Cosmic Ray Physics with ARGO-YBJ

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On behalf of the ARGO-YBJ Collaboration

4th Workshop on Air Shower Detection at High Altitude
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The ARGO-YBJ experiment

High Altitude Cosmic Ray Observatory @ YangBaJing,Tibet, China

Site Altitude: 4,300 m a.s.l. , ~ 600 g/cm^2

ARGO-YBJ physics goals

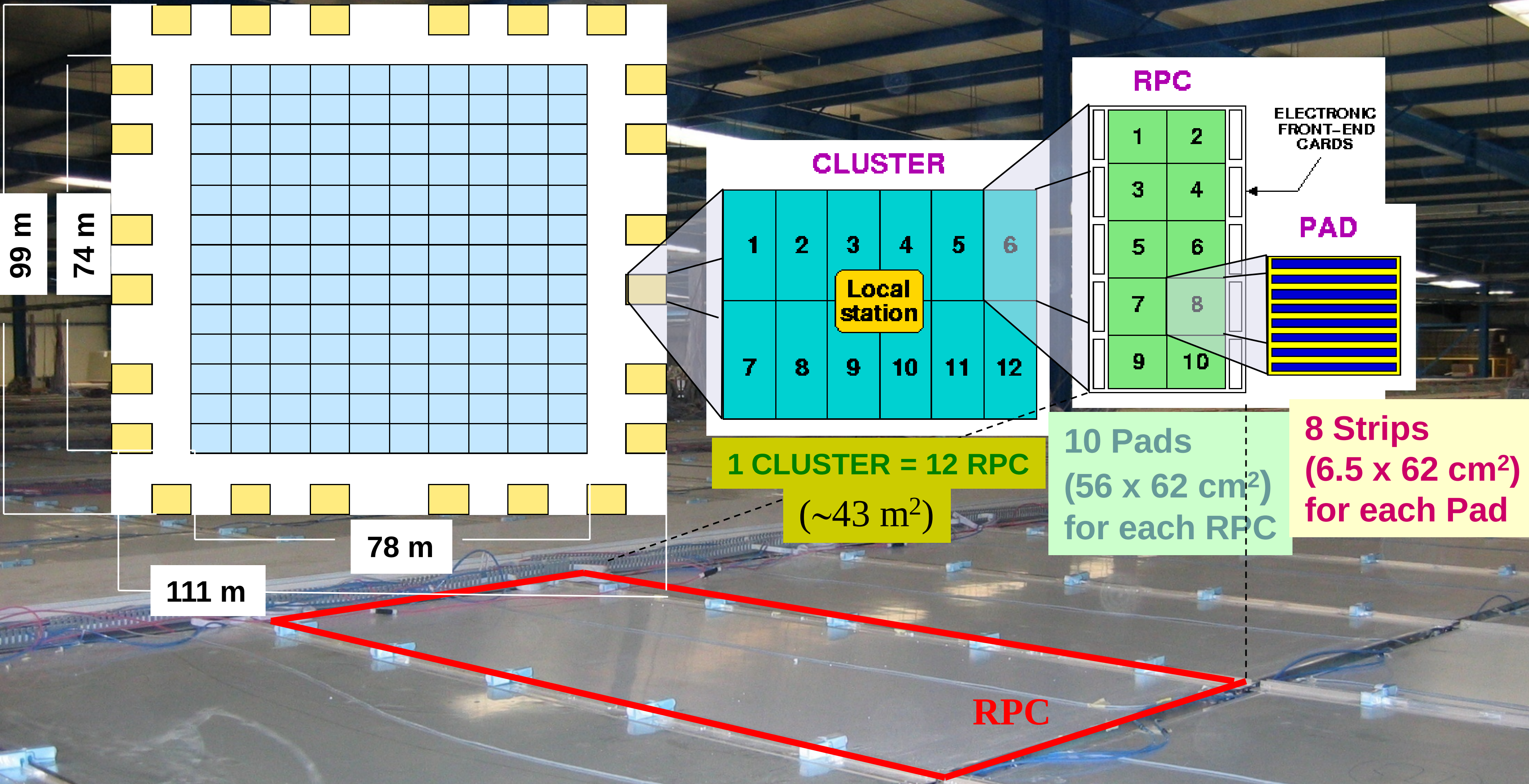
- **VHE γ-Ray Astronomy**: (see S. Vernetto's talk)
  (search for)/(study of) point-like (and diffuse) galactic and extra-galactic sources with few hundreds GeV energy threshold

- **Cosmic ray physics**:
  energy spectrum and composition (E_{th} few TeV),
  study of the shower space-time structure,
  flux anisotropies at different angular scales
  p-Air cross section measurement and hadronic interaction studies
  anti-p / p ratio at TeV energies,
  geomagnetic effects
  …..
- **Search for GRB's** (full GeV / TeV energy range)
- **…**

through the…

Observation of *Extensive Air Showers* produced in the atmosphere by primary γ's and nuclei

The ARGO-YBJ detector



Strip counting

Pad = space-time pixel

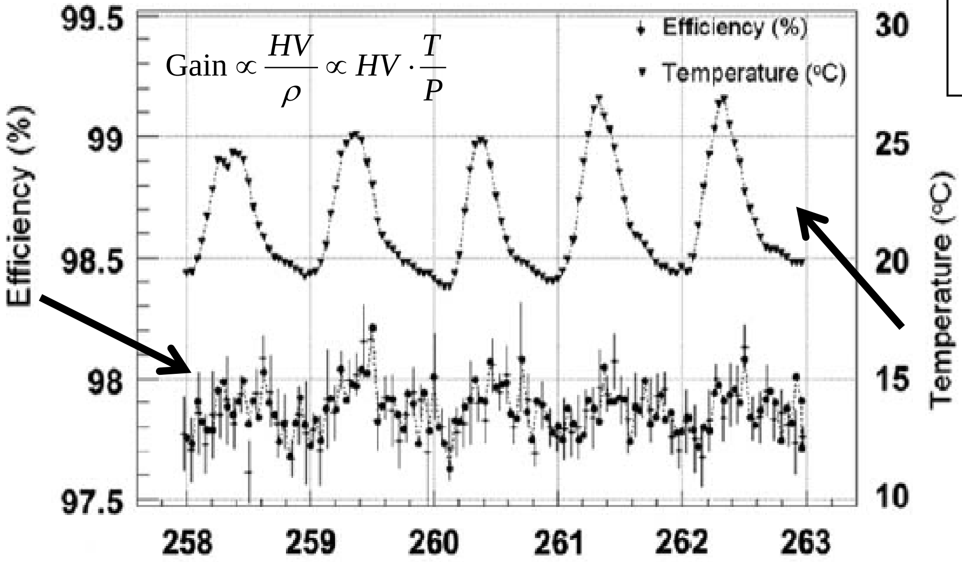
Time resolution ~1.7 ns

+ Analog charge read-out on “Big Pads”

RPC performance

ARGO-YBJ coll., NIM A (2009) 246

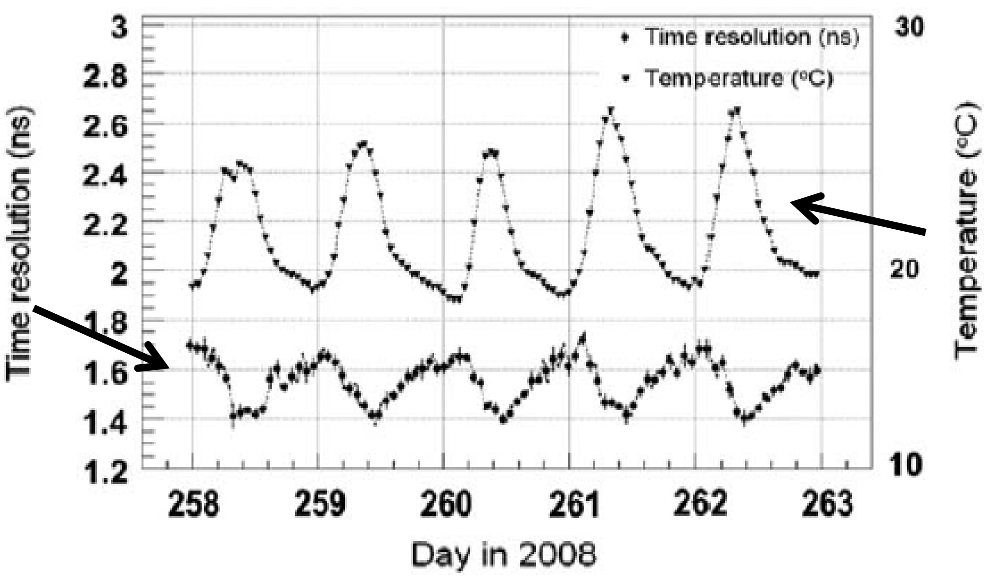
$C_2H_2F_4$ / Ar / i-C_4H_{10}
75 / 15 /10 %
7.2kV applied to 2mm gas gap
Streamer mode

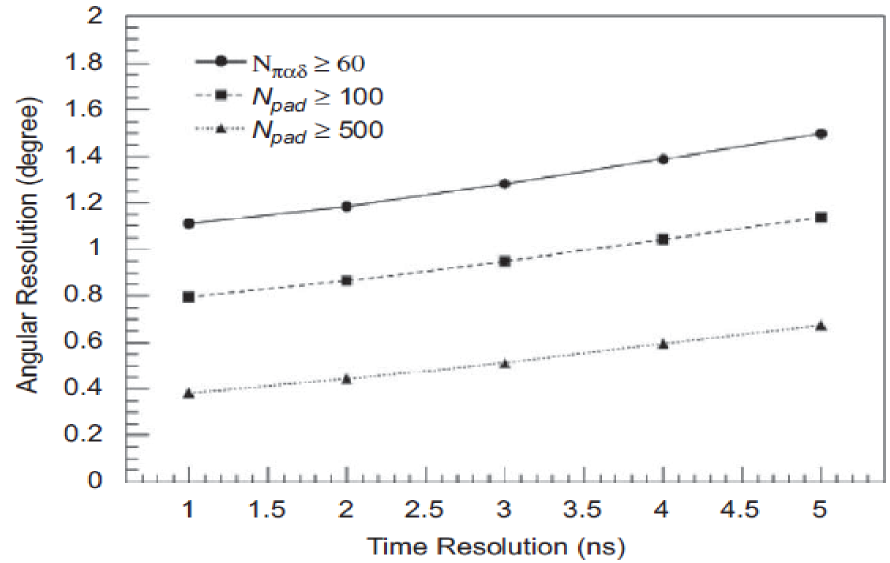


Continuous RPC monitoring.
Small efficiency and time resolution drifts with temperature:

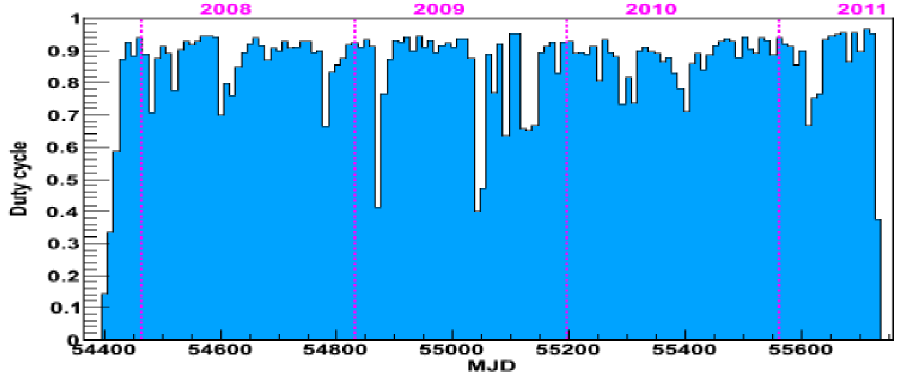
- 0.03% / °C
- 0.04 ns / °C

Angular resolution substantially unaffected





EAS reconstruction

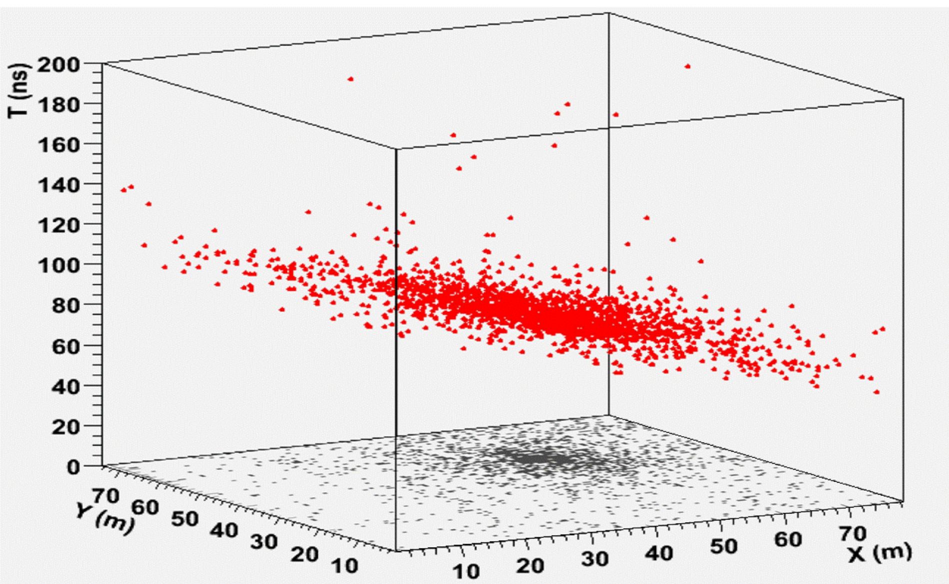


Event Rate ~ 3.5 kHz for N_{hit} >20 - Duty cycle ~ 86% - 10^{11} evts/yr – 100TB/yr

