Time structures in shower longitudinal development with ARGO-YBJ detector

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on behalf of

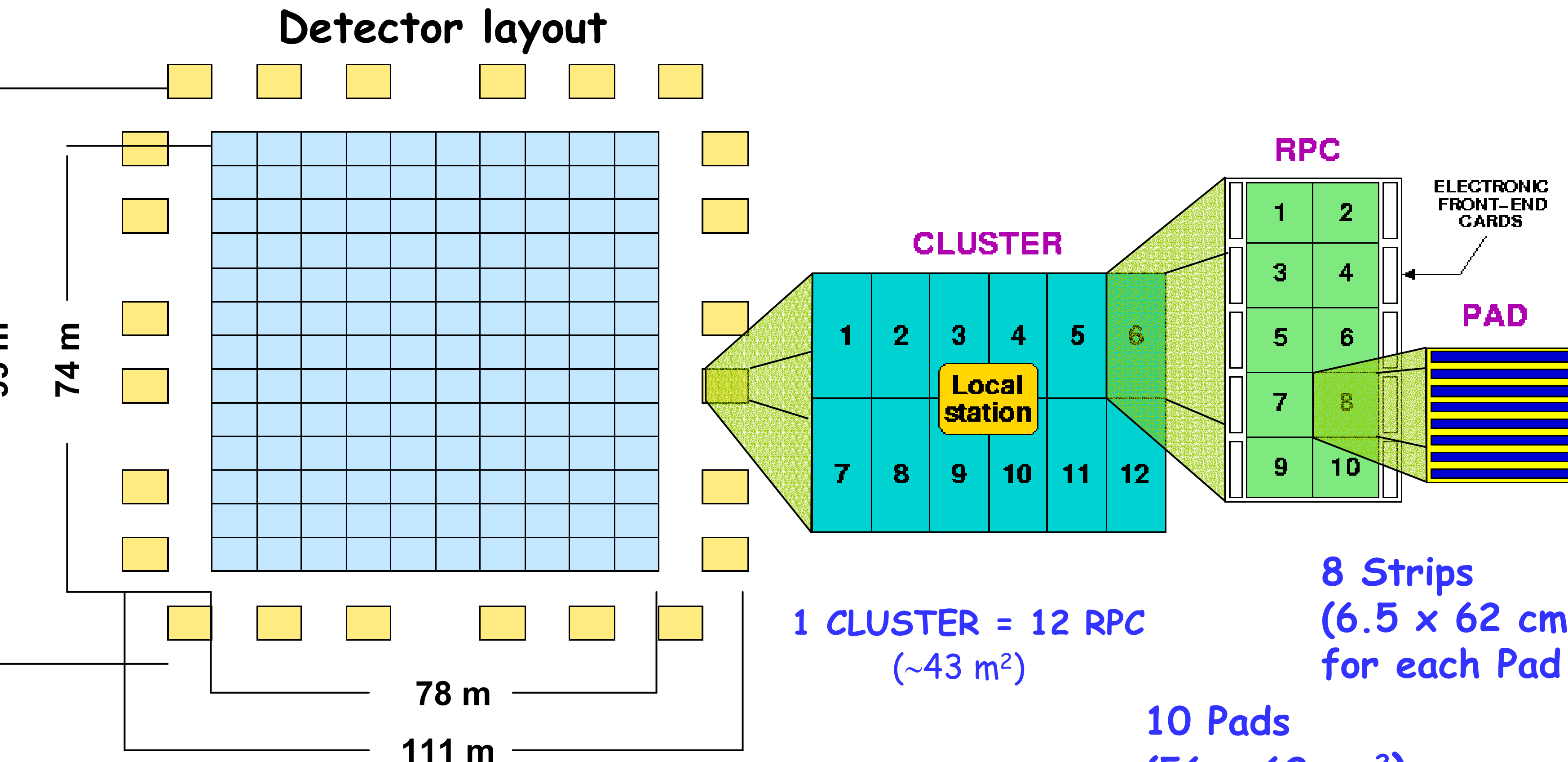
ARGO-YBJ Collaboration

• (Tibet), 4300 m a.s.l.

High Altitude Cosmic Ray Laboratory @ YangBaJing

(Site Coordinates: longitude 90° 31’ 50” E, latitude 30° 06’ 38” N)

ARGO-YBJ layout



1 CLUSTER = 12 RPC
(~43 m^2)

8 Strips
(6.5 x 62 cm^2)
for each Pad

10 Pads
(56 x 62 cm^2)
for each RPC

Layer (~92% active surface) of
Resistive Plate Chambers (RPC),
covering a large area (5600 m^2)
+ sampling guard ring
+ 0.5 cm lead converter

Main detector features and performances

- ✓ Active element: Resistive Plate Chamber ⇒ time resolution ~1 ns
- ✓ Time information from Pad (56×62 cm^2)
- ✓ Space information from Strip (6.5×62 cm^2)
- ✓ Full coverage and large area (~ 10,000 m^2)
- ✓ High altitude (4300 m a.s.l.)

▼

- good pointing accuracy ($\lesssim 0.5°$)
- detailed space-time image of the shower front
- capability of small shower detection (⇒ low E threshold)
- large aperture ($\rightarrow 2\pi$) and high "duty-cycle" ($\rightarrow$100%)

⇒ **continuous monitoring of the sky ($-10° < \delta < 70°$**

Arrival Direction Reconstruction

In EAS experiments for an event E the time t_{EP} can be measured on each fired detector unit P, whose position $(x_{P,} y_P)$ is well known

Primary direction cosines $\quad l_E = \sin\theta_E \cos\phi_E \quad \text{and} \quad m_E = \sin\theta_E \sin\phi_E$

