Antimatter search in the cosmic ray flux with ground-based experiments

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Anti-matter wanted: good salary offered

The matter-antimatter asymmetry is a long-standing problem in Physics and Astrophysics.

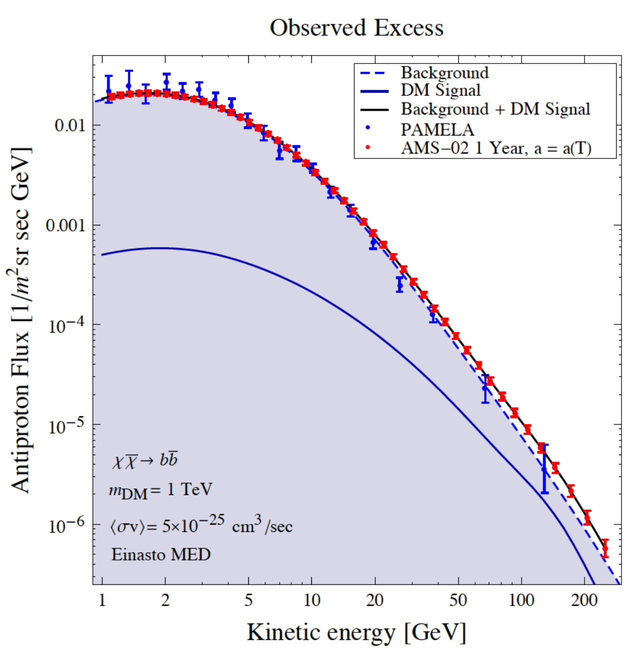
It is a problem “per se”, independently of DM and/or CR acceleration/propagation mechanisms (of course these other questions take it into considaration).

Motivations for antimatter search in CRs

We should distinguish between baryonic and leptonic antimatter.

Searching for **antiprotons** and **positrons** is important to:

- investigate the matter/antimatter symmetry in the Universe
- understand the CR origin and their propagation in the Galaxy (mostly CRs)
- probe the vicinity of a cosmic ray source (positrons)
- investigate the existence of Dark Matter (both channels)



Example from arxiv 1301.8079v2, Cirelli et Giesen

Theoretical models

Secondary production.

Most of the CR p observed near the Earth are secondaries produced in collisions of HE CRs with interstellar medium: p + N → p + X

Direct production by exotic sources

- Primordial Black Hole (PBH) evaporation
- DM neutralino annihilation
- Extragalactic sources in antimatter domains

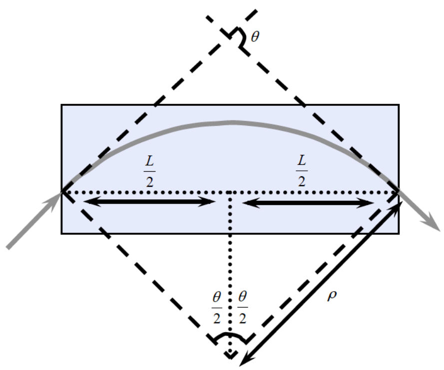
Anti-nuclei heavier than anti-hydrogen would surely have primary nature and their finding would be a breakthrough in antimatter search.

Matter/antimatter discrimination

We distinguish matter and antimatter by distinguishing their charge.
We do it only via magnetic spectrometry.

Dipole Magnet

a **dipole** with a **uniform dipolar field** deviates a particle by an angle θ

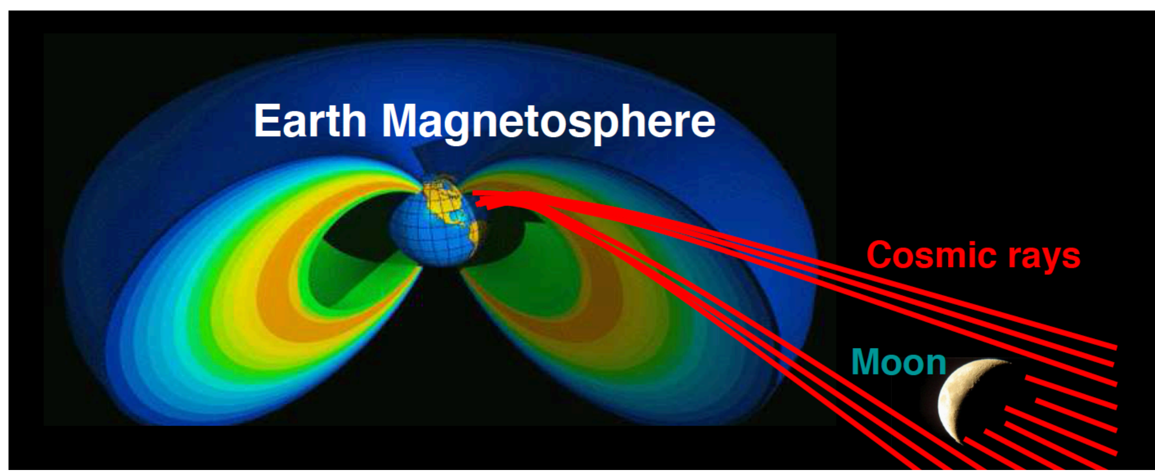


θ depends on length L and field B:

$$\sin\left(\frac{\theta}{2}\right) = \frac{L}{2\rho} = \frac{1}{2}\frac{LB}{(B\rho)}$$

if θ is small:

$$\sin\left(\frac{\theta}{2}\right) = \frac{\theta}{2} \rightarrow \boxed{\theta = \frac{LB}{(B\rho)}}$$



The Moon Shadow technique

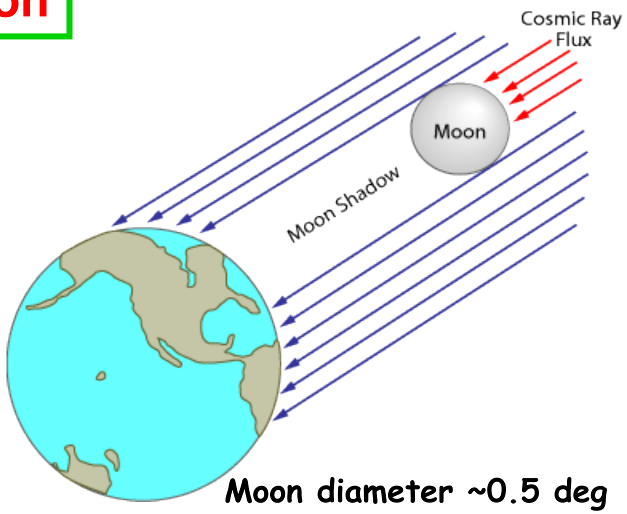
Cosmic rays are blocked by the Moon → **Deficit of cosmic rays in the direction of the Moon**

- 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 provides a direct check of the relation between size and primary energy for EAS arrays

- West displacement → **Energy calibration**

Everyone has his Moon, everyone gets his shadow, please do not argue

The Moon shadow technique is used by all ground-based experiments coping eith the antimatter search.

- EAS detectors apply it to look for antiprotons, exploiting the high duty-cycle.
- IACTS may apply it to look for positrons, exploiting the excellent hadron-rejection capability.