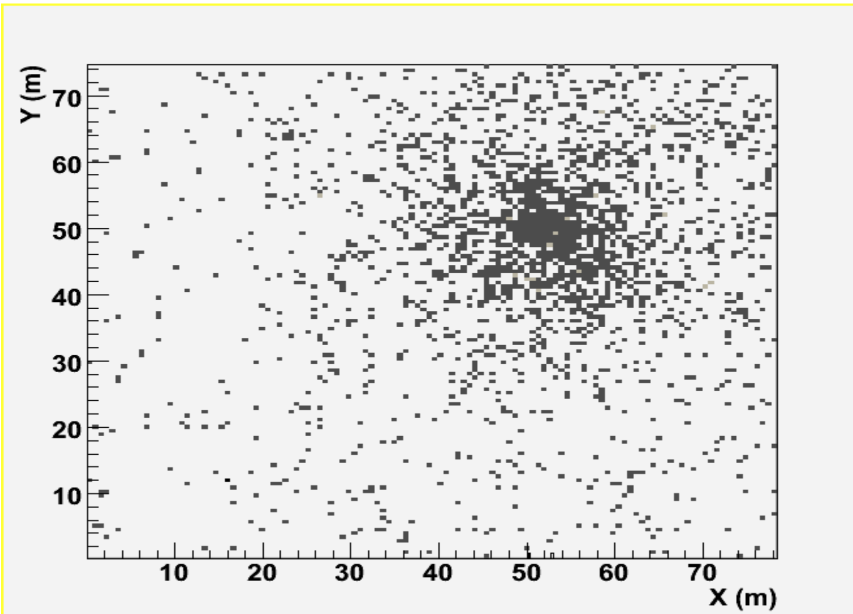
High space/time granularity
+ Full coverage
+ High altitude

→

detailed study on the EAS space/time structure with unique capabilities

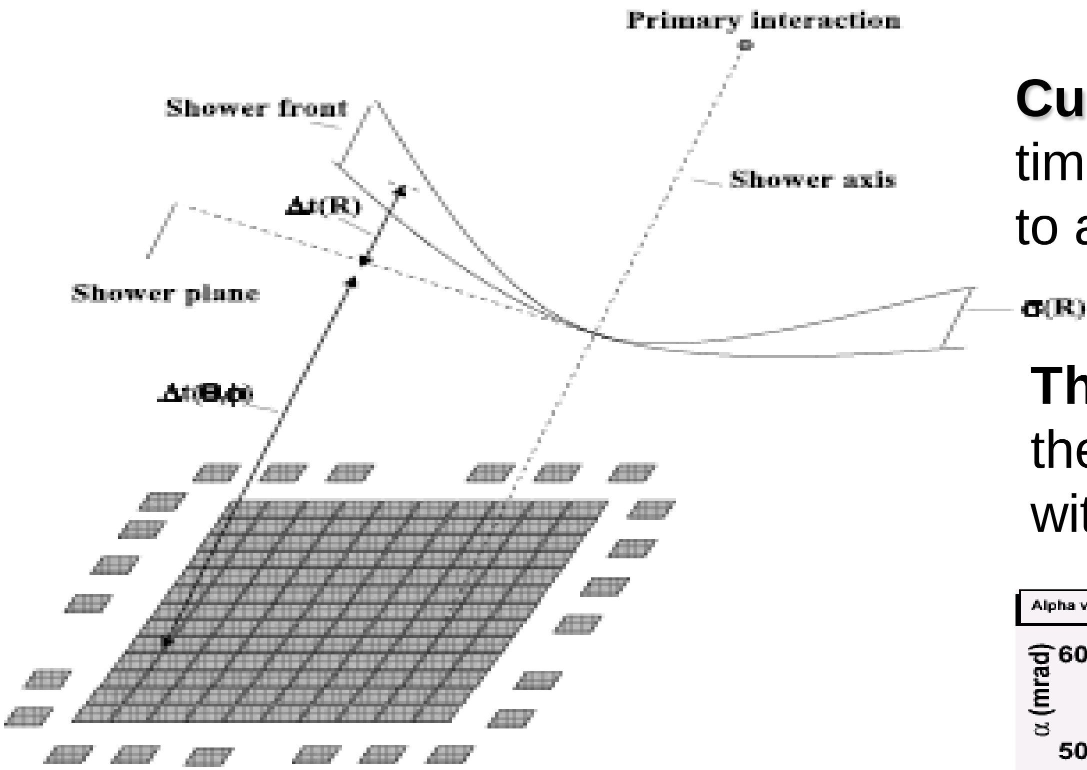


3-D view of a detected shower



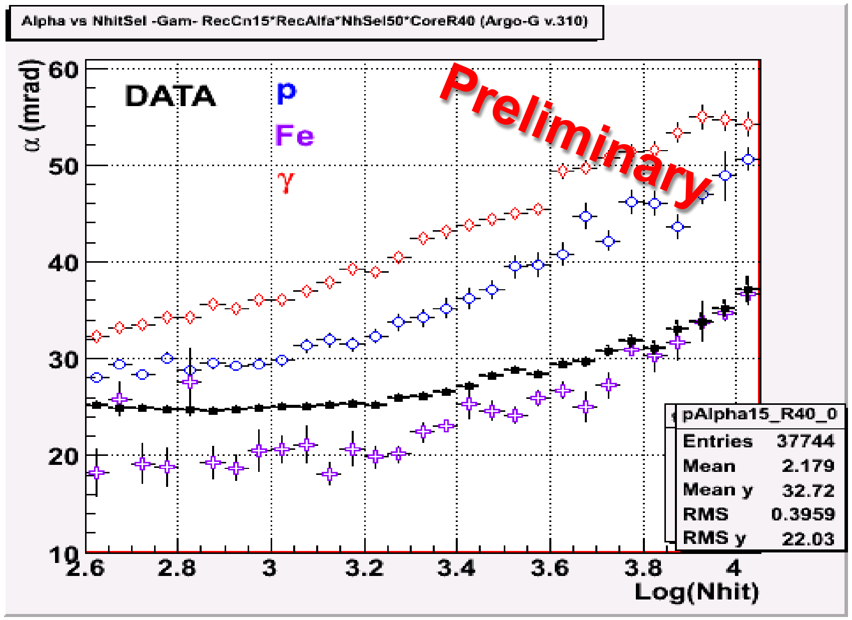
Top view of the same shower

Shower front time structure



Curvature:
time residuals **Δt(R)** with respect to a **planar fit**

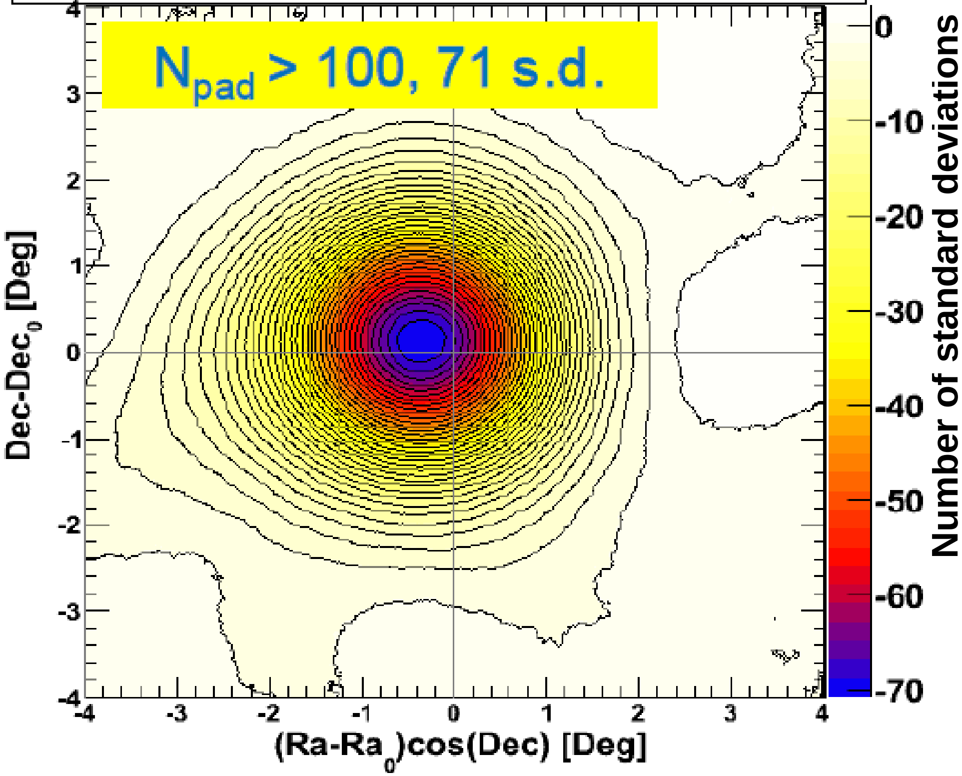
Thickness:
the RMS of time residuals **σ(R)** with respect to a **conical fit**

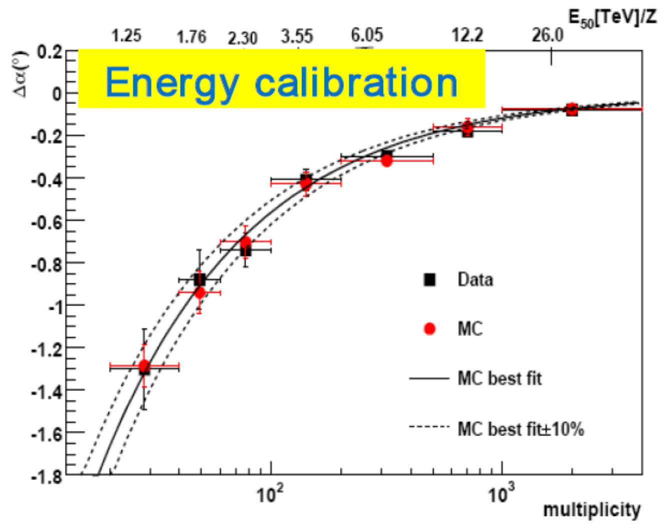


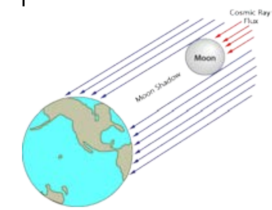
Conicity parameter α:
Give useful information on
shower age and/or primary mass

