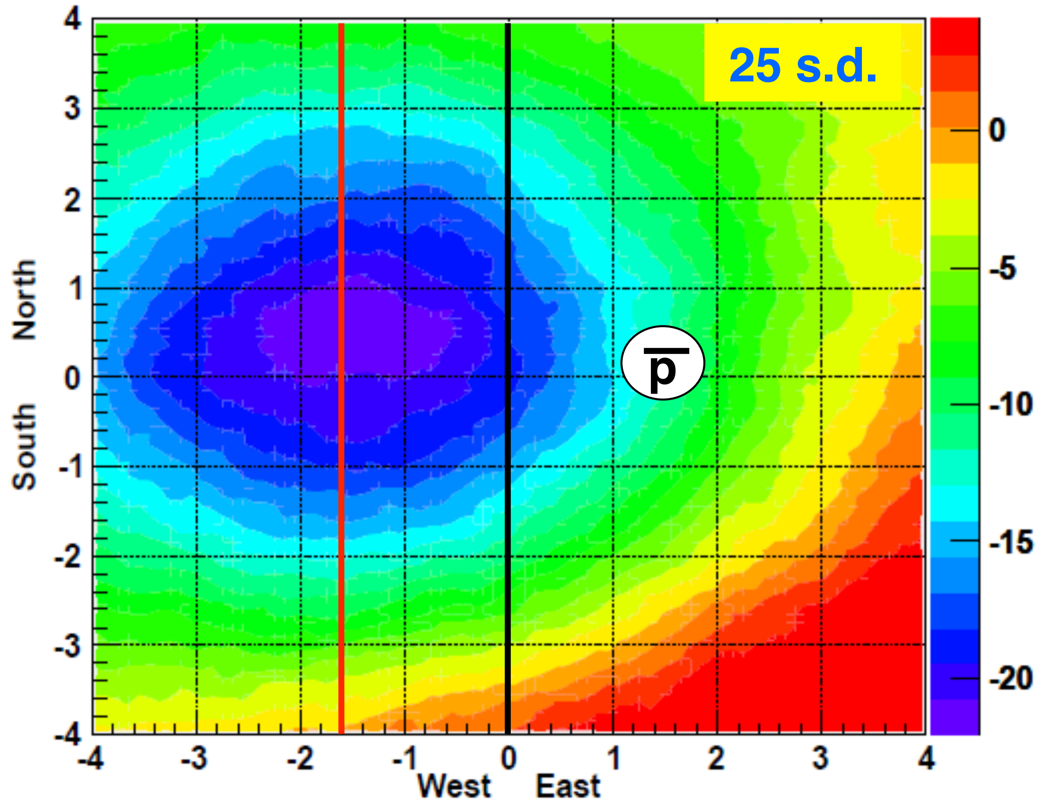


≈ 10 standard deviations / month

With the ARGO-YBJ detector we are able to observe the Moon shadow even without subtracting the background contribution.

The Earth Magnetic Field effect

20 < N 40 particles, the lowest multiplicity range investigated



The Moon is shifted Westward by about 1.5 deg !

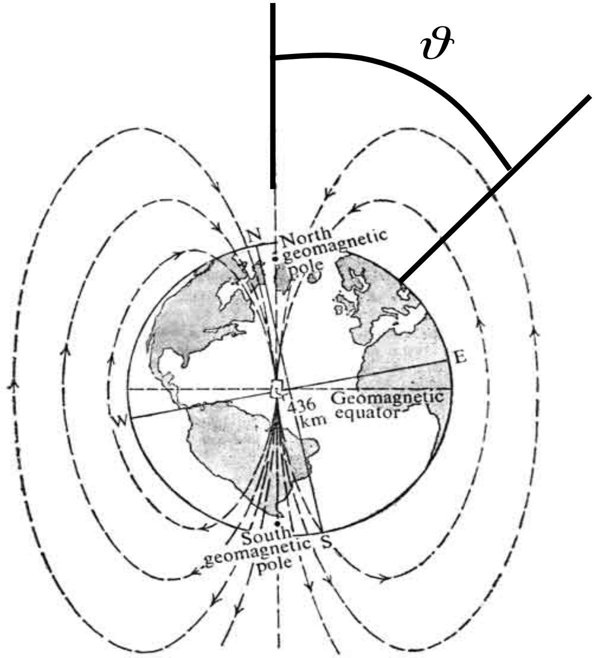
median energy ≈750 GeV
mode energy ≈500 GeV

A potential antiproton signal is expected Eastward within 1.5 deg from the actual Moon position (i.e., within 3 deg from the observed Moon position).

It's the first time that an EAS-array is able to observe a Moon shadow so shifted.

Earth static dipole approximation

We assume that the Geo Magnetic Field is due to pure dipole laying in the centre of the Earth.



For the YBJ site

- **positively charged primary CRs are displaced Westward by an angle**

$$\Delta\alpha \approx \frac{1.6^{0} \cdot Z}{E(TeV)}$$

This relation is valid only for quasi-vertical events and for high energies (>10 TeV).

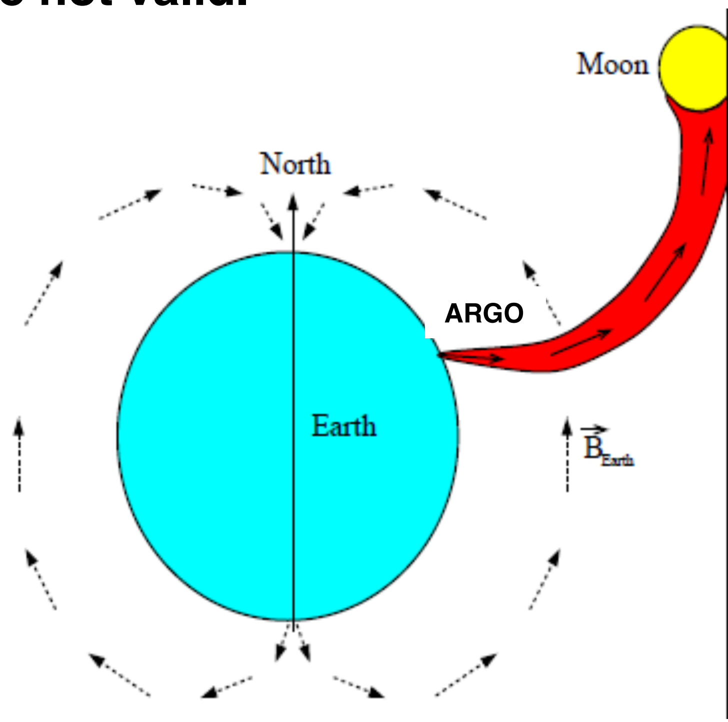
- **primary CRs are unaffected in the North-South direction as the East-West component of the GMF is negligible (≈10%) at YBJ.**

→ **We can measure angular resolution and pointing accuracy along the NS projection.**

Earth-Moon System Simulation

The observation of shadows due to **sub-TeV events** needs a **very detailed MC simulation of the Earth-Moon system**.
At very low energy analytical approximations are not valid.