$\theta_E = \text{zenith angle}$

$\phi_E = \text{azimuth angle}$

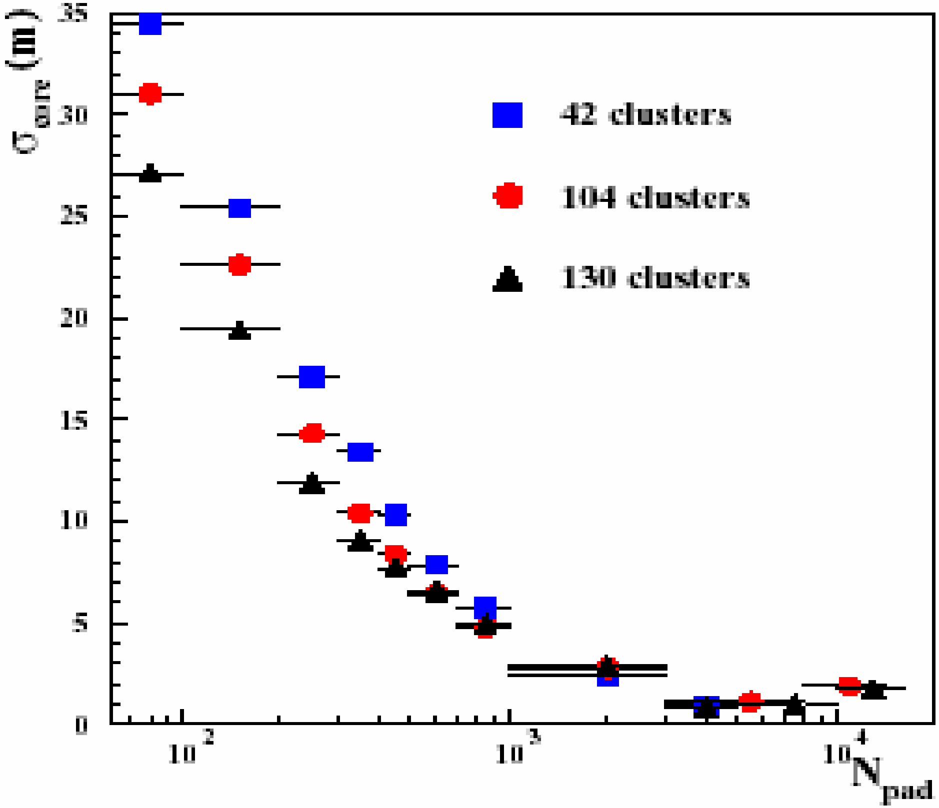
Planar Fit

$$\chi^2 = \sum_P \left(t_P - t_{0E} - \frac{x_P}{c} l_E - \frac{y_P}{c} m_E\right)^2$$

Conical Fit

$$\chi^2 = \sum_P \left(t_P - t_{0E} - \frac{x_P}{c} l_E - \frac{y_P}{c} m_E - \frac{R_P}{c}\alpha\right)^2$$

Core Reconstruction



Shower core position resolution of internal selected protons as a function the pad multiplicity for different detector dimensions.

Timing Calibration

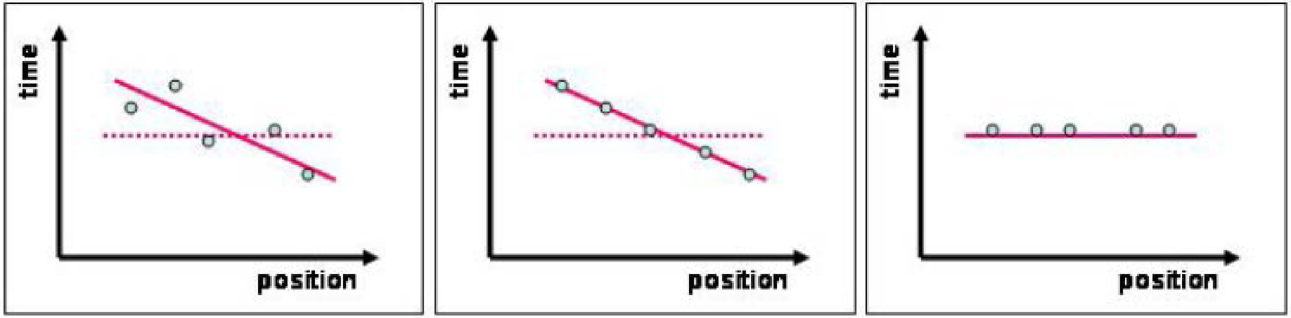
Taking into account the time offset Δ_P typical of the detector unit

Characteristic Plane-equation

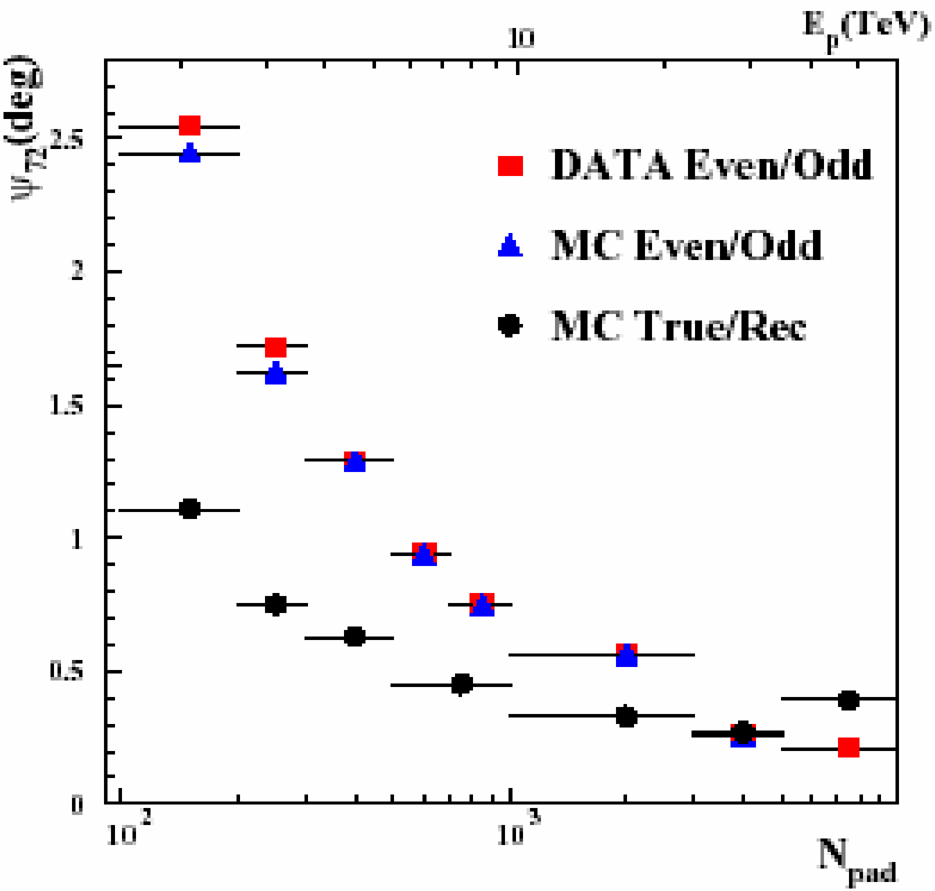
$$c(t_{EP} - \Delta_P - t_{0E}) = l_E x_P + m_E y_P$$

