

Cosmic Ray Physics with ARGO-YBJ



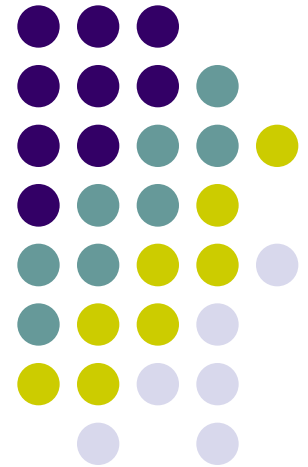
Ivan De Mitri



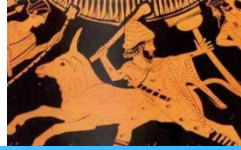
University of Salento and
Istituto Nazionale di Fisica Nucleare
Lecce, Italy



On behalf of the ARGO-YBJ Collaboration



The ARGO-YBJ experiment



ARGO-YBJ

High Altitude Cosmic Ray Observatory @ YangBaJing, Tibet, China

Site Altitude: 4,300 m a.s.l. , ~ 600 g/cm²

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 (see P. Montini's talk)

 - study of the shower space-time structure

 - flux anisotropies at different angular scales (see R. Iuppa's talk)

 - p-Air cross section measurement and hadronic interaction studies

 - anti-p / p ratio at TeV energies,

 - geomagnetic effects

.....

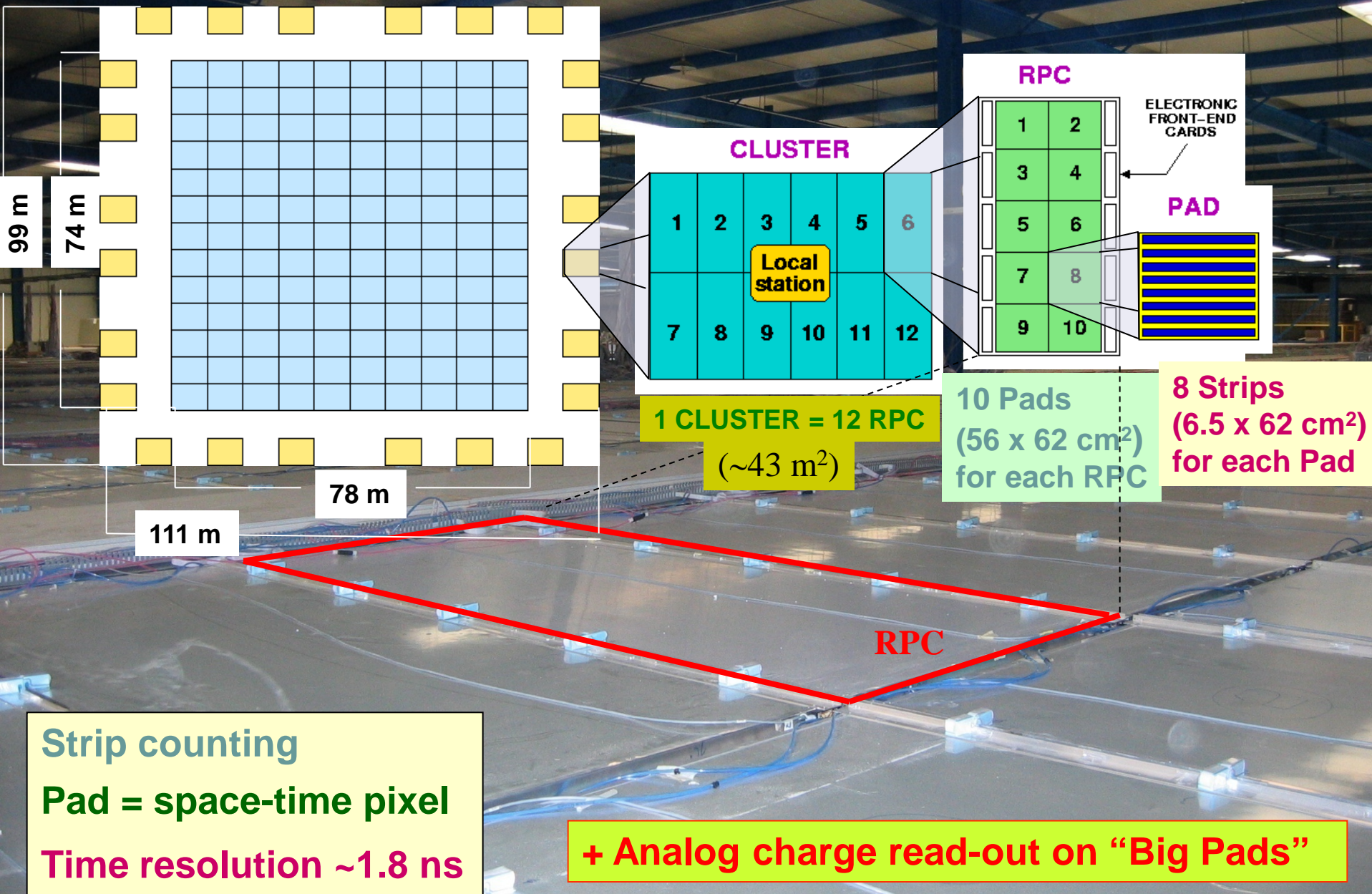
- **Search for GRB's** (full GeV / TeV energy range)

- ...

through the...

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

The ARGO-YBJ detector



RPC performance

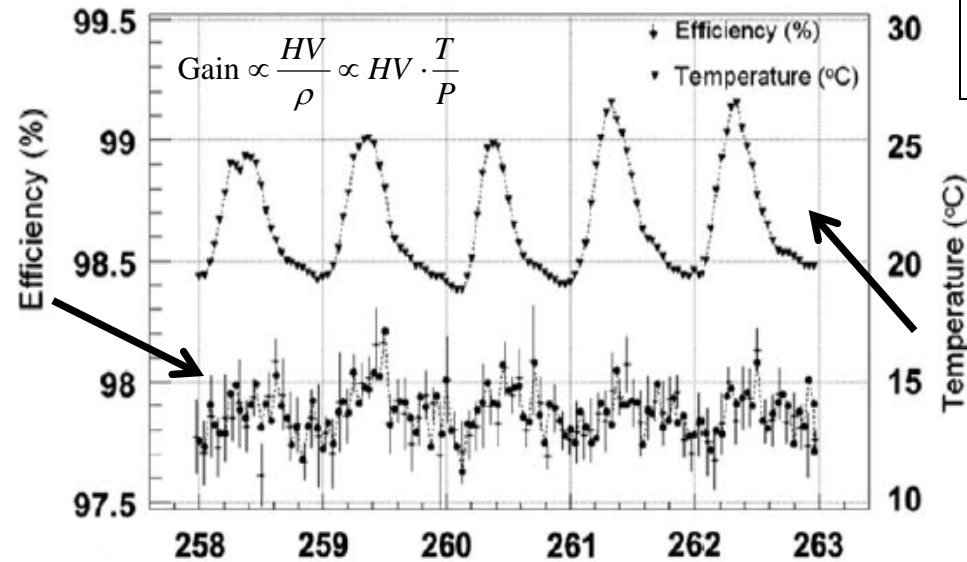
ARGO-YBJ coll., NIM A (2009) 246

$C_2H_2F_4 / Ar / i-C_4H_{10}$

75 / 15 / 10 %

7.2kV applied to 2mm gas gap

Streamer mode

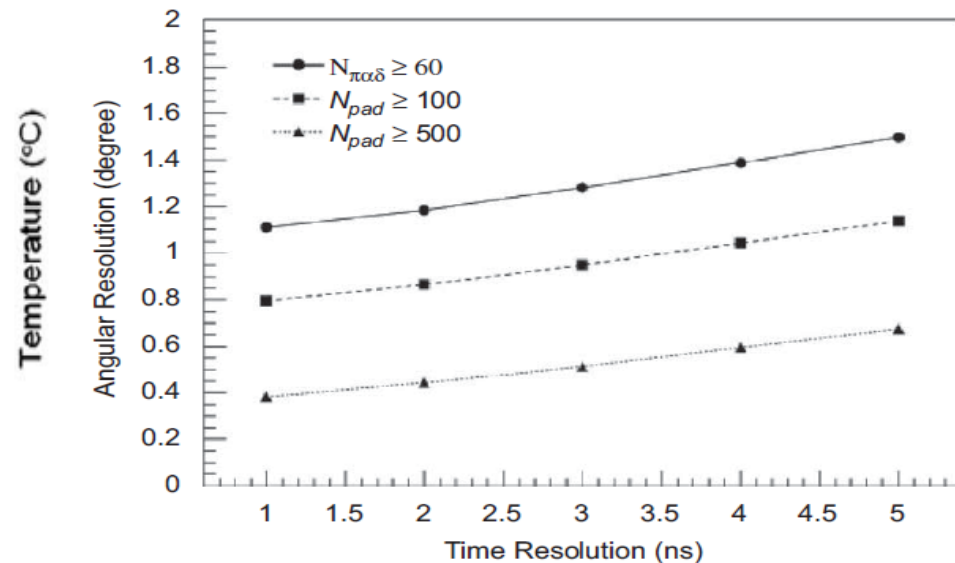
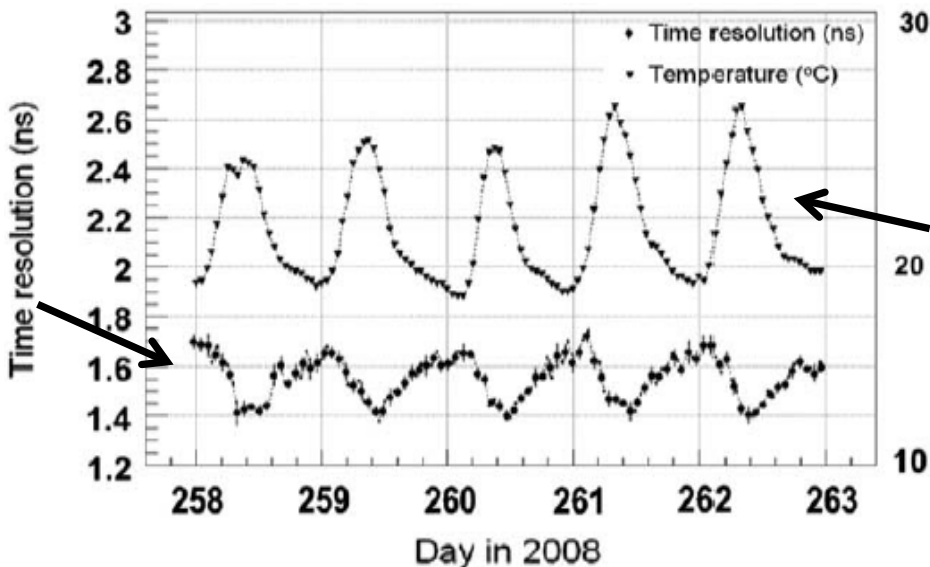


Continuous RPC monitoring.