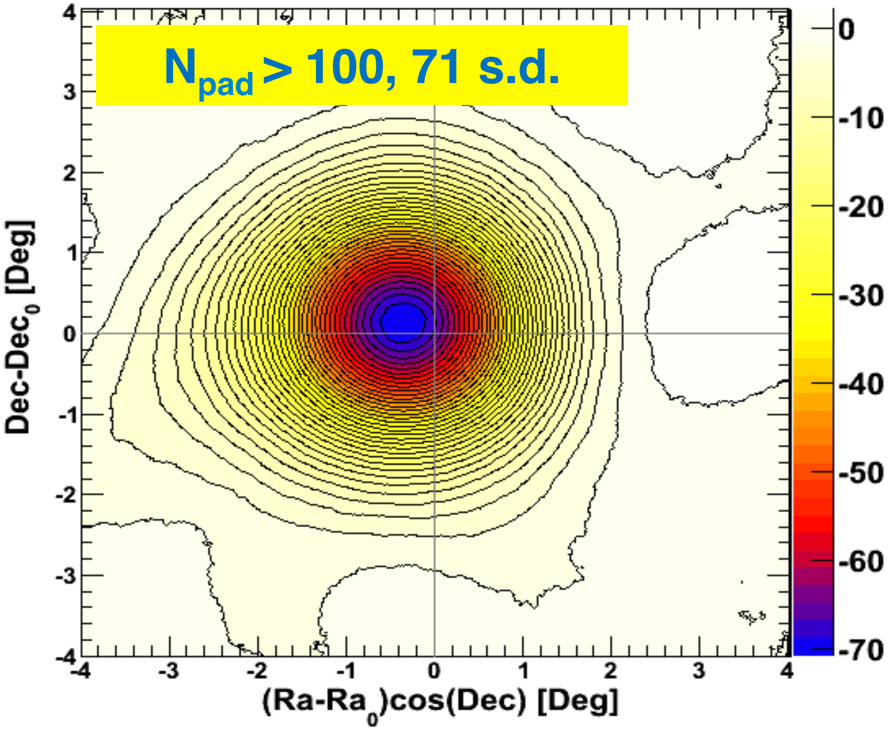
I will provide you with the example of ARGO-YBJ, but the situation is common to all other EAS detectors (past like Tibet Asg and Milagro or future like HAWC and LHAASO).
I will give some information also about MAGIC, which is the IACTS currently most studied in this field. Also in this case conclusions can be extended to other IACTS (mostly for the future CTA).

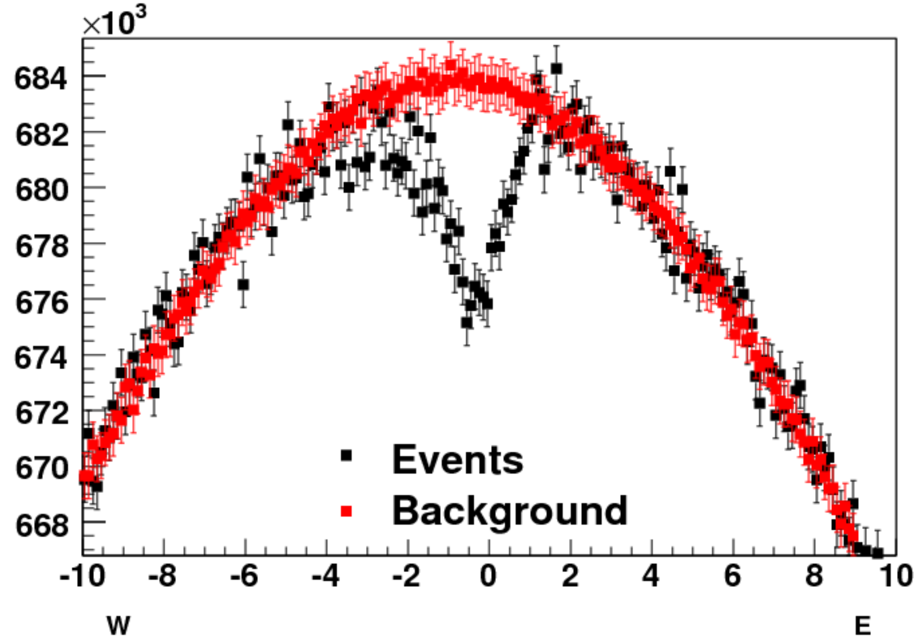
ARGO-YBJ: the observed Moon Shadow

Physical Review D 84 (2011) 022003

Data 2006 → 2010

N > 100 θ < 50°





≈ 10 standard deviations / month

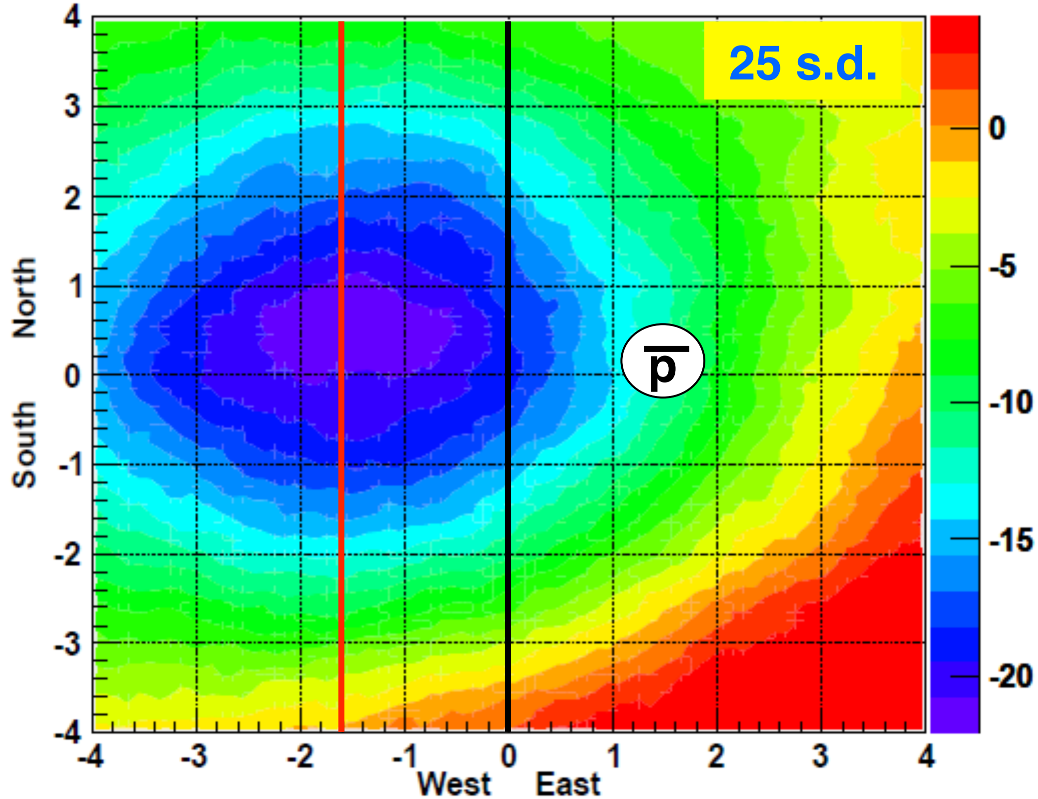
The ARGO-YBJ detector was able to observe the Moon shadow even without subtracting the background contribution.