1. Geo Magnetic Field simulation
2. CRs propagation in the Earth-Moon system
3. EAS development in the atmosphere (CORSIKA)
4. GEANT4 – based detector simulation
5. Event reconstruction

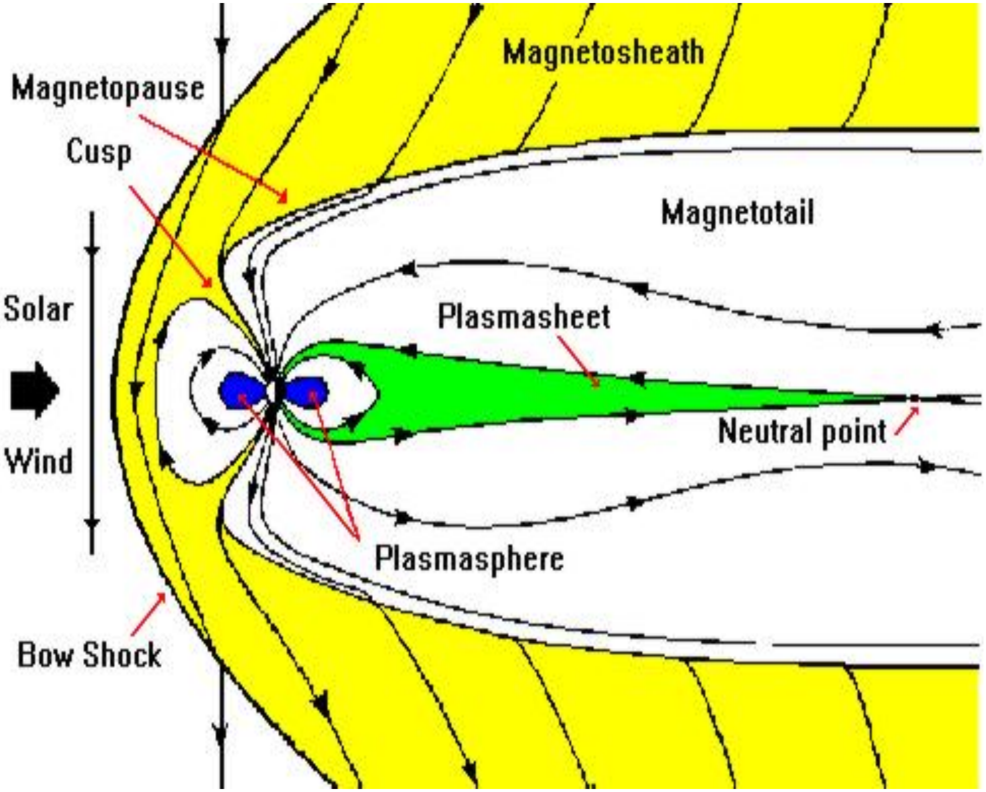


Leaving the Earth…

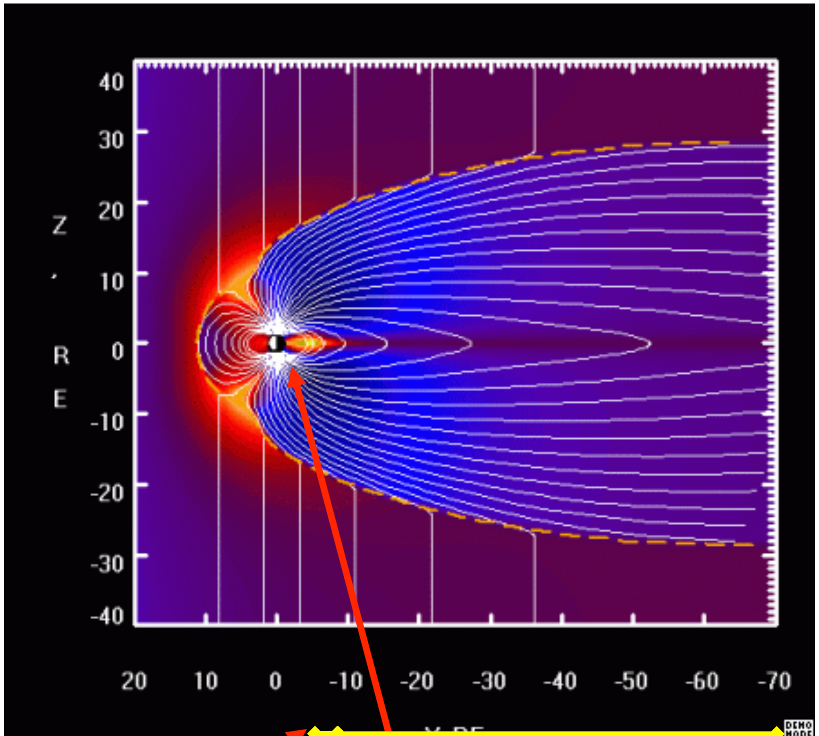
As far as the Moon, not only the geomagnetic field acts upon the CRs. We must take into account also the external fields, which deform the dipole-like course at large distance from the Earth.

In fact,

- The dipole contribution is mostly dominant within 20.000 km from the Earth, the panorama changes dramatically a little further.
- The axial symmetry breaking of the dipole field is due no longer only to the multi-pole (negligible) terms, but mainly to the impact of the solar wind on the magnetosphere.



The Tsyganenko model



Earth

max distance where the dipole approximation is acceptable: 2-3 Earth radii

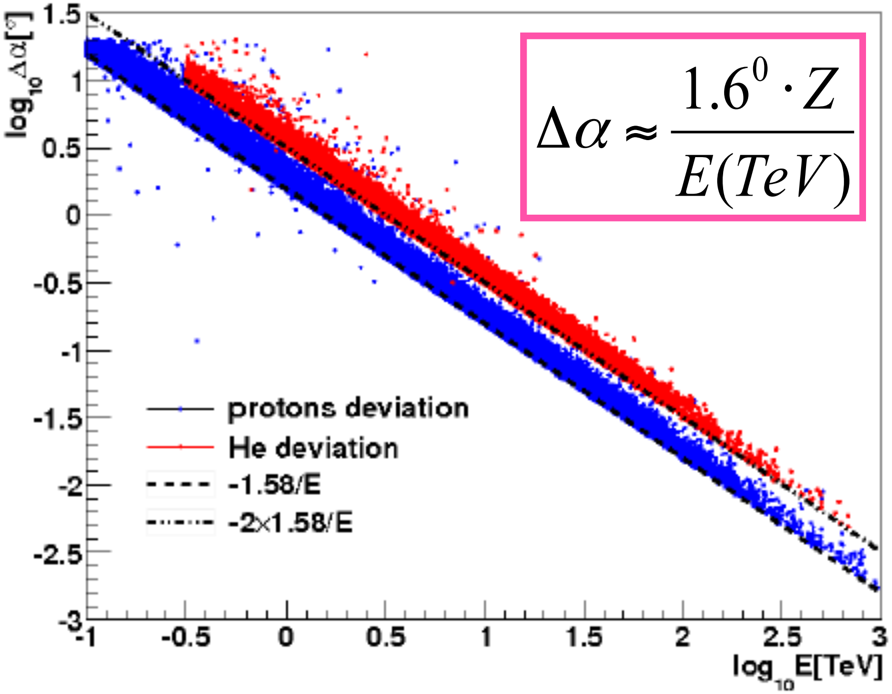
Moon distance: 60 Earth radii

The most accurate model to take into account

- **the orientation of the Earth's magnetic axis with respect to the direction of the incoming solar wind flow, which varies with time because of the Earth's diurnal rotation and its yearly orbital motion around the Sun;**