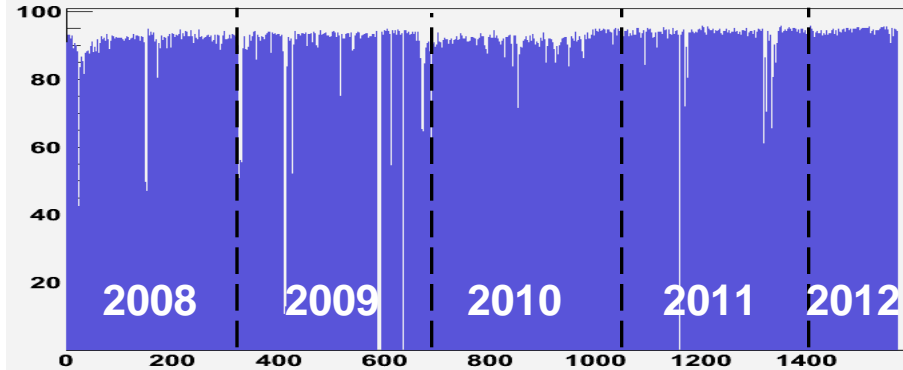
Small efficiency and time resolution drifts with temperature:

- 0.03% / °C
- 0.04 ns / °C

Angular resolution substantially unaffected



EAS reconstruction

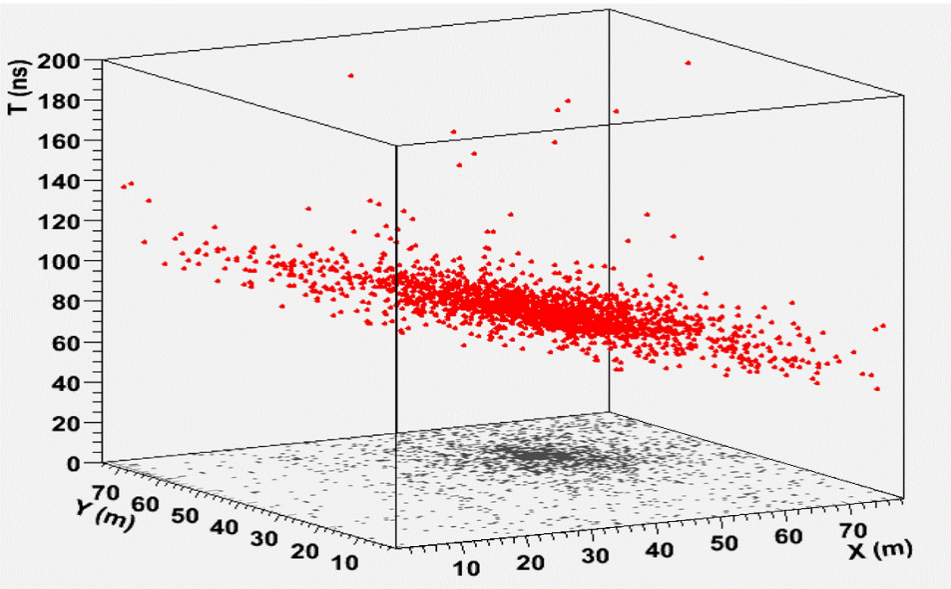


Event Rate ~ 3.5 kHz for $N_{\text{hit}} > 20$ - Duty cycle $\sim 86\%$ - 10^{11} evts/yr - 100TB/yr

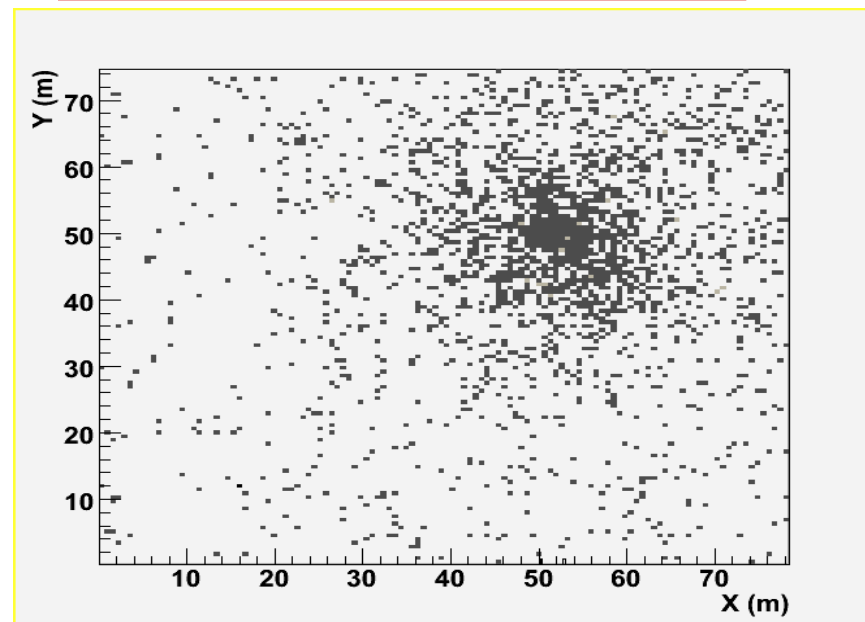
High space/time granularity
+ Full coverage
+ High altitude



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



3-D view of a detected shower

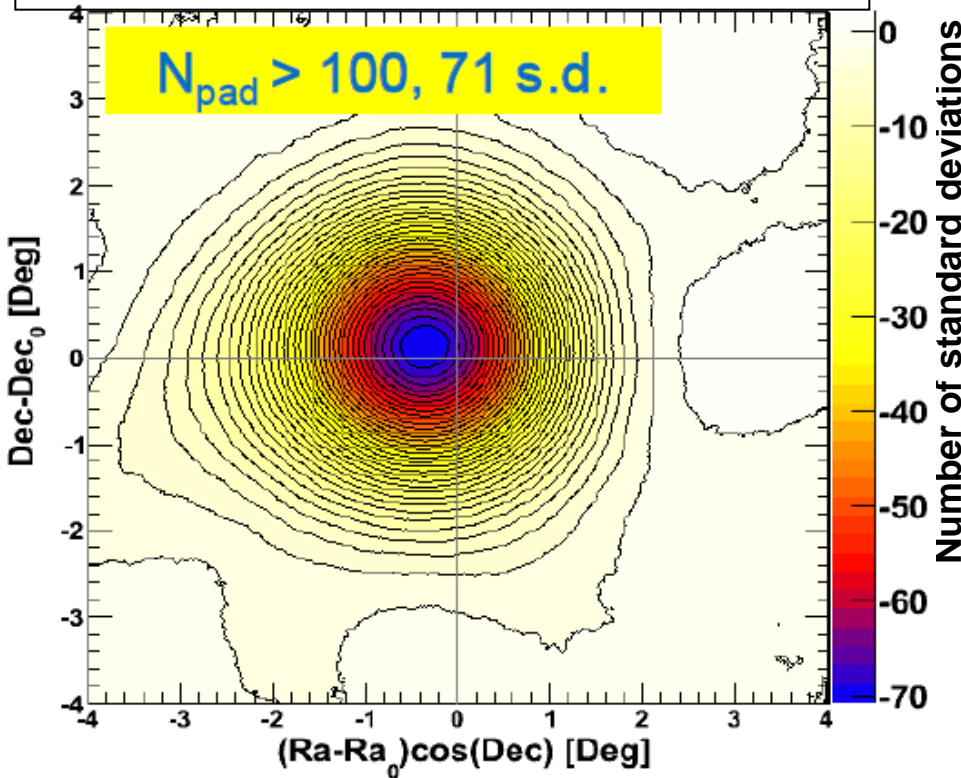


Top view of the same shower

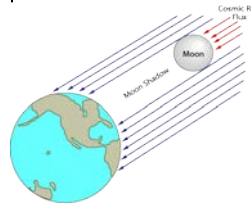
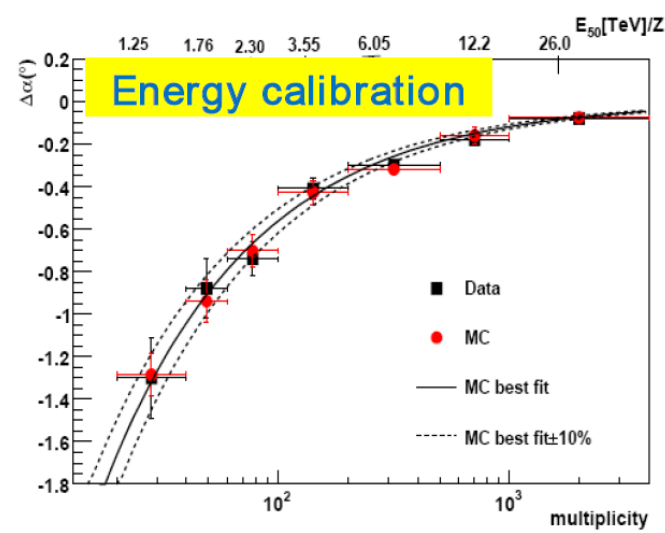
The Moon Shadow and the antip/p ratio

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

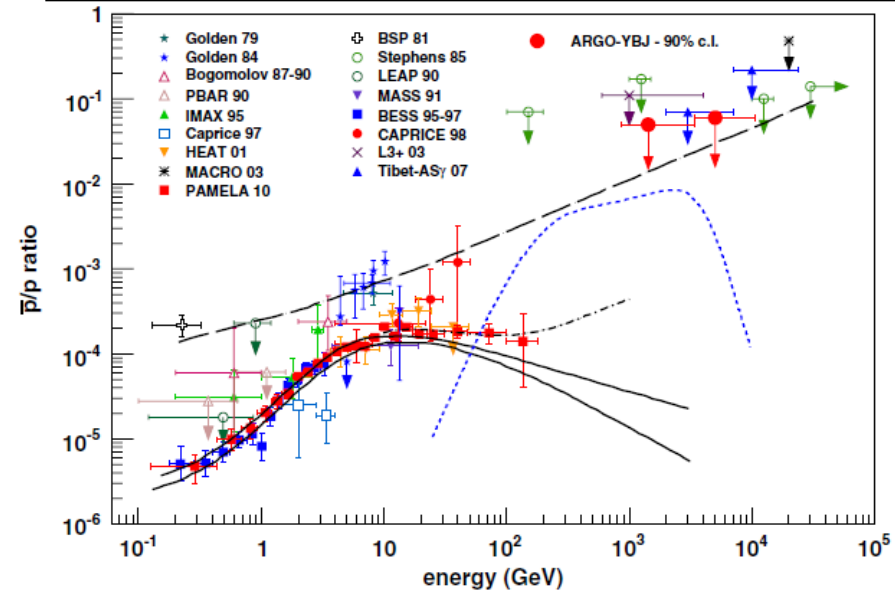
$N_{\text{pad}} > 100, 71 \text{ s.d.}$



- Size of the deficit \Rightarrow **angular resolution**
- Position \Rightarrow **pointing accuracy**
- West displacement \Rightarrow **Energy calibration** (Geomagnetic bending $\approx 1.57^\circ / E \text{ (TeV)}$)
- **Antiprotons** should give a shadow on the opposite side \Rightarrow **Upper limit**