ARGO-YBJ: 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

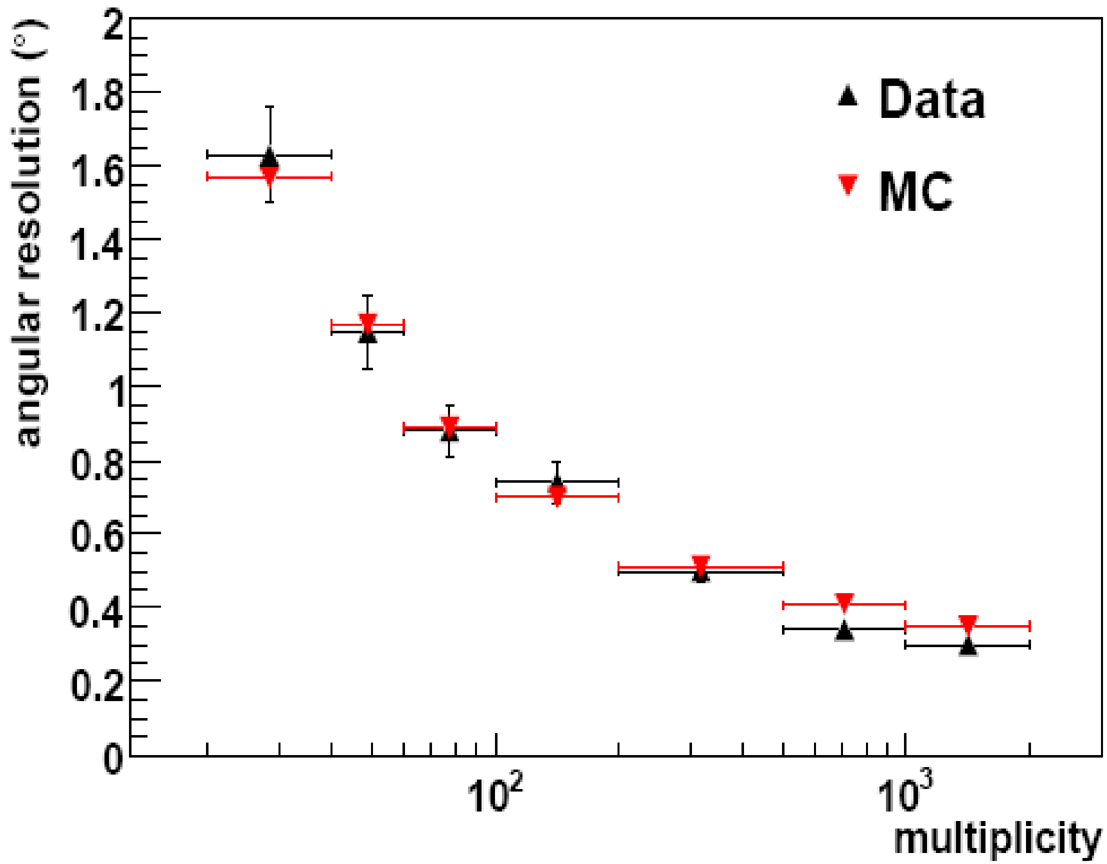


A potential antiproton signal is expected Eastward within 1.5 deg from the actual Moon position (i.e., within 3 deg from the observed Moon position).

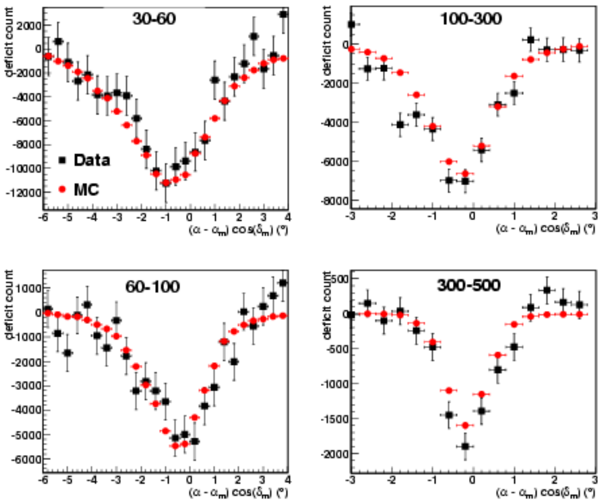
ARGO-YBJ: measurement of the angular resolution along the North-South projection

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%.**



ARGO-YBJ: East-West displacement



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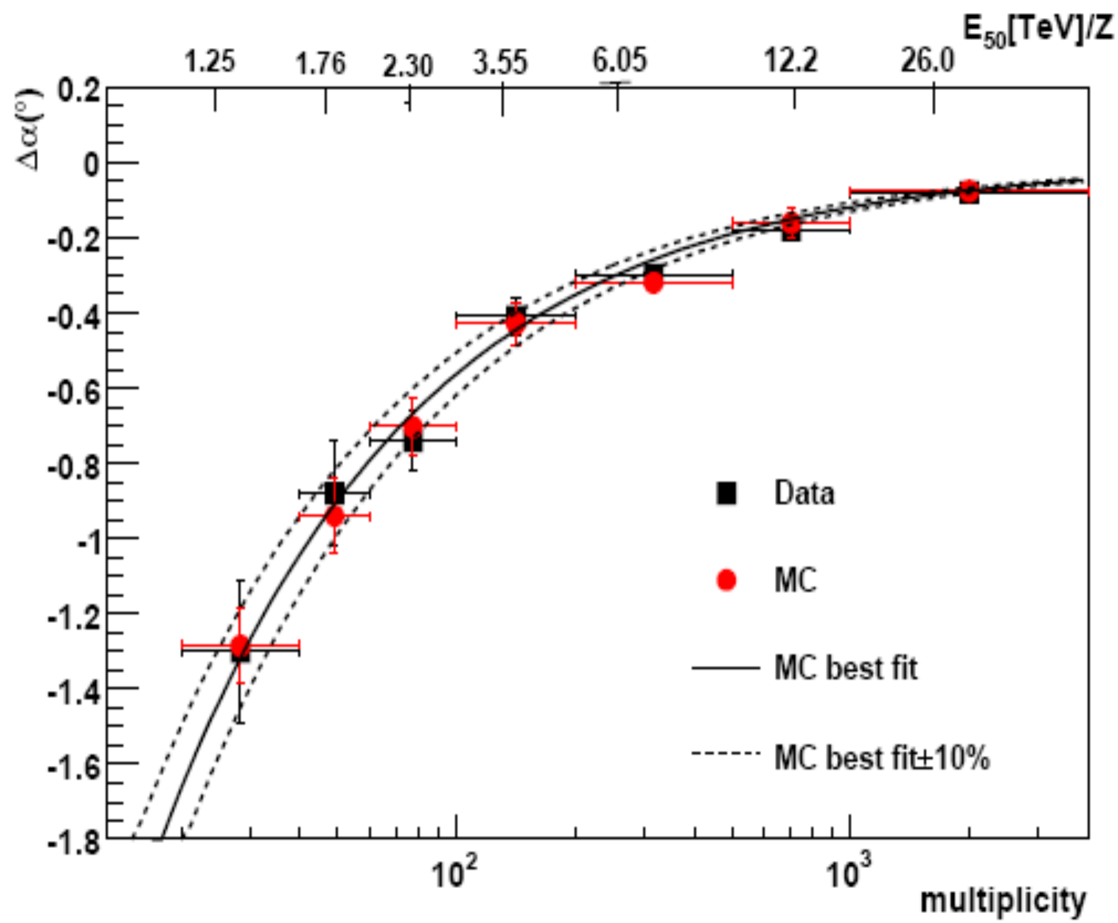


