22° European
Cosmic Ray Symposium

COSMIC RAY PHYSICS BY THE ARGO-YBJ EXPERIMENT

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INFN – Sezione di LECCE
on behalf of ARGO-YBJ collaboration

Outline

- Detector Layout
- The Moon Shadow
- Anti-p/p ratio
- Cosmic ray spectrum
- p-p cross section
- Cosmic ray anisotropy

ARGO-YBJ experiment

An unconventional EAS-array exploiting the full coverage approach at very high altitude, with the aim of studying

- ✓ VHE γ-Ray Astronomy
- ✓ Gamma Ray Burst Physics
- ✓ Cosmic Ray Physics

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

90 Km North from Lhasa (Tibet)

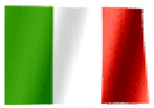
4300 m above the sea level

High Altitude Cosmic Ray Observatory @ YangBaJing

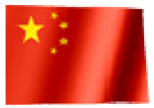
The ARGO-YBJ experiment

International Collaboration:

- ✓ **Chinese Academy of Science (CAS)**
- ✓ **Istituto Nazionale di Fisica Nucleare (INFN)**

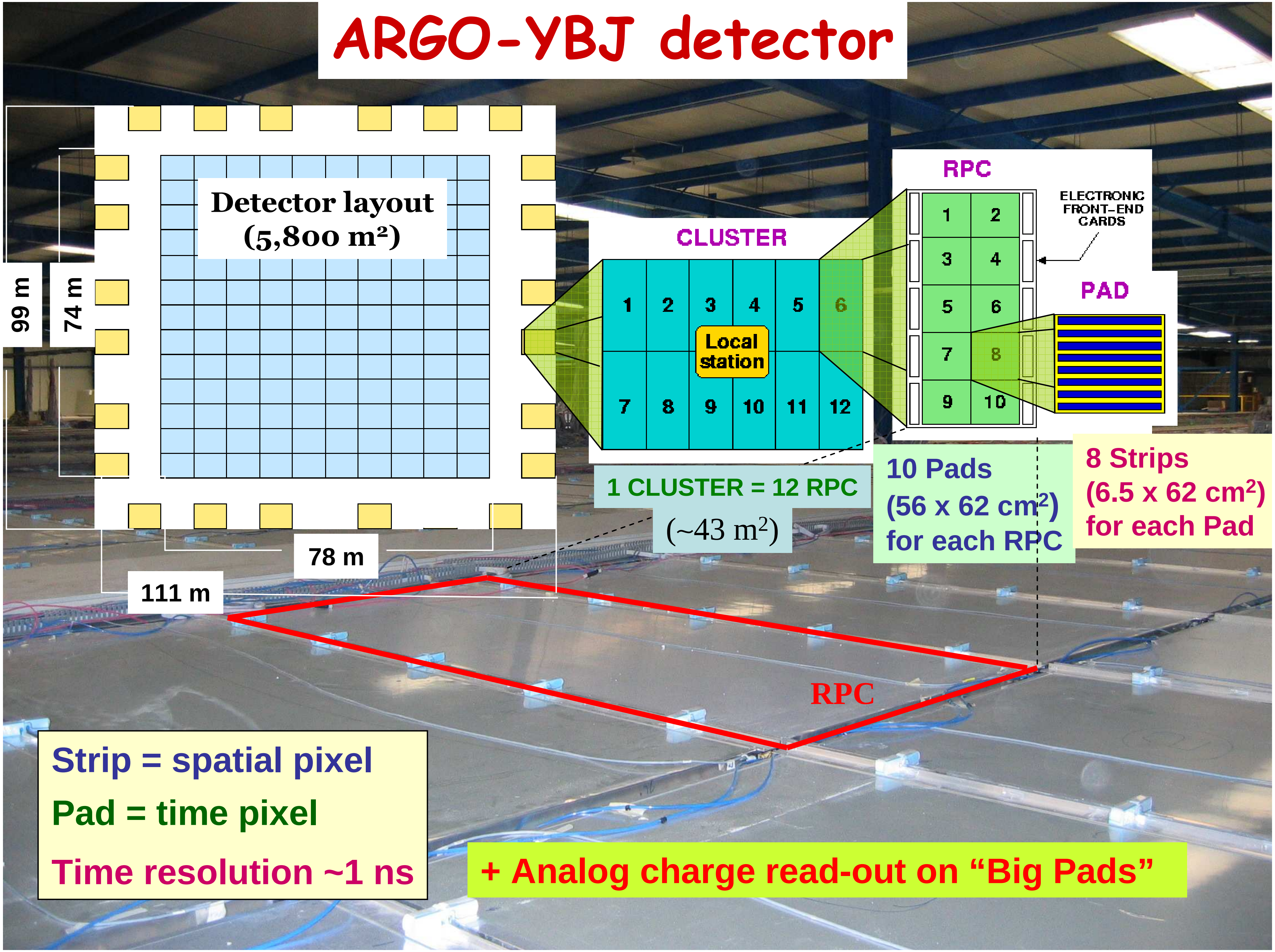


INFN and Dpt. di Fisica Università, Lecce
INFN and Dpt. di Fisica Universita', Napoli
INFN and Dpt. di Fisica Universita', Pavia
INFN and Dpt di Fisica Università "Roma Tre", Roma
INFN and Dpt. di Fisica Univesità "Tor Vergata", Roma
INAF/IFSI and INFN, Torino
INAF/IASF, Palermo and INFN, Catania



HeBei Normal Unversity, Shijiazhuang
IHEP, Beijing
Shandong University, Jinan
South West Jiaotong University, Chengdu
Tibet University, Lhasa
Yunnan University, Kunming

ARGO-YBJ detector



Strip = spatial pixel

Pad = time pixel

Time resolution ~1 ns

+ Analog charge read-out on "Big Pads"

Detector status

Detector completely installed since 2007
(central carpet + guard-ring, 153 clusters)

Data taking

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

Setup for analog charge readout installed on central carpet (130 cl)
Currently in data taking (Trigger ≥ 73 hits/cl)

Operational modes

Shower mode

Inclusive Trigger: N_{pad}>20 within 420ns on the central carpet

⇒ rate ~ 3.6 kHz (~220 GBytes/day)

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

Aims: cosmic-ray physics (threshold ~ 1 TeV)
VHE γ-astronomy (threshold ~ 300 GeV)
gamma-ray bursts

→ Session 6 (S.Vernetto)

Scaler mode

counting rates (≥ 1, ≥ 2, ≥ 3, ≥ 4 coincidences) for each cluster

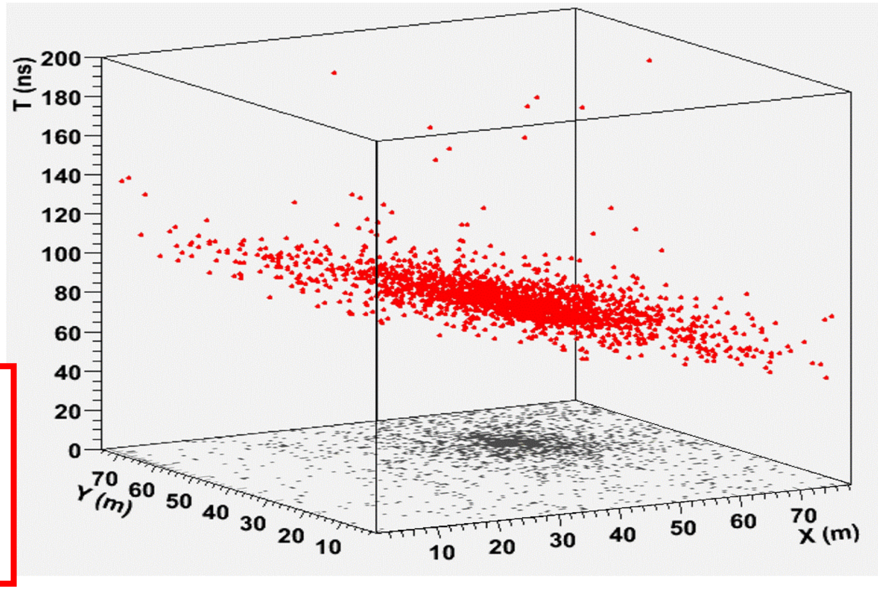
Aims: detector and environment monitor
flaring phenomena (gamma ray bursts, solar flares)
with a threshold of few GeV

→ Session 2 (P.Salvini)

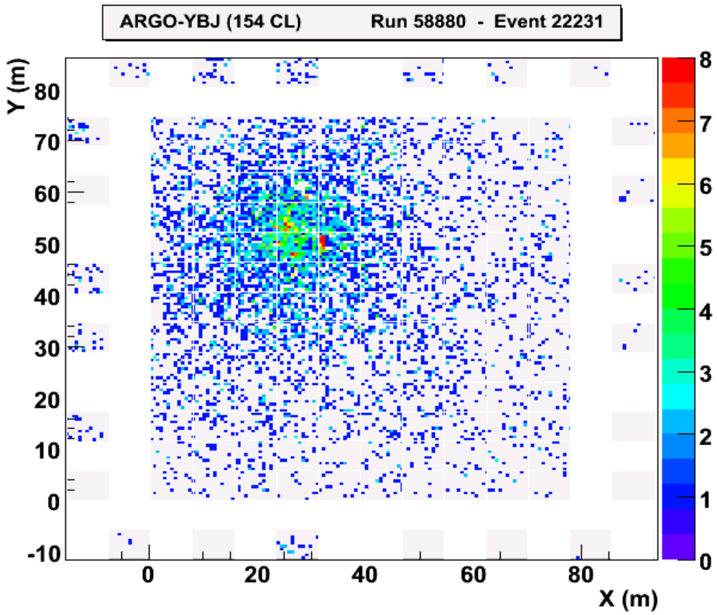
Shower mode:

Space pixel: 7 × 62 cm^2 (single strip)
Time pixel: 56 × 62 cm^2
(8 ORed strips = 1 Pad)
Time resolution: ≈ 1 ns

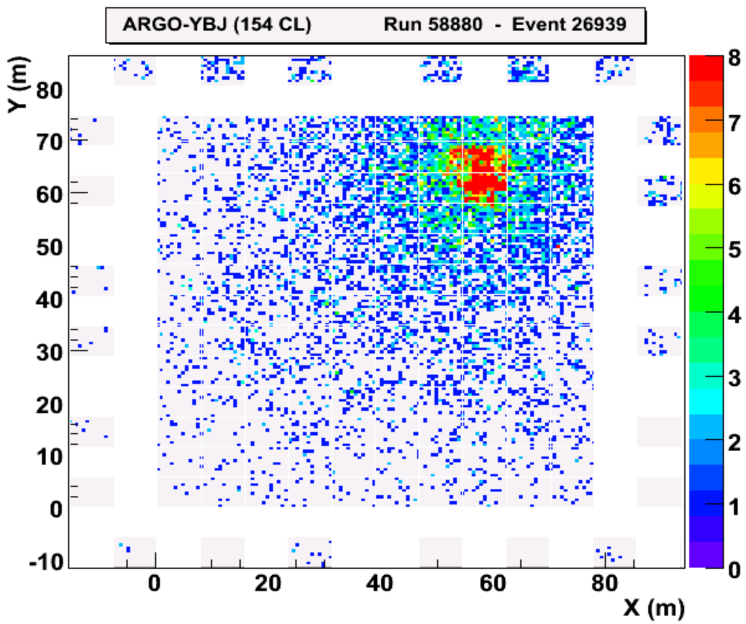
The size of pixels, the time resolution and the full coverage allow event reconstruction with unprecedent details



Real events !!