The Moon Shadow and the antip/p ratio

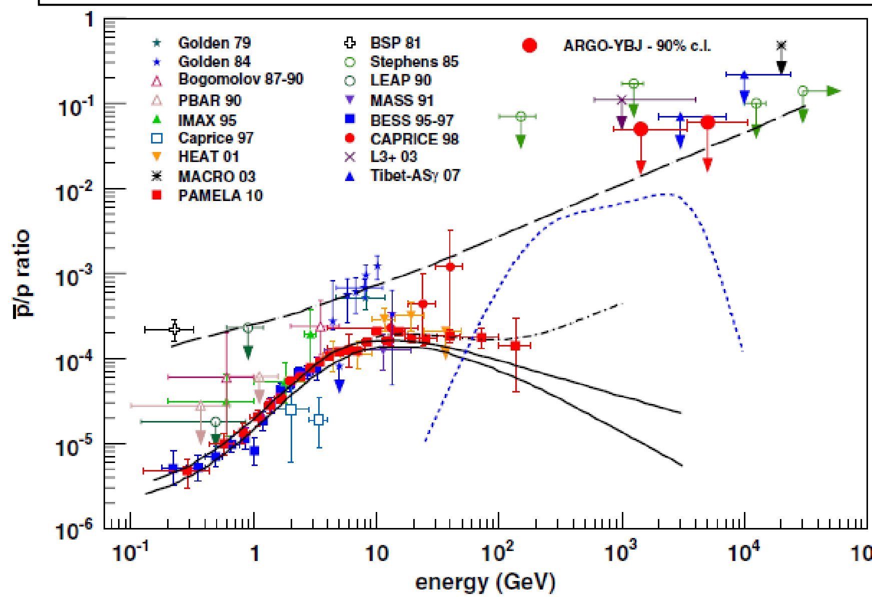
ARGO-YBJ coll., PRD 84 (2011) 022003







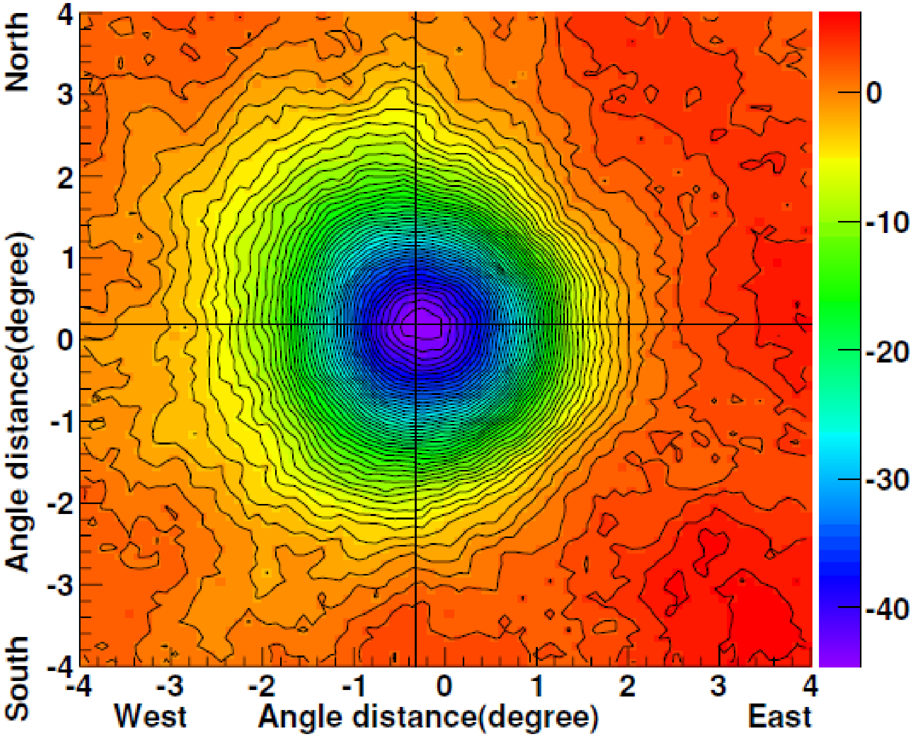
ARGO-YBJ coll., PRD 85 (2012) 022003

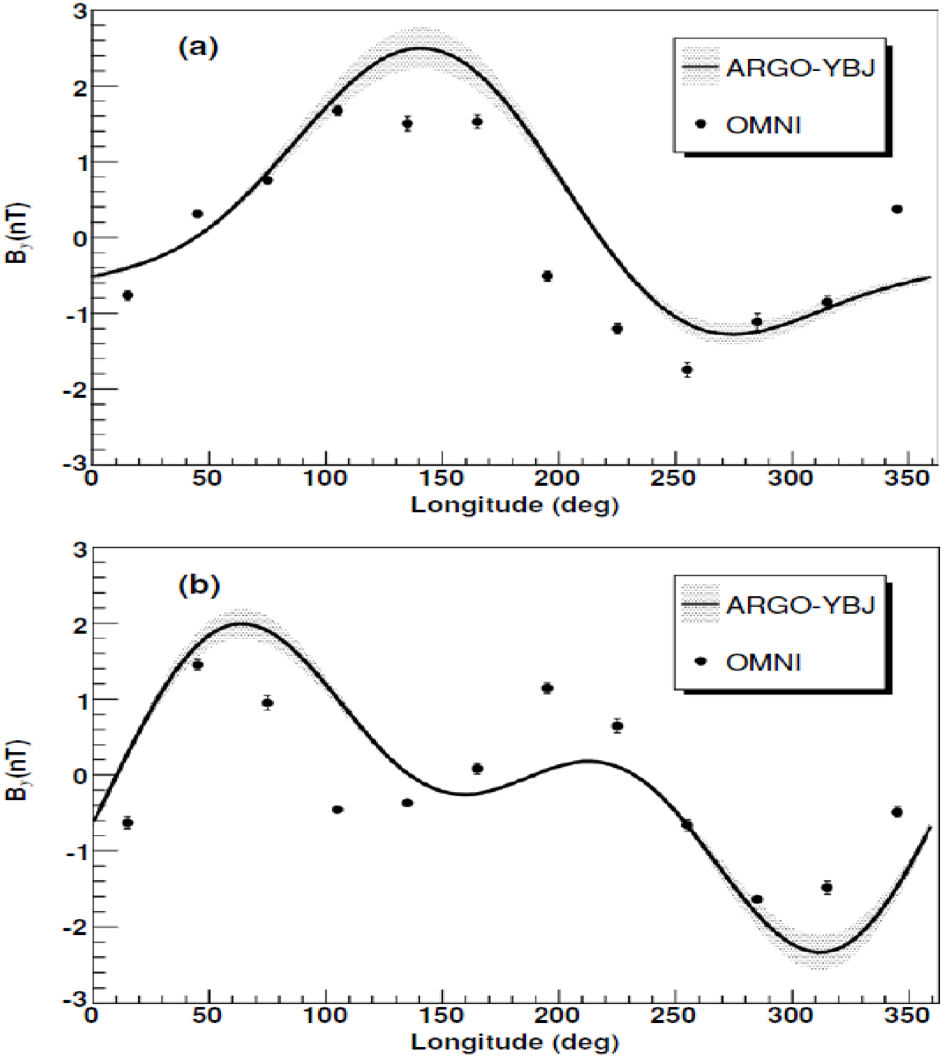


- Size of the deficit ⇒ **angular resolution**
- Position ⇒ **pointing accuracy**
- West displacement ⇒ **Energy calibration** (Geomagnetic bending ≈ 1.57° / E (TeV))
- **Antiprotons** should give a shadow on the opposite side ⇒ **Upper limit**

The Sun Shadow and the Inetplanetary Magnetic Field

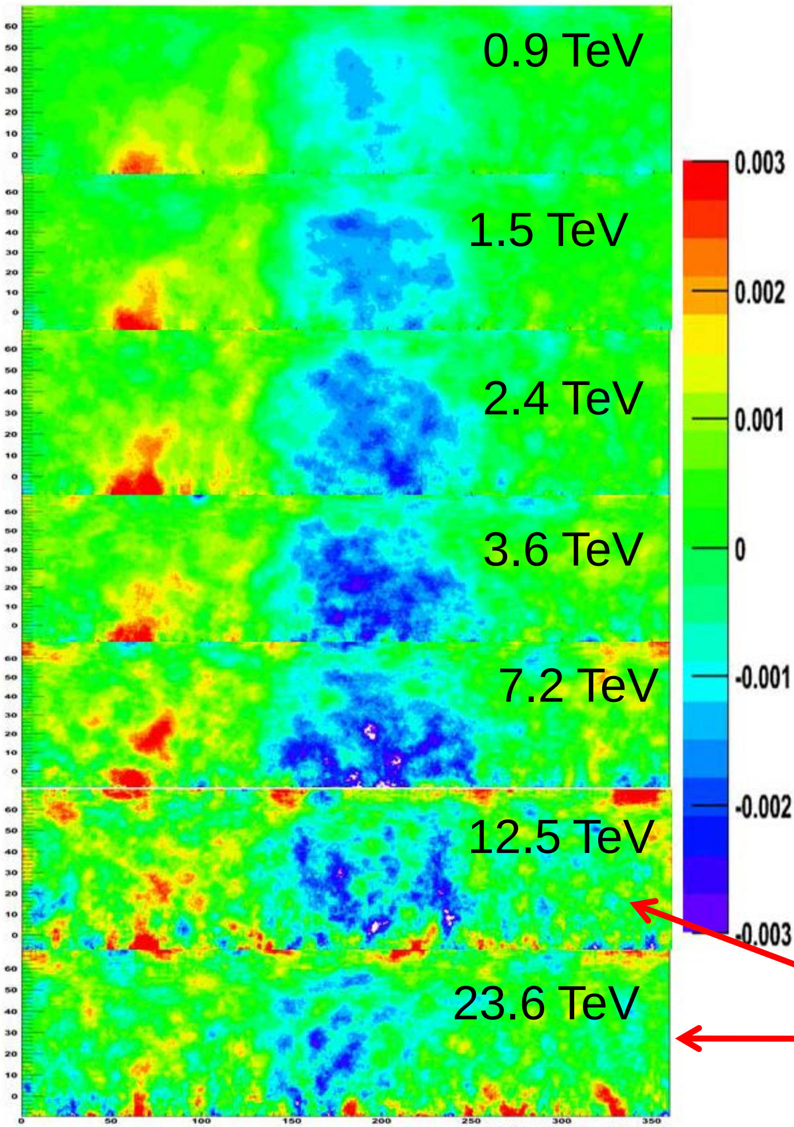
ARGO-YBJ coll., APJ 729 (2011) 113

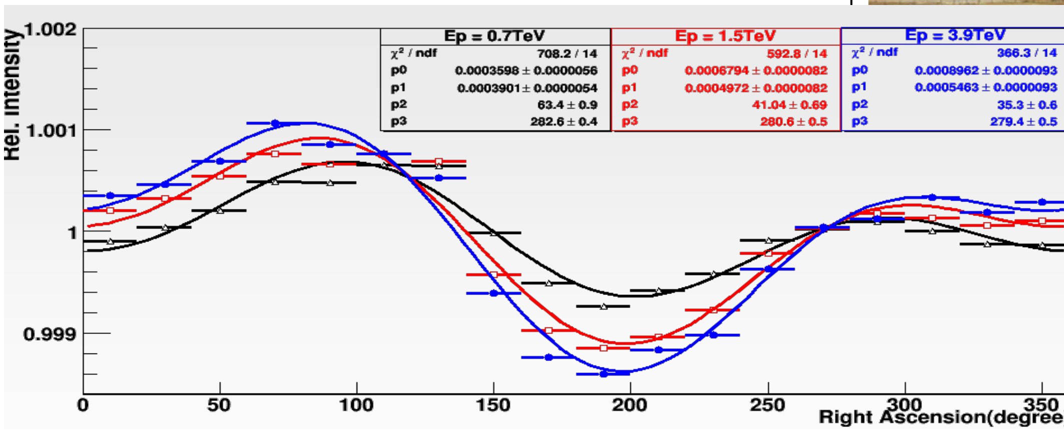




Sun shadow data are useful for an indirect measurement of the IMF caried by the solar wind near the Earth.
In agreement with the OMNI spacecraft data repository (NASA).

Large scale anisotropy (LSA)



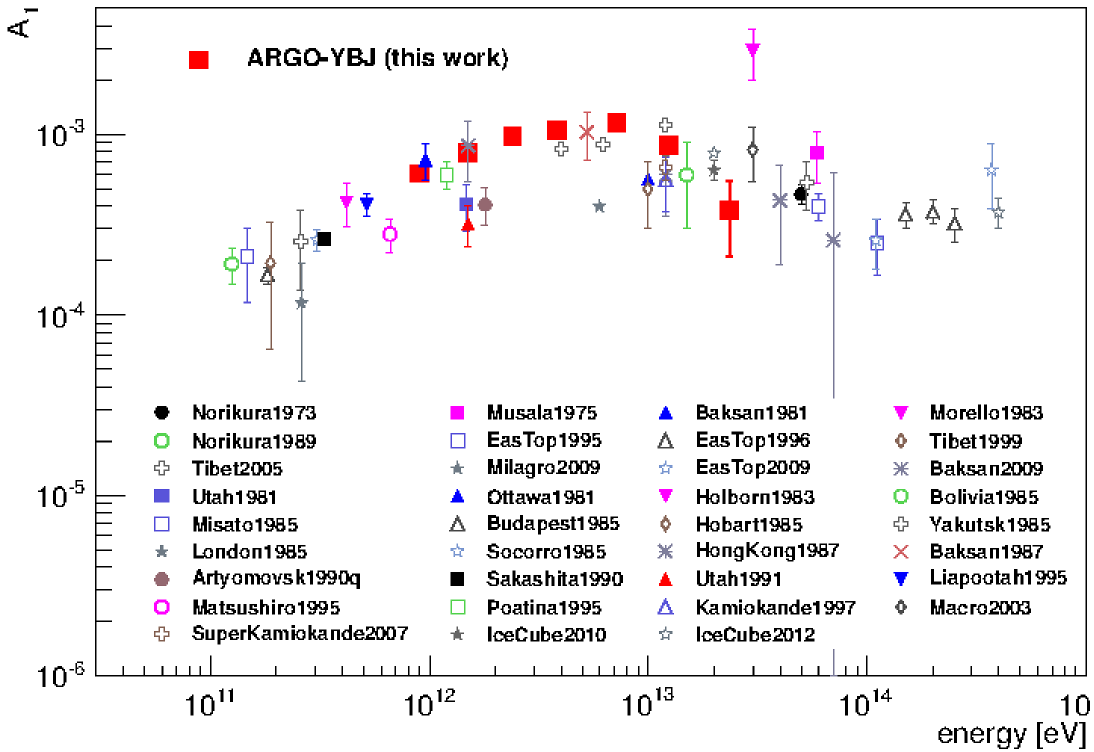


$$1 + A_1 cos(2\pi(x-\phi_1)/360) + A_2 cos(2\pi(x-\phi_2)/180)$$

First measurement with an EAS array in an energy region so far investigated only by underground muon detectors

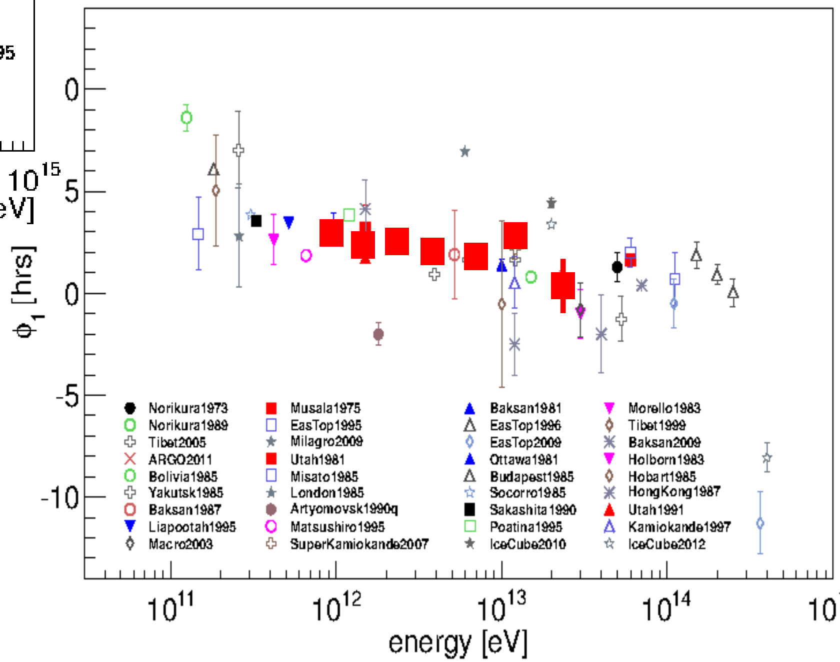
Structures appear to dissolve to smaller angular scale at high energy.