Measured EW displacement

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

Relation

multiplicity – primary energy

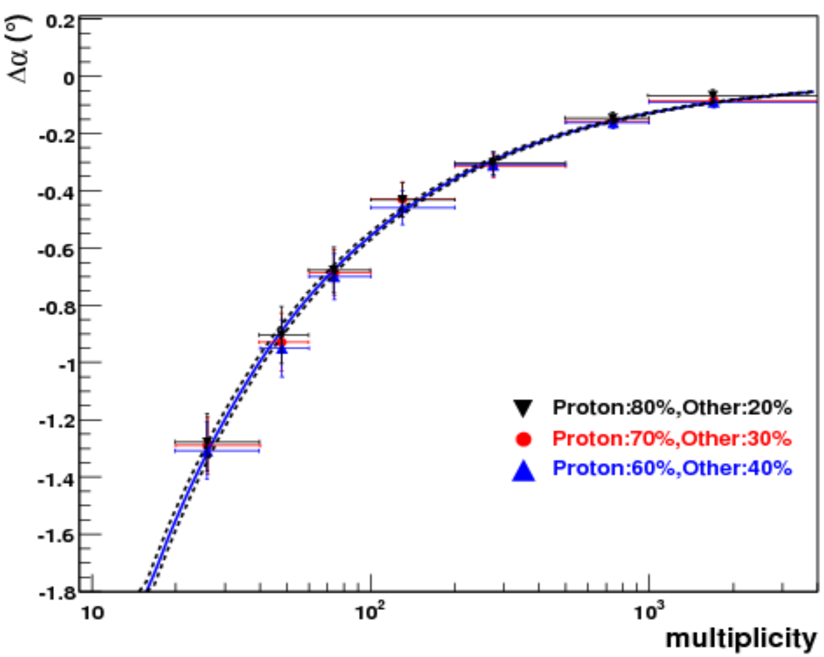
ARGO-YBJ: energy scale calibration

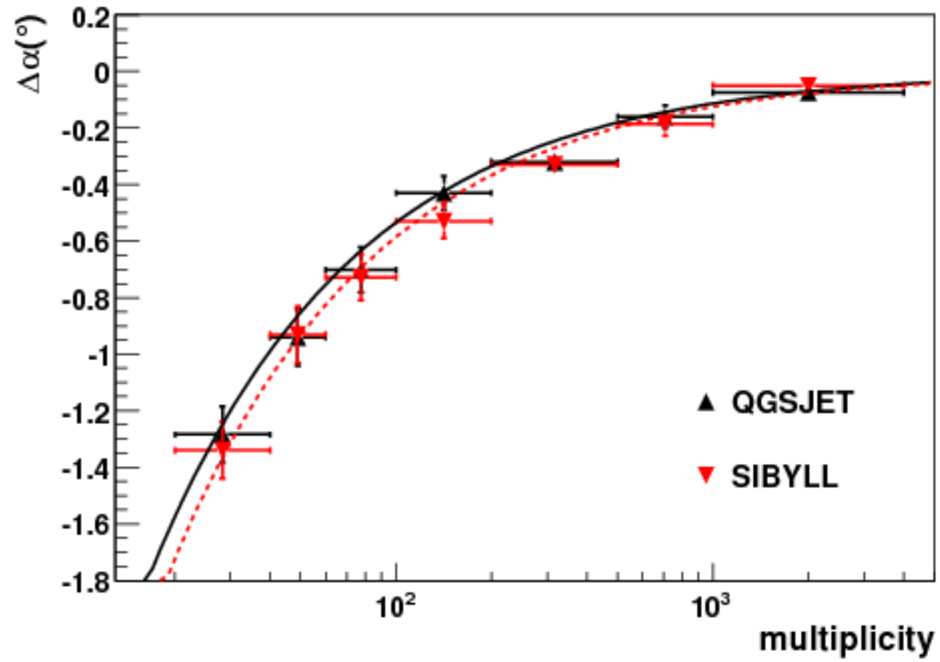
$$N \approx 21 \cdot (E_{TeV}/Z)^{1.5}$$

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%)**

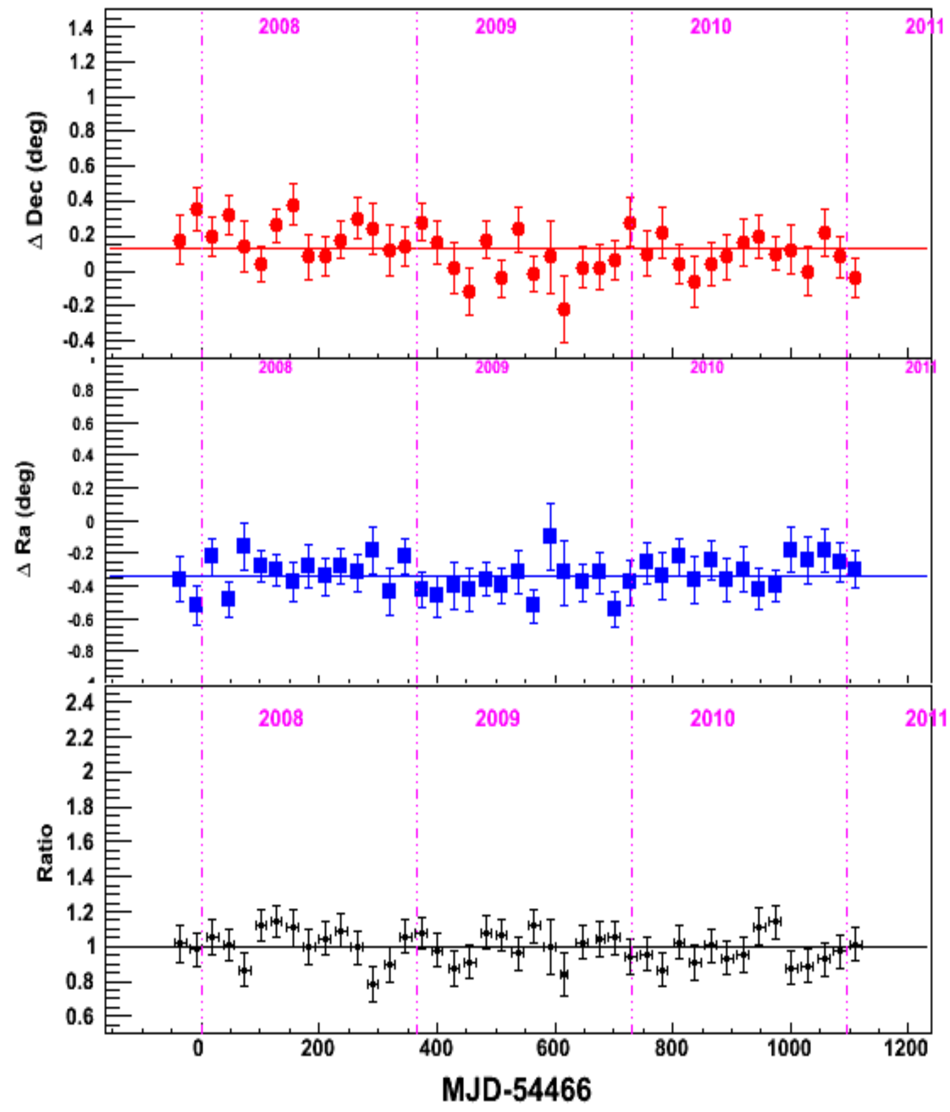




The energy scale uncertainty was estimated to be smaller than 13% in the energy range 1 – 30 (TeV/Z).