Number of fired Strips

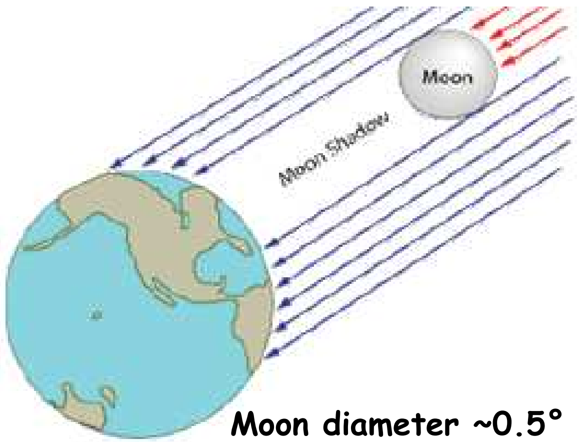


Moon shadow & angular resolution

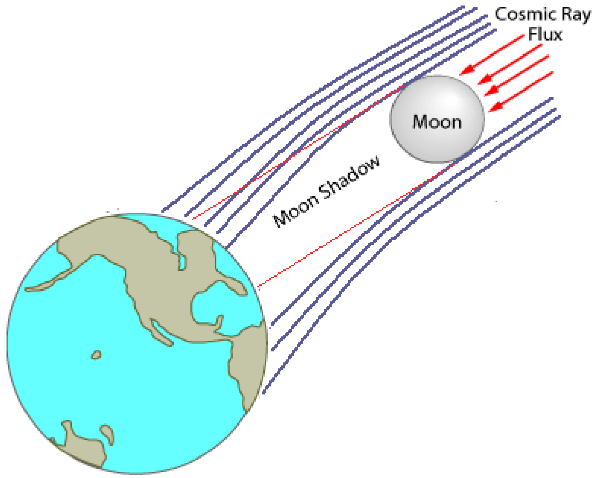
The Moon shadow

A deficit in the cosmic ray flux is expected from the Moon direction.

- Size of the deficit ⇒ angular resolution
- Position of the deficit ⇒ pointing accuracy



Moon diameter ~0.5°



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

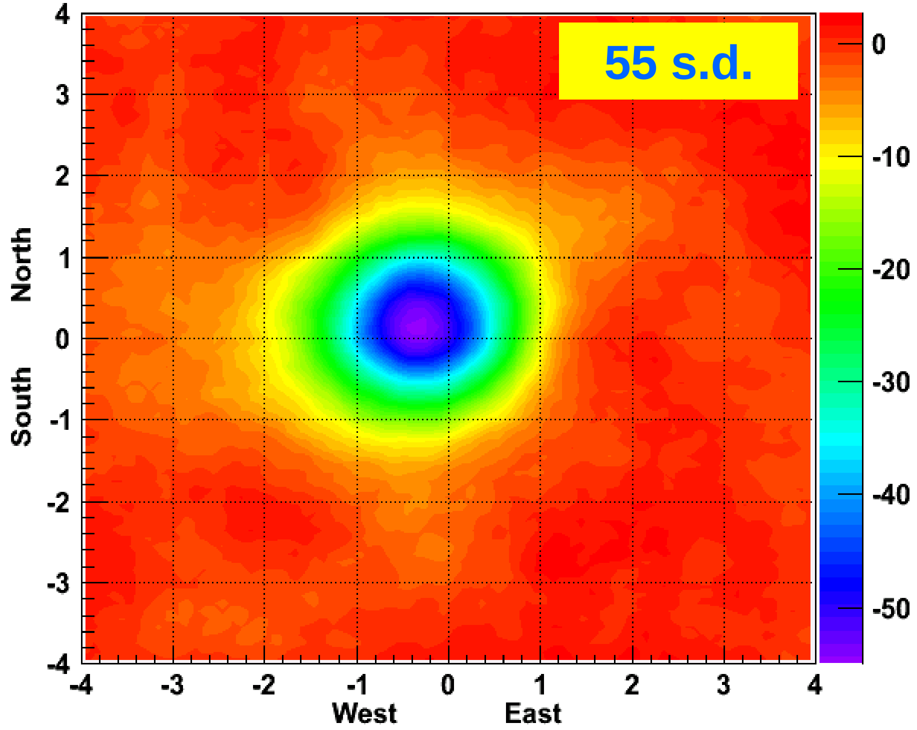
$$\Delta\theta \approx \frac{Z \times 1.6^{\circ}}{E\,[\mathrm{TeV}]}$$

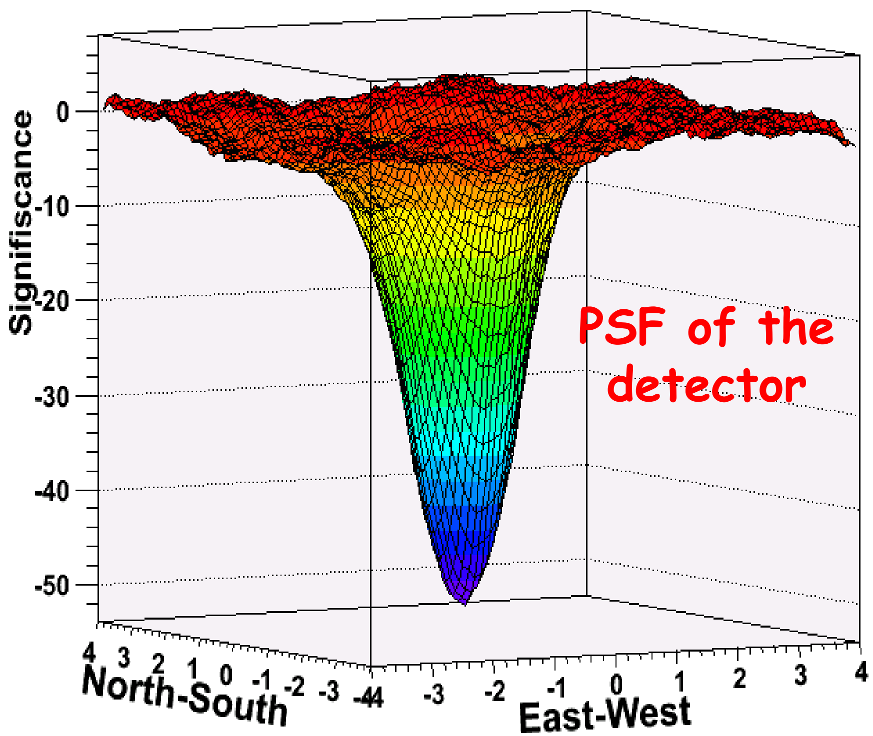
The deflection depends on the primary energy