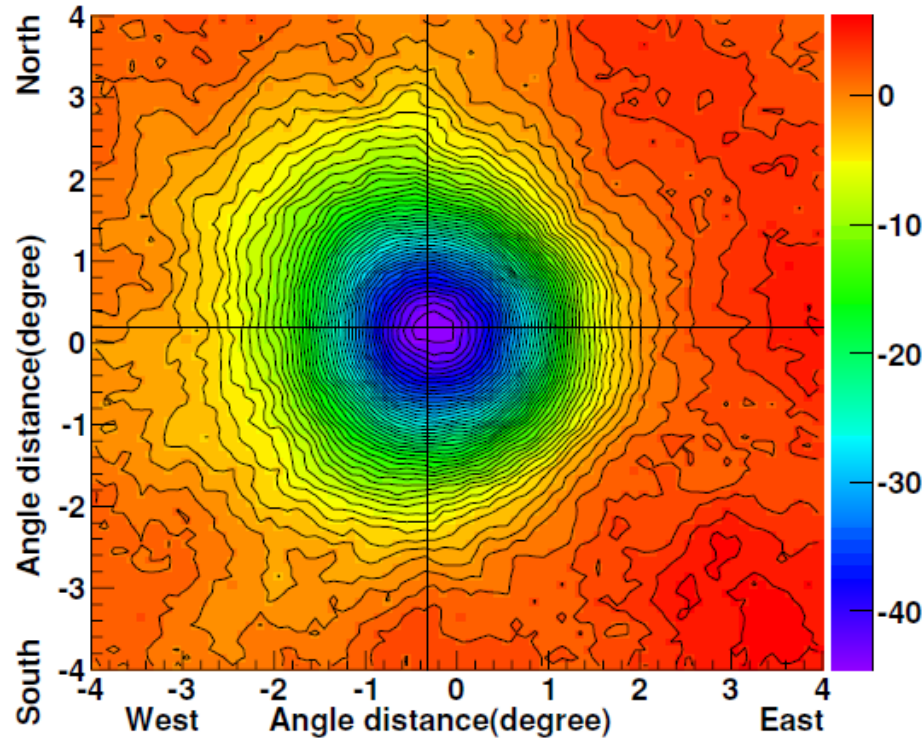


ARGO-YBJ coll., PRD 85 (2012) 022003

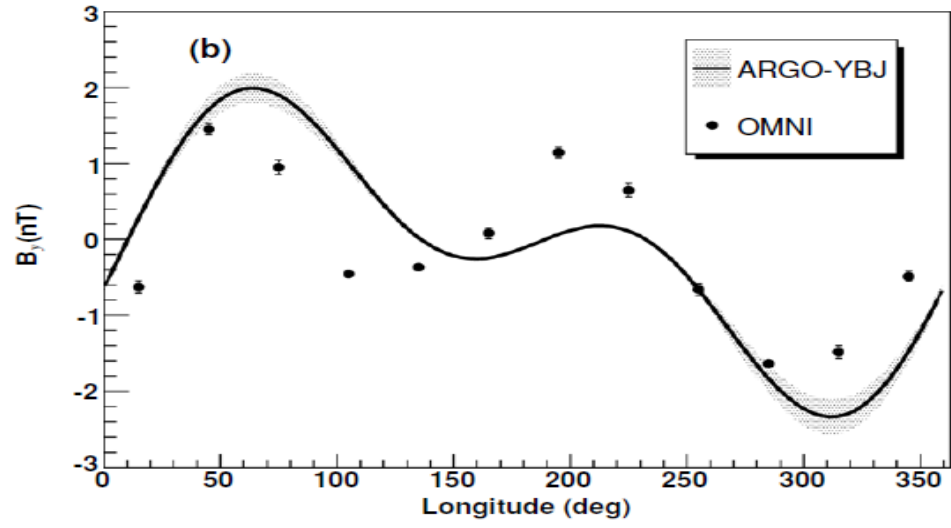
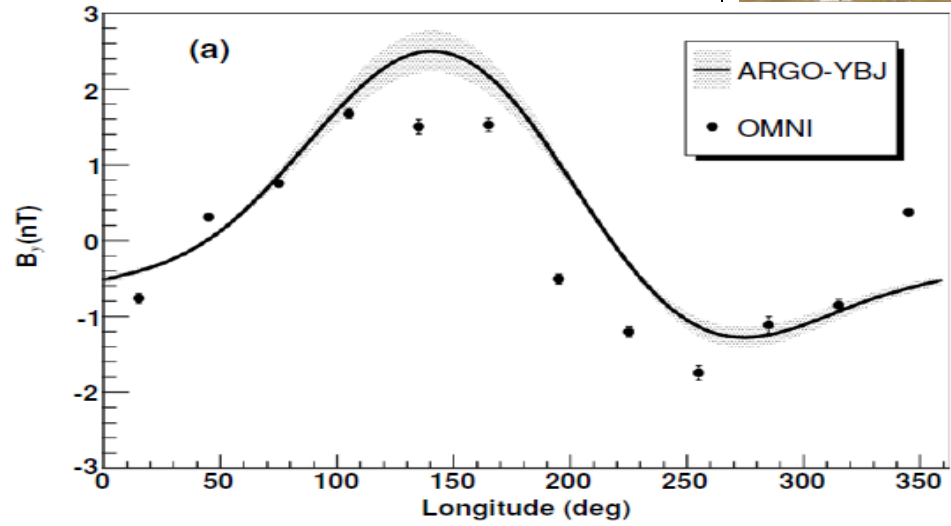


The Sun Shadow and the Interplanetary Magnetic Field

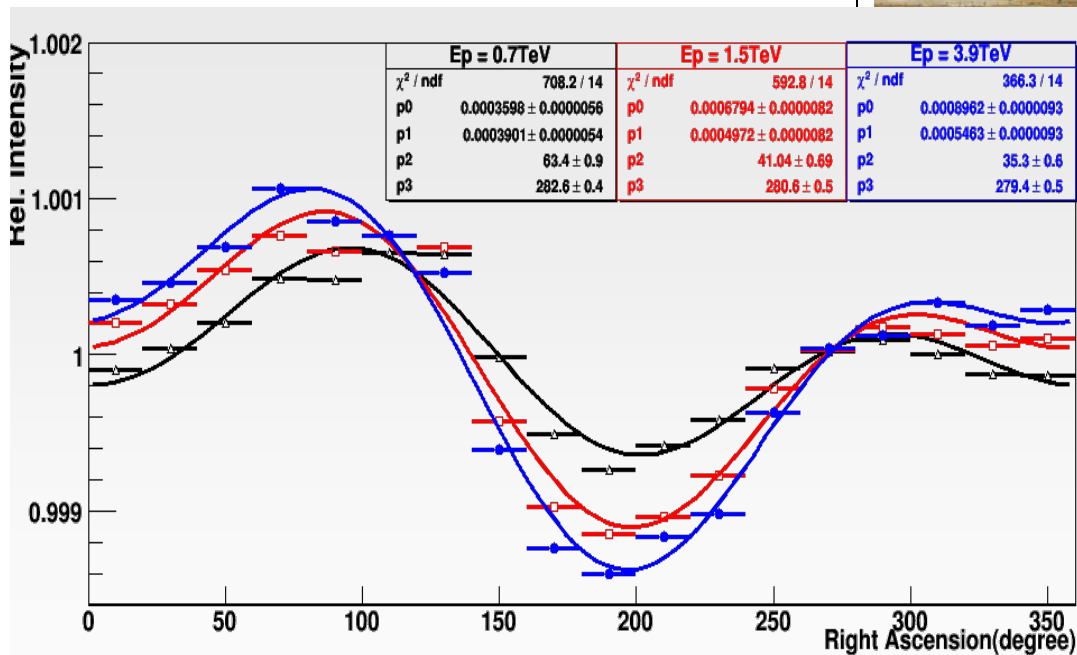
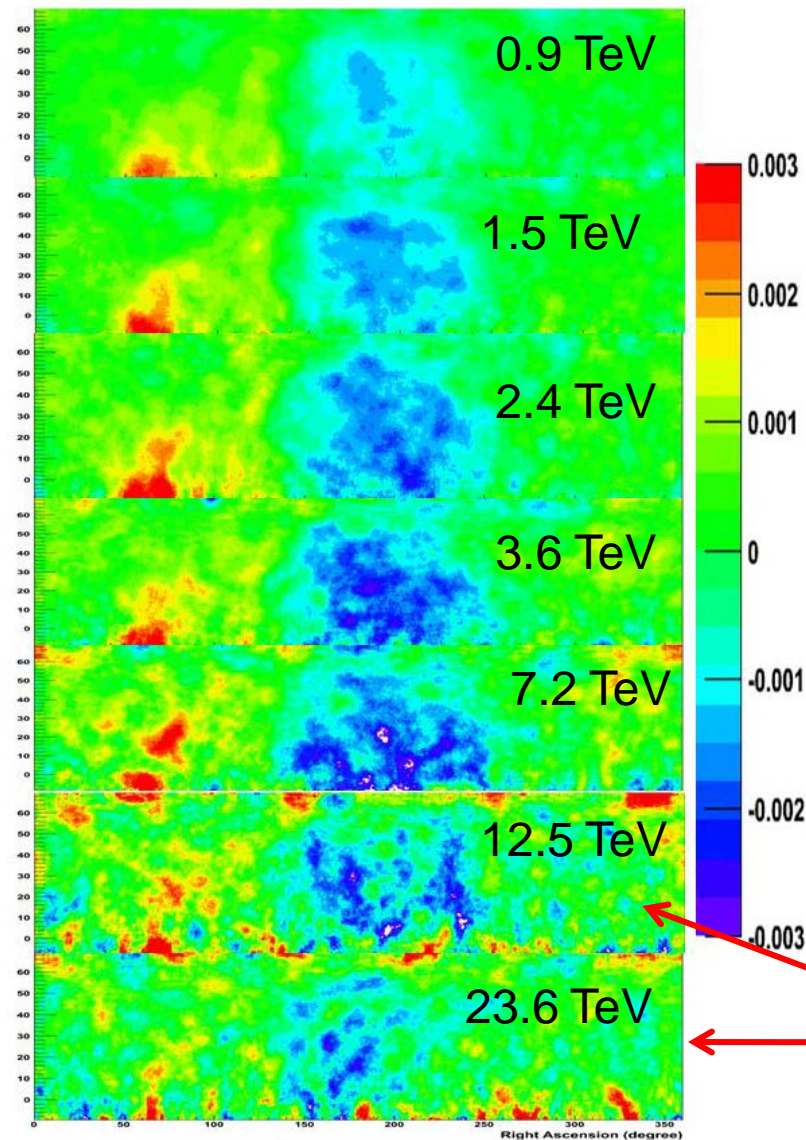
ARGO-YBJ coll., APJ 729 (2011) 113



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



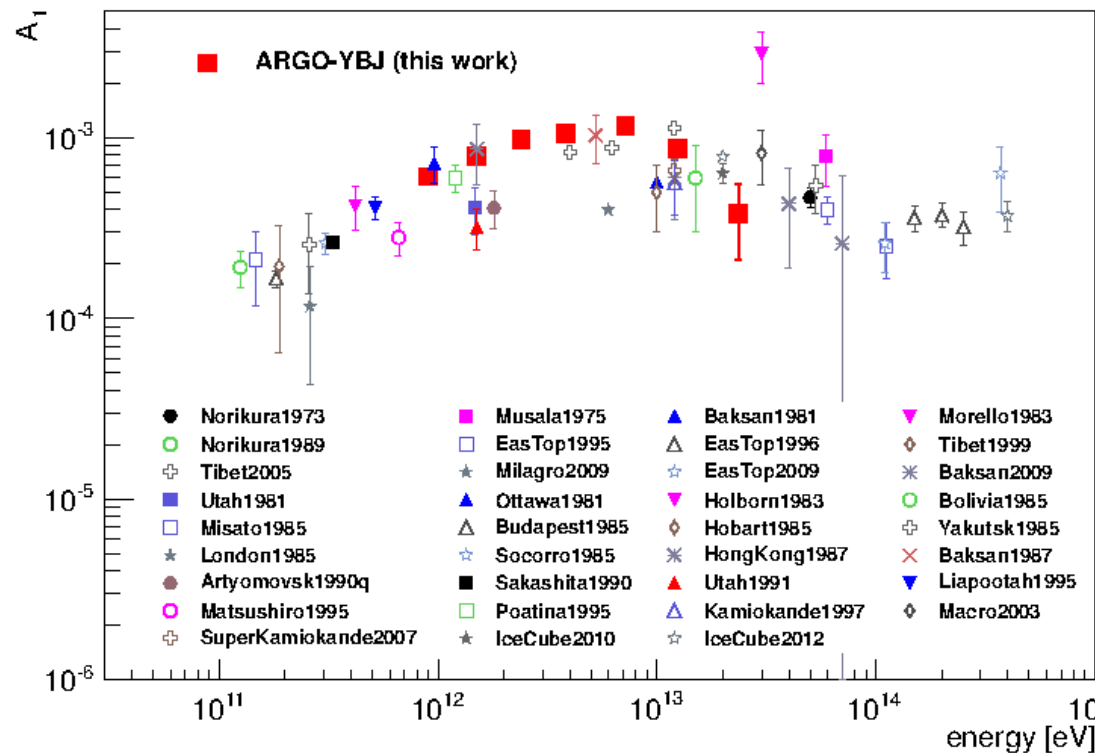
Large scale anisotropy (LSA)



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

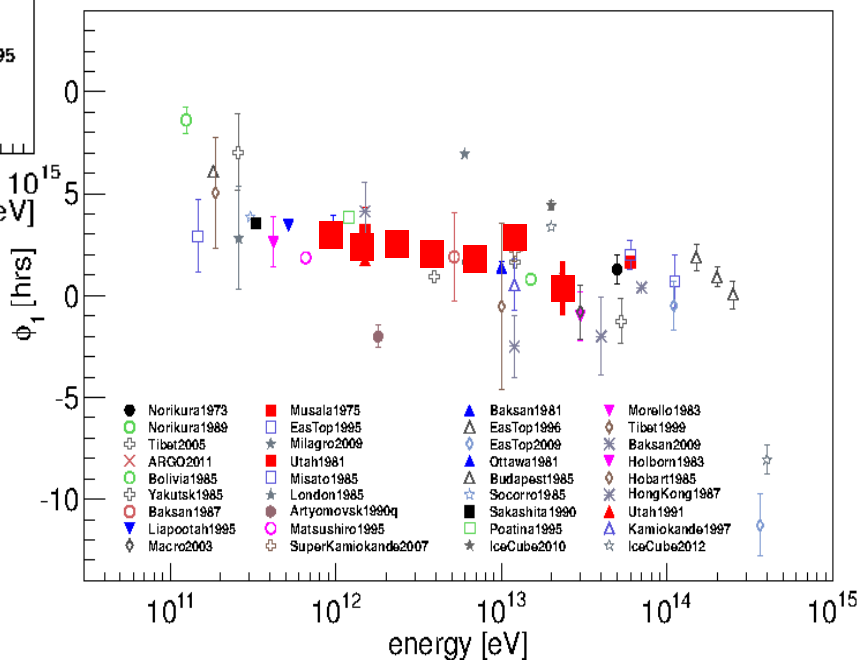
Structures appear to dissolve to smaller angular scale at high energy.