ARGO-YBJ: long-term stability

- 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%

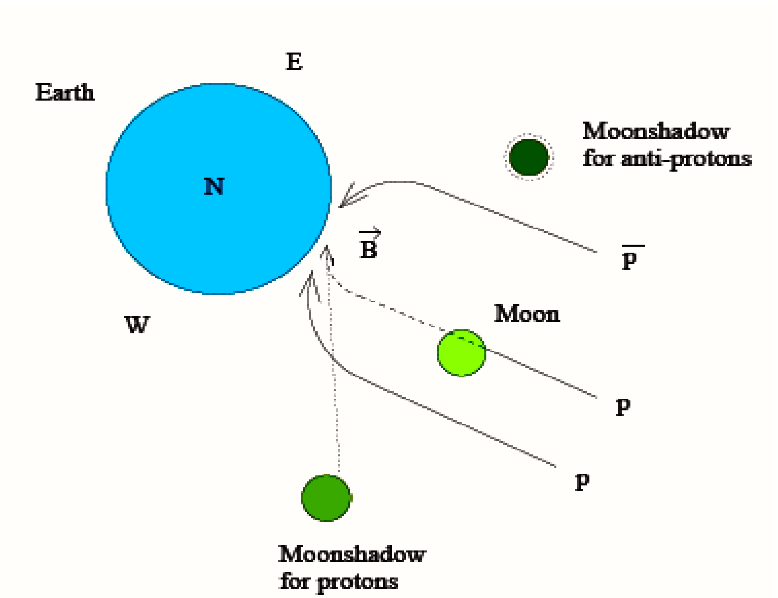


pbar/p ratio at TeV energy

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.

Once again, I will give you details for the case of ARGO-YBJ, but the analysis strategies were common to all experiments.

ARGO-YBJ: measurement of the pbar/p ratio

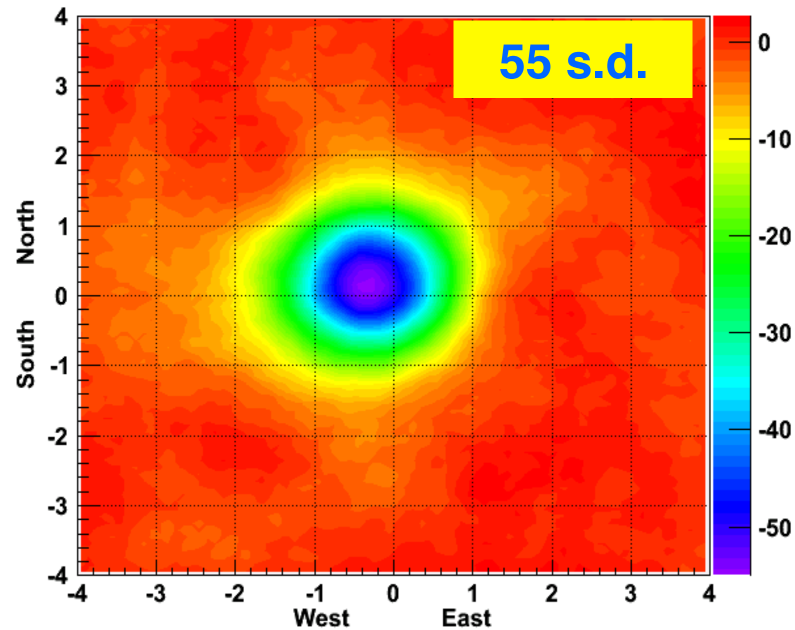
Data: 2006 → 2009 $\theta < 50°$ **3200 hours on-source**

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.**

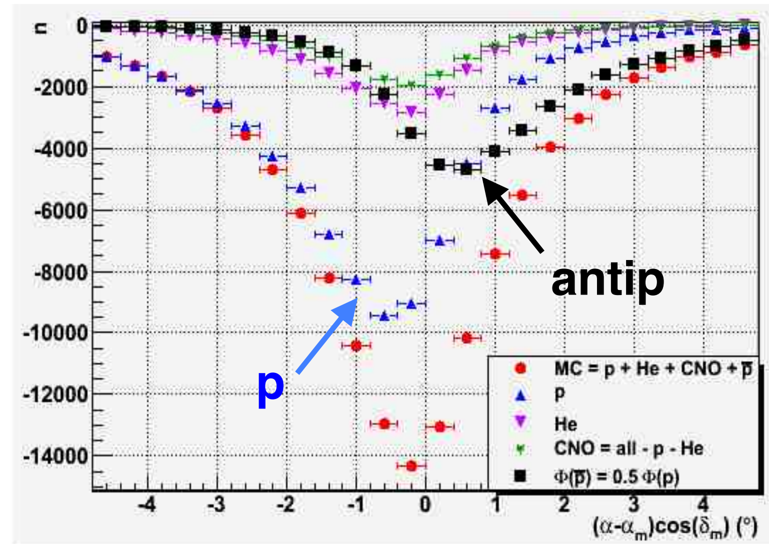


No evidence of the existence of antiprotons is found in this energy region.

ARGO-YBJ: likelihood method to estimate 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.

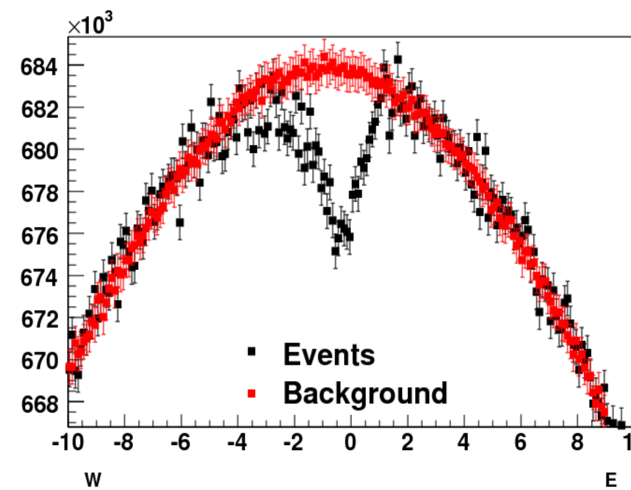


- **New MC signal:**

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

- **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.