LSA First harmonic amplitude and phase



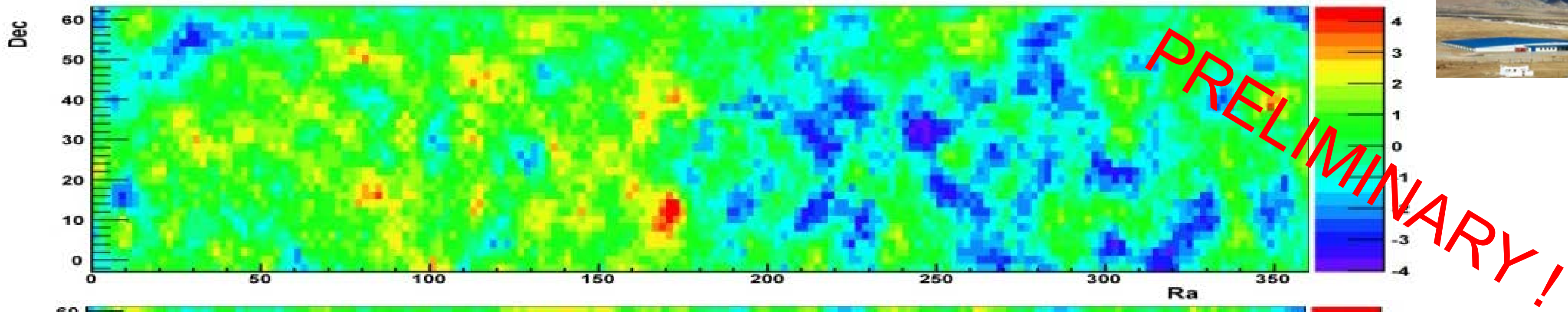
Measurement covering either the rise and the fall of the signal

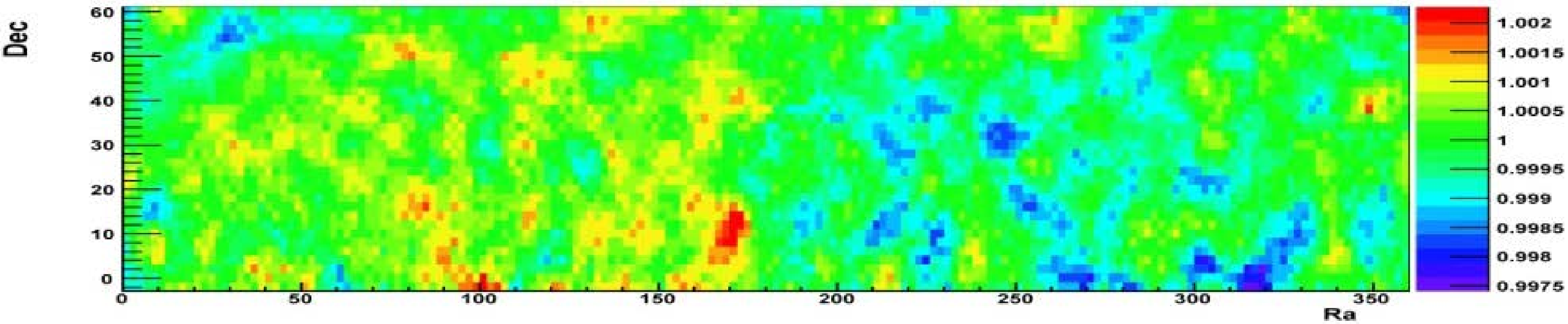
Uniform phase decrease



The Compton-Getting effect (in solar time)

Expected CR anisotropy due to Earth's orbital motion around the Sun

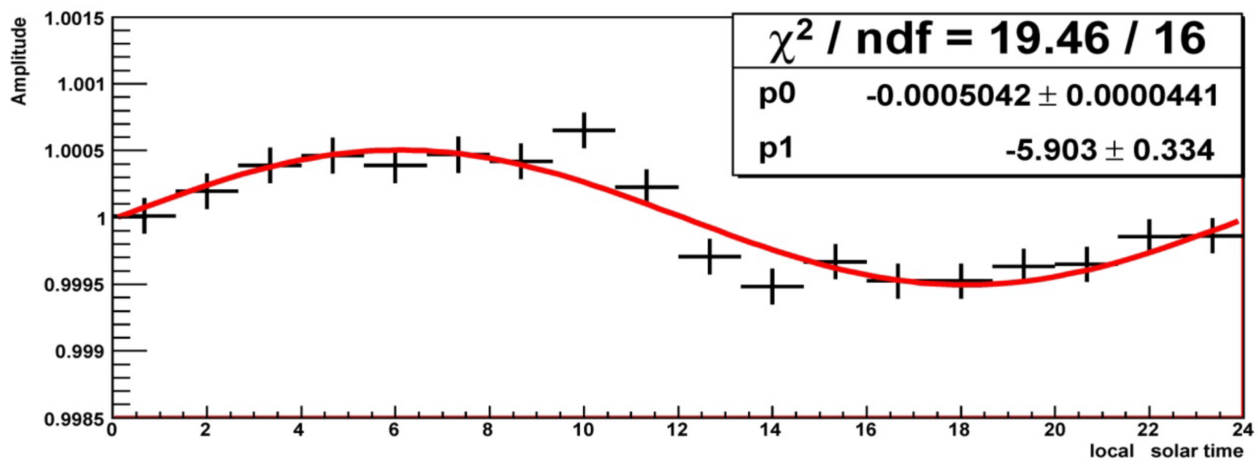




2008 – 2009

Nhit ≥ 500 → ≈ 8 TeV

to avoid solar effects on low energy CRs



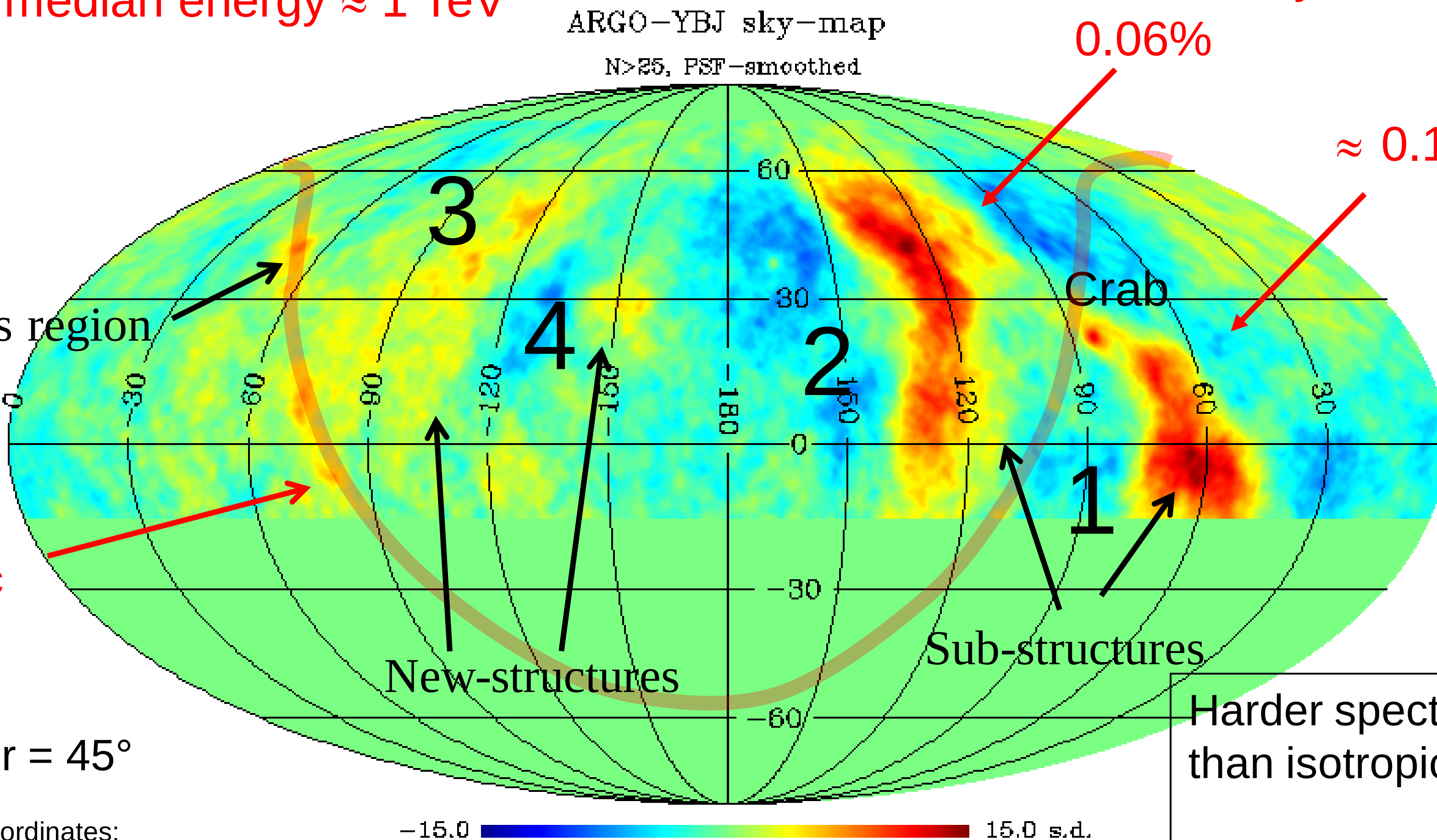
Medium Scale Anisotropy (MSA)

Map smoothed with the detector PSF for CRs

Proton median energy ≈ 1 TeV

Cosmic rays excess ≈ 0.06%

≈ 0.1%



Galactic Plane

Δt = 3 hr = 45°

Equatorial coordinates:
projection of the earth longitude and latitude

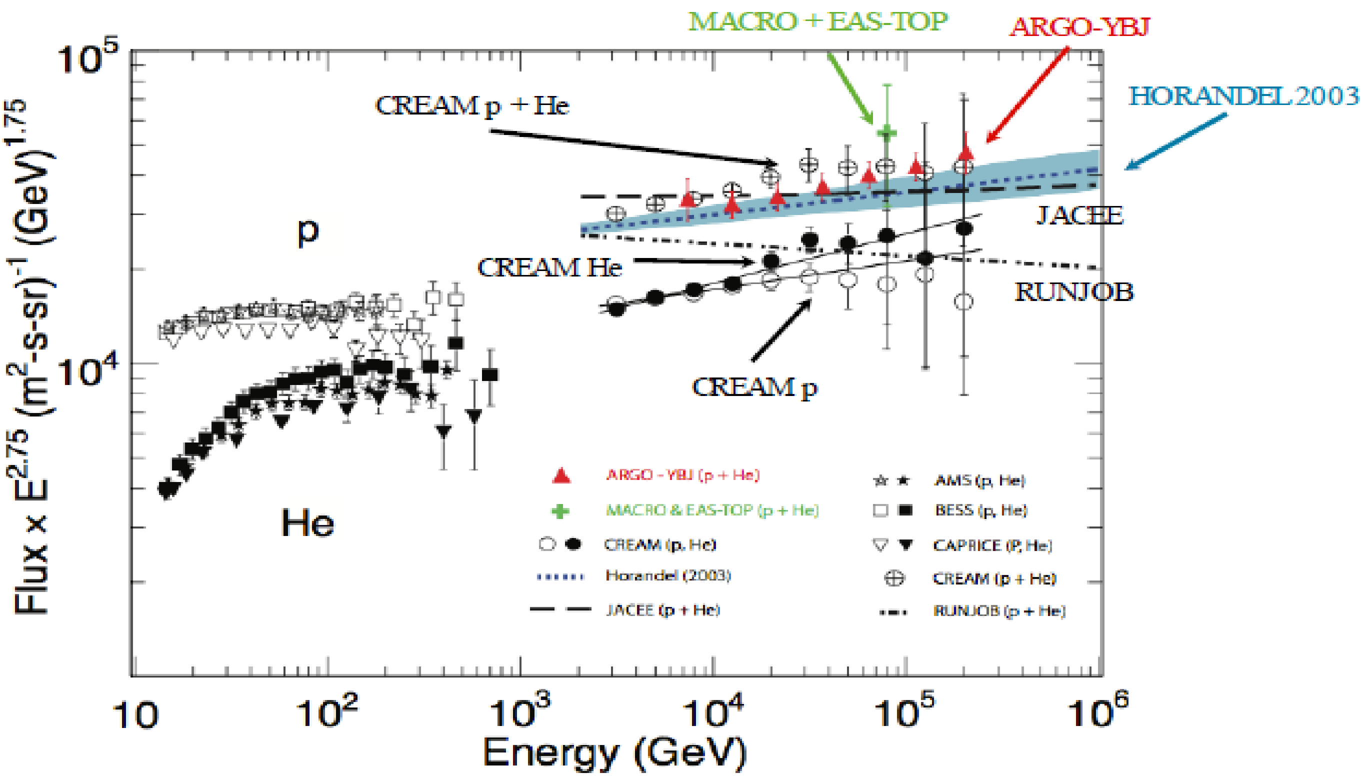
Harder spectra than isotropic CR

No evidence for time dependence

Light-component spectrum of CRs

Measurement of the *light-component* (p+He) spectrum of primary CRs in the energy region (5 – 250) TeV via a Bayesian unfolding procedure.

ARGO-YBJ coll., Phys. Rev D 85 (2012) 092005



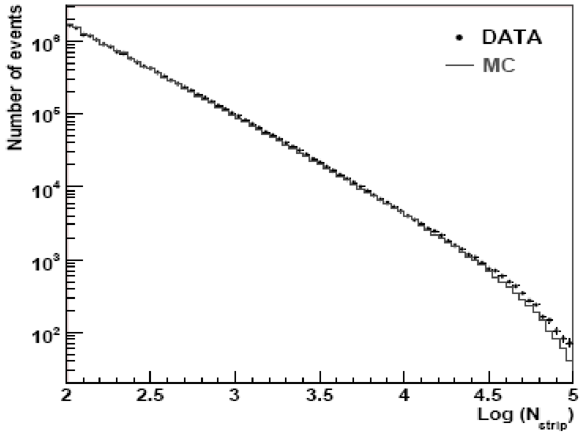
The contribution of heavier nuclei to the trigger is a few %

ARGO data agree with CREAM results

For the first time direct and ground-based measurements overlap for a wide energy range thus making possible the cross-calibration of the experiments.