- West displacement ⇒ Energy calibration

All data: 2006 → 2009

N > 100   θ < 50°





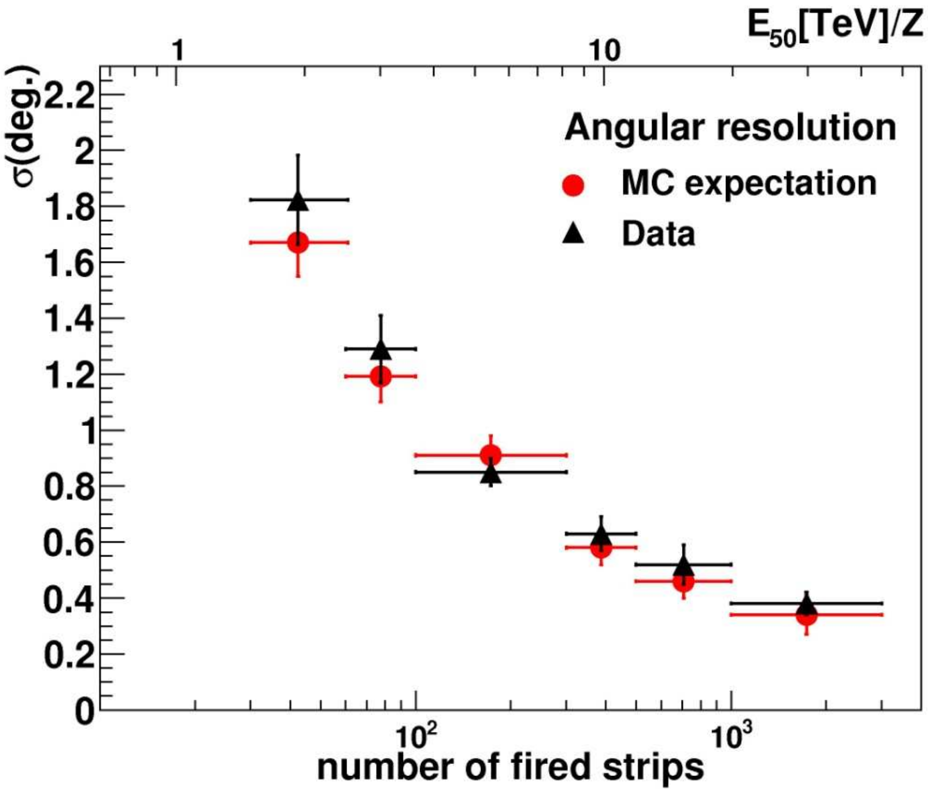
3200 hours on-source

≈ 9 standard deviations / month

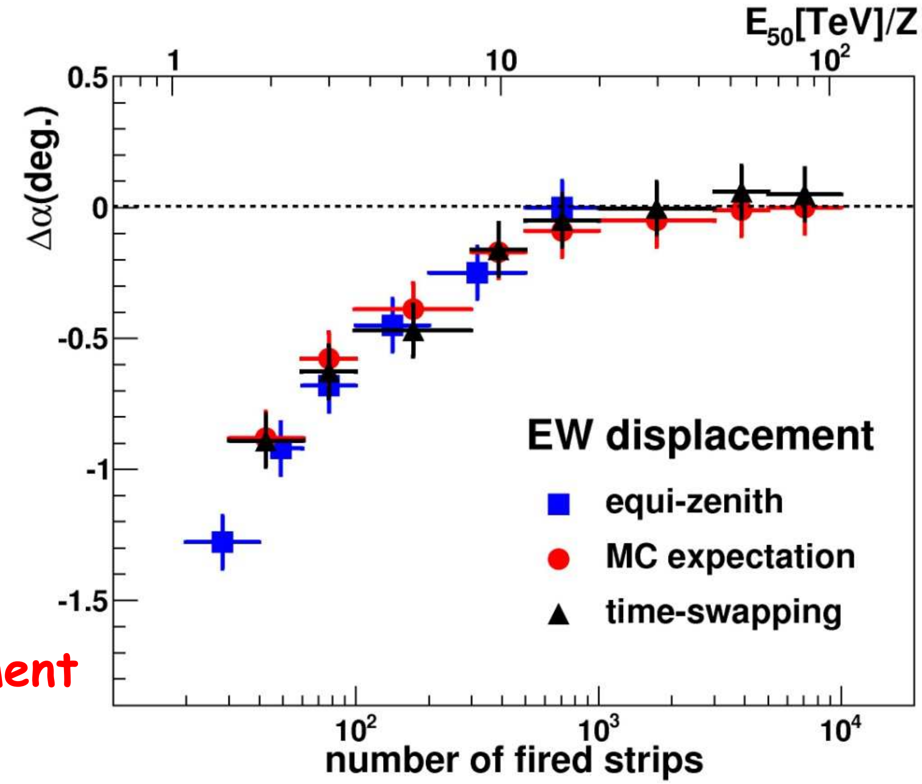
The deficit surface is the convolution of the PSF of the detector and the widespread Moon disc:

$$RMS \simeq \sigma \sqrt{1 + \left(\frac{R}{2\sigma}\right)^2}$$

Moon Shadow analysis



Measured angular resolution



Measured EW displacement

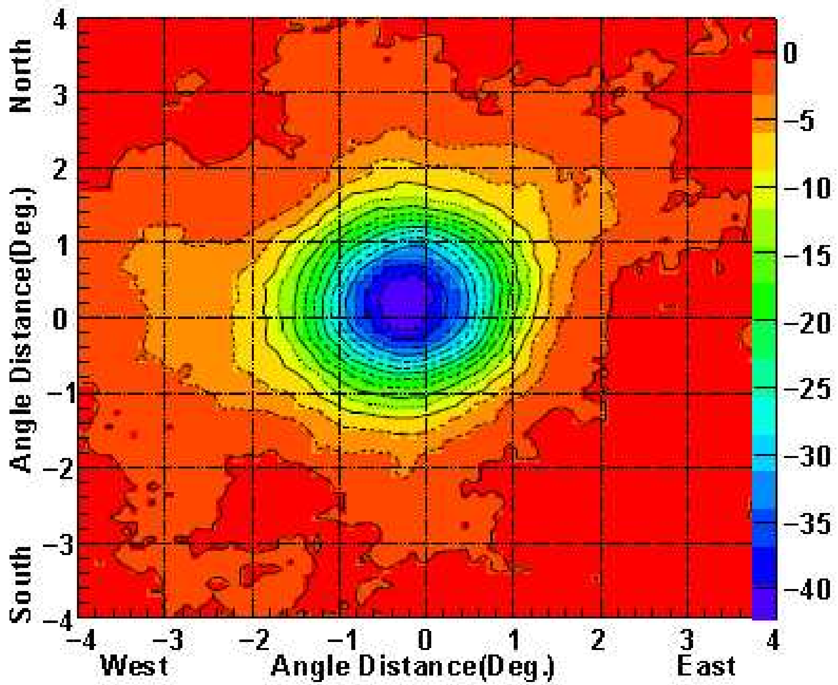
The Sun shadow

✓Measuring the Interplanetary Magnetic Field

✓Exploring the Solar Magnetic Field

✓The deficit significance and position correlated with solar activity

At present, particularly quiet phase between 2 solar cycles



Data set: 2007 – 2009

$N_{hit} > 100$ Zenith < 50°

- Observed N-S displacement of the shadow from the Sun position mostly due to the IMF (measuring such field)
- Modulation caused by SMF (depending on the solar activity)

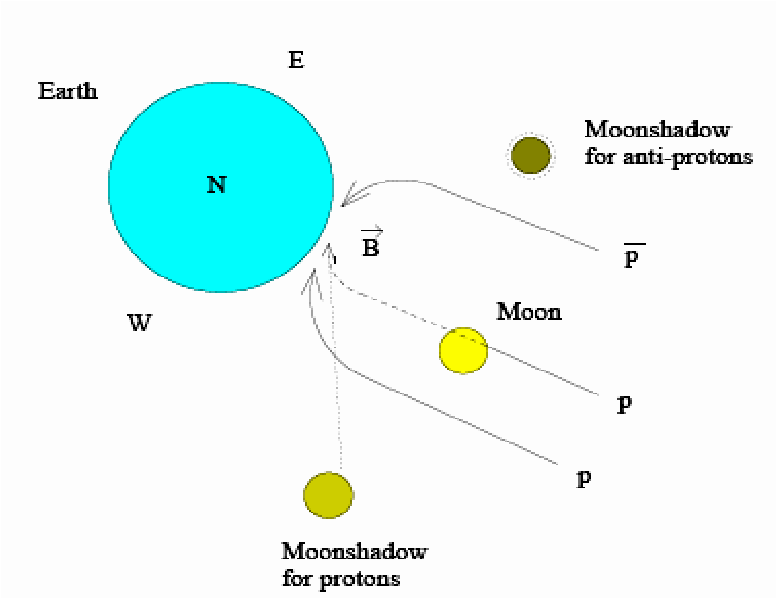
Cosmic rays

$\bar{p}/p$ 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 is large and the angular resolution small enough we can distinguish between the 2 shadows.

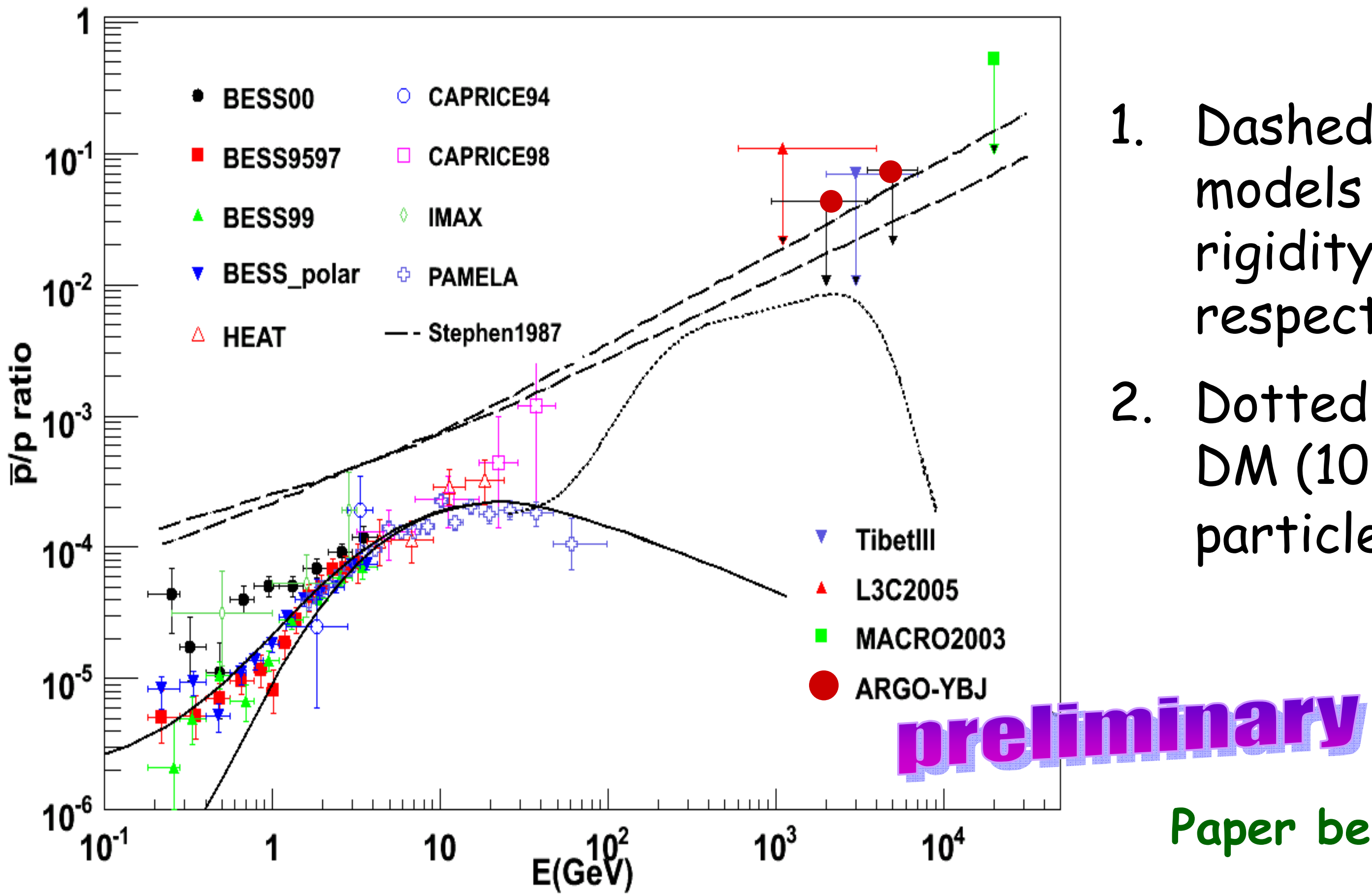
If no event deficit on the antimatter side is observed, an upper limit on antiproton content in Cosmic Rays can be calculated.