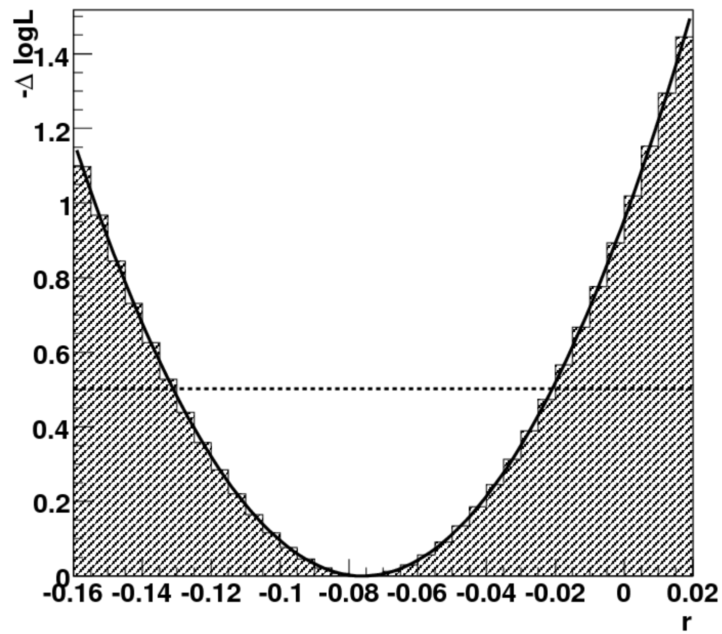
The expected events E_i are calculated by subtracting the new simulated signal from the background (red points).

ARGO-YBJ: likelihood method to estimate the u.l.

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

$r_{min} = -0.076 \pm 0.055$ **for 40 < N < 100**

$r_{min} = -0.144 \pm 0.085$ **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.)

ARGO-YBJ: 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.) ➔ $r_{antip/p} < 0.06$

ARGO-YBJ: effect of the spectral index

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

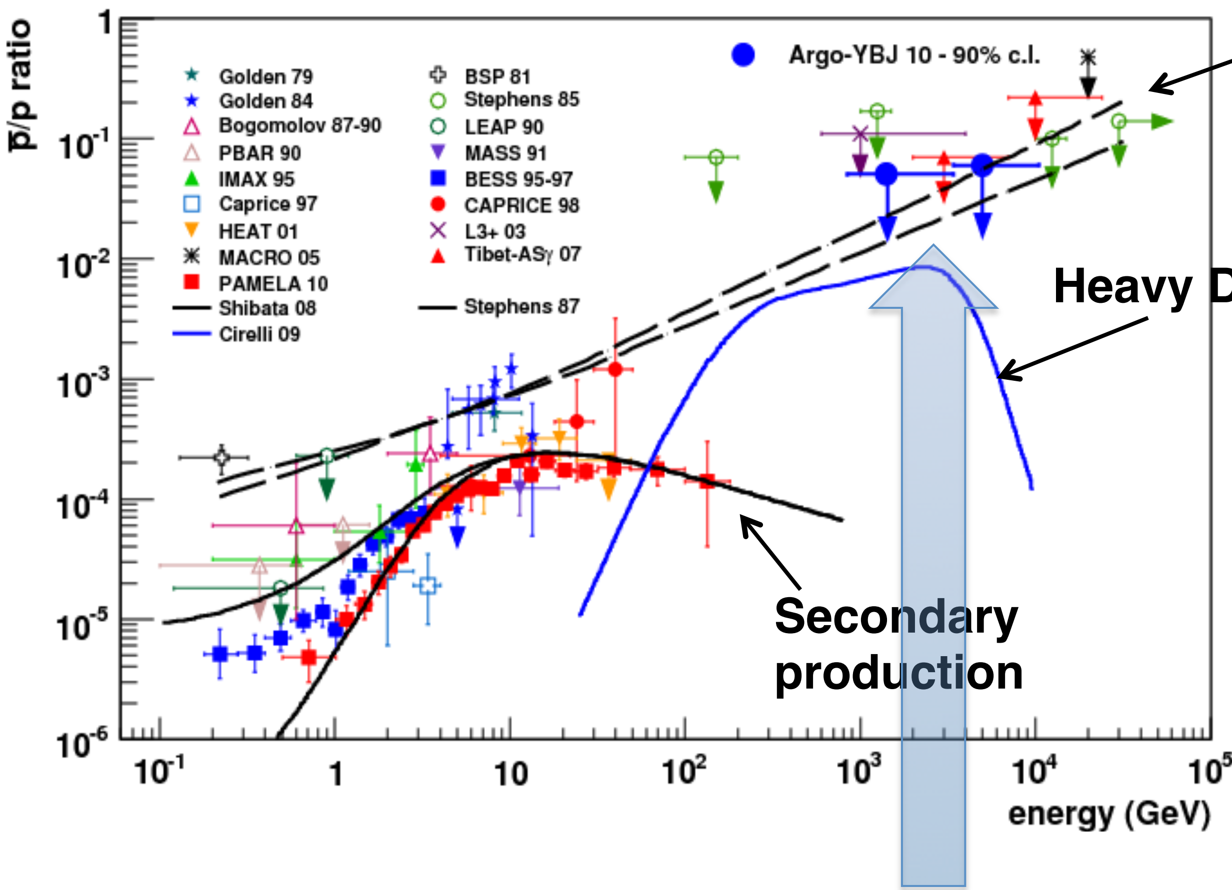
Many unknown factors contribute to its value, mostly related to the diffusion coefficient inside galaxy. To investigate this point, primary antiprotons are assigned different spectral indices,

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 pbar/p



Antigalaxies contribution for different diffusion coefficients, 0.6, 0.7

Heavy DM contribution (Cirelli 2009)

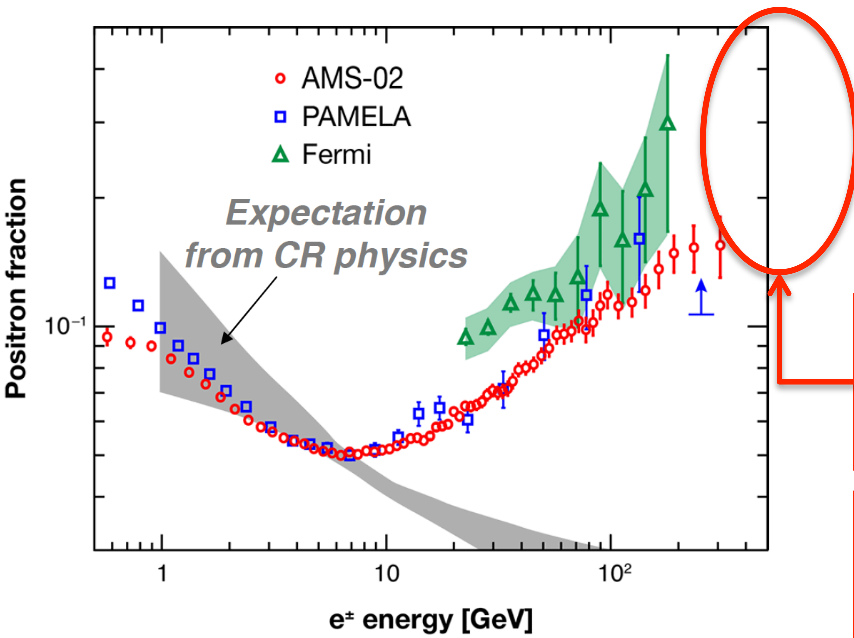
In this energy range the p fraction in CR is ≈70%

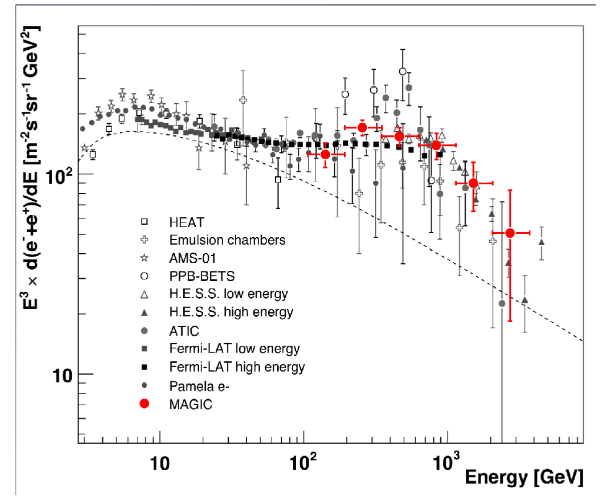
5% at 1.4 TeV at 90% c.l.
6% at 5 TeV at 90% c.l.