LSA First harmonic amplitude and phase



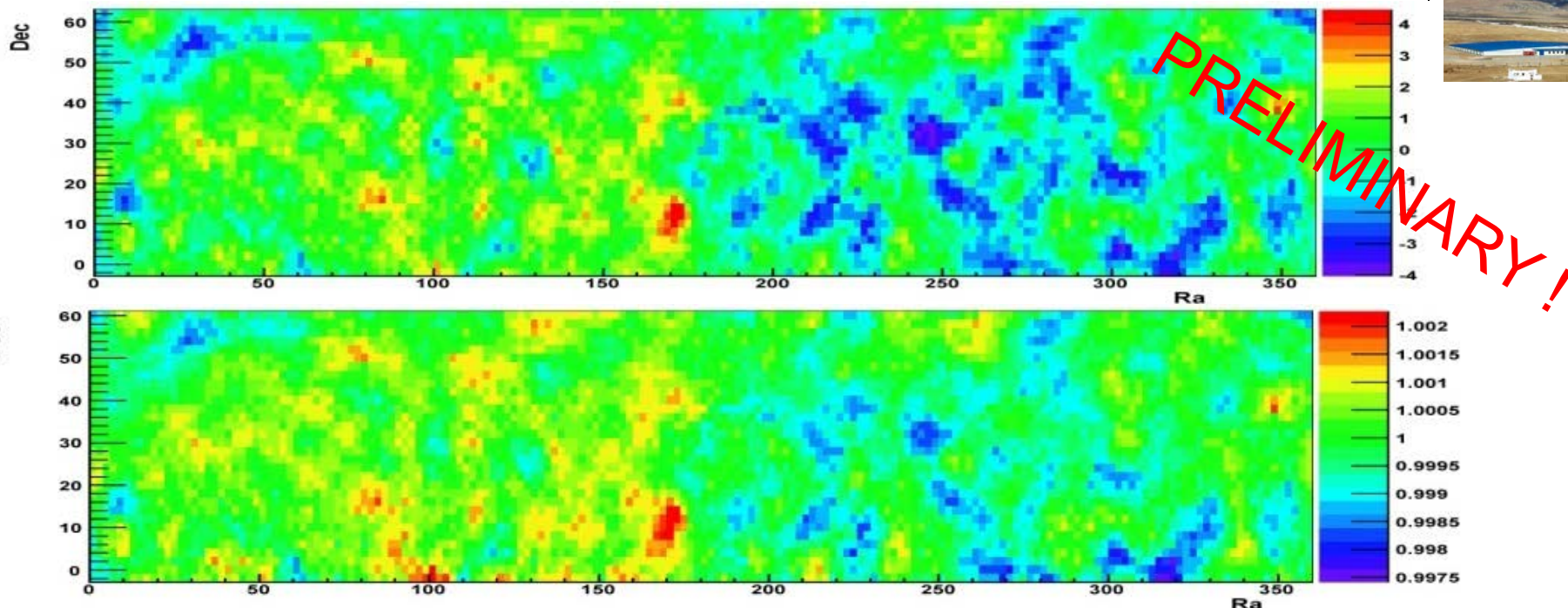
Measurement covering either the rise and the fall of the signal

Uniform phase decrease



The Compton-Getting effect (in solar time)

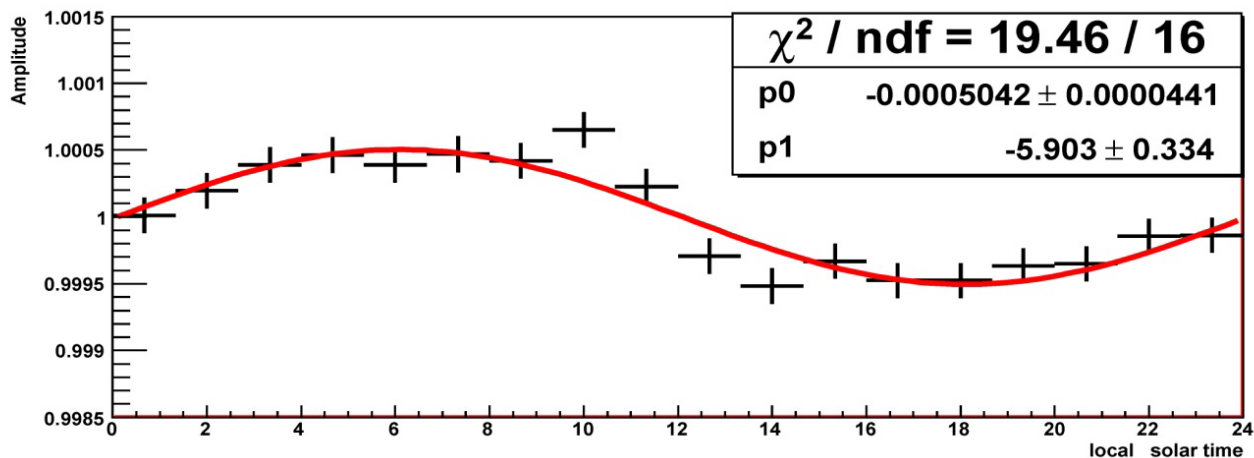
Expected CR anisotropy due to Earth's orbital motion around the Sun



2008 – 2009

$N_{hit} \geq 500 \rightarrow \approx 8 \text{ TeV}$

to avoid solar effects on
low energy CRs



Medium Scale Anisotropy (MSA)



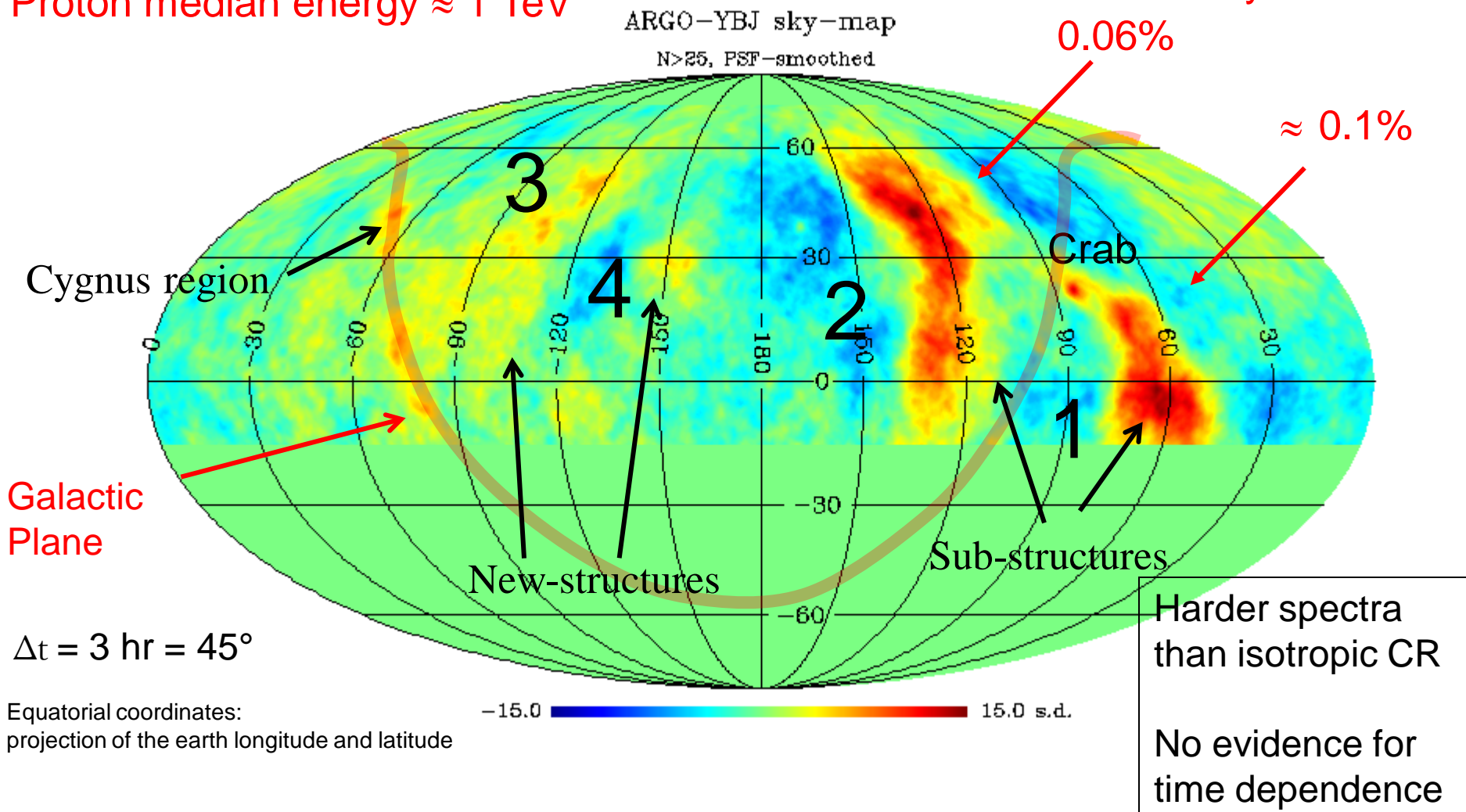
(see R. Iuppa's talk)

Map smoothed with the detector PSF for CRs

Proton median energy ≈ 1 TeV

Cosmic rays excess $\approx 0.06\%$

$\approx 0.1\%$

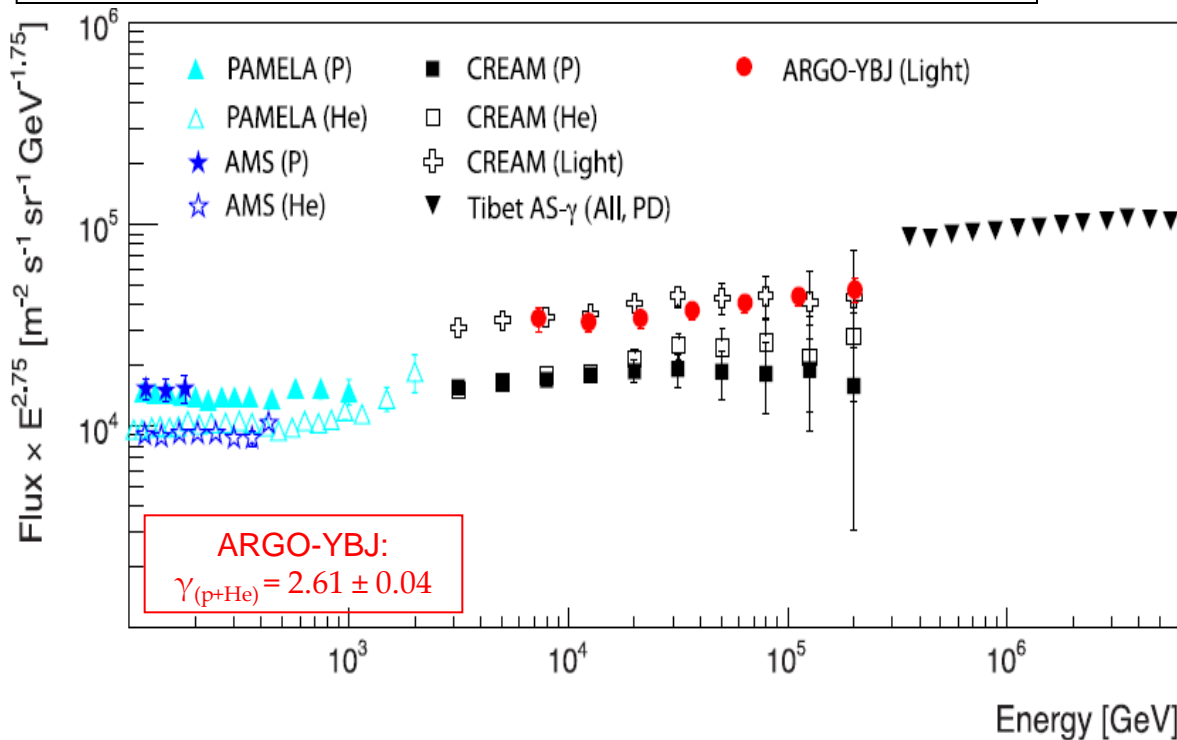


Light-component spectrum of CRs



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



(see P. Montini's talk)

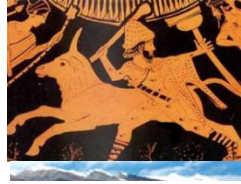
For the first time direct and ground-based measurements overlap for a wide energy range thus making possible the cross-calibration of the experiments.