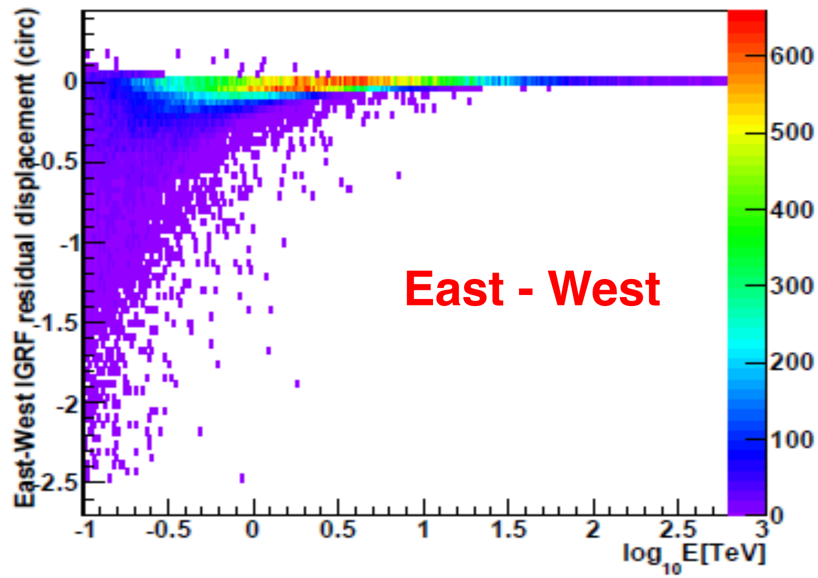
- **the state of the solar wind, in particular, the orientation and strength of the Interplanetary Magnetic Field.**

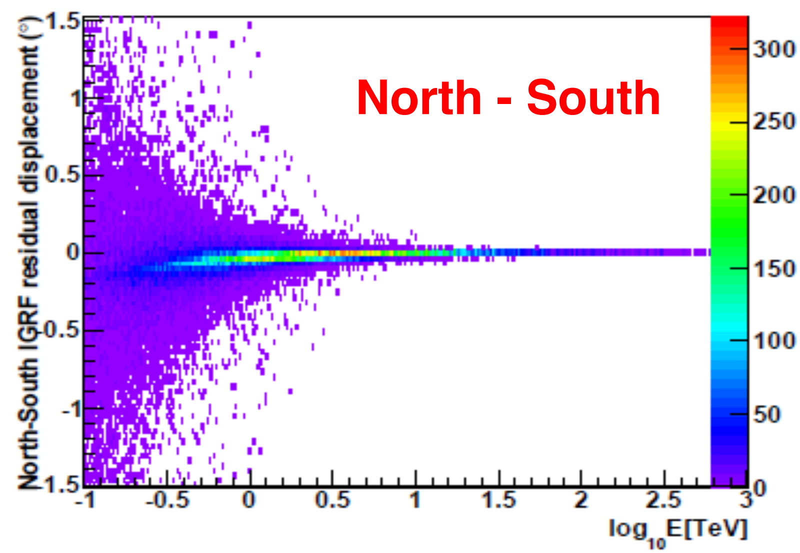
Simulation results



Deviation induced by GMF on p and He nuclei
as a function of the primary energy

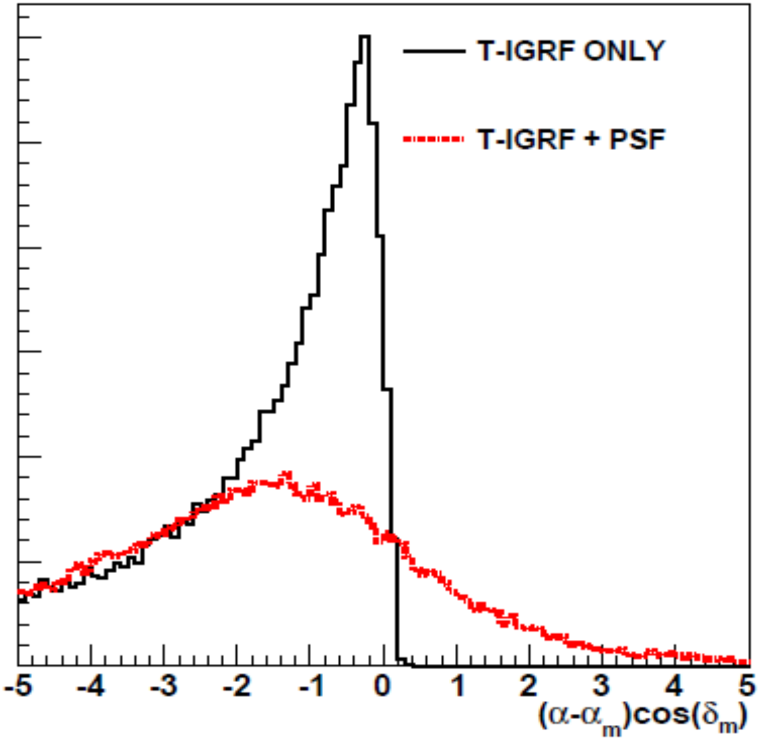
The analytical approach underestimates the EW shift in particular for sub-TeV events





Detector PSF effect

The detector angular resolution provides not only the smearing but also a further displacement of the signal peak in the EW projection, due to the folding with the asymmetrical deflection induced by the GMF.



Relation between the observed signal width and the detector angular resolution

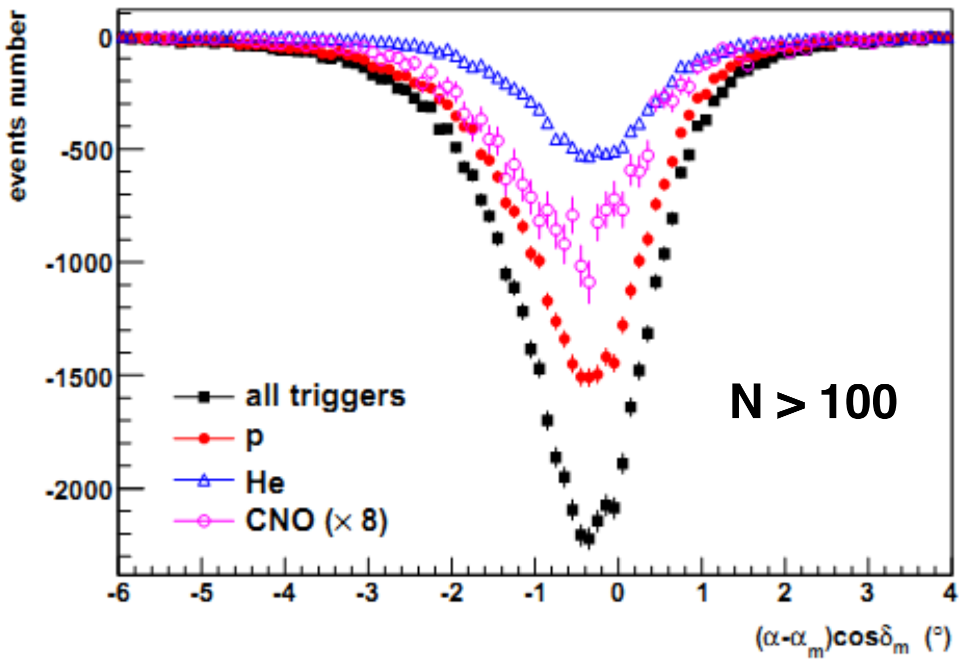
$$RMS = \sigma_\theta \sqrt{1 + \left(\frac{r_m}{2\sigma_\theta}\right)^2}$$