3 orders of magnitude above the expected secondary production (to be soon published by AMS-02 at just one tenth energy). Even next generation experiments (better angular resolution and higher statistics, but higher energy) will hardly reach this sensitivity.

Positrons/electrons 1

Anti-matter is not only anti-protons, but also positrons (actually, since 2008, this is the channel giving us more surprises).





What about the TeV scale? The ratio seems to go well above 20%: two orders of magnitude more than the pbar/p ratio. **Easier**?

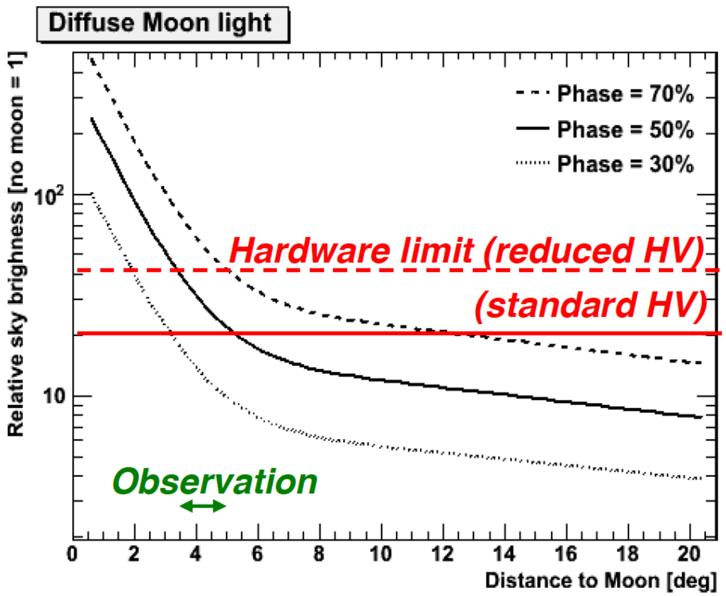
No: e+/- are less than 10^{-3} of CRs above 1 TeV and the flux decreases (power law index 3/4). You need:

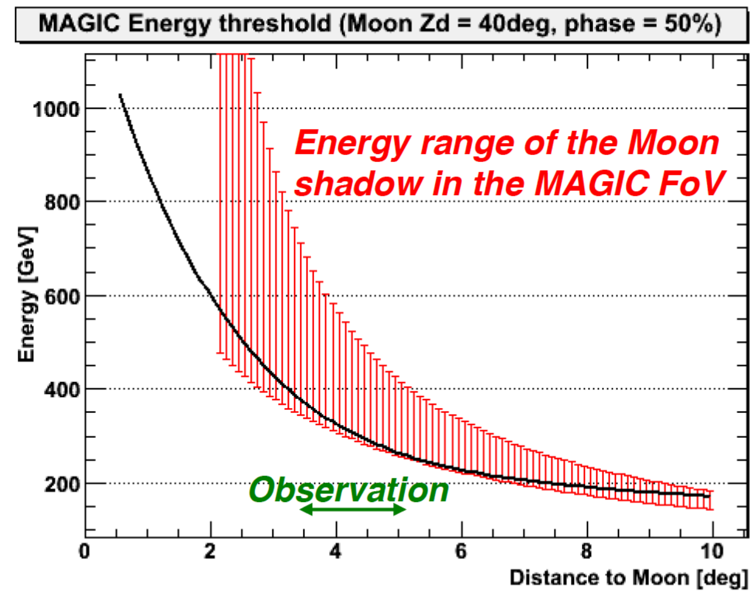
- a large area.
- an excellent electron/hadron separation.
- a good angular resolution because of the high rigidity.

Detection techniques:
- PAMELA & AMS: Strong magnet in space
- Fermi: Earth magnetic field

Positrons/electrons 2

- a large area → out of satellites domain
- **an excellent electron/hadron separation** → **IACTS more sensitive than EAS arrays**
- a good angular resolution because of the high rigidity





Current observation with **MAGIC** (example):
- Target energy range: 300-700 GeV
- Distance to Moon: 3.5°-5°
- Possible only with Moon phase < 50% (limited observation window)

Estimated sensitivity for MAGIC:
- e- shadow: ~40h (~2 years)
- e+ shadow: ~600h (25 years->unfeasible)

Good chances for CTA if optimized for the job.

Conclusions

Anti-protons:
Really hard for EAS detectors to reach the needed sensitivity with the Moon shadow technique. It will be important:

- to lower the energy threshold:
  - better magnetic separation;
  - higher flux.
- to improve the separation hydrogen from heavier elements.
- to improve the angular resolution.

All that will be surely necessary. Perhaps not sufficient.

Positrons:
Indications from satellite-borne experiments are really intriguing. The TeV scale might be decisive to puzzle out the positron excess. The experimental framework seems more encouraging than for antiprotons.

- Absolute fluxes lower than for hadrons.
- Background rejection essential (IACTs have great advantages).
- High anti-matter/matter ratio expected.

Anti-nuclei heavier than anti-hydrogen:
Never observed, even with direct measurements. Interesting field, but also there AMS-02 will probably bring the sensitivity at 100-200 GeV/nucleon at a level prohibitive for ground-based detectors.

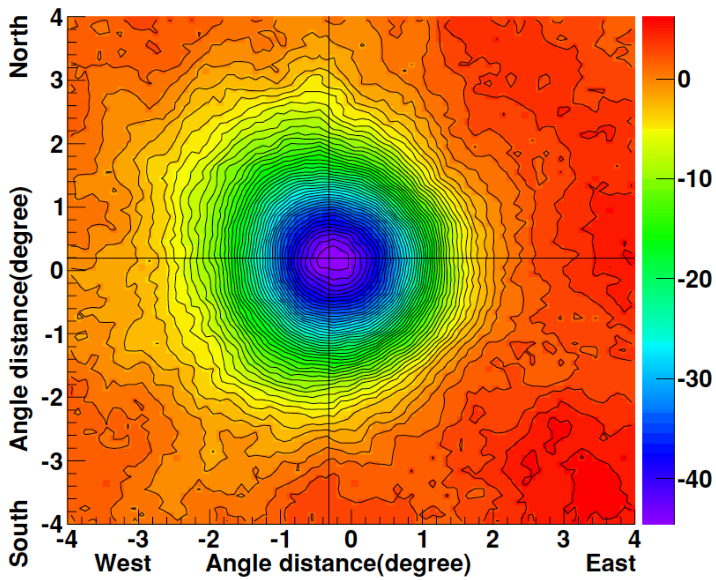
- Lower flux (~2-7 times depending on the energy).
- hydrogen background:
  - hydrogen/helium discrimination (at 0 level)
- Better magnetic separation (factor 2).
- Worse angular resolution (factor 1.5 for EAS arrays, mostly for the core determination).