Δ_P= residual correction + systematic correction

- Residuals correction reduces the differences between fit time and measured time
- Systematic correction guarantees the removal of the complete offset

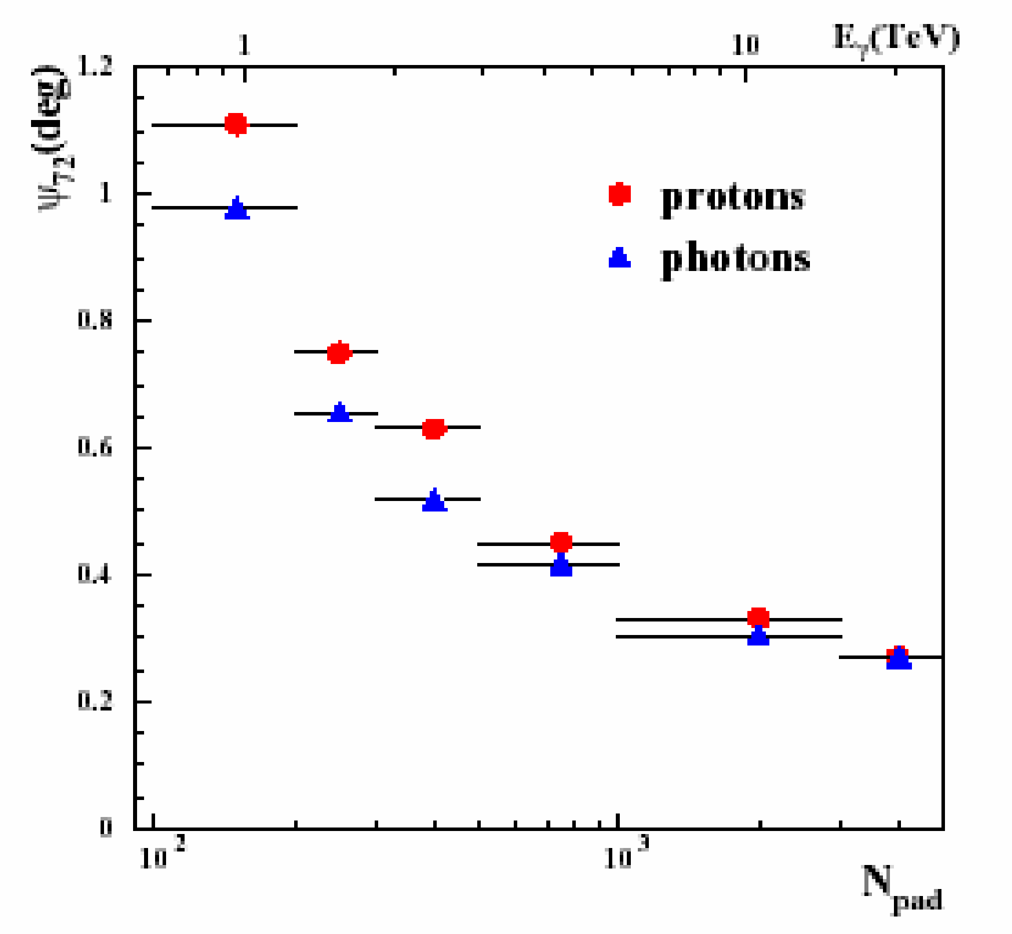


Angular Resolution



The opening angle ψ_{72} as a function of pad multiplicity measured with ARGO-130 compared with MC simulations. The upper scale shows the estimated median energy for proton-induced showers. The error bars refer to the width of the pad multiplicity bins.