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 $(\sec\theta - 1)$

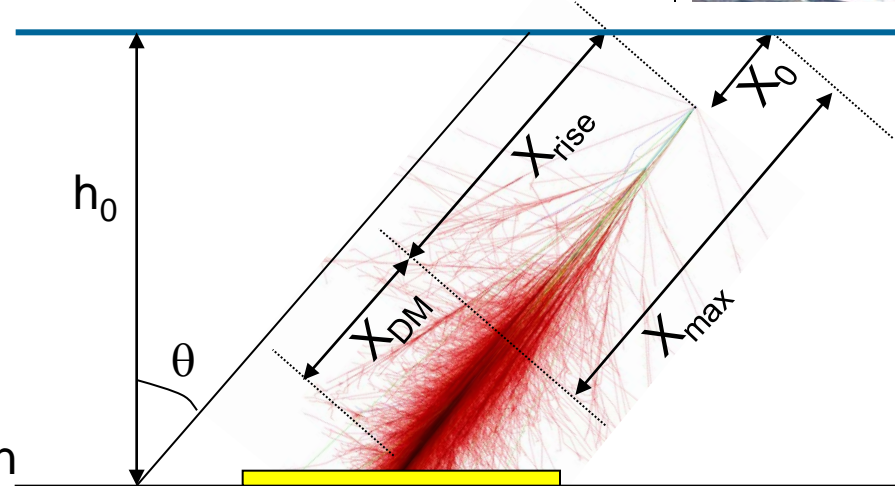
$$I(\theta) = I(0) \cdot e^{-\frac{h_0}{\Lambda}(\sec\theta - 1)}$$

for fixed energy and shower age.

The length Λ is connected to the p interaction length by the relation $\Lambda = k \lambda_{\text{int}}$ 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: $\sigma_{\text{p-Air}} \text{ (mb)} = 2.4 \cdot 10^4 / \lambda_{\text{int}} \text{ (g/cm}^2\text{)}$

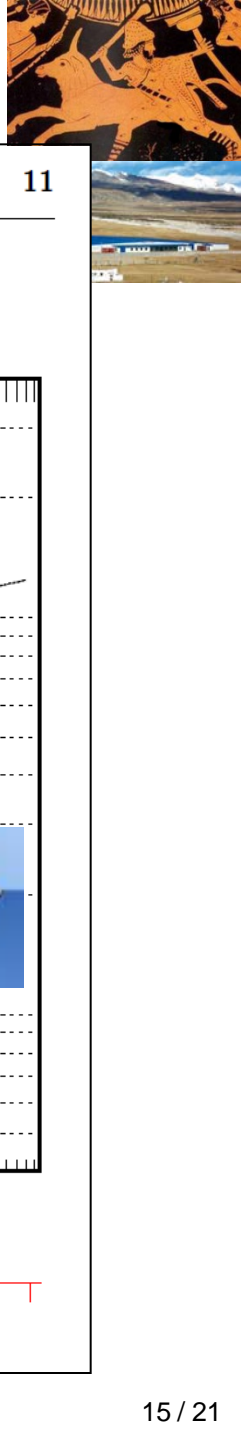
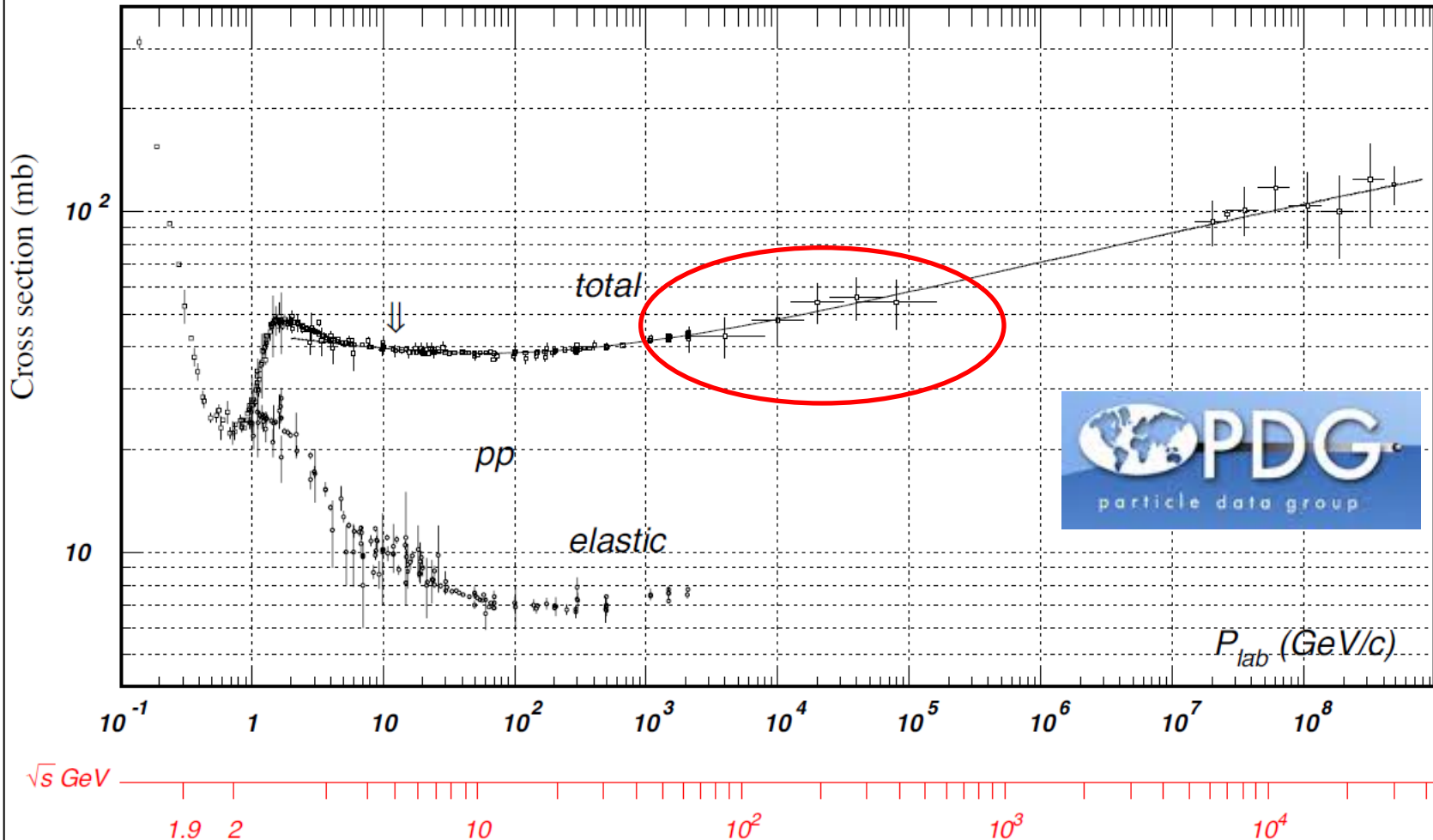


ARGO-YBJ Coll., Phys. Rev D 80, 092004 (2009)

- **Constrain** $X_{\text{DM}} = X_{\text{det}} - X_{\text{max}}$
- **Select** deep showers (large X_{max} , i.e. small X_{DM}) to access exponential tail and reduce shower fluctuations → cut on R_{s70} (strip concentration parameter)
- **Exploit** detector features (space-time pattern) and location (depth).

The total p-p cross section

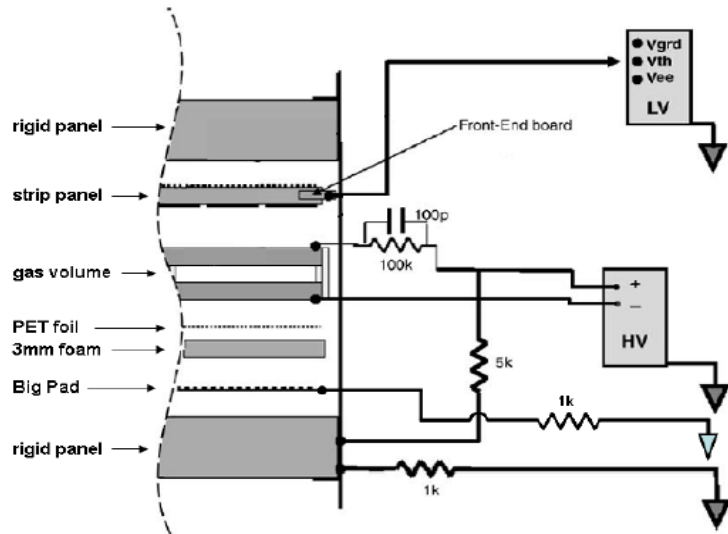
...ARGO-YBJ data in the Review of Particle Properties 2012





The RPC analog readout

Readout of the charge signal on $1.39 \times 1.23 \text{ m}^2$ “big pads” (two / RPC)



Different gain scales (G_0, \dots, G_7) used to cover a **wide range in particle density**:

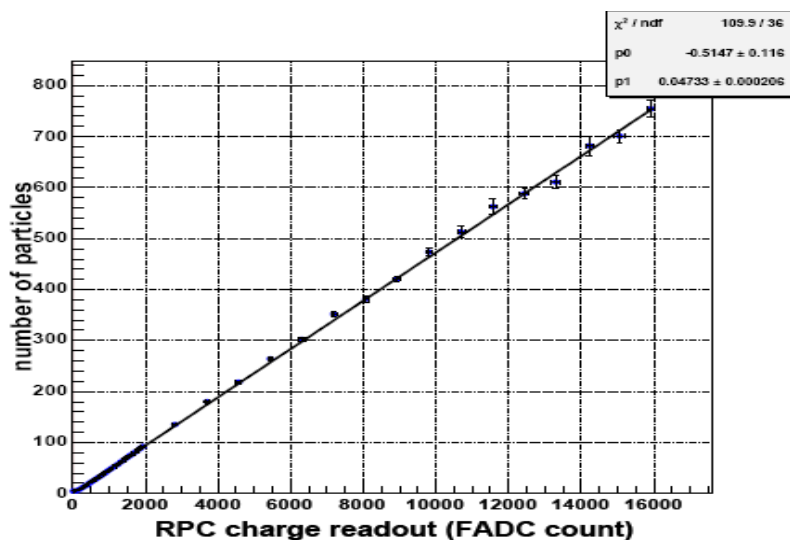
$$\rho_{\text{max-strip}} \approx 20 \text{ particles / m}^2$$

$$\rho_{\text{max-analog}} \approx 10^5 \text{ particles / m}^2$$

Intrinsic limit at few particles per cm^2 , due to space charge effects of the streamer discharge: the so called *dead zone*.

Calibration procedure

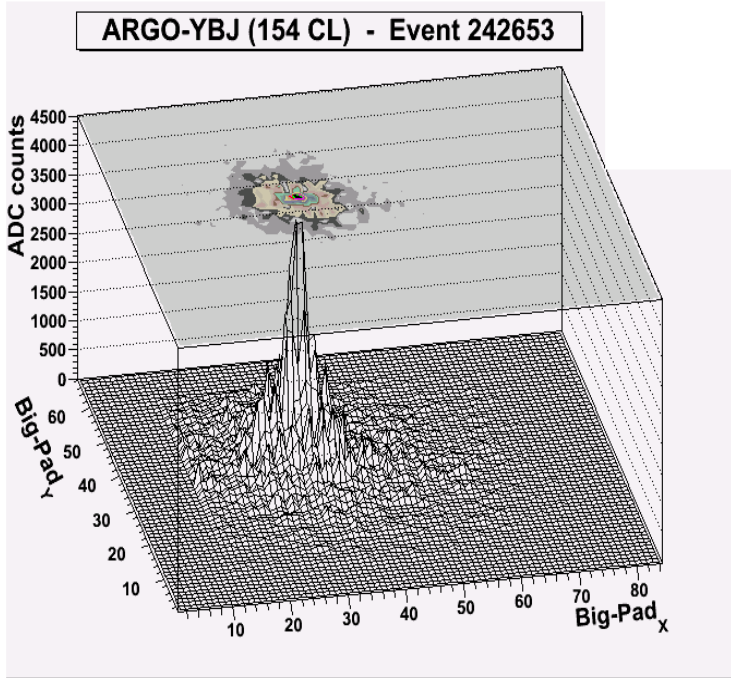
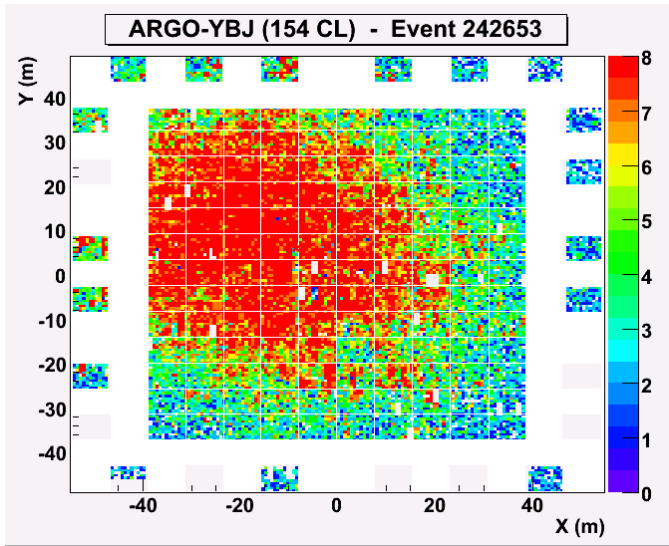
Correction for Pressure and Temperature effects