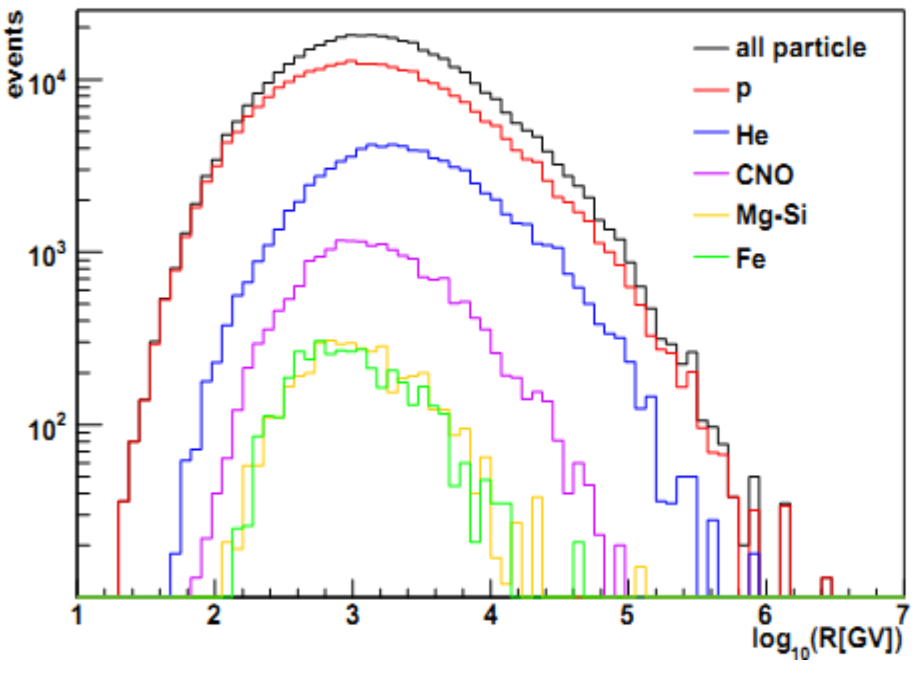
→ **RMS / $\sigma_\theta \approx$ 20% if $\sigma_\theta = 0.2^o$**

$\approx$ 1.7% if $\sigma_\theta = 0.7^o$

The contribution of the Moon size to the spread (RMS) of the signal Is (not) dominant when σ_θ is low (high), i.e. at high (low) energy.

The circular symmetry of the signal is broken by the GMF only along the EW direction. Along the NS direction the signal is mostly affected by the angular resolution which can be then measured.