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

Median E ~2 TeV: 90% C.L. Upper limit **4.2%**

Median E ~5 TeV: 90% C.L. Upper limit **7.4%**



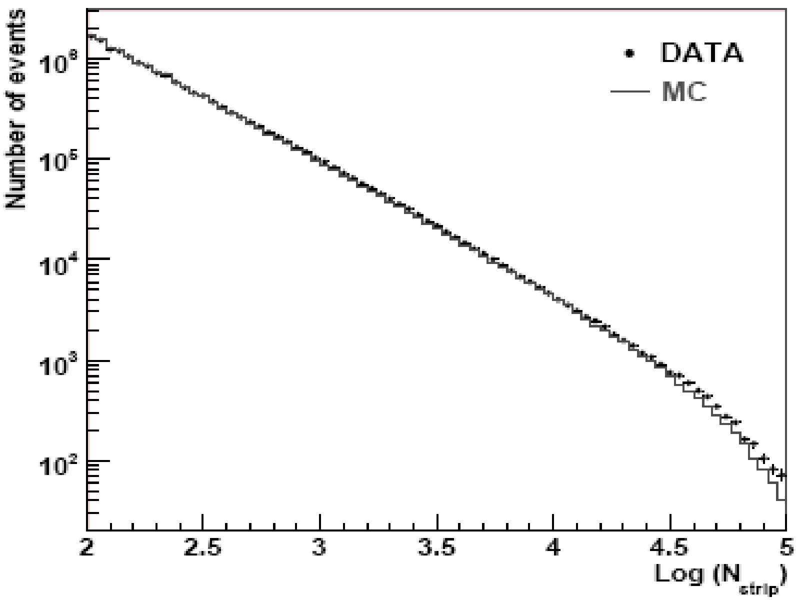
1. Dashed lines: antistars models for different rigidity, 0.6, 0.7 respectively
2. Dotted line, the heavy DM (10 TeV WIMP) particle contribution.

Paper being submitted

Light-component spectrum of CRs

Extract the *light-component* (p+He) spectrum of primary CRs starting from the measured strip multiplicity spectrum

and using a Bayesian unfolding procedure



$$P(E_i) \propto \sum_{j=1}^{n_M} P(E_i \mid M_j) \cdot P(M_j)$$

$$P(E_i \mid M_j) = \frac{P(M_j \mid E_i) \cdot P(E_i)}{\sum_{l=1}^{n_E} P(M_j \mid E_l \mid) \cdot P(E_l)}$$

$$P(E_i) = \frac{N(E_i)}{\sum_{E'} N(E')} \qquad P(M_j) = \frac{N(M_j)}{N_{tot}}$$

$N(M_j)$ **from experimental data**

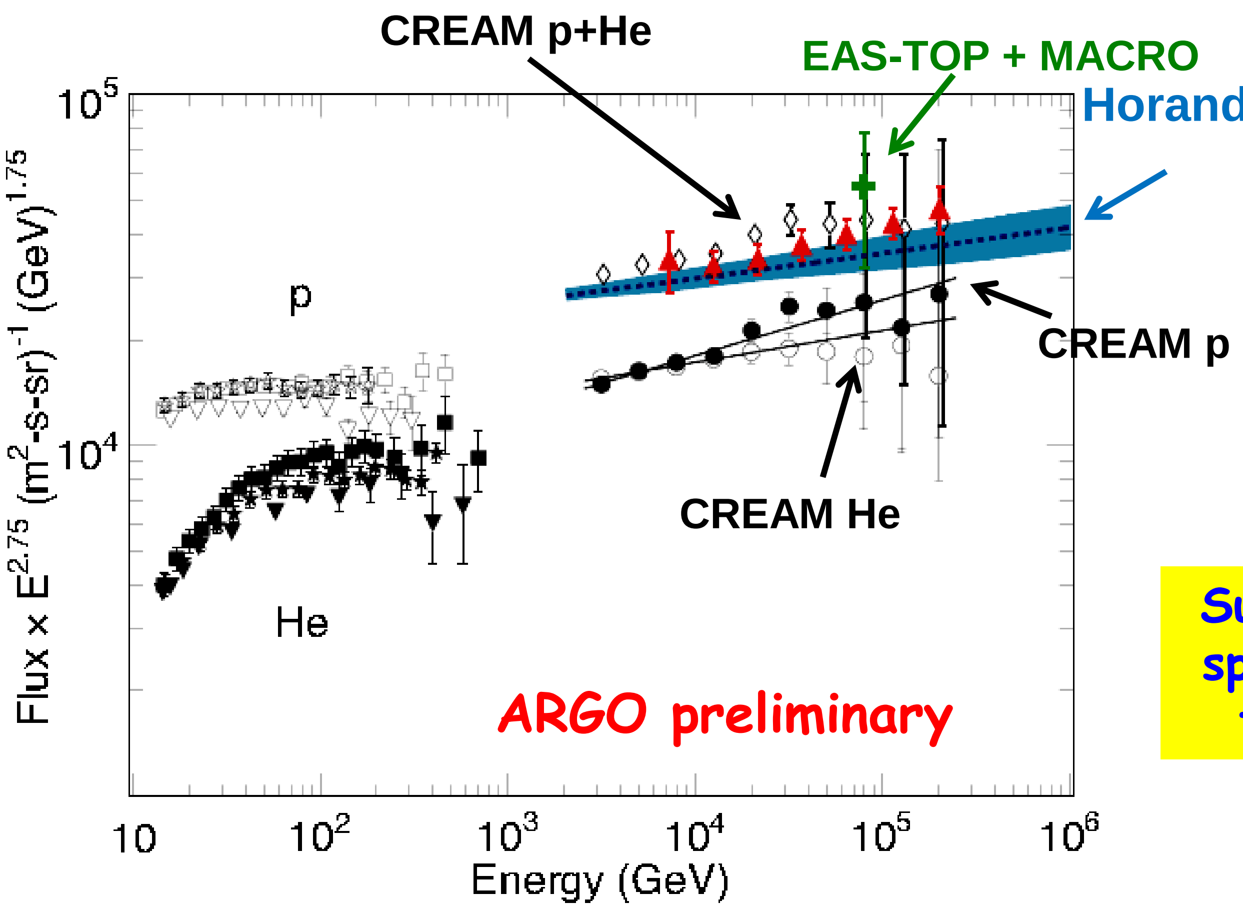
$P(M_j \mid E_i)$ **computed by MC simulation**

Light-component spectrum of CRs

Measurement of the spectrum in the energy region (5 – 200) TeV

Strip multiplicity range: (500 ÷ 50000)

CNO < 2%



Fit spectral index:
$\gamma = -2.61 \pm 0.04$

ARGO data agree with CREAM results

Suggesting that the proton spectrum is flatter than in the lower energy region

Paper being submitted

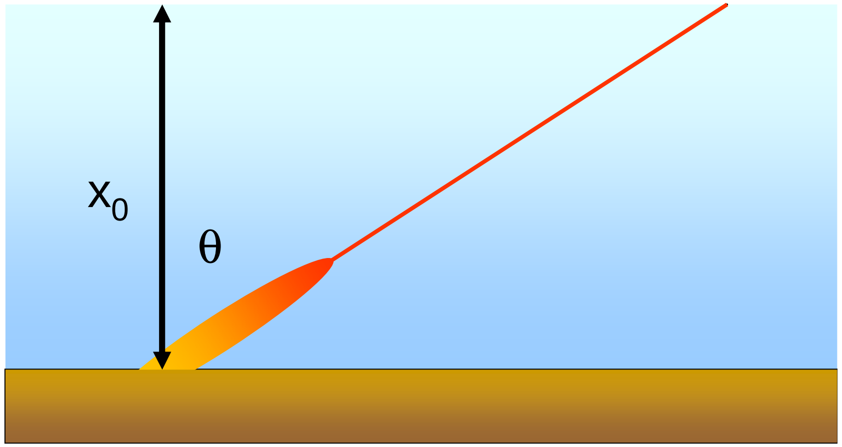
Flux attenuation and p-Air cross section

Shower frequency vs *(secθ-1)*:

$$I(\theta) = I(0) \cdot e^{-\frac{x_o}{\Lambda_{abs}}(\sec(\theta)-1)}$$

$\Downarrow$

Measure the flux attenuation



For <u>fixed energies</u> and shower ages:

$$\Lambda_{abs} = k\,\lambda_{\rm INT}$$

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

$\Rightarrow$ $\sigma_{p\text{-}Air}$ $\Rightarrow$ $\sigma_{p\text{-}p}$

- **k is determined by MC simulations, selecting energy and age ranges by means of the actual experimental observables (number of fired strips, hit density, lateral profile, ..)**

It depends on the interaction model details, but also on the set of experimental observables, energy, ...)

Data selection

- **Event selection based on:**

  (a) "shower size" on detector, N_{strip} (strip multiplicity)

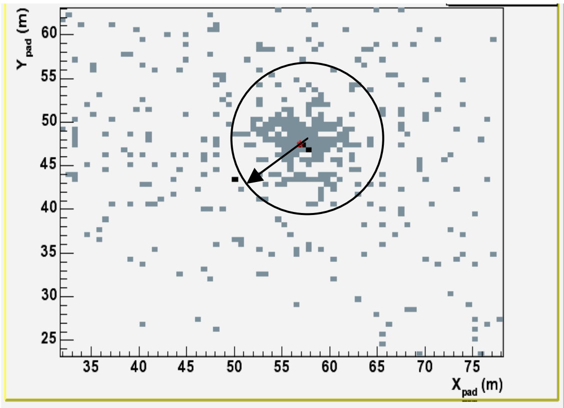
  (b) core reconstructed in a fiducial area (64 x 64 m^2)

  (c) constraints on Strip density (> 0.2/m^2 within R_{70})

  and shower extension (R_{70} < 30m)

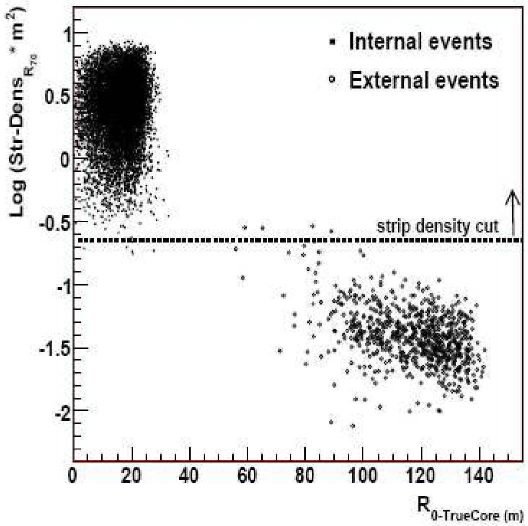
N_{strip} is used to get defferent E sub-samples