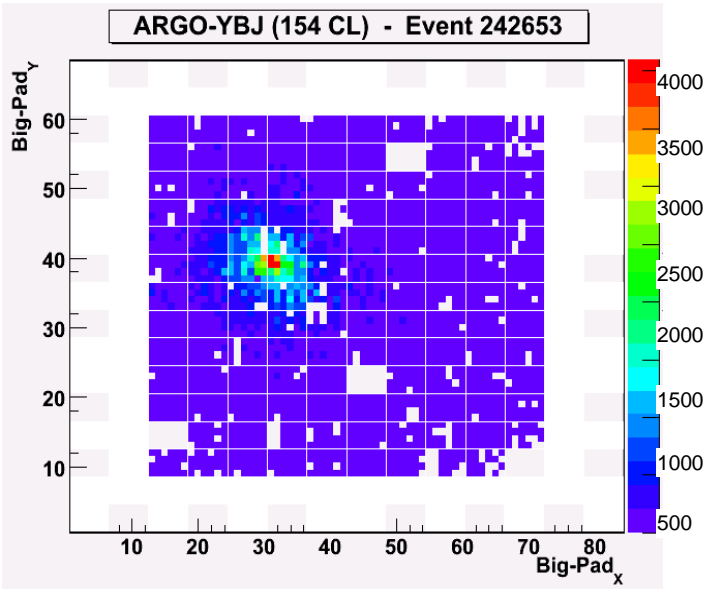
The RPC analog readout



Real event



Strips
(digital)



BigPads
(analog)

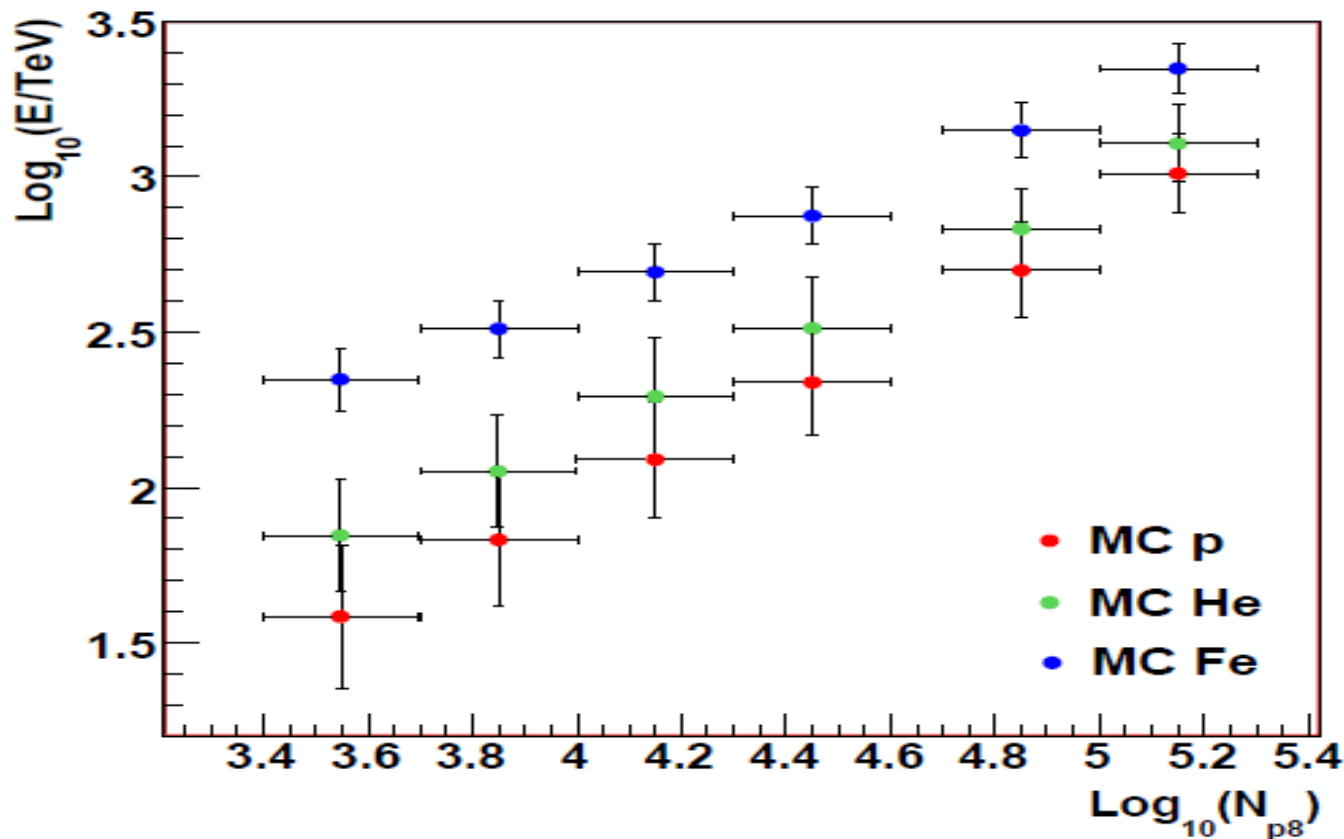
- ✓ Extend the covered **energy range**
- ✓ Access the **LDF** down to the shower core
- ✓ Sensitivity to **primary mass**
- ✓ Info/checks on **Hadronic Interactions**

The truncated size as energy estimator



N_{p8} (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
($\theta < 15^\circ$)

Vertical error bars:
RMS(Energy)

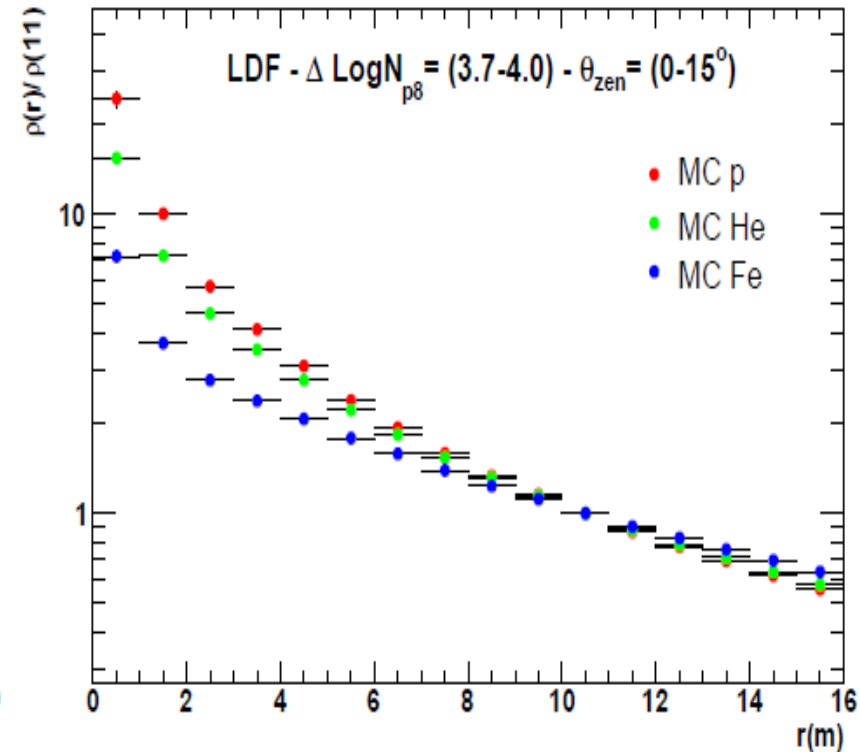
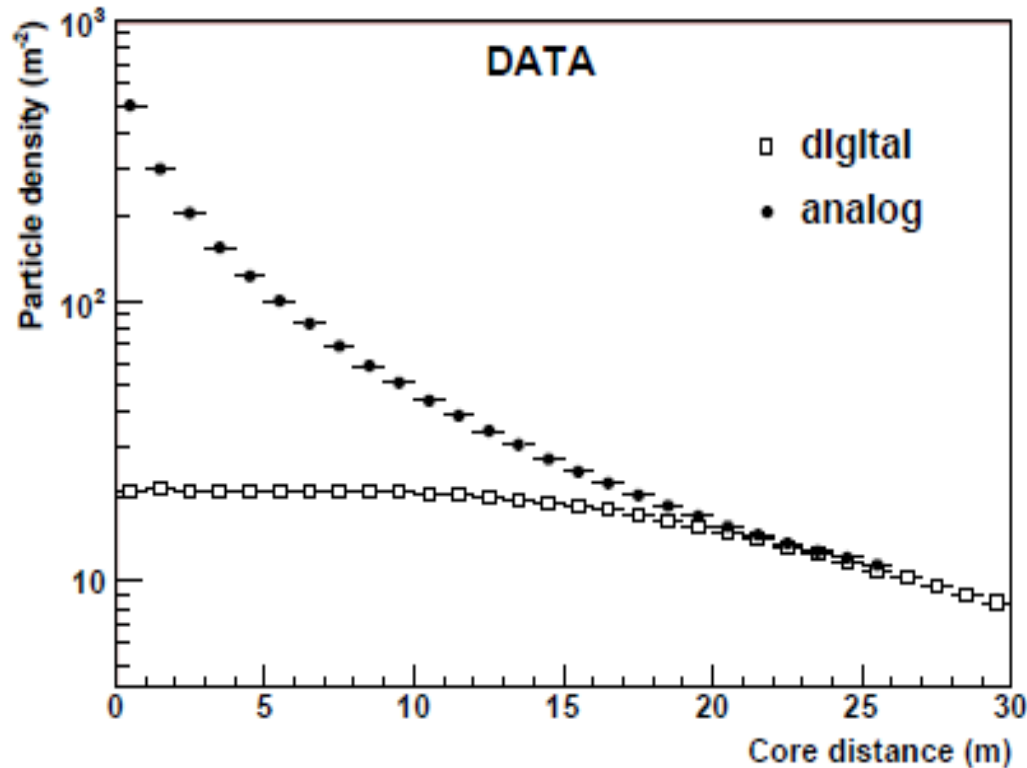
Lateral Distribution Function

With the analog data we can study the LDF without saturation near the core. Well fitted by modified NKG function