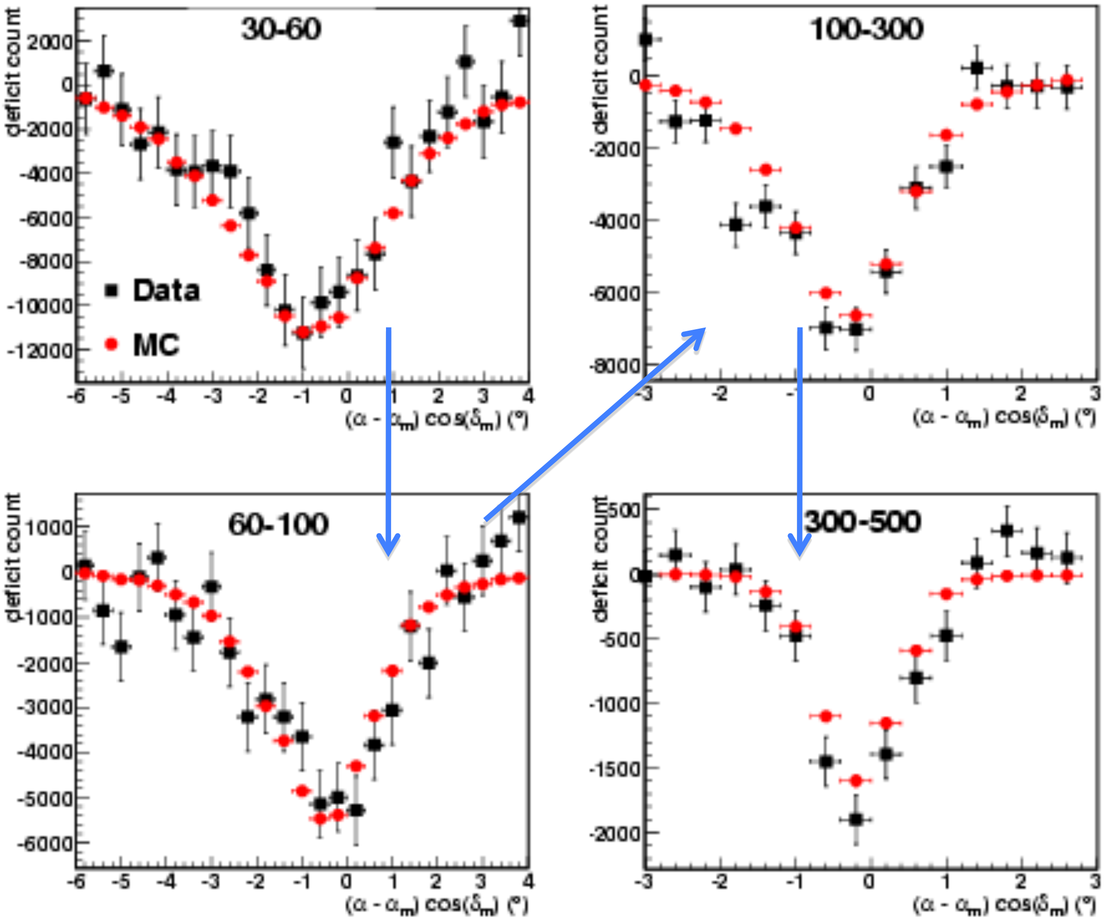




Contribution of different nuclei to the Moon shadow deficit

Rigidity distribution

Moon shadow: East-West projection

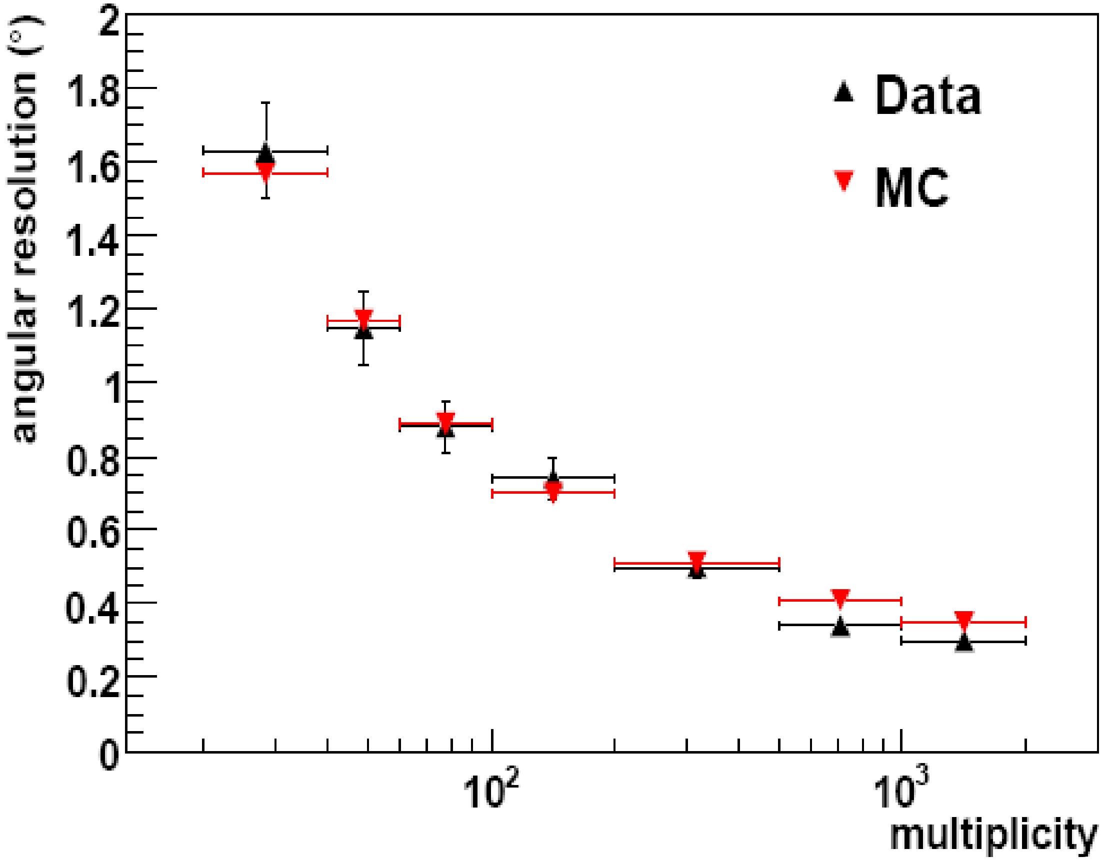


The higher the energy the lower the West displacement induced by the GMF.

Measurement of the angular resolution

Angular resolution measured along the NS direction, not affected by the geomagnetic field

- **The PSF of the detector is Gaussian for N > 200.**
- **For lower multiplicities it can be described with an additional Gaussian, which contributes for about 20%.**



East-West displacement

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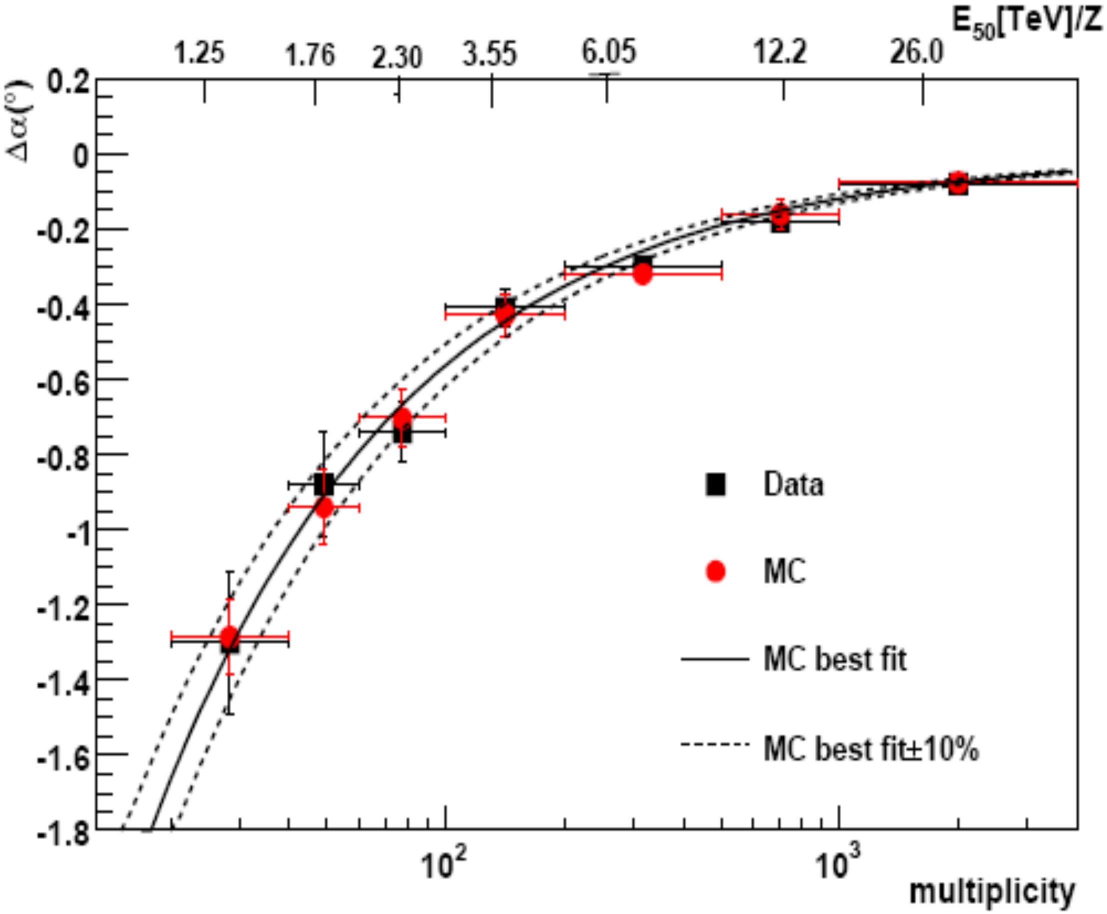
Measured EW displacement