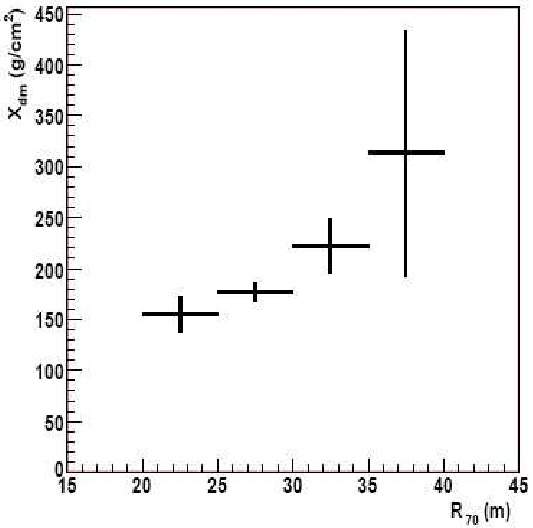
R_{70}: radius of circle including 70% of hits



Full Monte Carlo simulation:

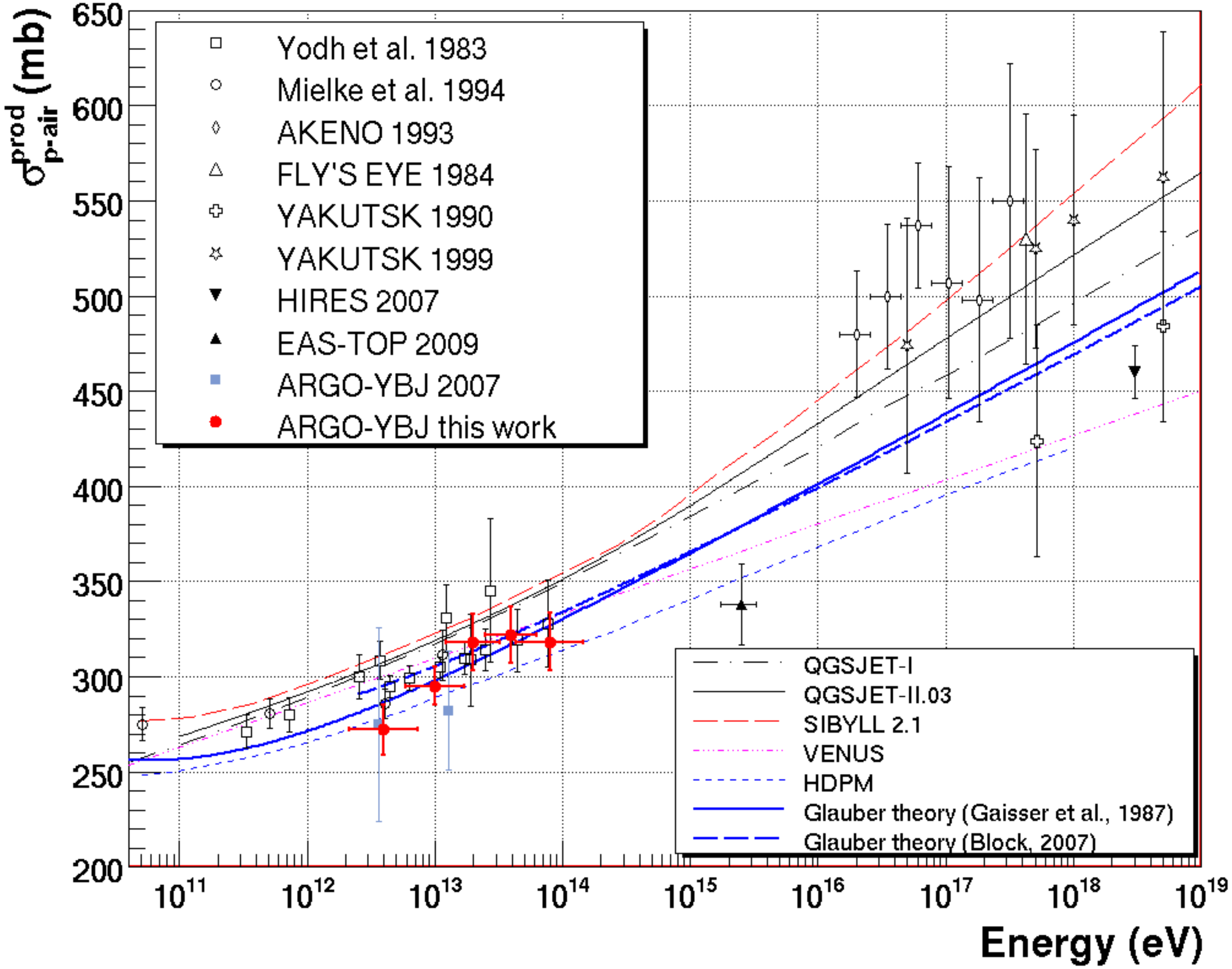
- ✓ Corsika showers
- ✓ QGSJET I and II, SYBILL interaction models
- ✓ GEANT detector simulation





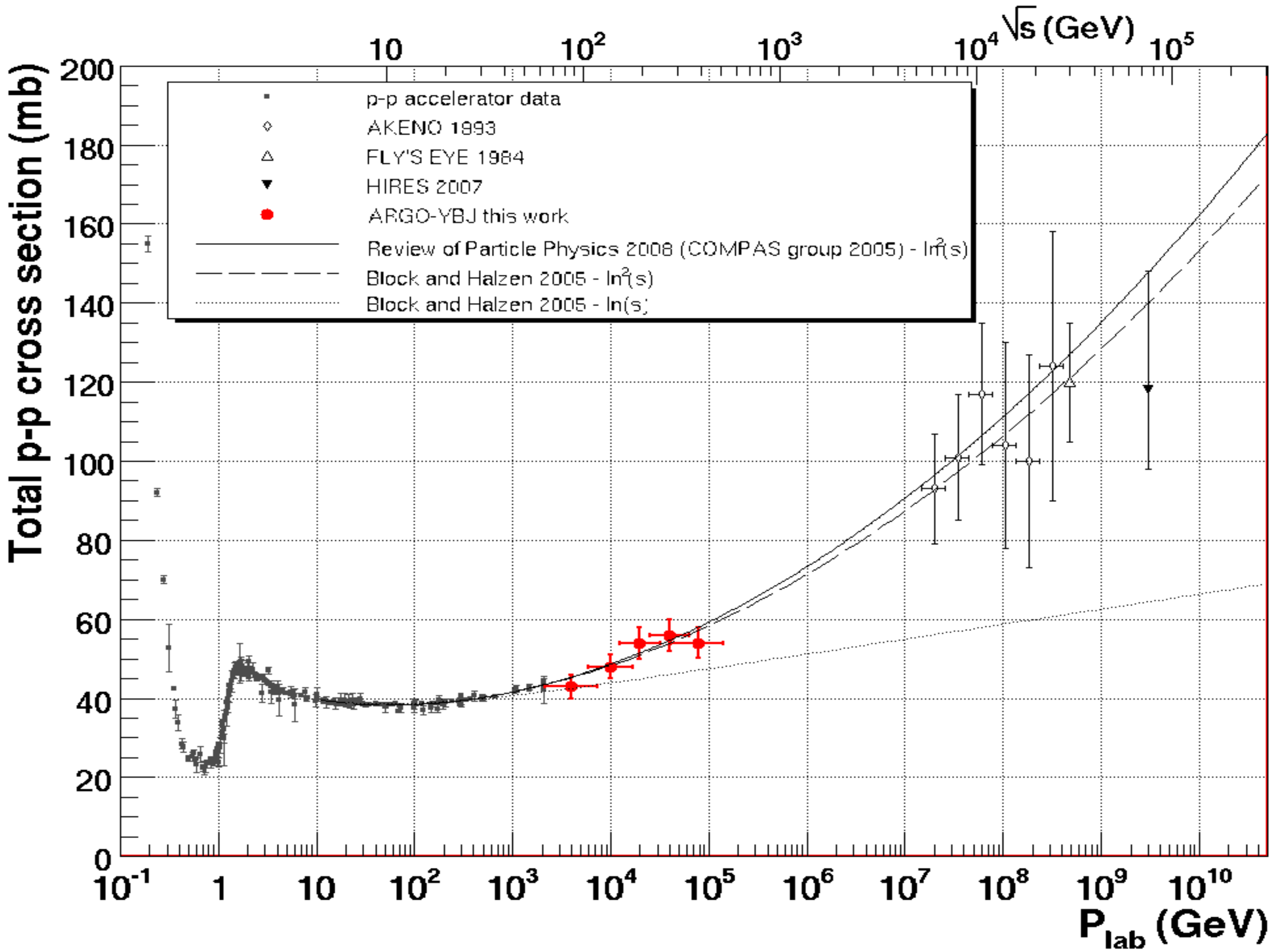
Proton-Air cross section measurement

Phys. Review D80 (2009) 092004.



Total p-p cross section

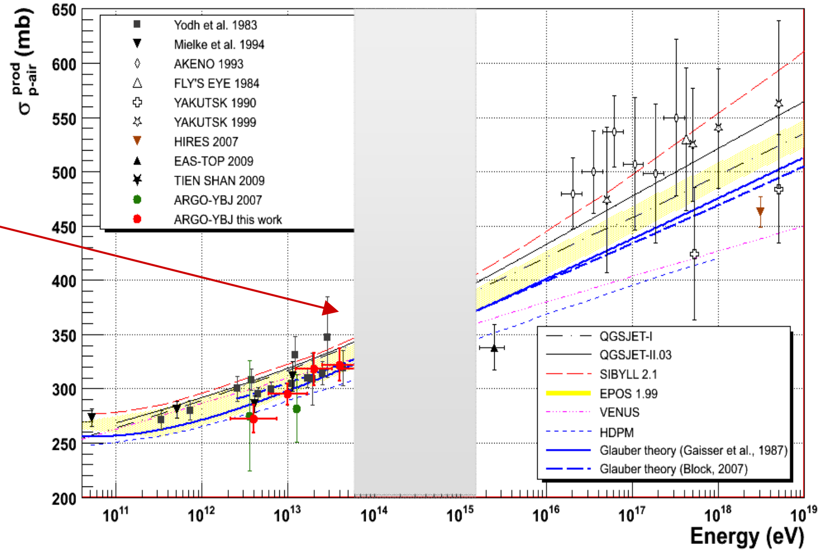
(inferred by means of the Glauber theory)



- ✓ No data from accelerators available at these energies
- ✓ The $\log^2(s)$ asymptotic behaviour is favoured