Directions: sun shadow

Integrate over longer distances: the Sun shadow

- field integral higher (better magnetic separation).
- Strong variability of the magnetic field
- Geomagnetic field to be accounted for and subtracted.

In the end, it could be used for a stacked analysis with the moon shadow data (not great improvements expected).



Example from ARGO-YBJ

It is possible to measure the IMF, but if the IMF is assumed to be known from dedicated experiments, the Sun itself becomes a magnetic spectrometer.

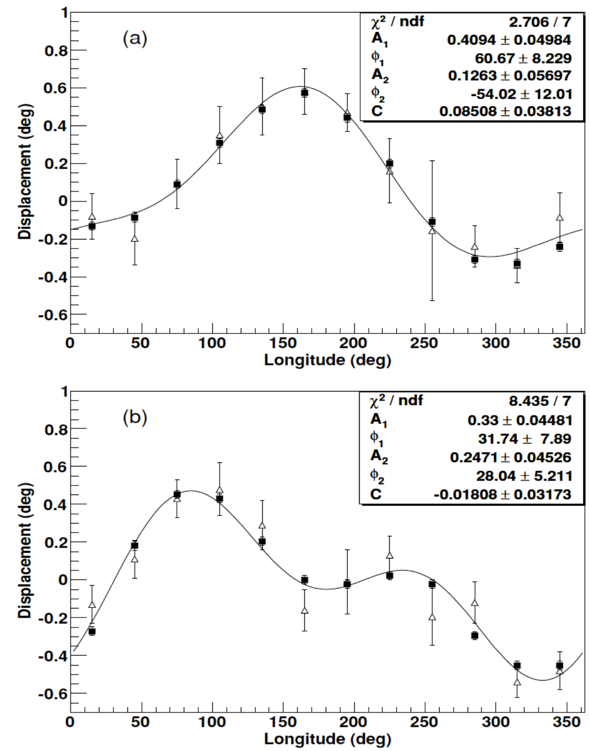
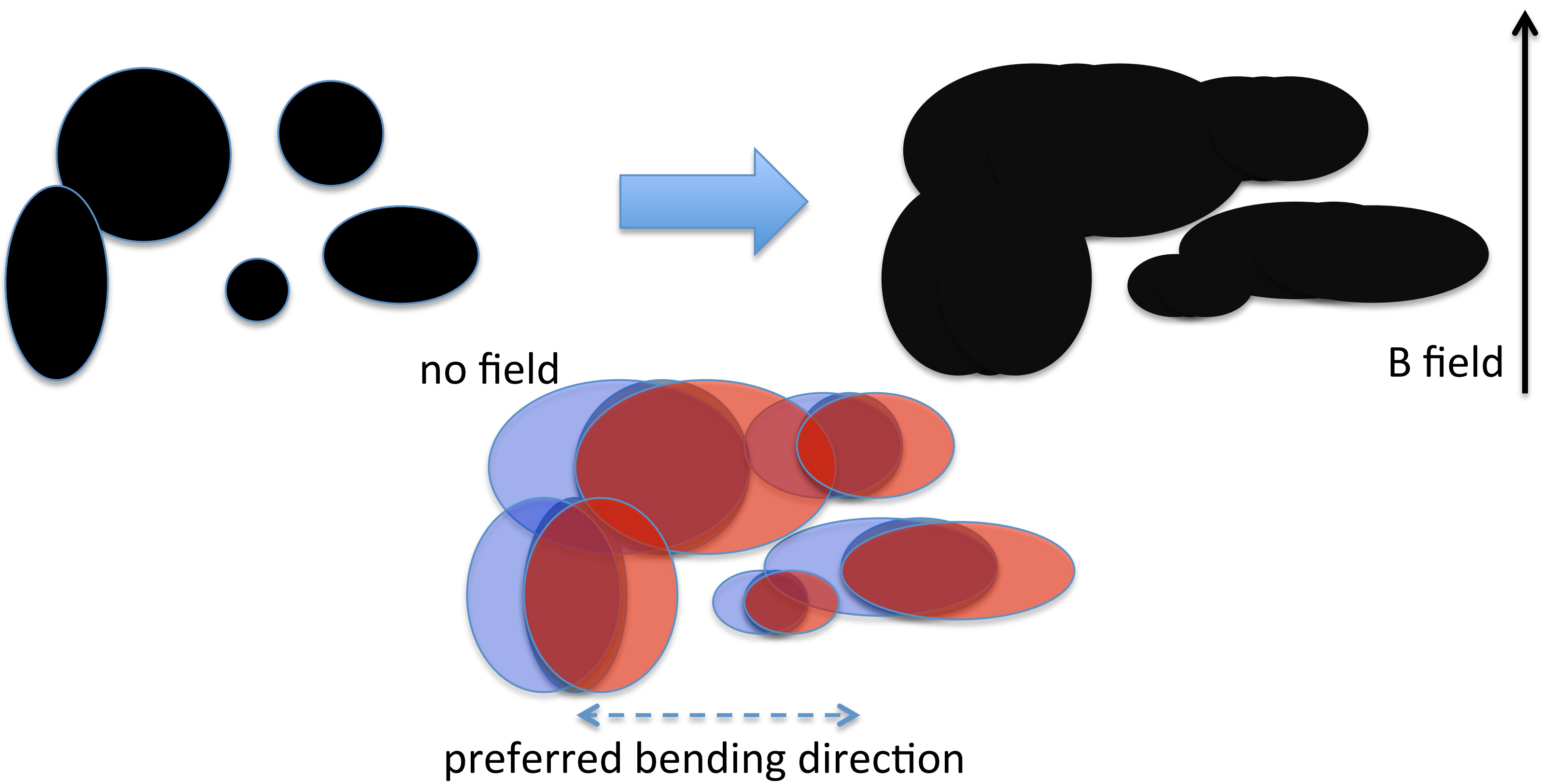


Figure 2. Shift of the center of the Sun shadow along the north–south direction during a complete Carrington period. The horizontal axis gives the Carrington longitude and the vertical axis is the angular displacement of the center of the shadow. In the upper panel (a), the observation (triangles) in the period G_1 reveals that the shadow walks toward north in nearly half of the Carrington period and toward south in the rest of the period. The curve is a fit with a harmonic functional form. The squares represent the displacements of the calculated Sun shadows. In the lower panel (b), a similar shift of the shadow but with different pattern is observed in period G_2, i.e., the shadow moves from side to side twice per Carrington period. C, A_i, and ϕ_i ($i = 1, 2$) are parameters (0th and ith order coefficients and phase shifts) of the second-order harmonic functional form.

Directions: medium and small-scale anisotropies

Small excesses or deficits (~10° or less) should evolve with rigidity in a coherent way, strongly depending on the closest part of the CR path to the Earth (diffusion through galactic magnetic fields accounts only for large scale features).The principle is the same as the Moon shadow.



Thank you.