Angular Resolution



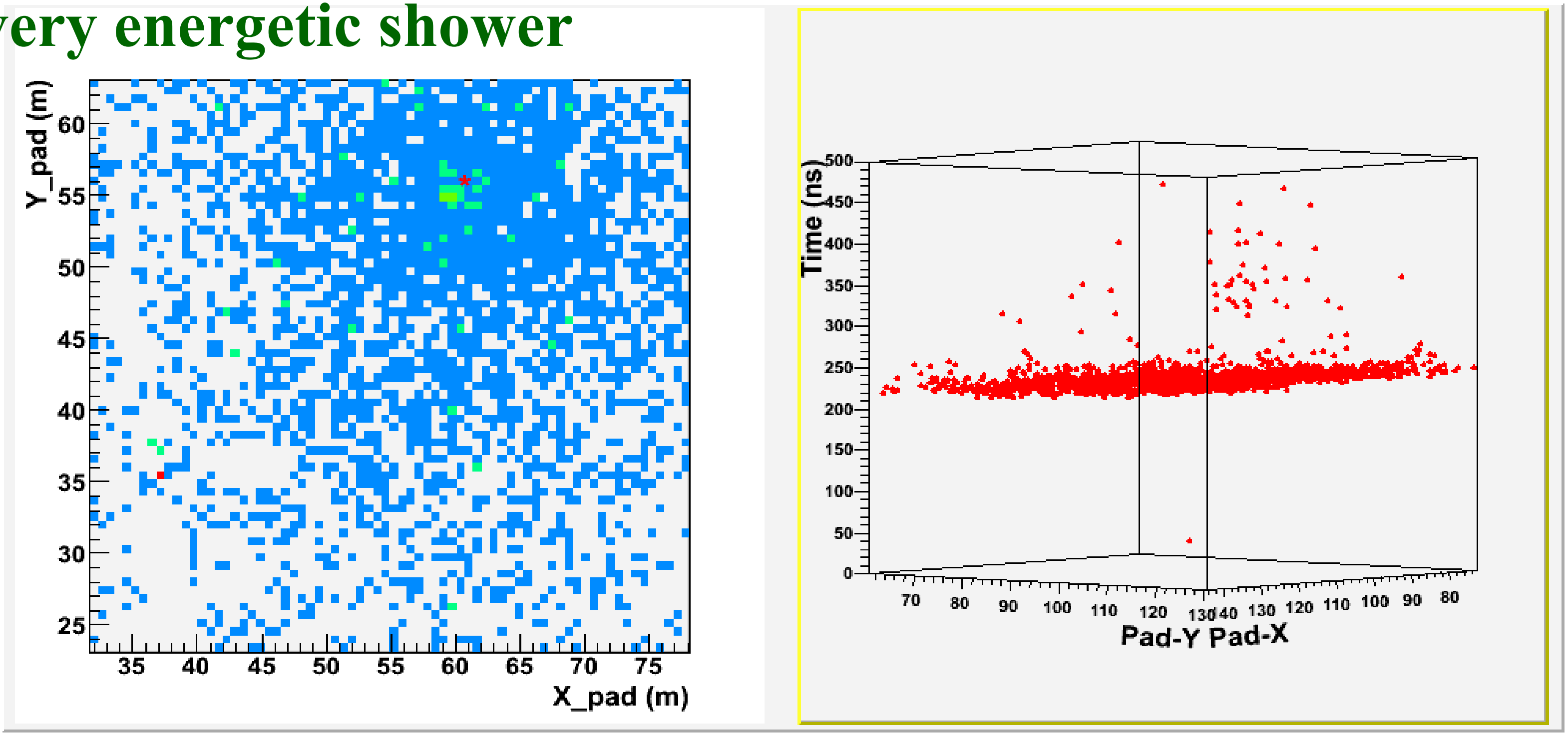
The opening angle ψ_{72} as a function of pad multiplicity for protons and photons. The error bars refer to the width of the pad multiplicity bins. The upper scale shows the estimated median energy for photon-induced events.

ARGO-YBJ performance

High space/time granularity of ARGO-YBJ detector

⇒ capability of detecting several kinds of events, characterized by different topologies and time structures. Deeply inspect a wide and possibly unexpected EAS phenomenology.