Light-component spectrum of CRs

Extract the primary energy spectrum starting from the measured particle multiplicity spectrum at ground



$$P(M) = \frac{N(M)}{N_{tot}}$$

Choose an initial value for P(E)

$$P_0(E)$$

Use the Bayes theorem

$$P(E|M) = \frac{P(M|E)P(E)}{P(M)}$$

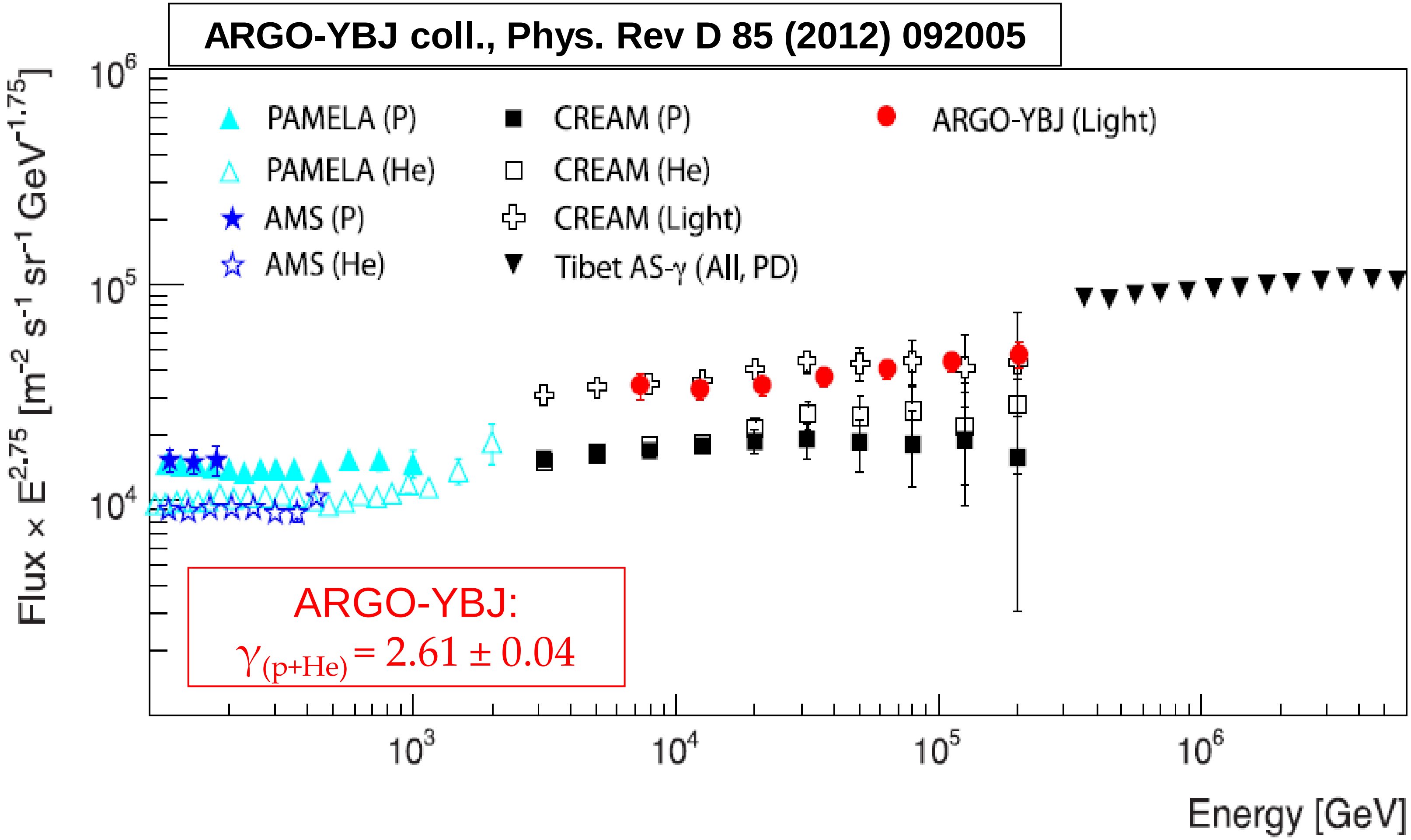
P(M|E) eval. from Monte Carlo events

$$N(E) = N(M)P(E|M)$$

$$P(E) = \frac{N(E)}{N_{tot}}$$

Iterate this procedure until variations on P(E) are neglegible

Light-component spectrum of CRs



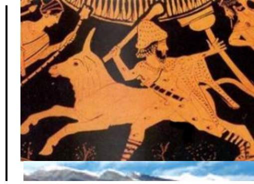
Two new approaches in order to extend the energy region up to few PeV, by using:

- The RPC analog readout

-Hybrid approach using the atmospheric Cerenkov detectors installed at YangBaJing

Both analysis are now in progress.

Measurement of p-air cross section



Use the shower frequency vs (secθ -1)

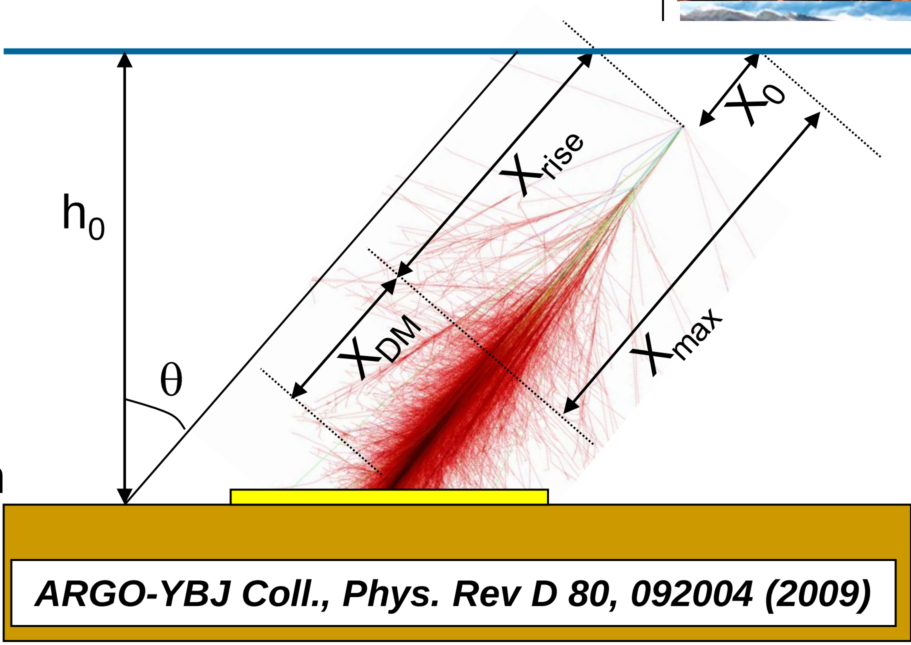
$$I(\theta) = I(0)\cdot e^{-\frac{h_o}{\Lambda}(\sec\theta - 1)}$$

for fixed energy and shower age.

The lenght Λ is connected to the p interaction lenght by the ralation **Λ = k λ_{int}** where k is determined by simulations and depends on:

- **hadronic interactions**
- **detector features and location (atm. depth)**
- **actual set of experimental observables**
- **analysis cuts**
- **energy, ...**

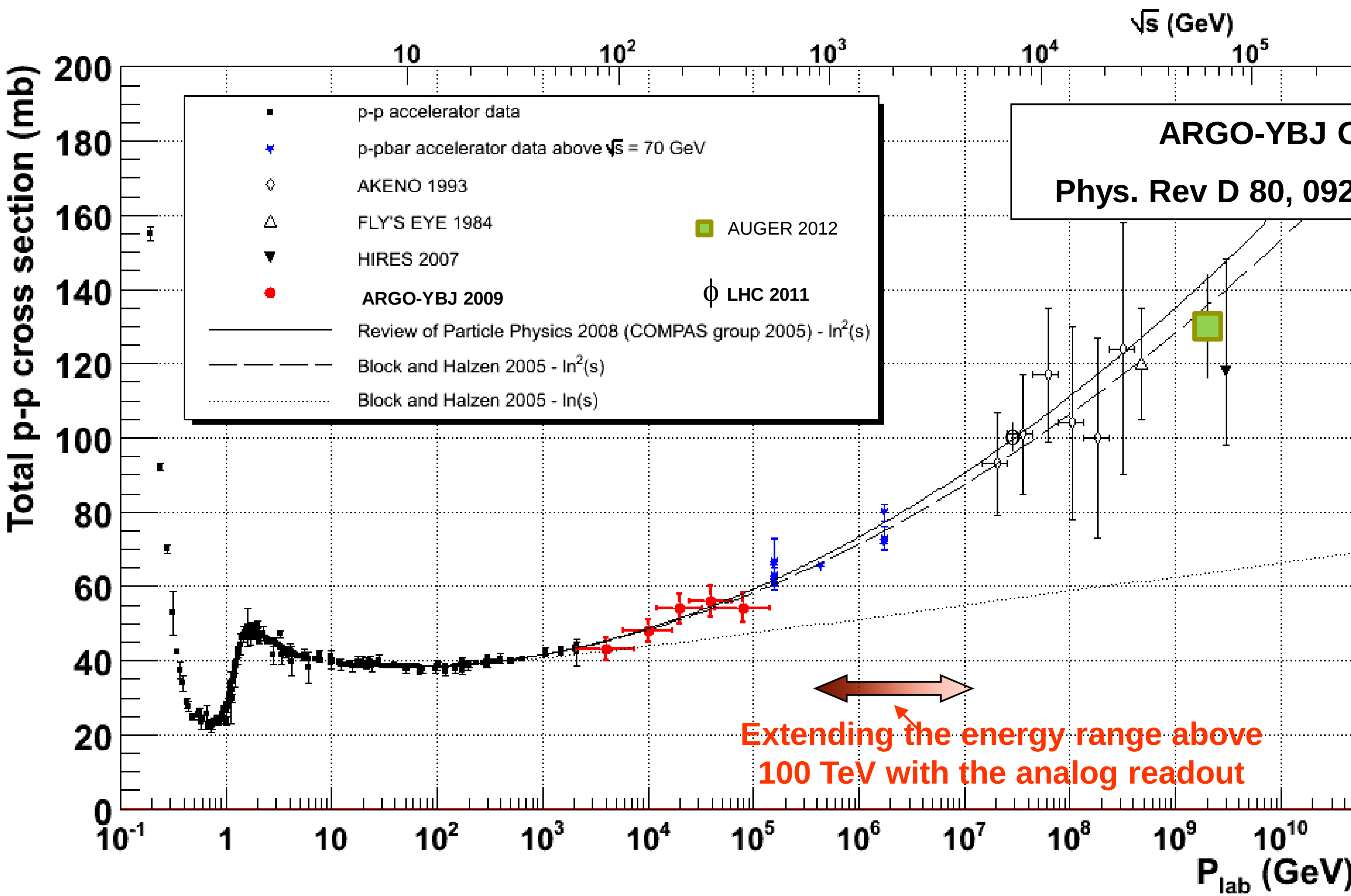
Then: **$\sigma_{p\text{-}Air}$ (mb) = 2.4 10^4 / λ_{int}(g/cm^2)**



ARGO-YBJ Coll., Phys. Rev D 80, 092004 (2009)

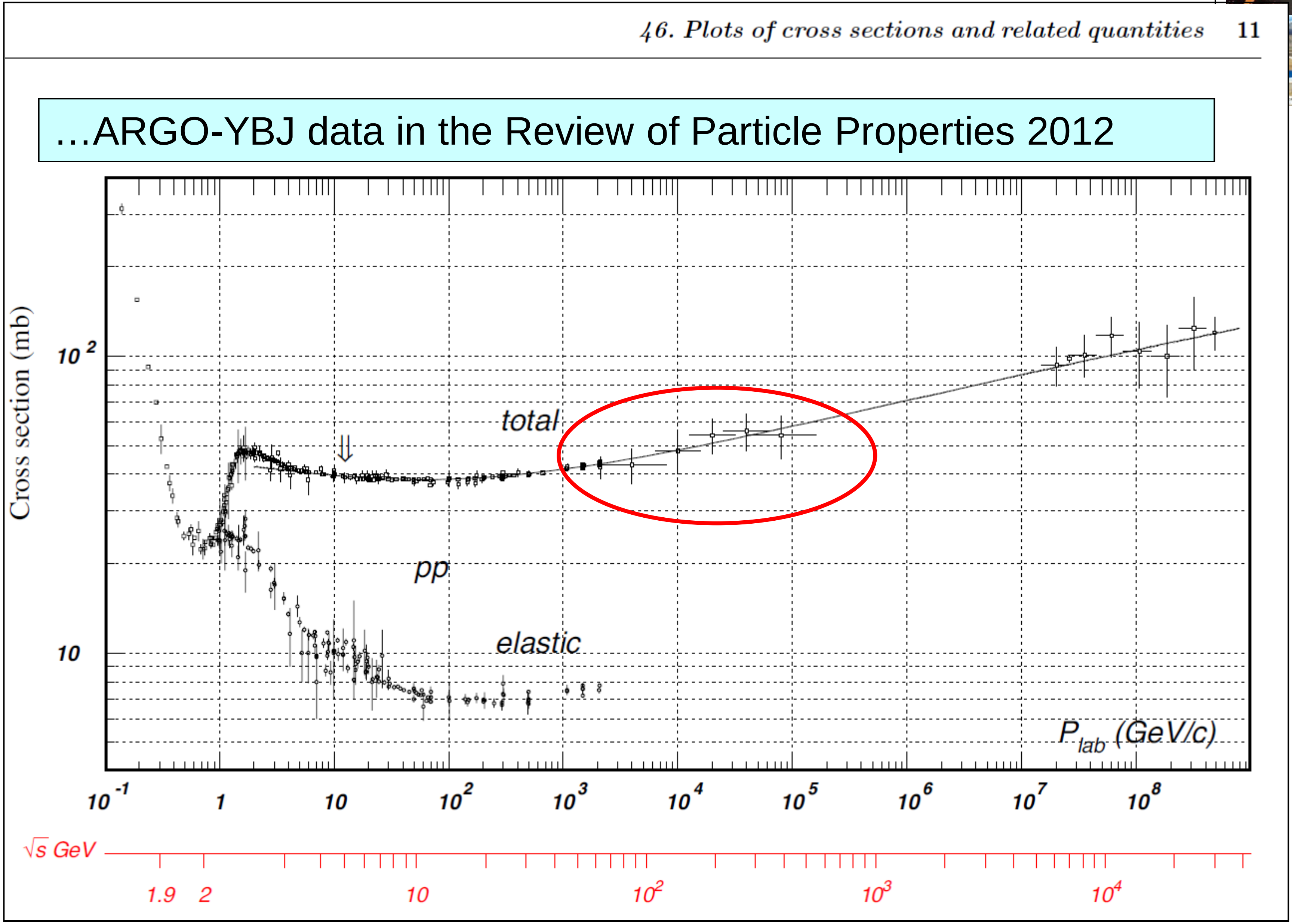
- **Constrain** $X_{DM} = X_{det} - X_{max}$
- **Select** deep showers (large X_{max}, i.e. small X_{DM}) to access exponential tail and reduce shower fluctuations → cut on Rs_{70} (strip concentration parameter)
- **Exploit** detector features (space-time pattern) and location (depth).