$$\Delta\alpha = -12.6^{o} \cdot N^{-0.68}$$

Relation

multiplicity – primary energy



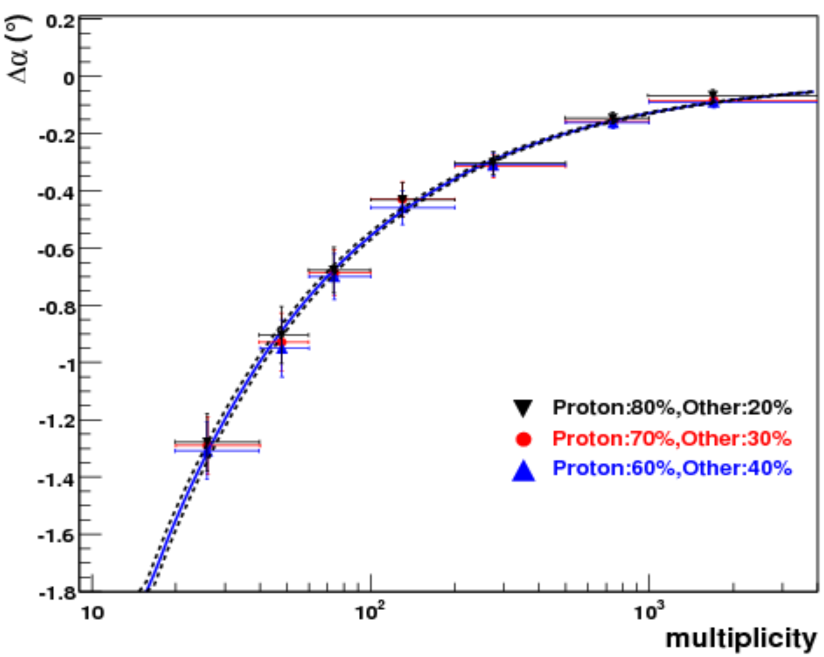
Energy scale calibration

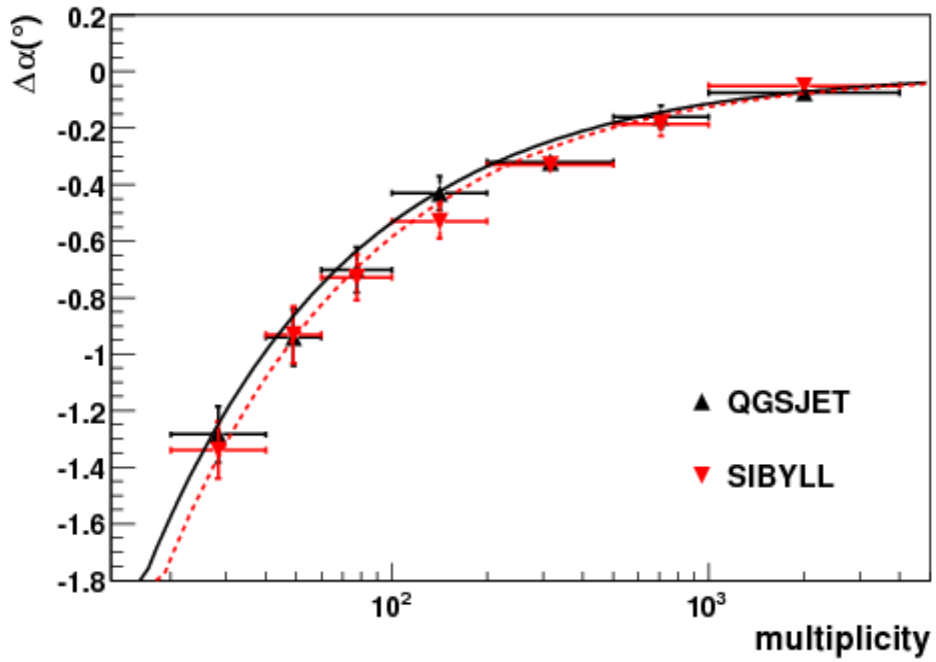
$$N \approx 21 \cdot (E_{TeV}/Z)^{1.5}$$

1 – 30 (TeV/Z)

Two systematic uncertainties may affect the Multiplicity-Energy relation:

- **the assumed primary CR chemical composition (7%)**
- **the uncertainties of different hadronic models (12%)**

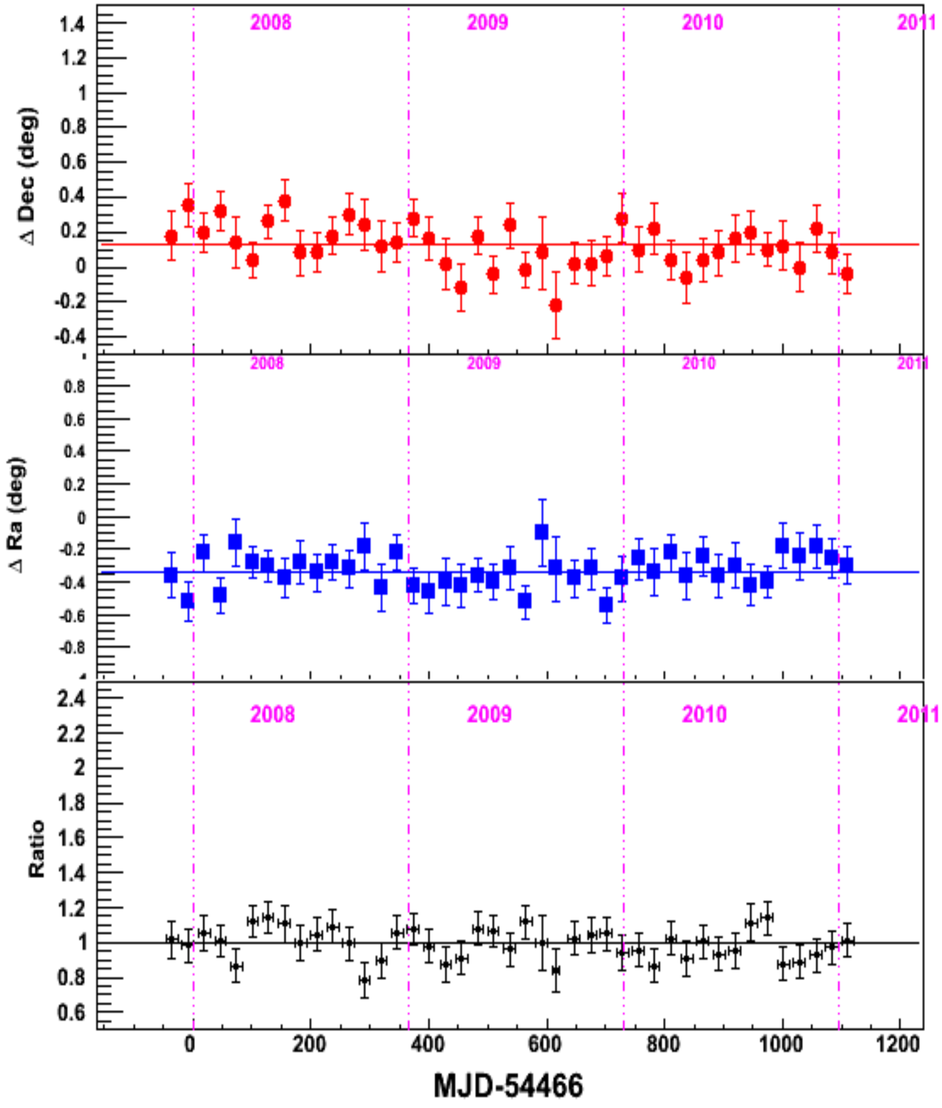




The energy scale uncertainty is estimated to be smaller than 13% in the energy range 1 – 30 (TeV/Z).