A very energetic shower

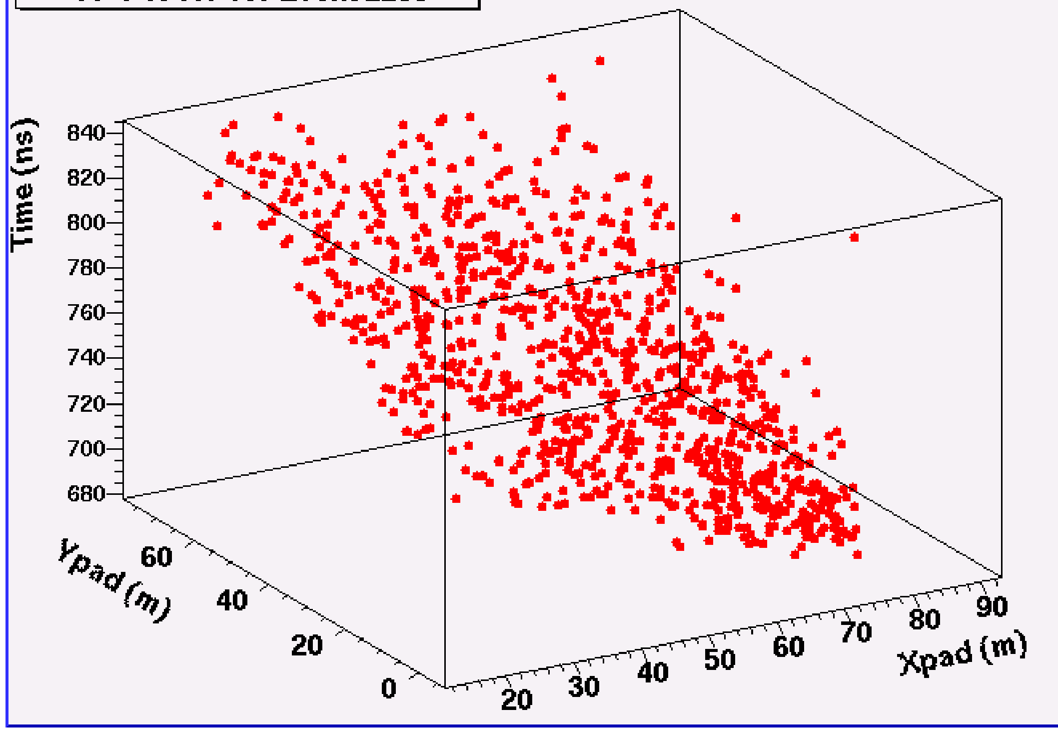


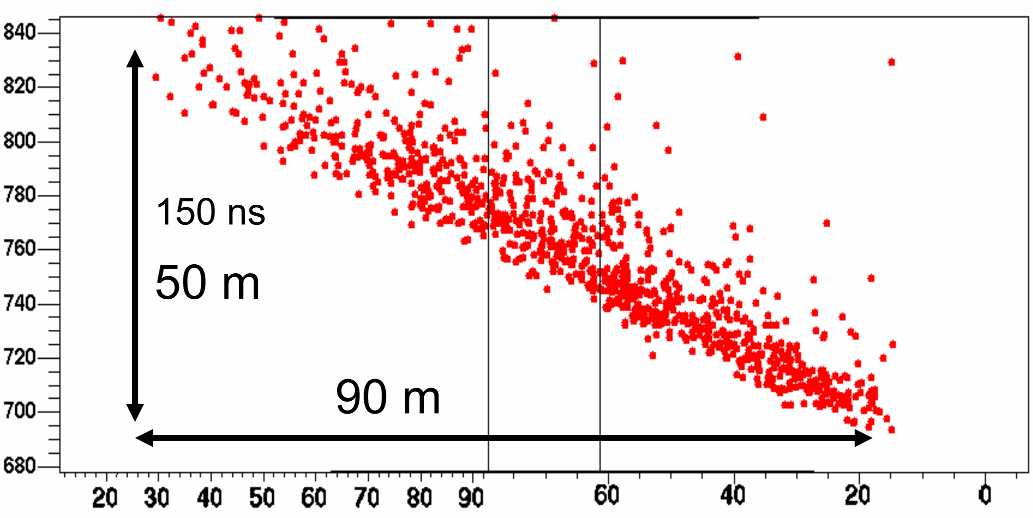
A unique way to study EAS

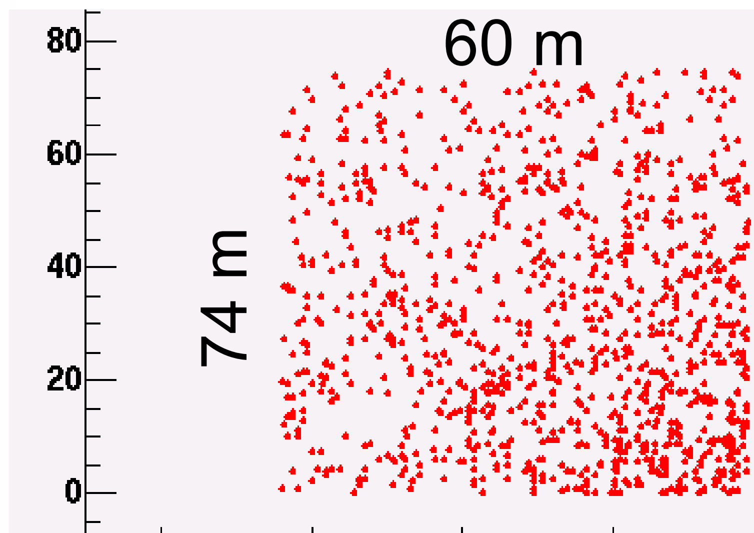
Full space-time reconstruction

Shower topology

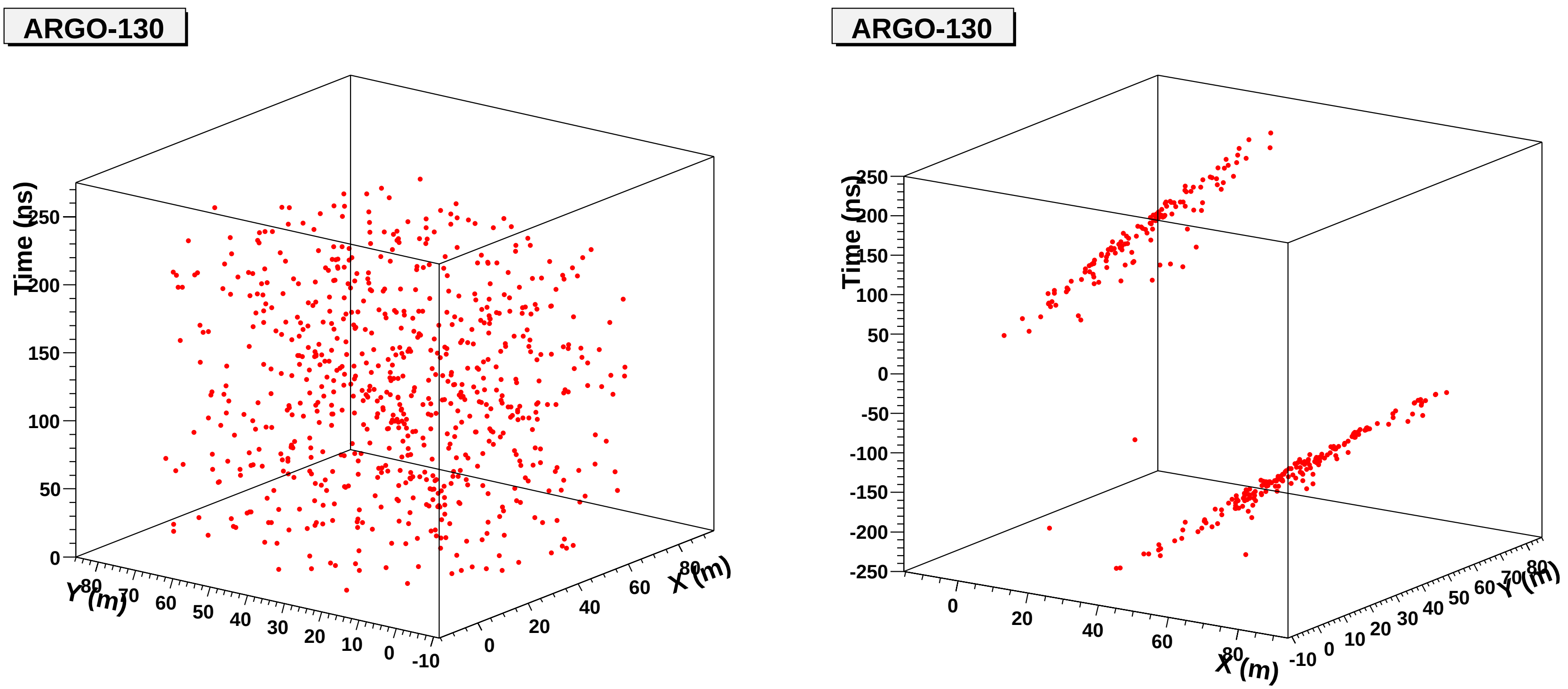
Structure of the shower front







Time structure of EAS front

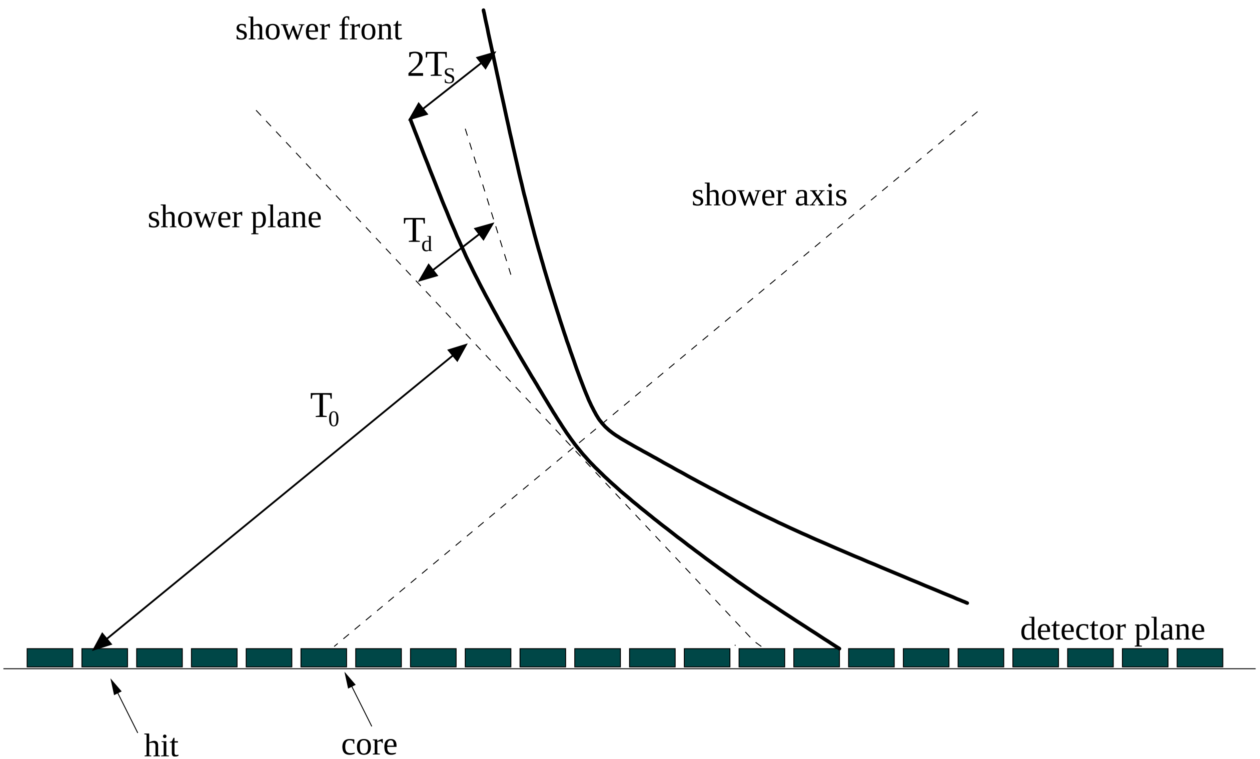


Events with large rms of time residual respect to a conical fit

Time structure of EAS front

- The high space-time granularity of the ARGOYBJ detector allows a fine sampling of the shower front close to the core.