The total p-p cross section



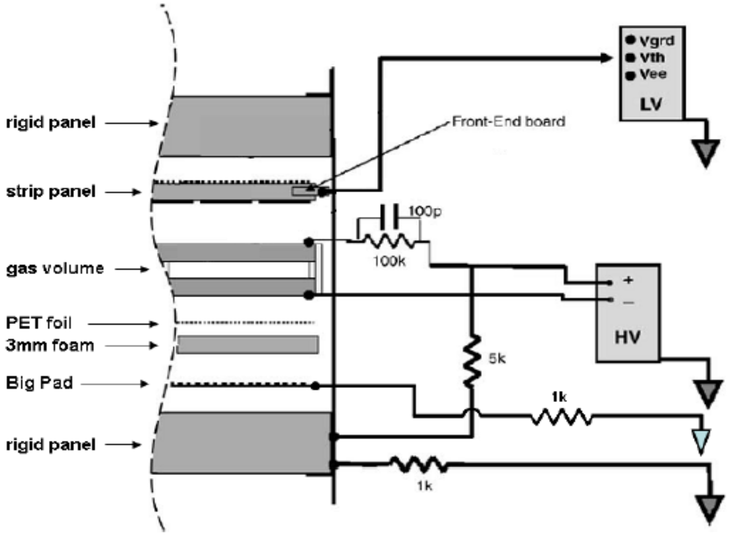
- Energy interval scarcely explored by p-p (and pbar-p) accelerator experiments
- The $\log^2(s)$ asymptotic behaviour is favoured

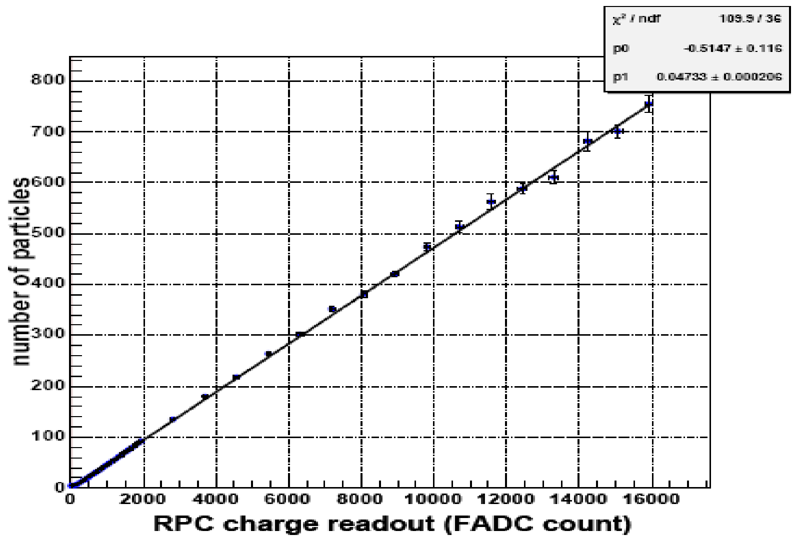
The total p-p cross section

The RPC analog readout

Readout of the charge signal on 1.39 × 1.23 m² "big pads" (two / RPC)





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

$$\rho_{\text{max-strip}} \approx 20 \text{particles} / \text{m}^2$$

$$\rho_{\text{max-analog}} \approx 10^4 \text{particles} / \text{m}^2$$

Intrinsic limit at about one particle per cm², due to space charge effects of the streamer discharge: the so called *dead zone.*

Calibration procedure

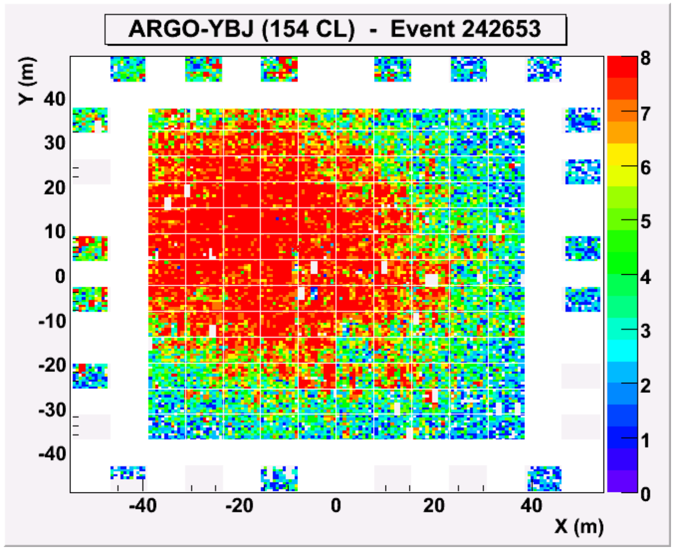
Correction for Pressure and Temperature effects

The RPC analog readout

Real event

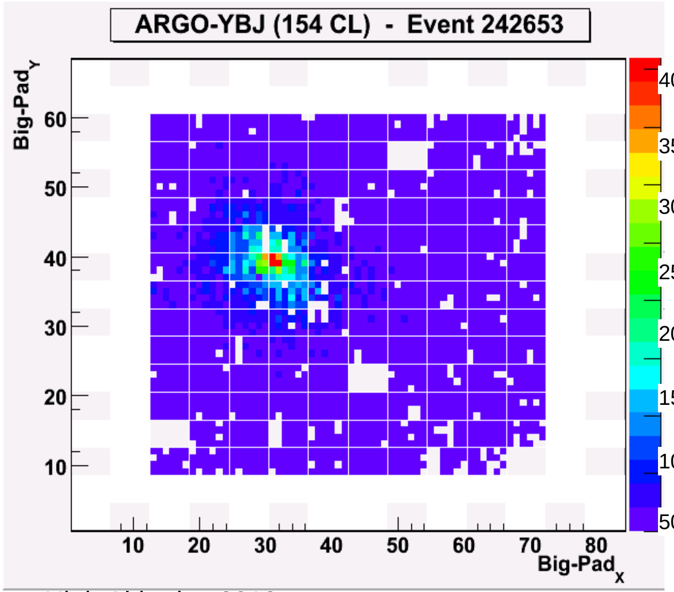
Strips

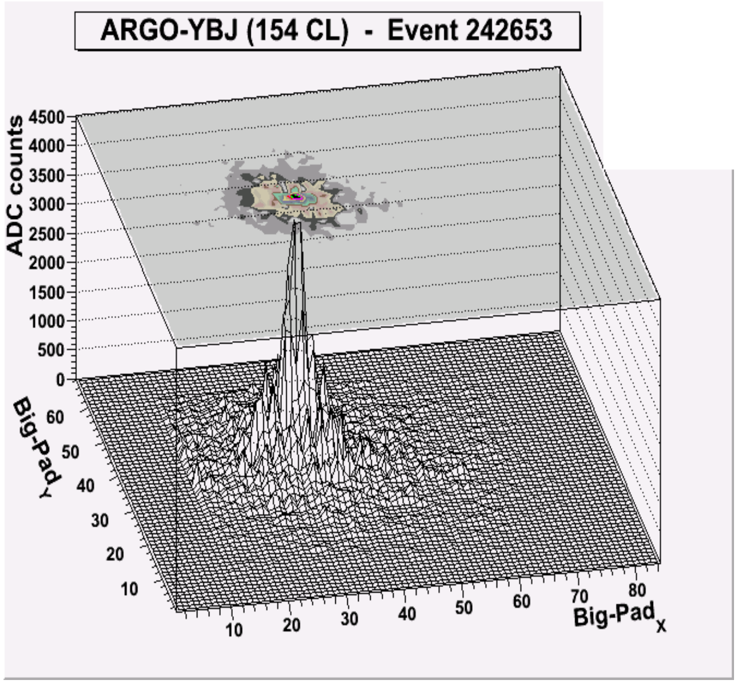
(digital)



BigPads

(analog)



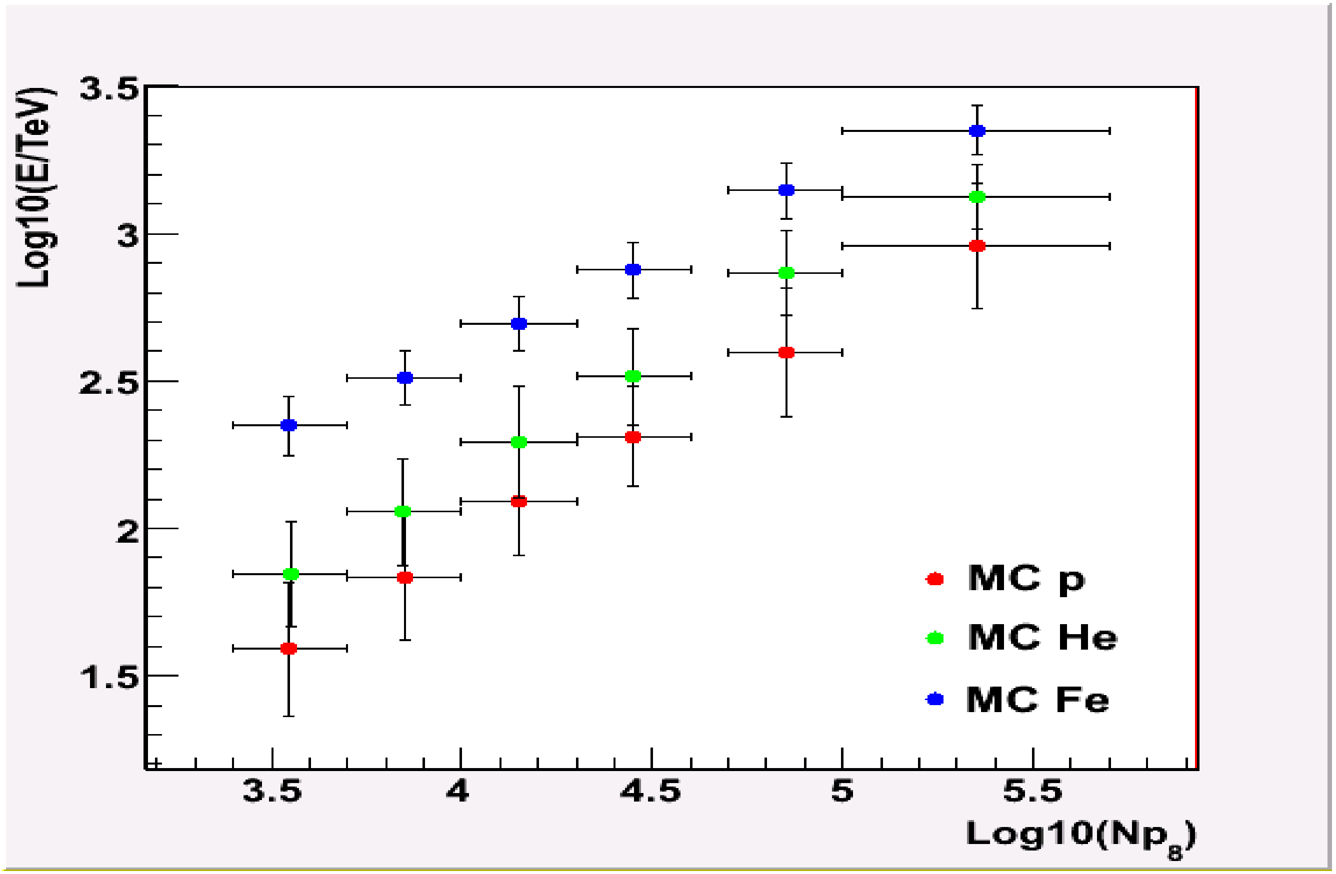


- ✓ Extend the covered **energy range**
- ✓ Access the **LDF** down to the shower core
- ✓ Sensitivity to **primary mass**
- ✓ Info/checks on **Hadronic Interactions**

The truncated size as energy estimator

Np_8 (number of particles within 8m from the core):

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

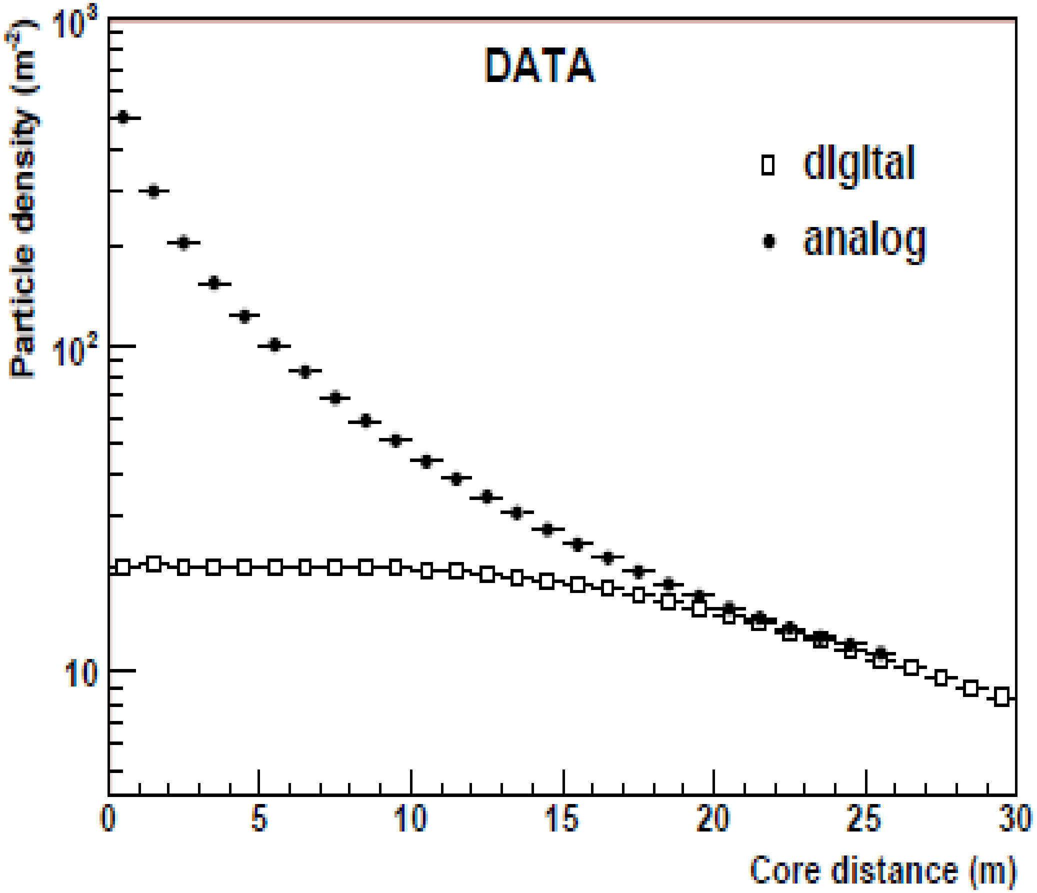


QGSJET-II based MC samples

Vertical error bars: RMS(Energy)

Lateral Distribution Function

With the analog data we can study the LDF without saturation near the core



Tests are in progress in order to have:

- ✓ **Better resolution on X_{dm} and then lower systematics on the cross section measurement**
- ✓ **Better energy determination / shower reconstruction**
- ✓ **Sensitivity to the hadronic interaction model**
- ✓ **Sensitivity to shower age (primary mass)**


Lateral Distribution Function

Several function used to fit the LDF shape in the range 0.5 m < R < 15.5 m from the core.