Long-term stability of the detector

- $N_{pad}>100$: 10 s.d./month
- A tool to monitor the stability of the data and reconstruction
- Right figures: one point per month !
- Position stable at a level of 0.1°
- Angular resolution stable at a level of 10%



Measurement of the $\bar{p}/p$ ratio: 2006 → 2009

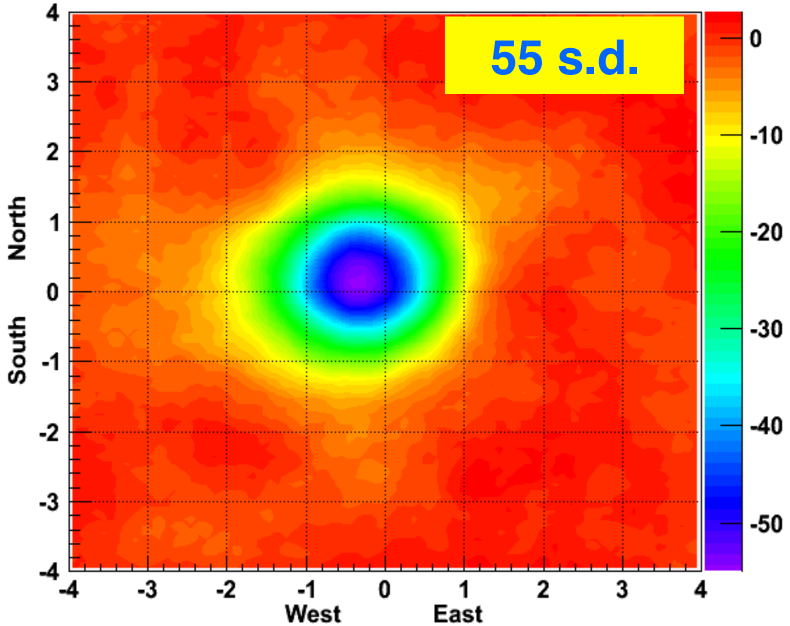
Data: 2006 → 2009 $\theta < 50°$ 3200 hours on-source

We selected 2 multiplicity bins in the region of lower ARGO-YBJ sensitivity

Event selection:

- **40 < N < 100: total significance of the deficit 34 s.d. median energy 1.4 TeV , n. of events 183000, angular resolution ~1 deg.**

- **N > 100: total significance of the deficit 55 s.d., median energy 5 TeV, n. of events 46500, angular resolution ~0.6 deg.**

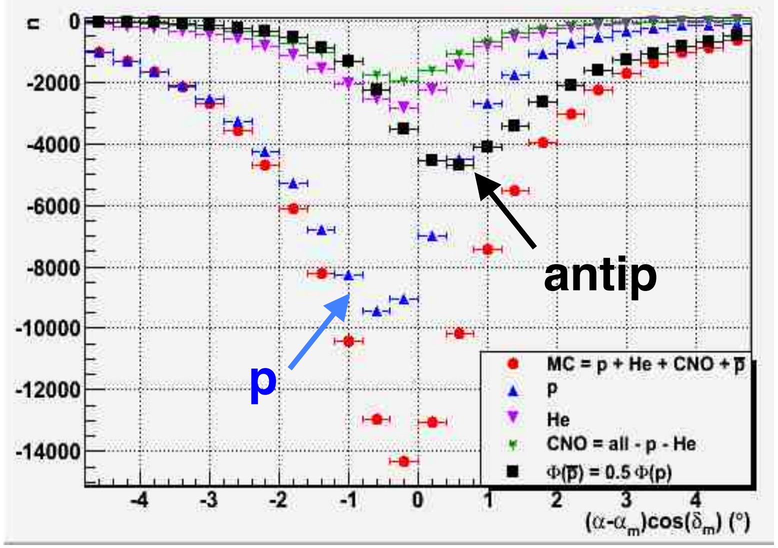


No evidence of the existence of antiprotons is found in this energy region.

The likelihood method for the estimate of the u.l.

Without functions to parameterize the expectations, we compare directly MC with data.

A fraction *r* of the simulated events is assumed to be antip. In such a way, the number of events hampered by the Moon in a certain time remains unchanged.

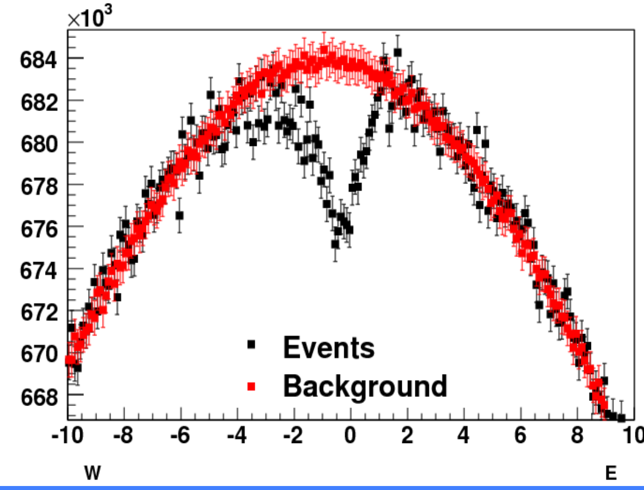


- **New MC signal:**

$$\Phi(matter) \rightarrow \Phi(\bar{p}) + (1-r)\cdot\Phi(matter)$$

- **Likelihood function:**

$$\log L(r) = \sum_{i=1}^{B} N_i \ln[E_i(r)] - E_i(r) - \ln(N_i!)$$



The N_i measured events are represented in black.

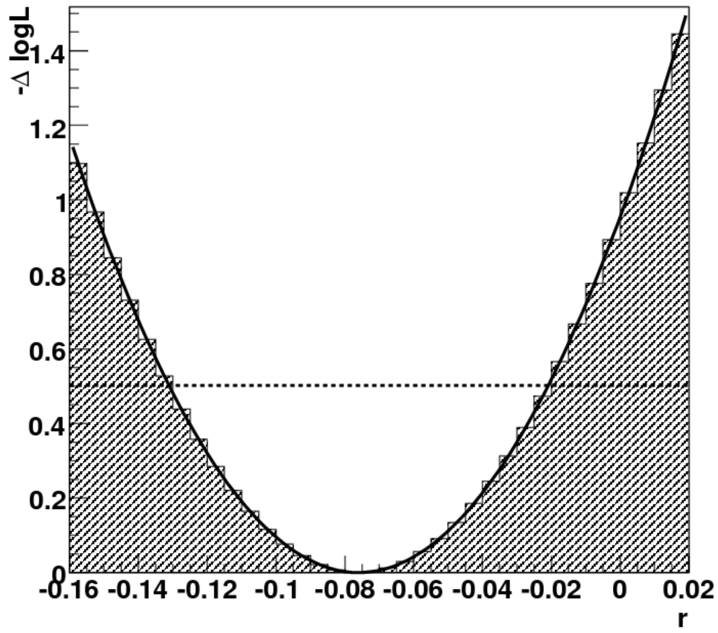
The expected events E_i are calculated by subtracting the new simulated signal from the background (red points).

The likelihood method for the estimate of the u.l.

The **r**-values which maximize the *likelihood* are:

r_{min} = -0.076 ± 0.055 for 40 < N < 100

r_{min} = -0.144 ± 0.085 for N > 100



The corresponding upper limit according to the unified Feldman & Cousins approach (1998) are:

$r_{u.l.}$ = 0.034 (90% c.l.)