- The time structure of the shower disk has been studied as a function of the distance to the shower axis up to 40 m in 1 m bins.
- The curvature and shower thickness have been investigated in the energy range between few TeV up to 20 TeV.

Time structure of EAS front



❖The <u>curvature</u> (T_d) of the shower front as the mean of time residuals with respect to a planar fit

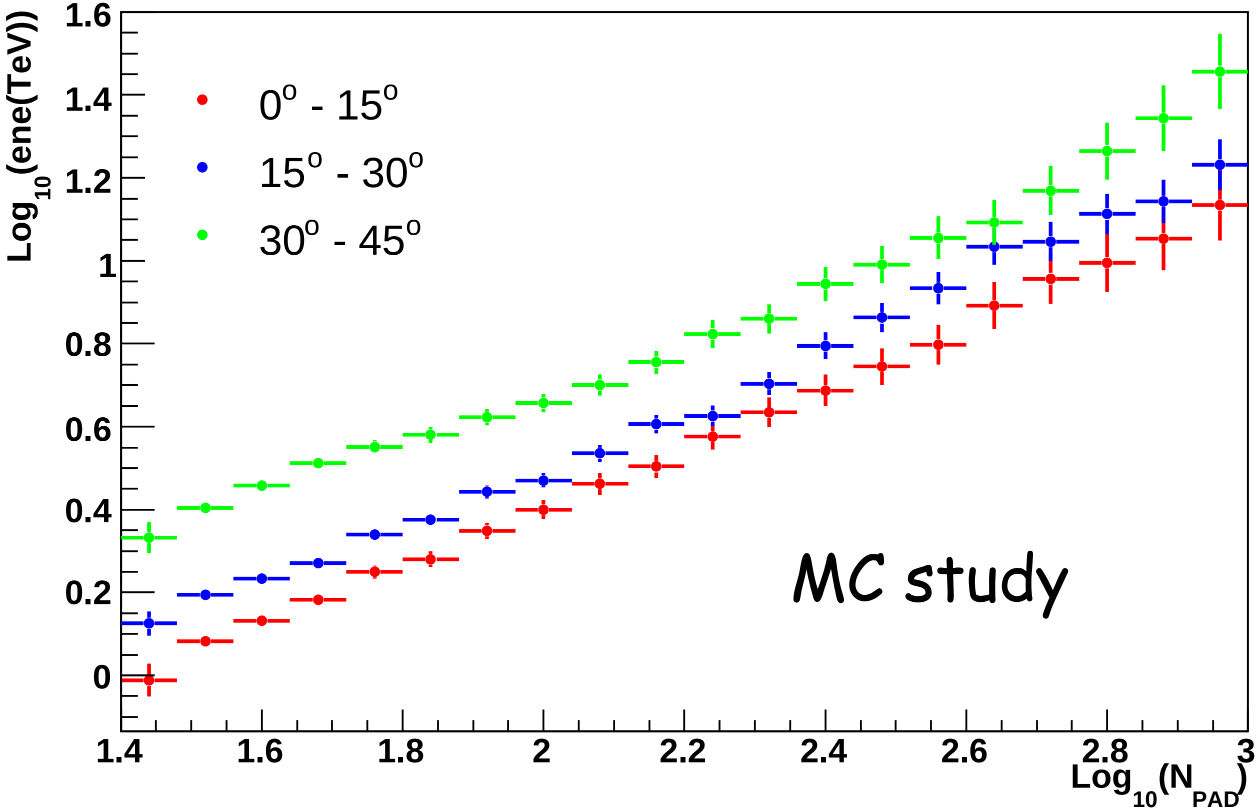
❖The <u>shower thickness</u> (T_S) of the shower front as the root mean square (RMS) of time residuals with respect to a conical fit