A NKG-like function found to reasonably reproduce the LDF shape in the above distance interval

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

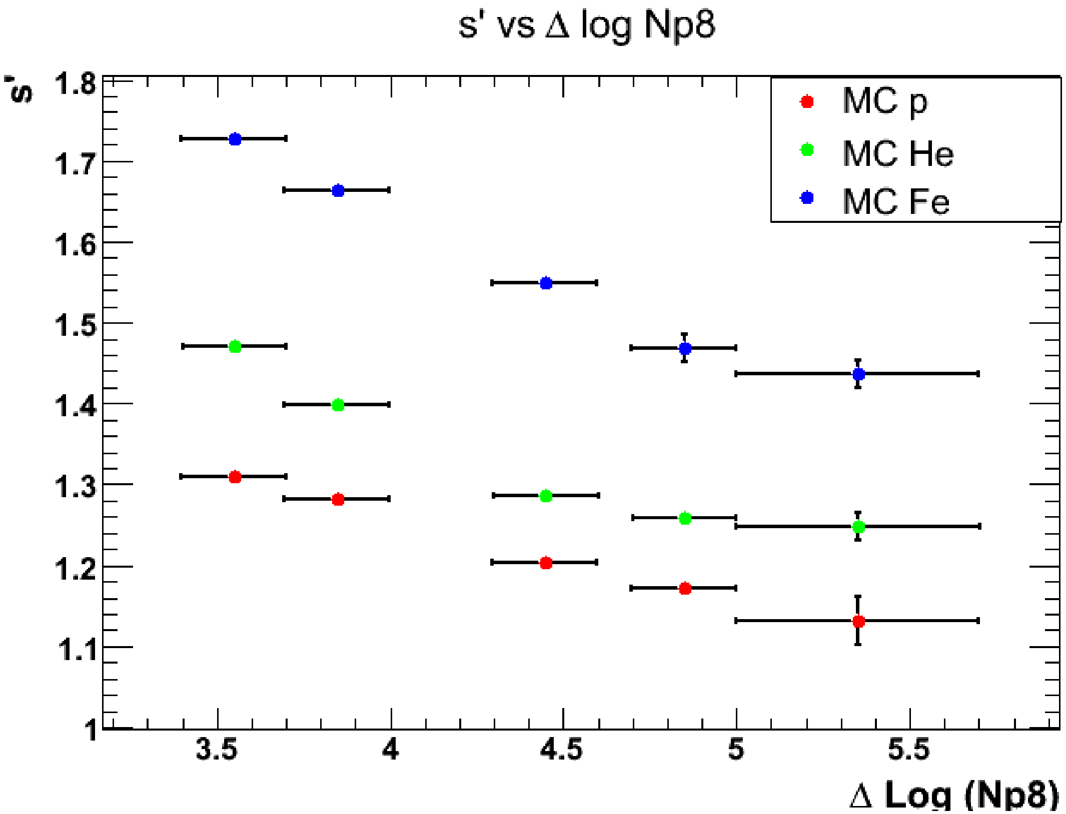
$r_M = r_M^{(YBJ)}/4 = 30.3$m: fixed

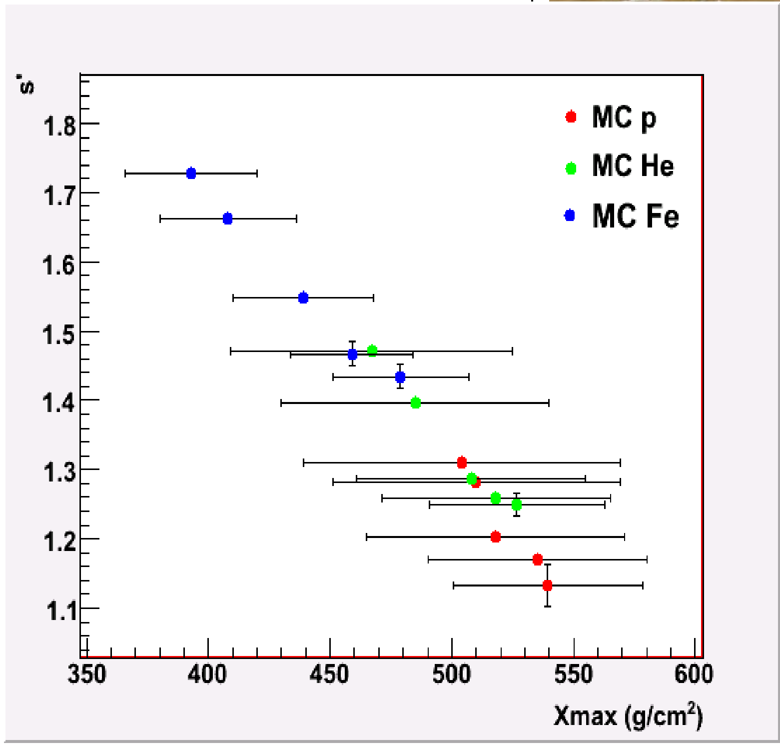
Normalization factor *A* and *s'*: free parameters

Remarks:

- ***s'*: 'lateral shower age', describing the slope of the radial distribution of charged particles**
- **In principle, *s'* differs from the 'longitudinal age' *s* (reflecting the longitudinal shower development)**
- **In practice *s' and s are highly correlated*...**

Shower age vs truncated size

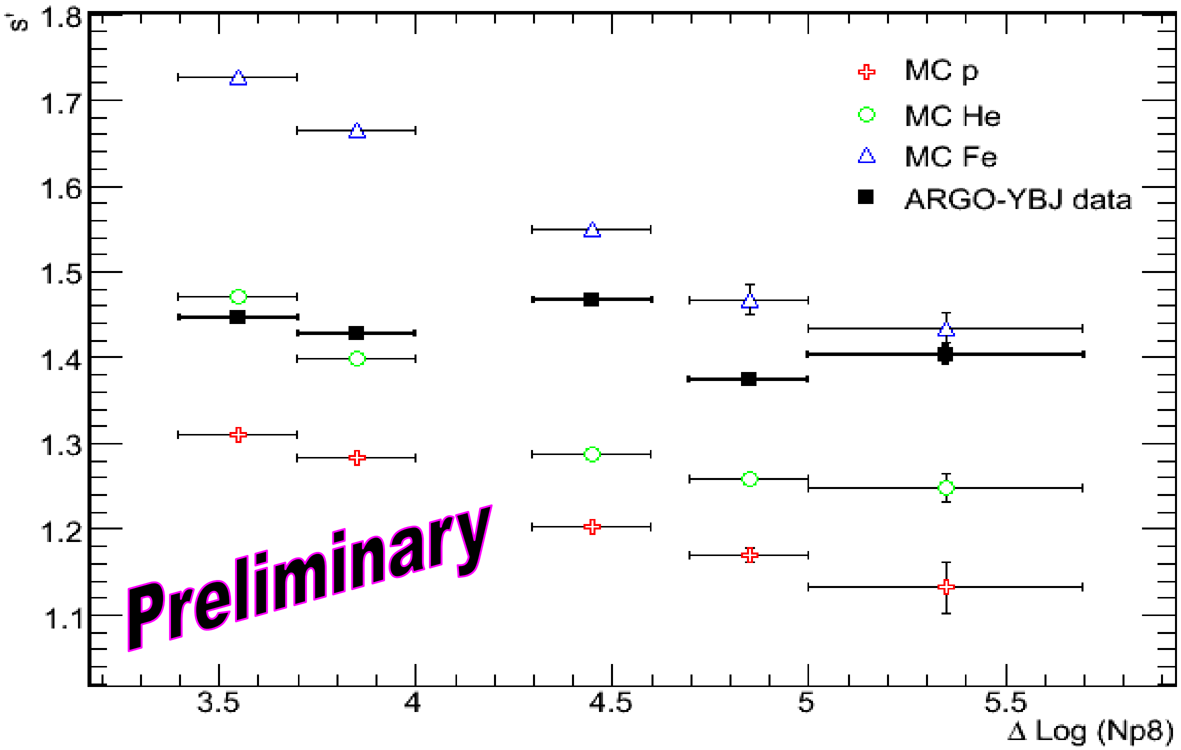


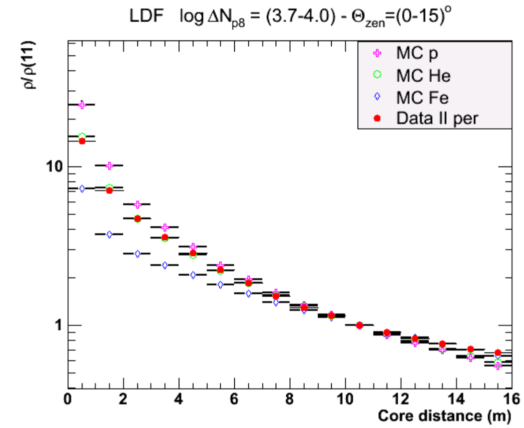


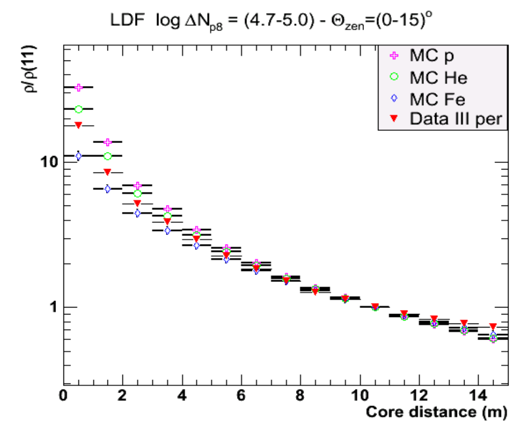
The s' parameter is correlated to the X_{max} position, **whatever the primary is.**

⇒ **Possibility to get hints on (a) shower age and (b) primary mass**

Shower age vs truncated size





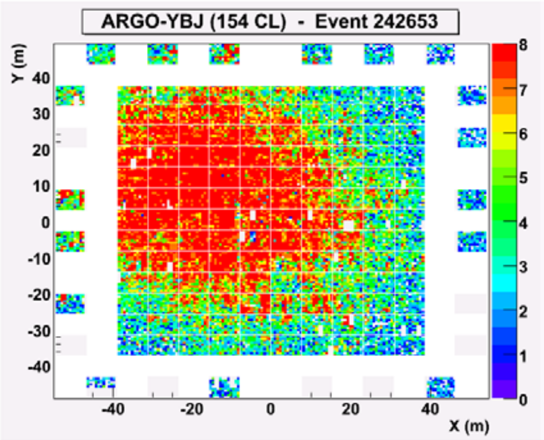


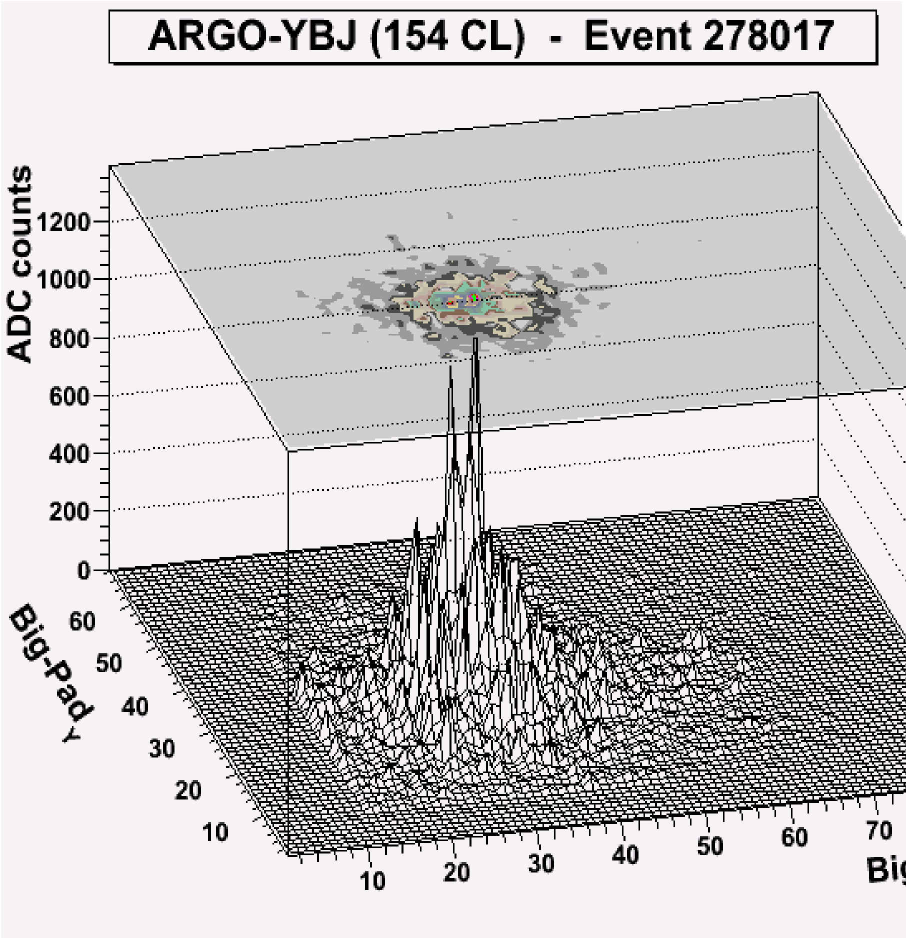
- **The ARGO-YBJ data lie between the expectations from extreme pure compositions (p and Fe)**
- **A trend towards a heavier composition for increasing energy can be envisaged. Cross checks are in progress.**

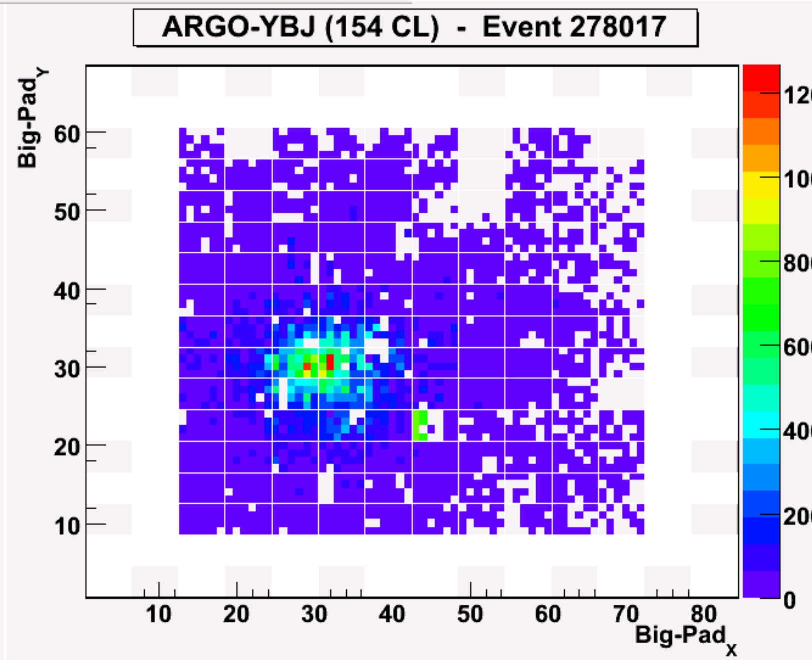
Multicore events with analog data

Preliminary results show the feasibility of these studies.