$r_{u.l.}$ = 0.041 (90% c.l.)

Ratio upper limits

The assumed proton fraction is 73% for 40 < N < 100 and 71% for N > 100.

Since the anti-shadow was assumed to be the mirror image of the proton shadow, we assume for the antiprotons the same median energy.

$$\frac{\Phi(\bar{p})}{\Phi(p)} = \frac{1}{0.73} \frac{\Phi(\bar{p})}{\Phi(matter)} < 0.05$$

As a consequence we quote the ratios:

- **40 < N < 100: total significance of the deficit 34 s.d.**
  r < 0.034 (90 % c.l.) ➔ $r_{antip/p} < 0.05$
- **N > 100: total significance of the deficit 55 s.d.**
  r < 0.041 (90 % c.l.) ➔ $r_{antip/p} < 0.06$

Effect of different spectral index

Since the spectral index of antip is unknown, there is no reason to assume the proton spectral index.

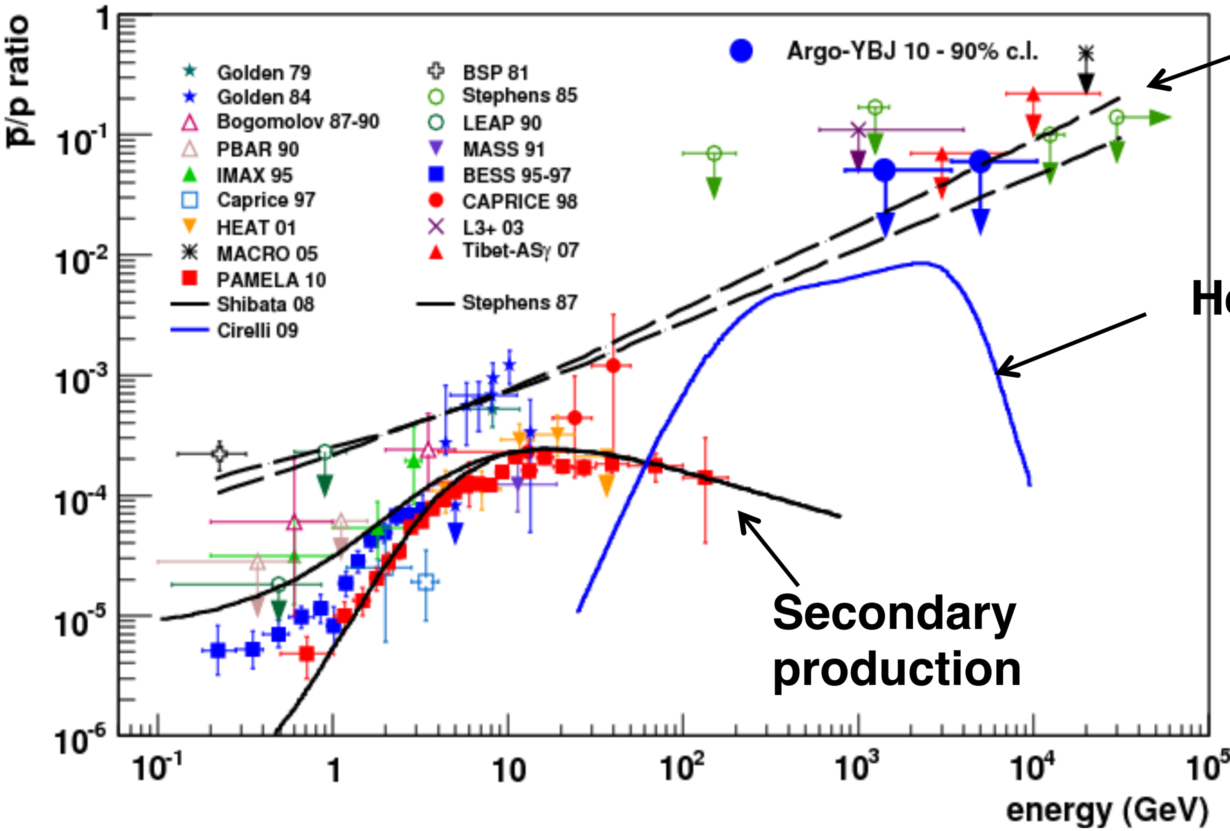
Many unknown factors contribute to its value, mostly related to the diffusion coefficient inside galaxy. To investigate this point, primary antiprotons are assigned different spectral indices,

The effect of different spectral indices

index	90% upper limit(40-100)	90% upper limit(>100)
2.0	3%	4%
2.2	4%	4%
2.4	4%	4%
2.6	5%	5%
2.8	5%	7%
3.0	6%	7%

The limits of the antiproton/proton ratio change of 20% - 30% with the spectral index,

Upper limits on $\bar{p}/p$ by ARGO-YBJ



Antigalaxies contribution for different diffusion coefficients, 0.6, 0.7

Heavy DM contribution (Cirelli)

In this energy range the p fraction in CR is ≈70%

5% at 1.4 TeV at 90% c.l.
6% at 5 TeV at 90% c.l.

In the few-TeV energy range these limits are the lowest available.

Summary

- The Moon shadow has been observed with >70 s.d. significance.
- The effective angular resolution for the set of selected events are measured to be 1 deg for 40<N<100 and 0.6 deg for N>100 hits.
- The overall pointing accuracy is better than 0.02 deg in the EW projection and better than 0.2 deg in the NS direction.
- No event deficit on the antimatter side is observed.
- With the assumed flux composition and antiproton spectrum the upper limit of the antiproton content is 0.05 at 1.4 TeV and 0.06 at 5 TeV (90% c.l.).
- In the few-TeV energy range these limits are the lowest available.
- Moon shadow study: *Physical Review D 84 (2011) 022003*.
- Antip/p paper in preparation.

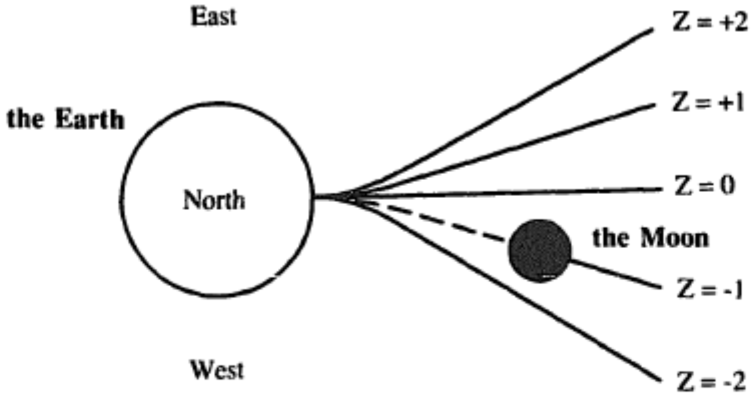
Outlook

- Improvement of the angular resolution with new reconstruction algorithms.
- Taking into account also the Sun shadow data.
- Further data integration (full statistics: 5 years)

→ **Sensitivity well below the 1% level in the few-TeV range.**

In addition

- CRs spectroscopy



→ **Improved results in the near future**