The Sample

- 10^6 well reconstructed events
- Core in 20 x 20 m^2
- Hit multiplicity > 200
- Quality cut on χ^2/ndof

Multiplicity – Energy correlation

Multiplicity -> Average primary energy (0-15°)



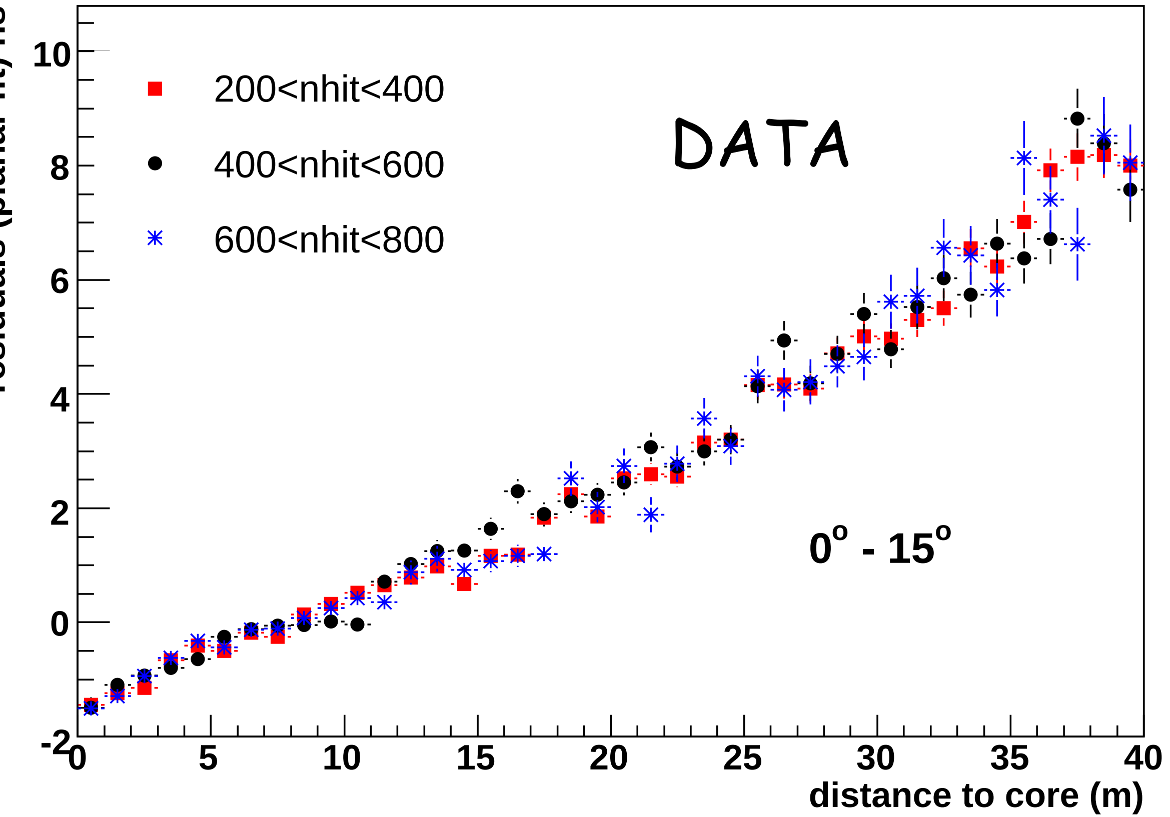
200 N_{pad} -> 4 TeV

400 N_{pad} -> 7 TeV

600 N_{pad} -> 11 TeV

800 N_{pad} - > 15 TeV

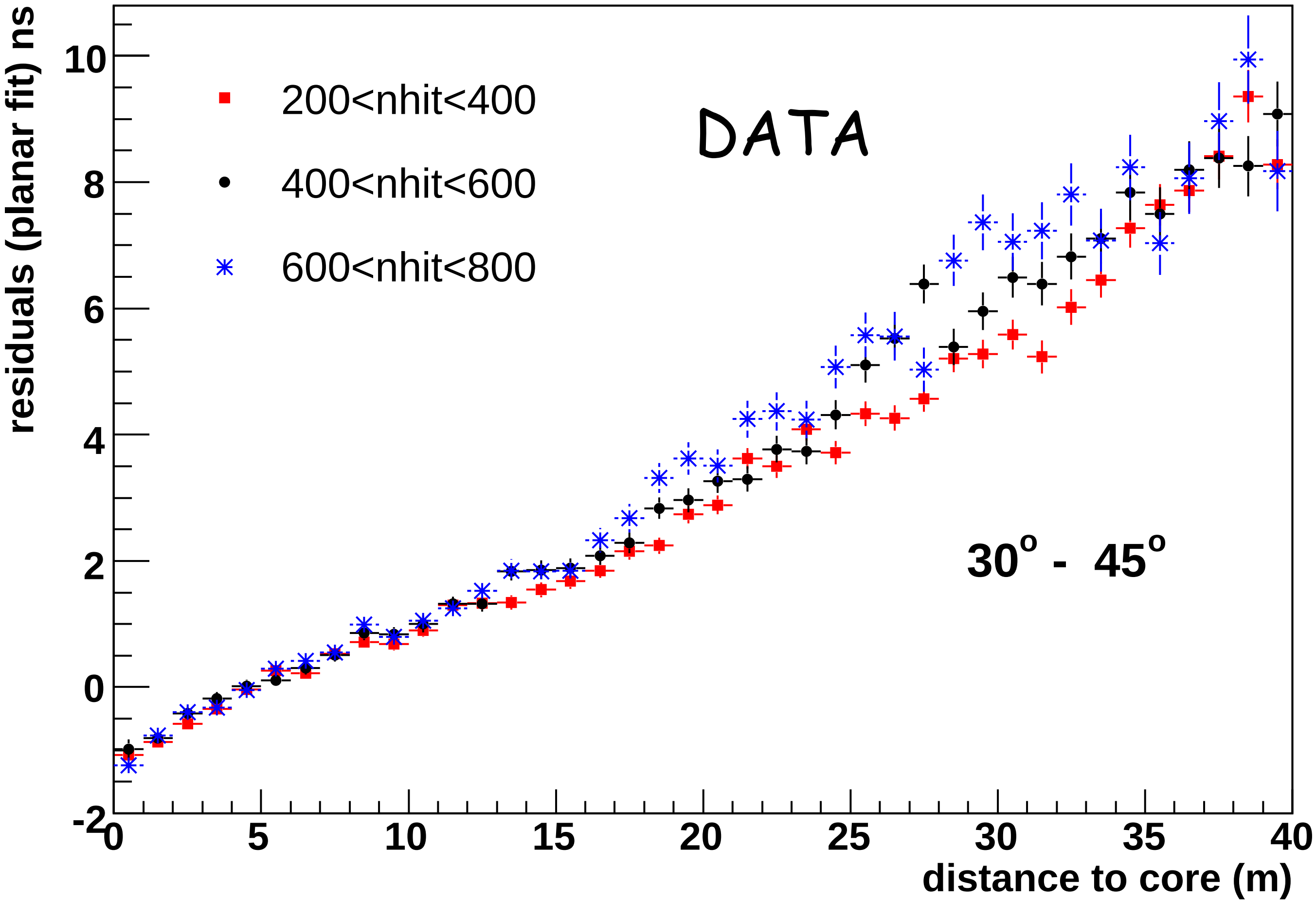
Curvature



- mean of time residuals with respect to a planar fit as a function of the distance