Hadronic physics, p_t distributions,..



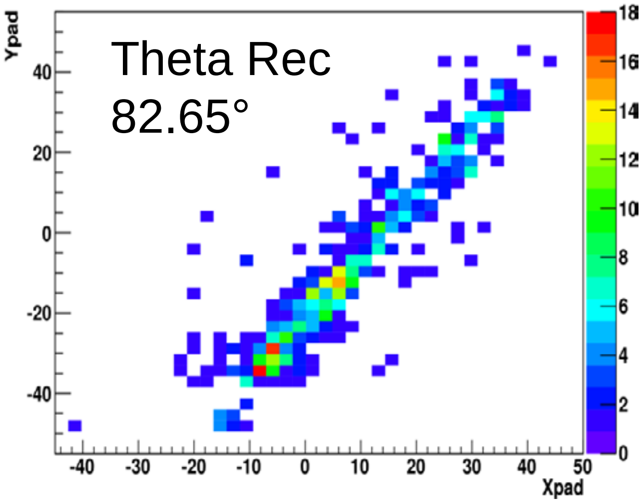


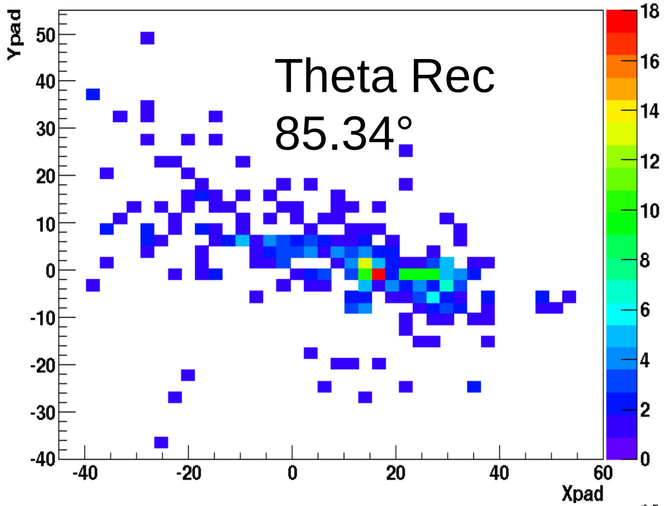


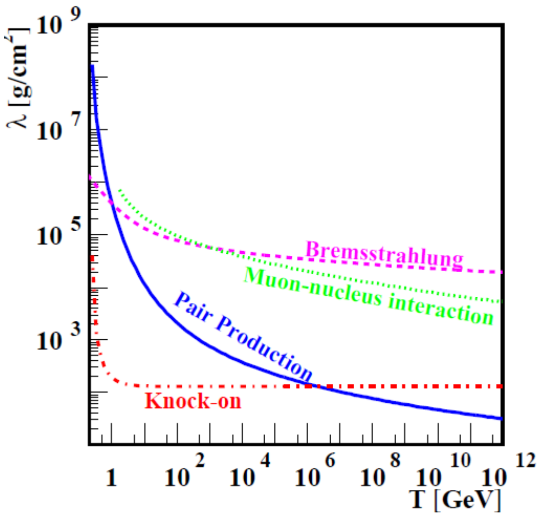
Horizontal Air Showers

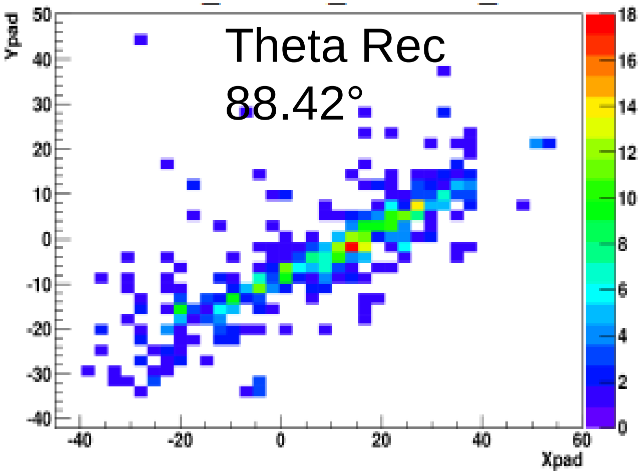
- High energy muon induced events
- Energy spectra
- …….

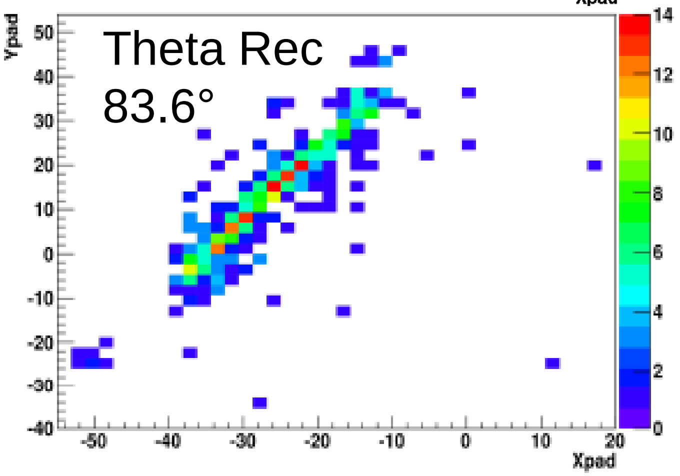
$\theta > 70° \rightarrow 1248\ g/cm^2$
$\theta > 80° \rightarrow 2458\ g/cm^2$



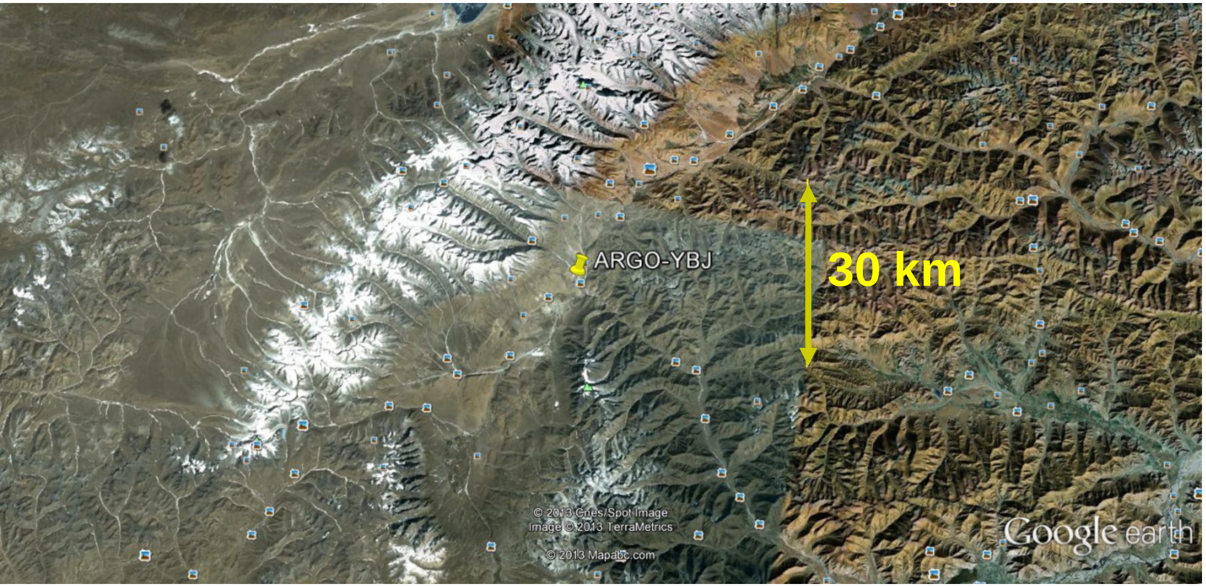






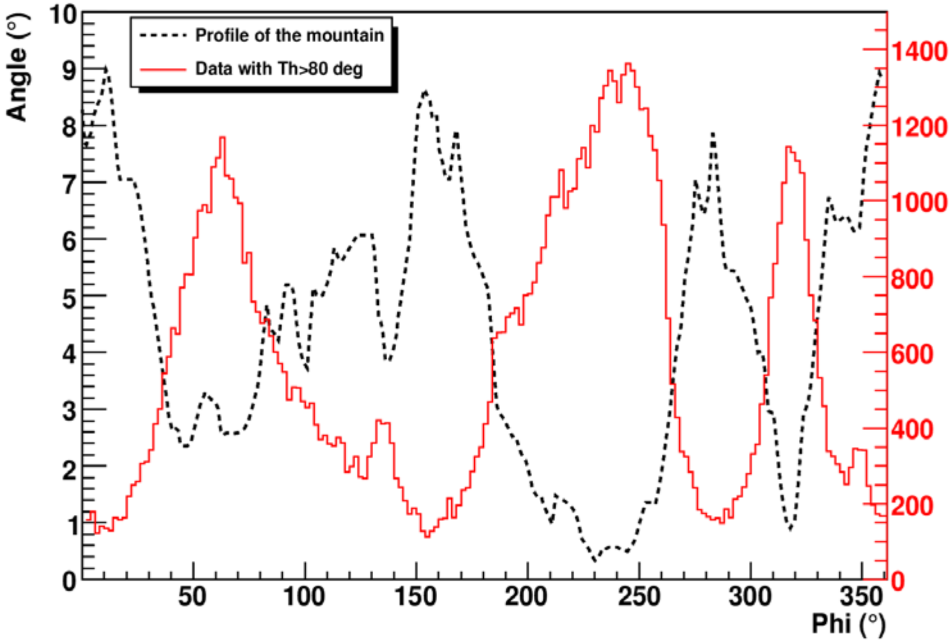


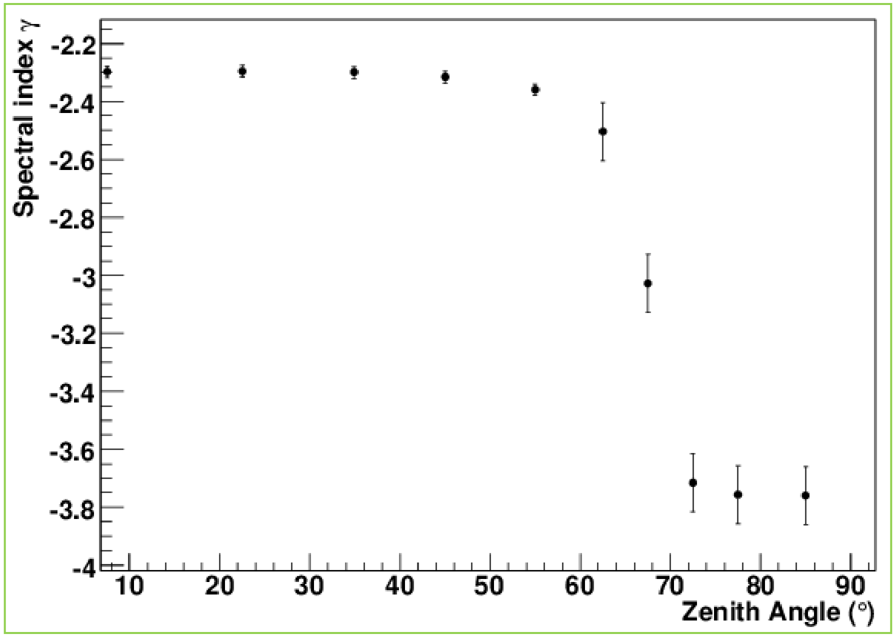
Horizontal Air Showers



The HAS flux is anticorreelated with nearby mountain profile

The spectral index of the multiplicity distribution shows a sharp transition at large zenith angle (muon signature).





Summary and Outlook (not including gammas)

20 years

- First R&D in the ‘90s. Proposal in 1996. Test carpet at YBJ in 1998.
- Full detector in stable data taking since Nov. 2007 (first data in 2006)
- Trigger Rate ~3.5 kHz - Dead time 4%
- 220 GB/day transferred to IHEP (China) / CNAF (Italy) data centers
- End of data taking: February 2013
- Detailed analysis of the Moon shadowing effect (pointing, energy scale)
- Measurement of CR light component energy spectrum below 100TeV
- Study of the CR anisotropy at different angular scales
- Measurement of the CR antip/p flux ratio in TeV energy range
- Monitoring of the IMF by the Sun shadow displacement
- Measurement of the p-air and p-p cross sections up to 100TeV
- Geomagnetic effects on particle distributions at ground
- Extending the energy range to the PeV region by the RPC charge readout
- LDF near the shower core and shower age estimation
- Time structure of the shower front
- Hadronic interactions and primary mass sensitivity
- .....several new analysis in progress: final results within the next two years