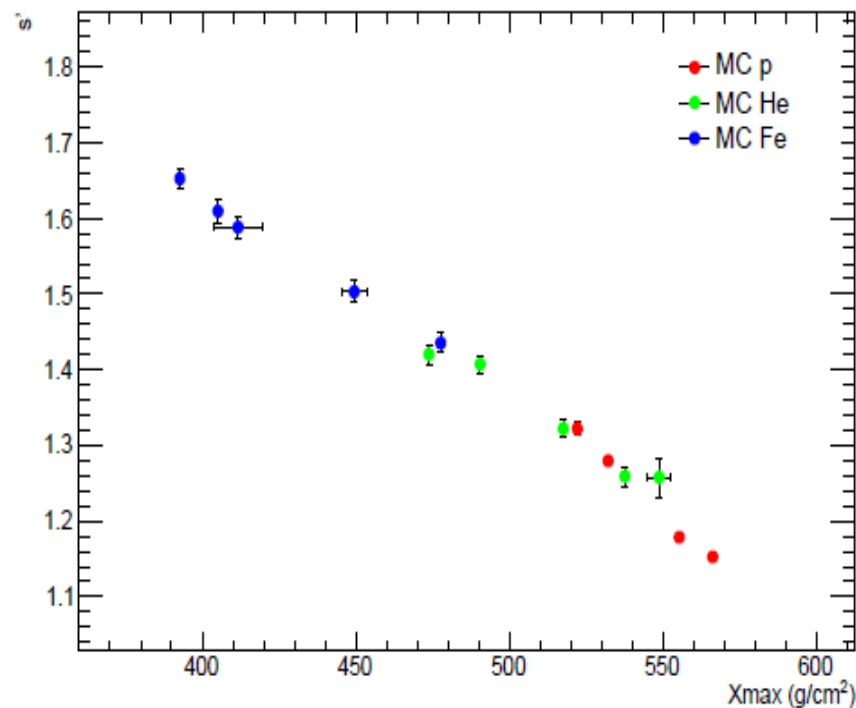
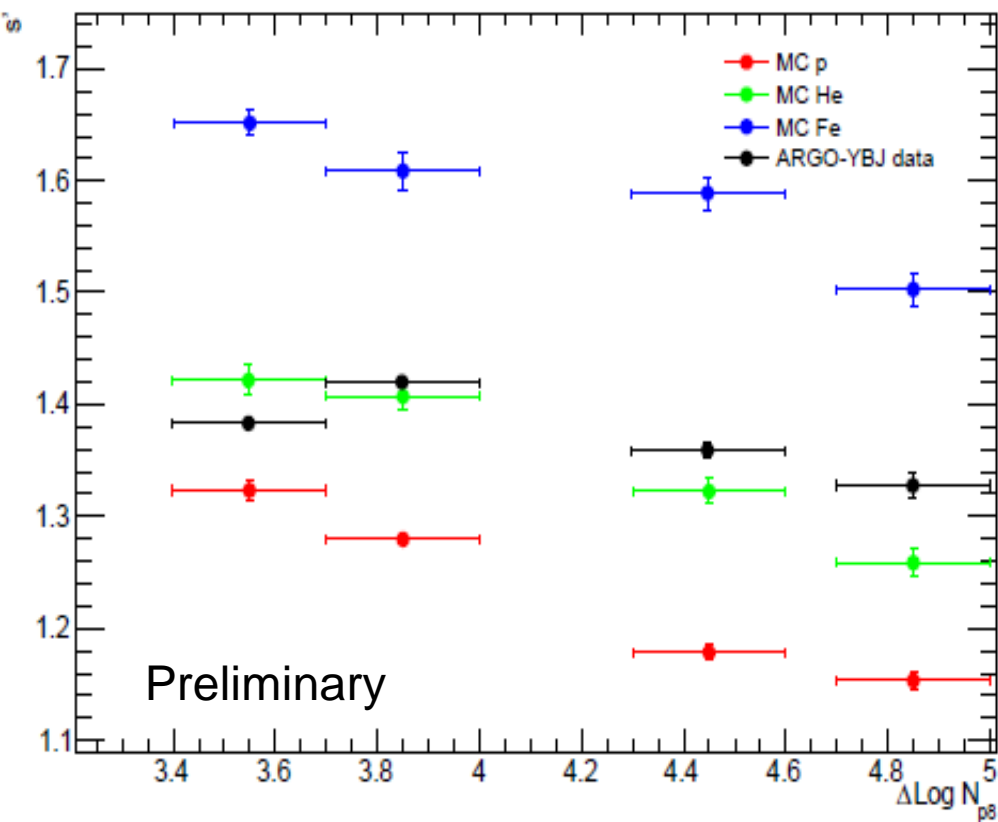


$$\rho'_{NKG} = A \cdot \left(\frac{r}{r_M} \right)^{s'-2} \cdot \left(1 + \frac{r}{r_M} \right)^{s'-4.5}$$

The LDF slope s' is related to the shower age.



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

Summary and Outlook (not including gammas)



- First ideas 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 next year**

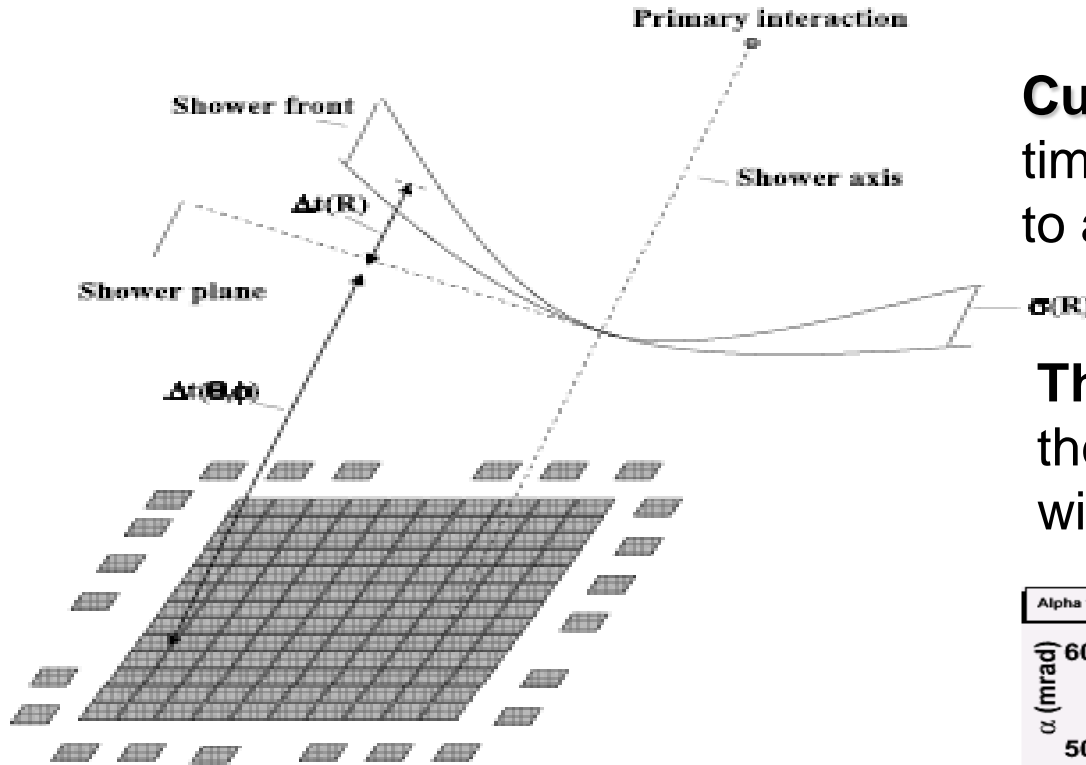
see C. Zhen's talk
for future projects

20 years



More stuff...

Shower front time structure



Curvature:

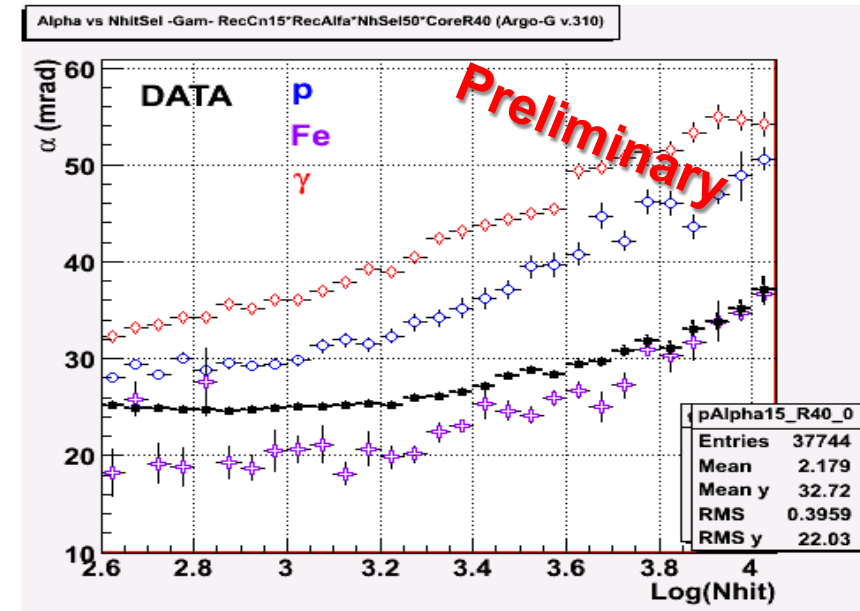
time residuals $\Delta t(R)$ with respect to a **planar fit**

Thickness:

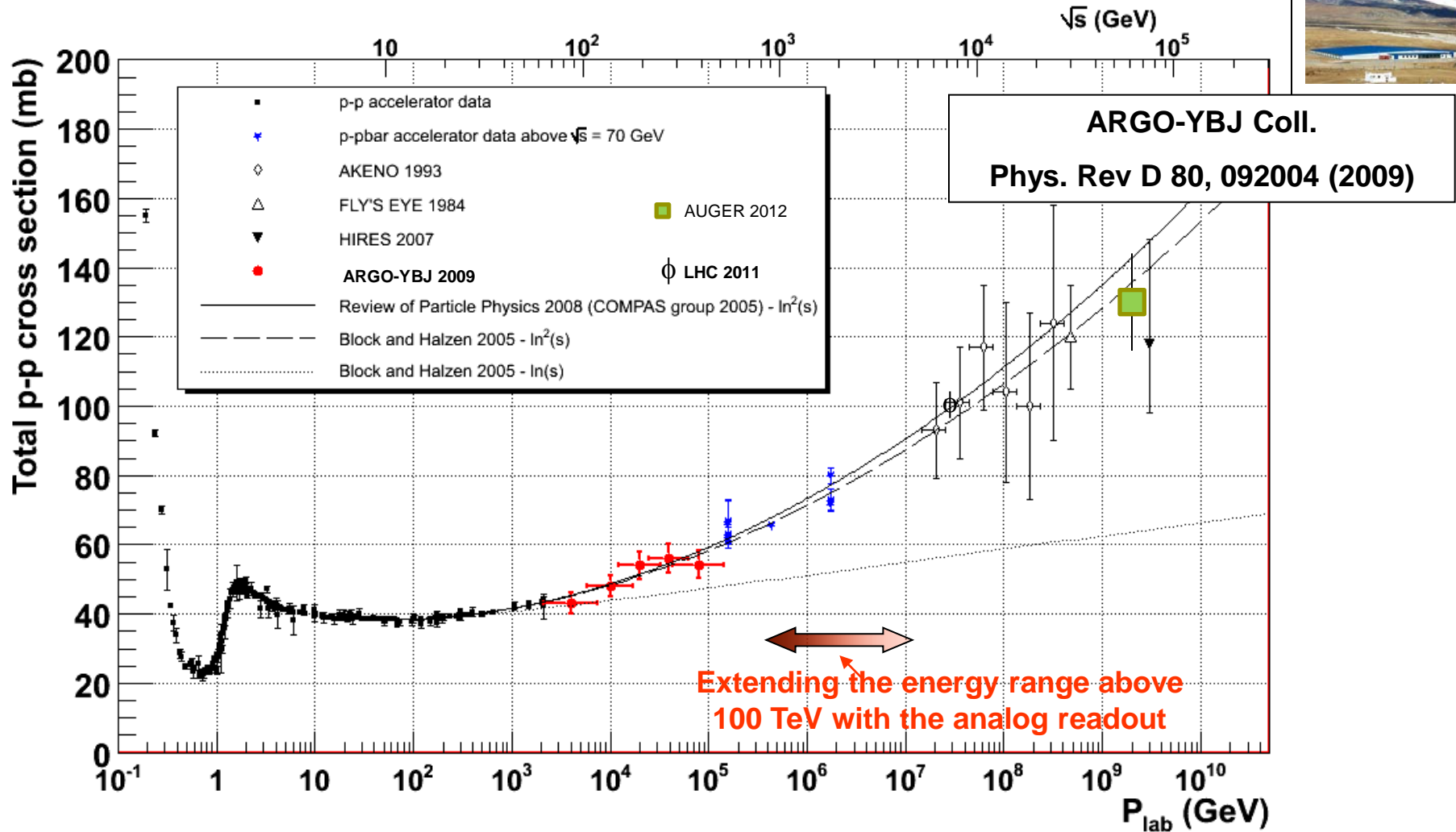
the RMS of time residuals $\sigma(R)$ with respect to a **conical fit**

Conicity parameter α :