Next steps in the analysis

- Use the analog RPC charge readout to extend the Energy range
- Better estimate systematics



Selection improvements coming from:

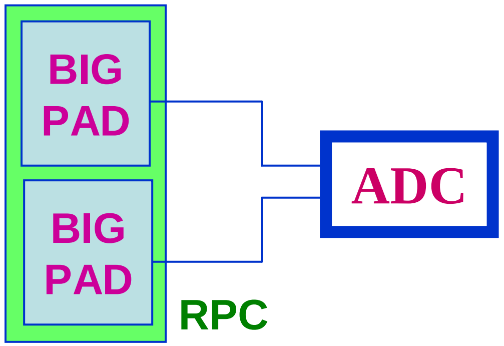
(a) More detailed informations on the shower time structure, longitudinal development and lateral density profile (LDF)

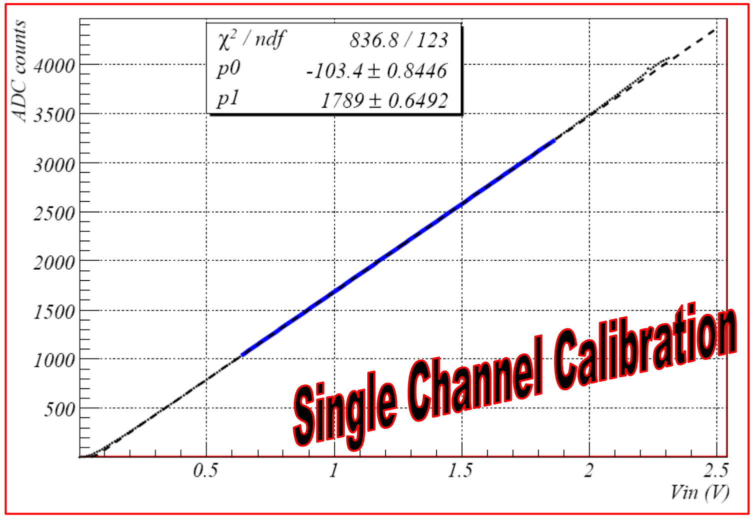
(b) Better constraints on shower Xmax (→ lower systematics)

... also given by the RPC charge information

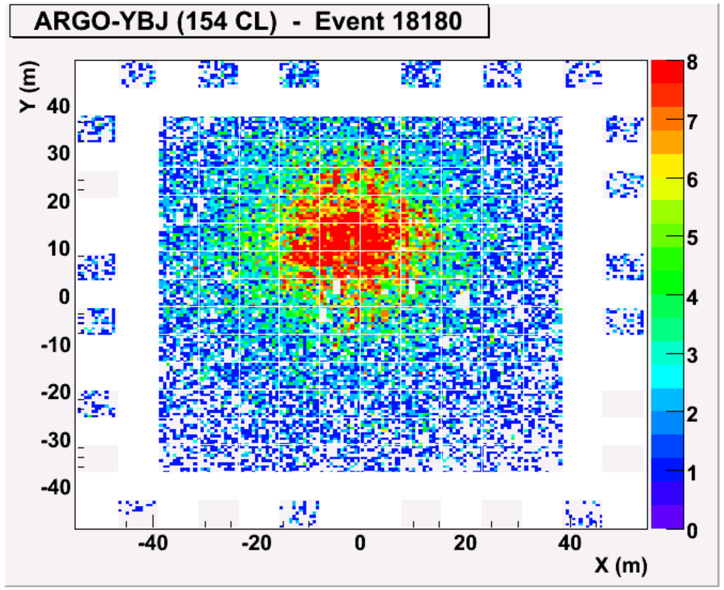
Analog charge read-out

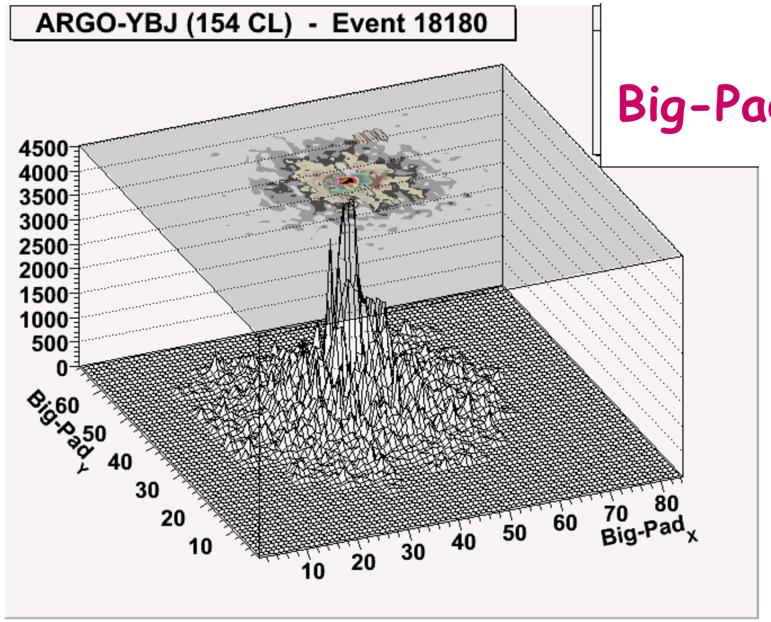
Read-out of the charge induced on "Big Pads"





Strip top view

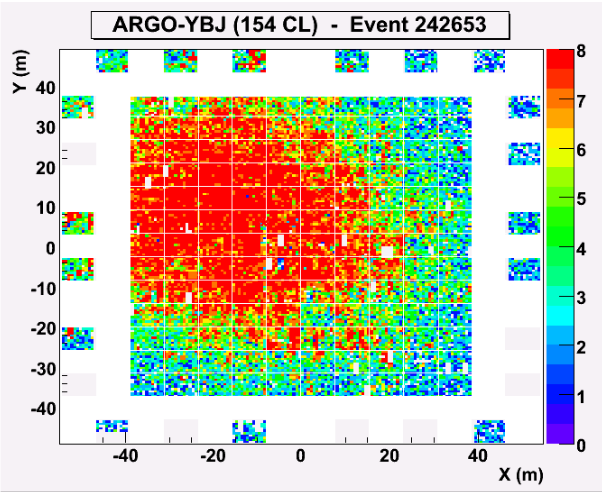




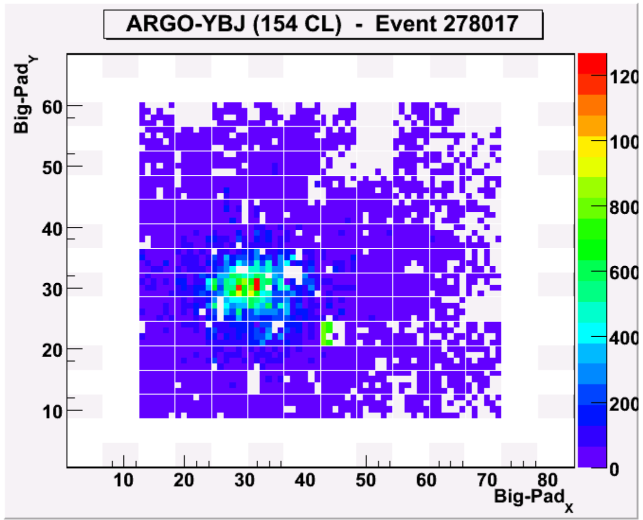
Big-Pad 3-D view

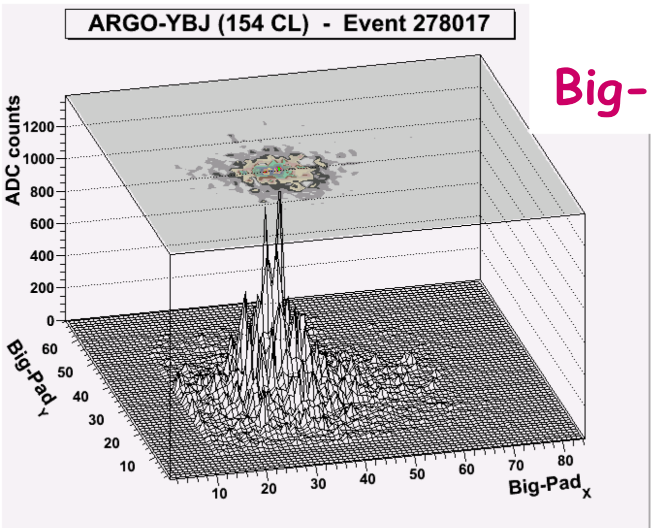
Imaging the shower front structure

Strip top view



Big-Pad top view

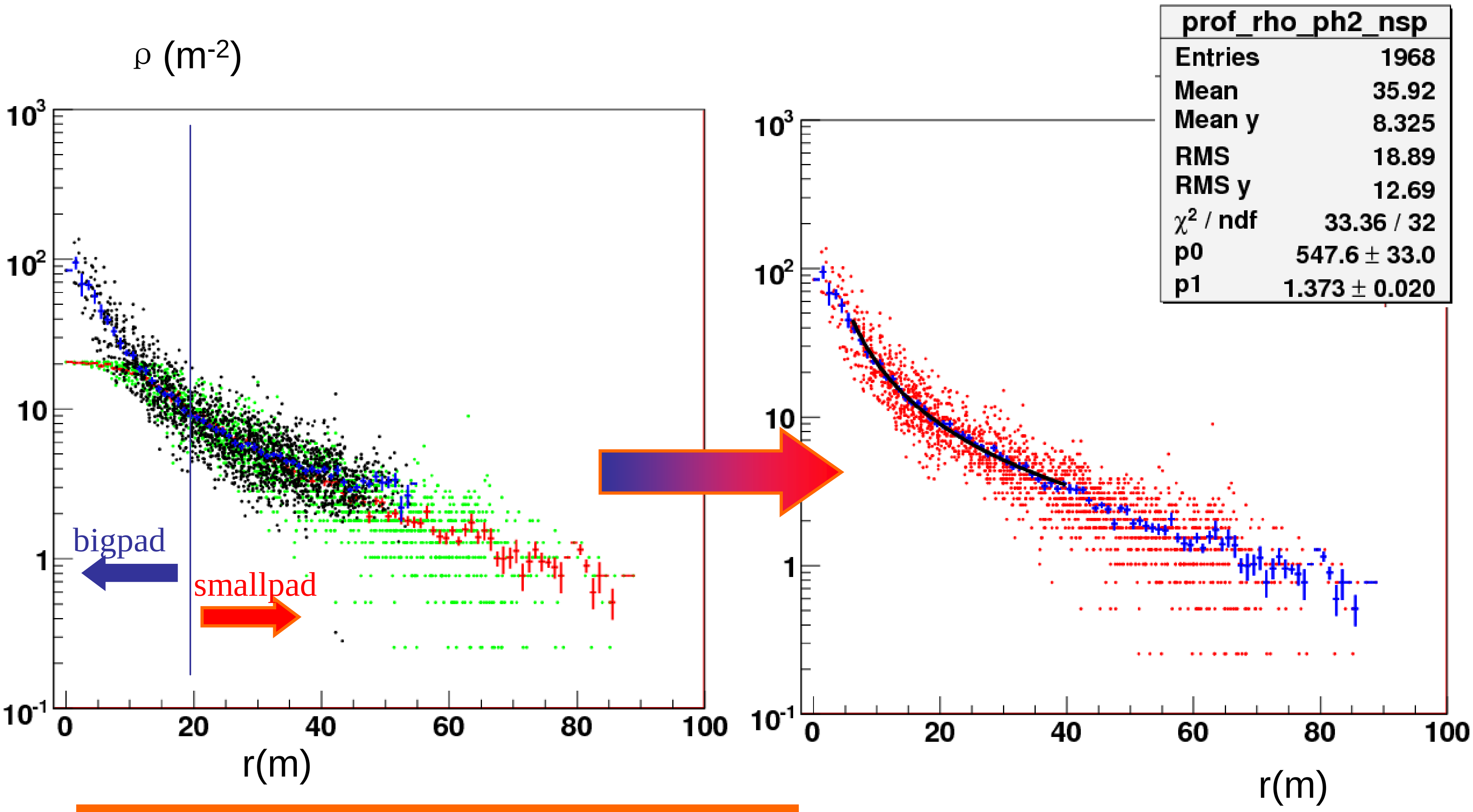




Big-Pad 3-D view

Shower structure and LDF near the core much better studied without saturation by the charge readout system

Lateral density distribution of showers



lateral distribution: NKG function

$$\rho(r) = C(s)\frac{N_e}{r_M^2}\left(\frac{r}{r_M}\right)^{s-2}\left(1+\frac{r}{r_M}\right)^{s-4.5}$$

$$\longrightarrow \quad \rho(r) = p_1 \cdot r^{p_2}$$

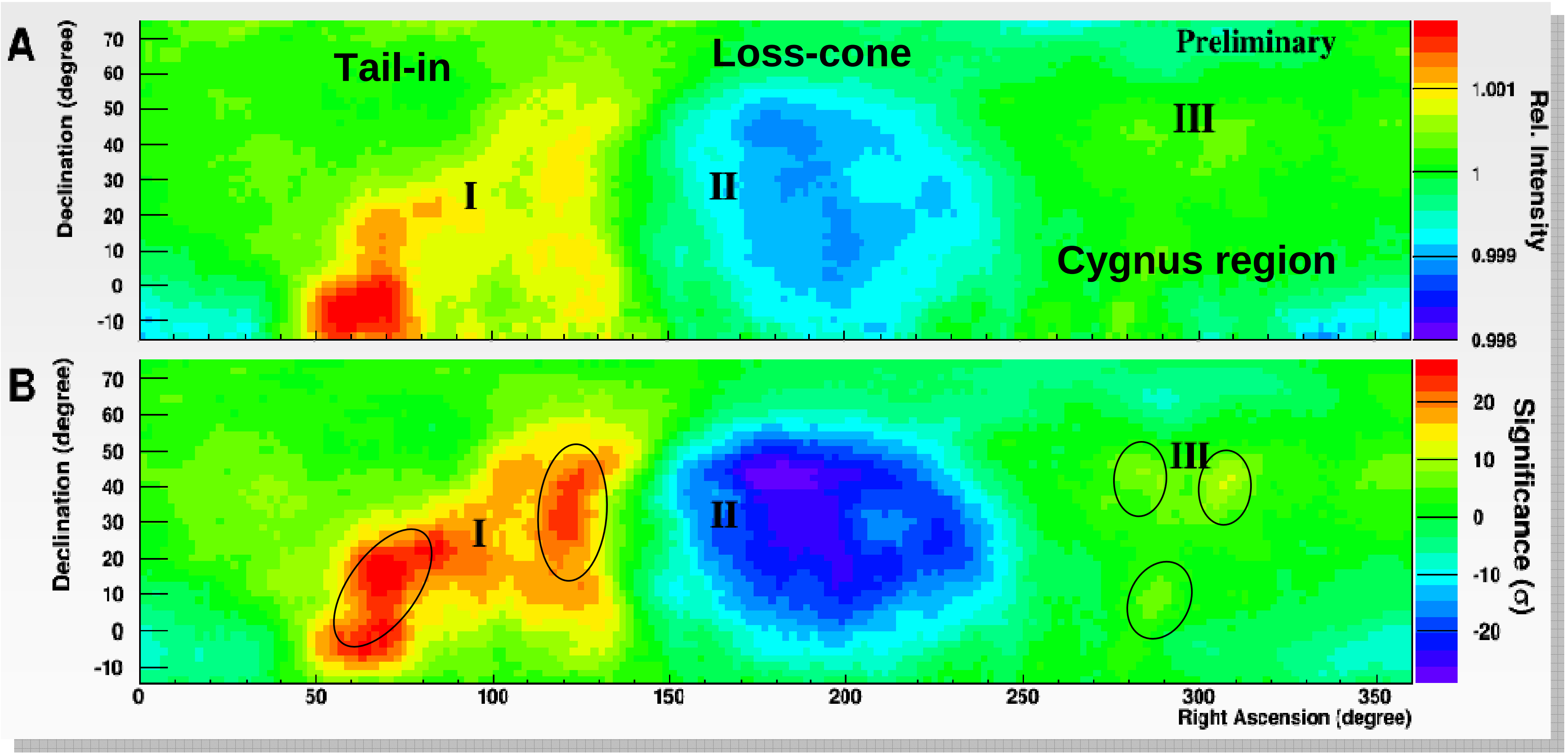
→ **Possible correlation with Xmax ...**

Cosmic ray anisotropy

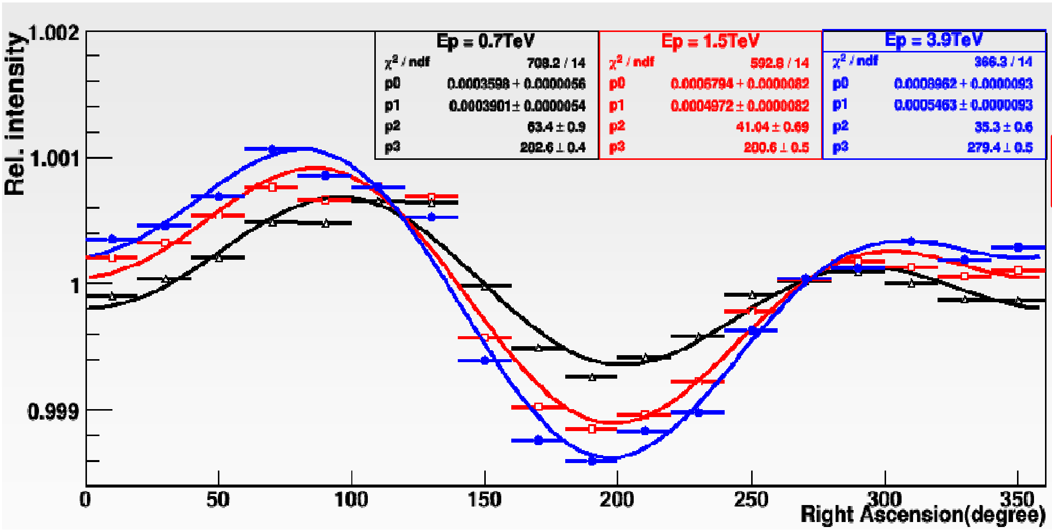
ARGO-YBJ detector is able to observe cosmic radiation anisotropies in all scales (both large and intermediate), at ~TeV energies

CR large scale anisotropy

ARGO-YBJ DATA: 2008 and 2009



1D CR anisotropy for different energies



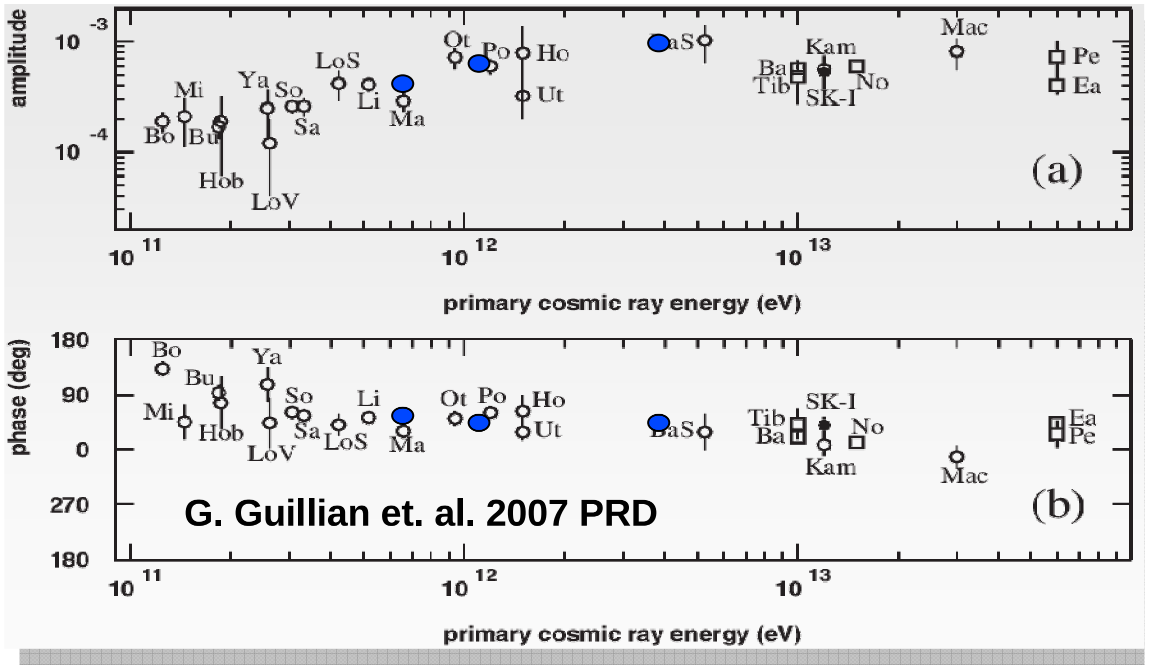
Fit function:

$$1 + A_1 cos(2\pi(x-\phi_1)/360) + A_2 cos(2\pi(x-\phi_2)/180)$$

0.7 TeV

1.5 TeV

3.9 TeV



Agree with diffusion model: larger amplitude for higher energy (Candia J. et al, 2003)