Give useful information on **shower age and/or primary mass**



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

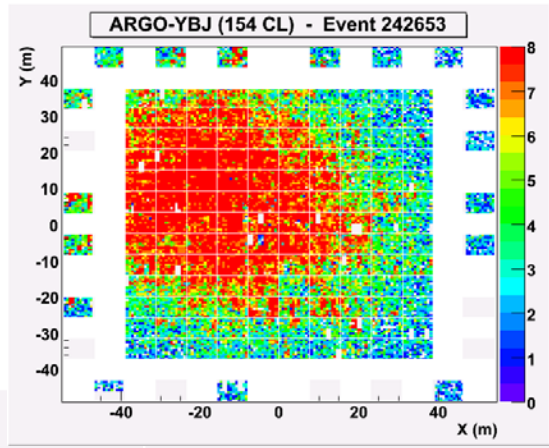
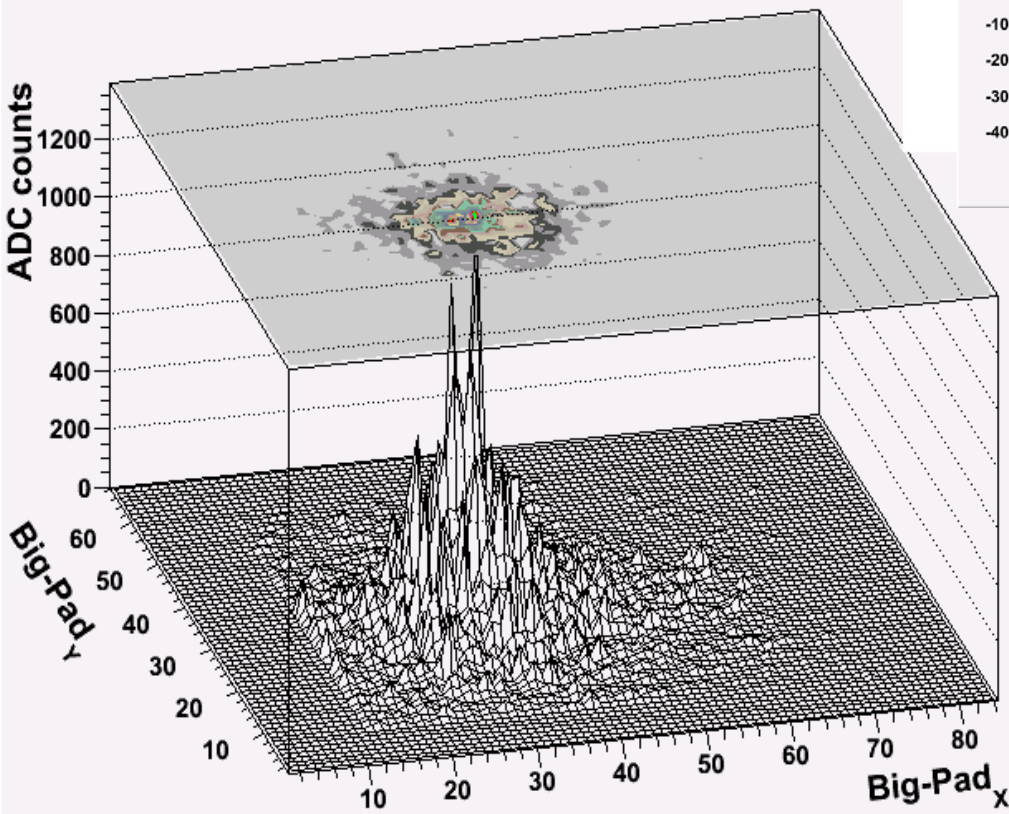
Multicore events with analog data

Preliminary results show the feasibility of these studies.

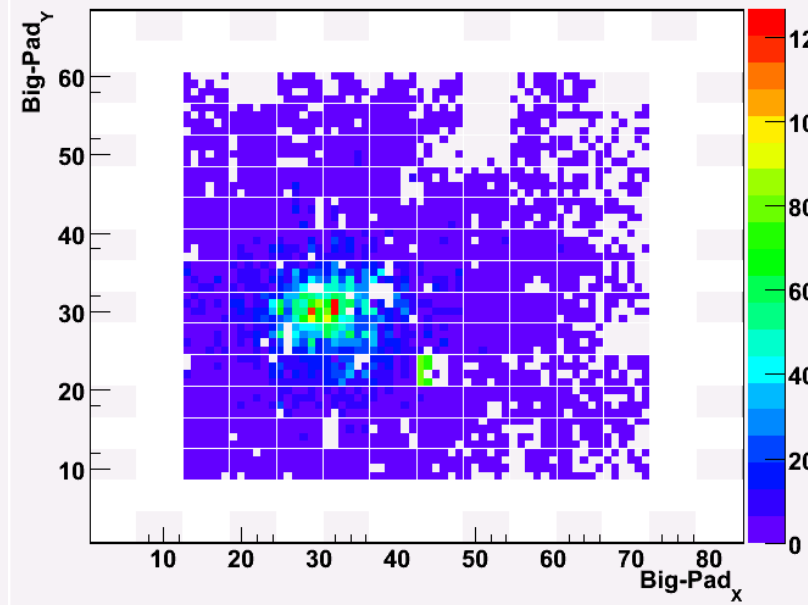
Hadronic physics, p_t distributions,...



ARGO-YBJ (154 CL) - Event 278017



ARGO-YBJ (154 CL) - Event 278017

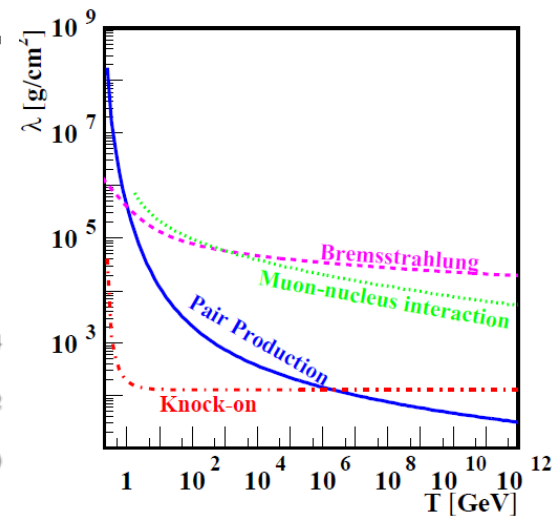
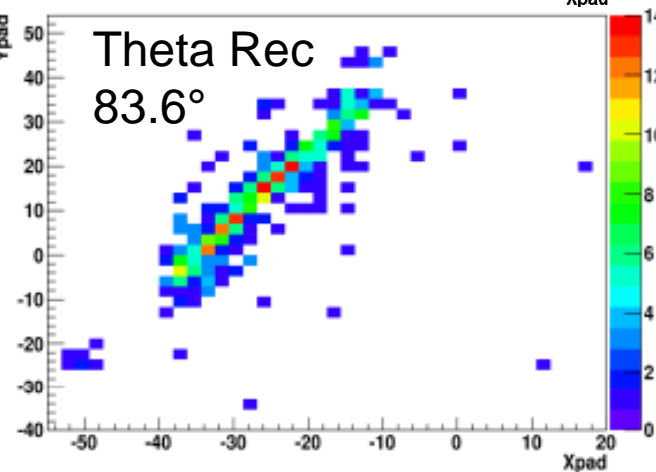
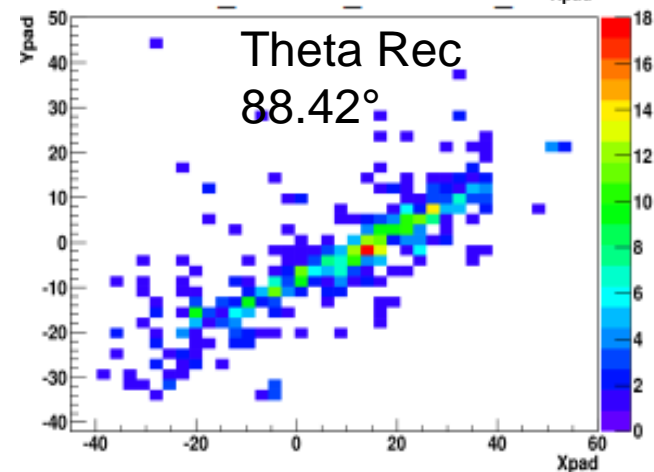
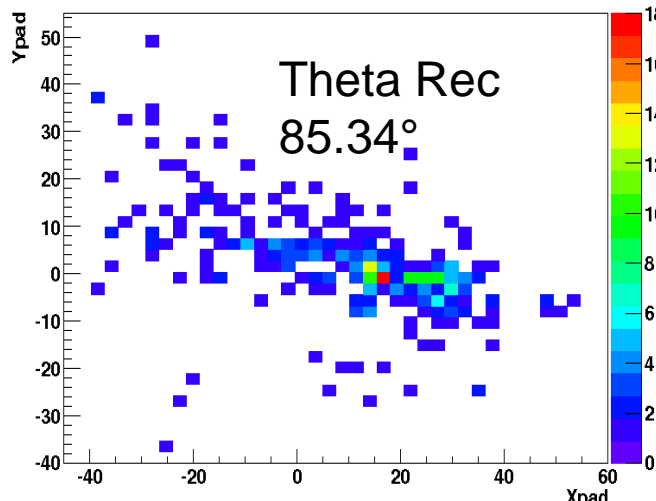
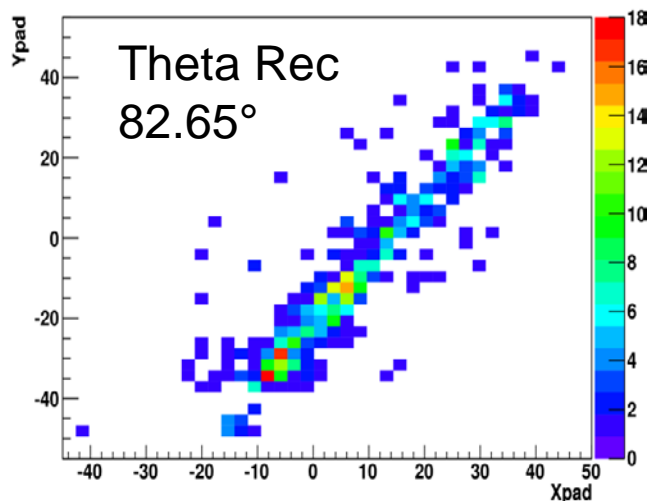


Horizontal Air Showers

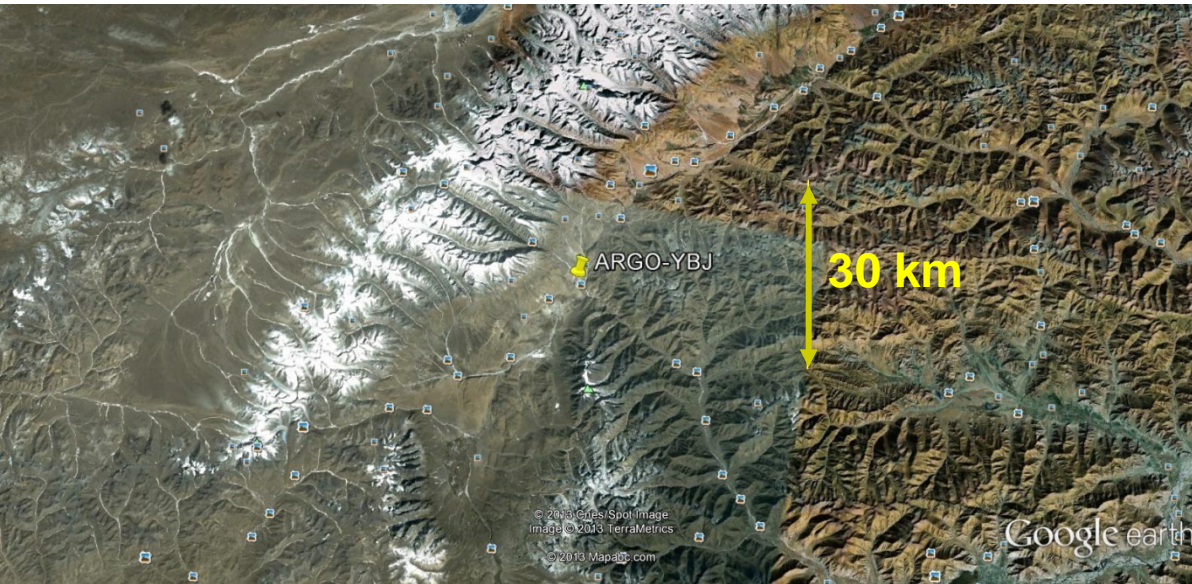
- High energy muon induced events
- Energy spectra
-

$$\theta > 70^\circ \rightarrow 1248 \text{ g/cm}^2$$

$$\theta > 80^\circ \rightarrow 2458 \text{ g/cm}^2$$



Horizontal Air Showers



The HAS flux is anticorrelated with nearby mountain profile

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