Intermediate scale anisotropy

Data set: 584 days

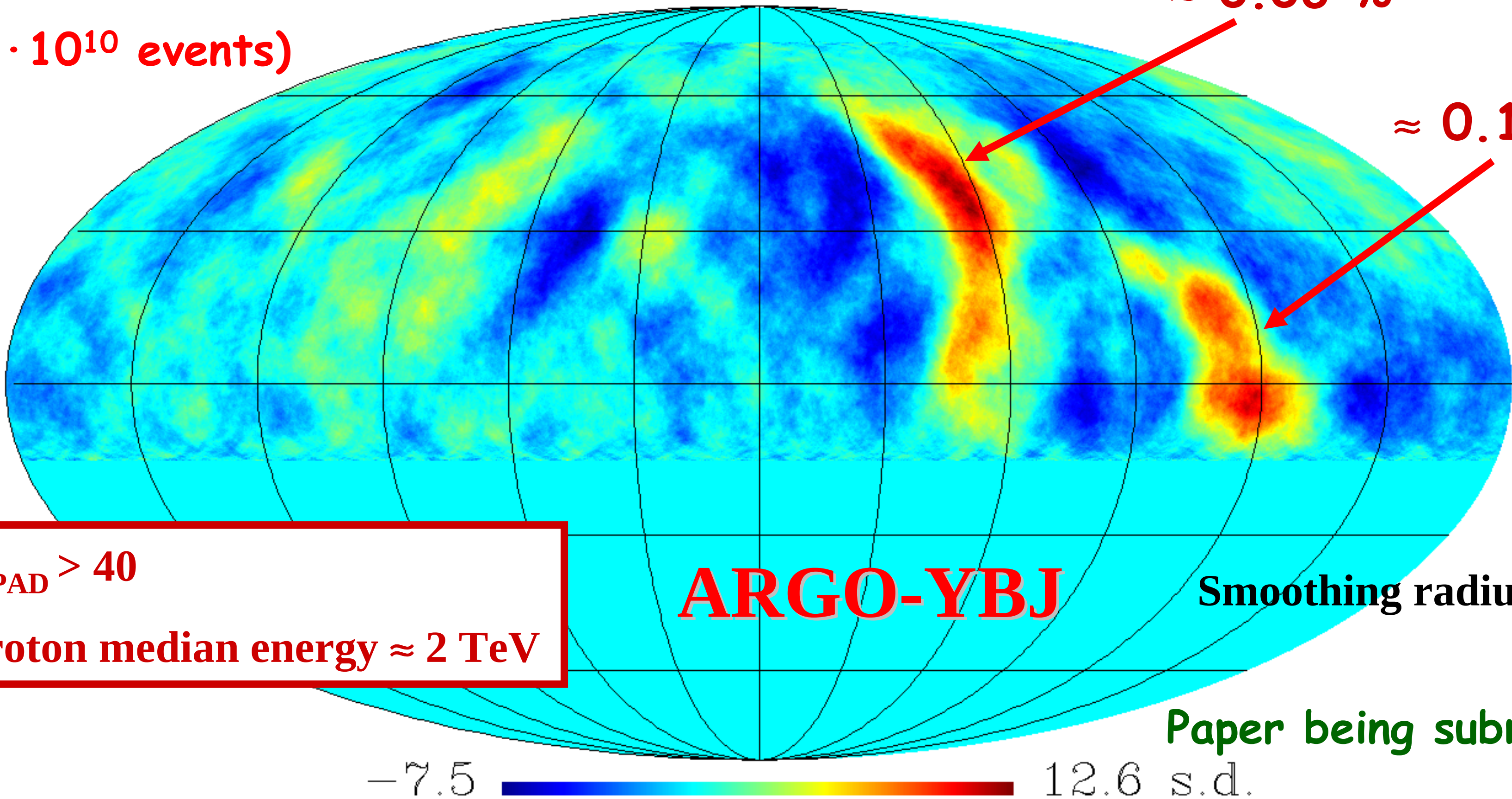
(2007 Dec – 2009 Nov)

($9 \cdot 10^{10}$ events)

CR excesses

≈ 0.06 %

≈ 0.1%



$N_{PAD} > 40$

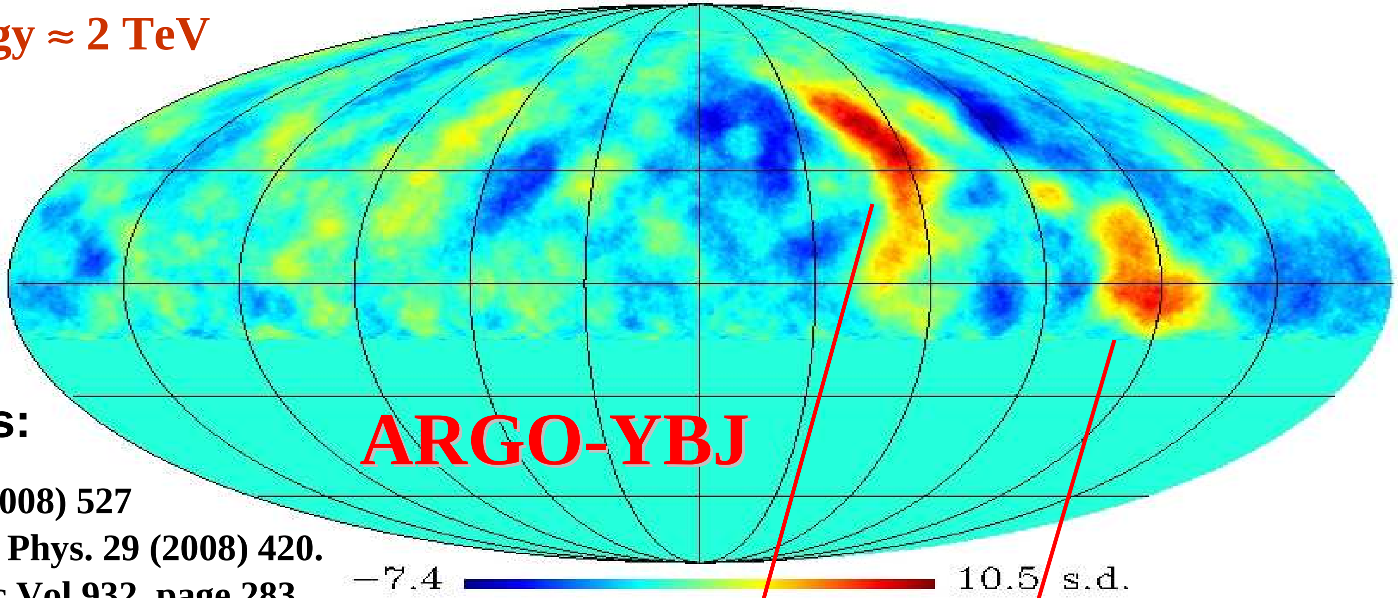
Proton median energy ≈ 2 TeV

ARGO-YBJ

Smoothing radius = 5°

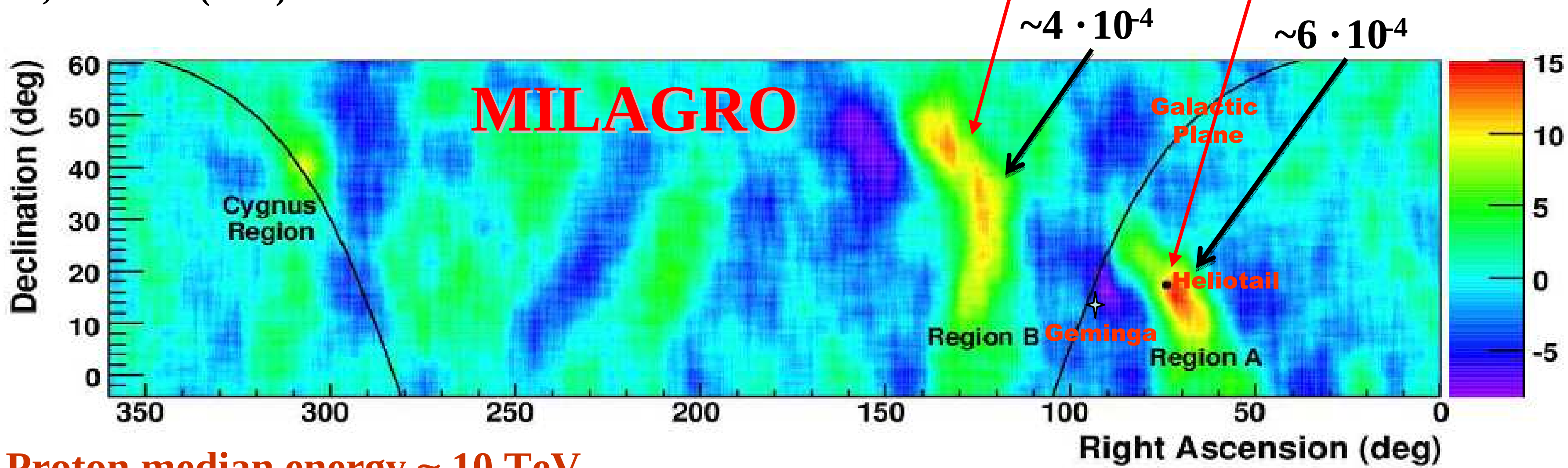
Paper being submitted

Proton median energy ≈ 2 TeV



Several explanations:

Salvati & Sacco, A&A 485 (2008) 527
Drury & Aharonian, Astrop. Phys. 29 (2008) 420.
K. Munakata ,AIP Conf Proc Vol 932, page 283
Salvati, A&A 513 (2010) A28



Proton median energy ≈ 10 TeV

Conclusions

- ✓ ARGO-YBJ detector (central carpet + guard ring) is taking data since November 2007 (duty-cycle > 90%, 3.6 kHz rate)

- ✓ Very detailed shower structure imaging, also thanks to the analog charge readout system

- ✓ Angular resolution as expected (Moon shadow)

- ✓ Several results from Cosmic Rays:

  - ❑ p-p cross section
  - ❑ Limit on antiproton flux
  - ❑ First measurement of CR light-component spectrum
  - ❑ Large and intermediate scale anisotropies