to the shower axis for different pad multiplicities and for zenith angles < 15°.

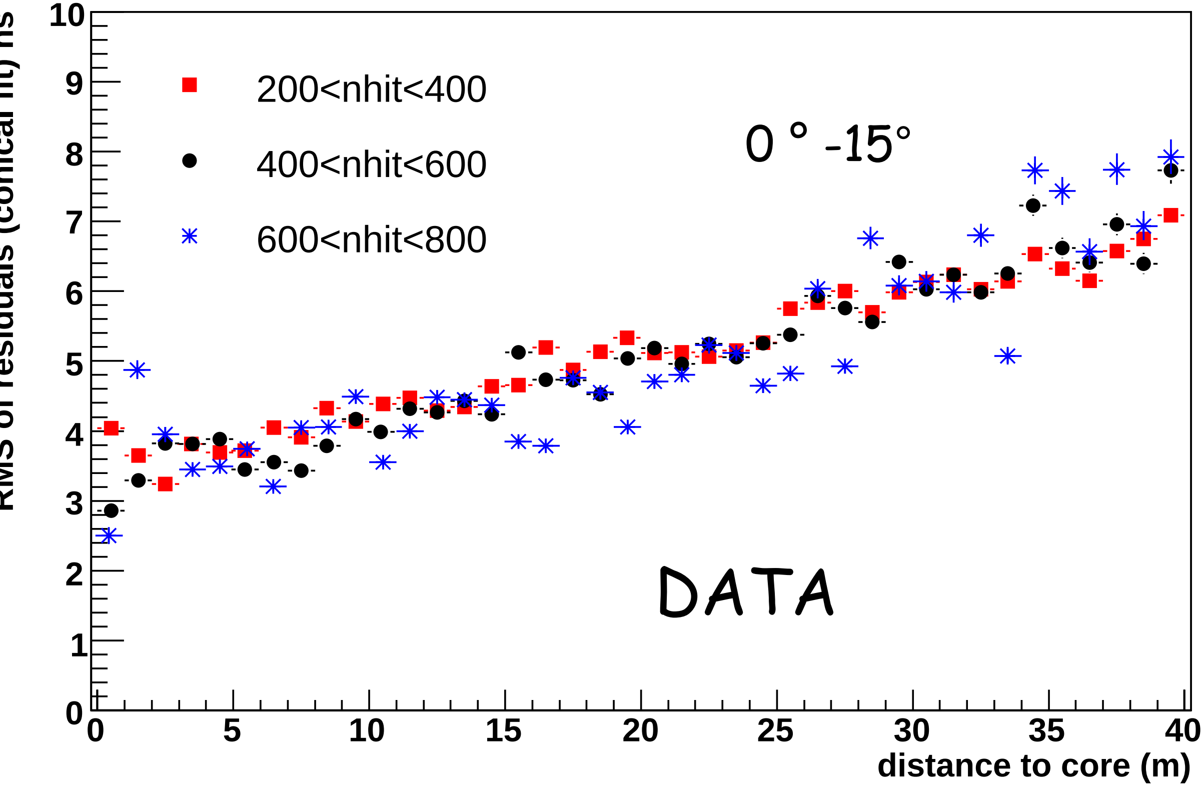
- The deviation from a planar fit increases with distance (up to about 8 ns a 40 m) and depends only weakly on hit multiplicity in the considered energy range.

Curvature



residuals (planar fit) ns
10
8
6
4
2
0
-2
0
5
10
15
20
25
30
35
40
distance to core (m)
200<nhit<400
400<nhit<600
600<nhit<800
DATA
30° - 45°

Thickness of shower front



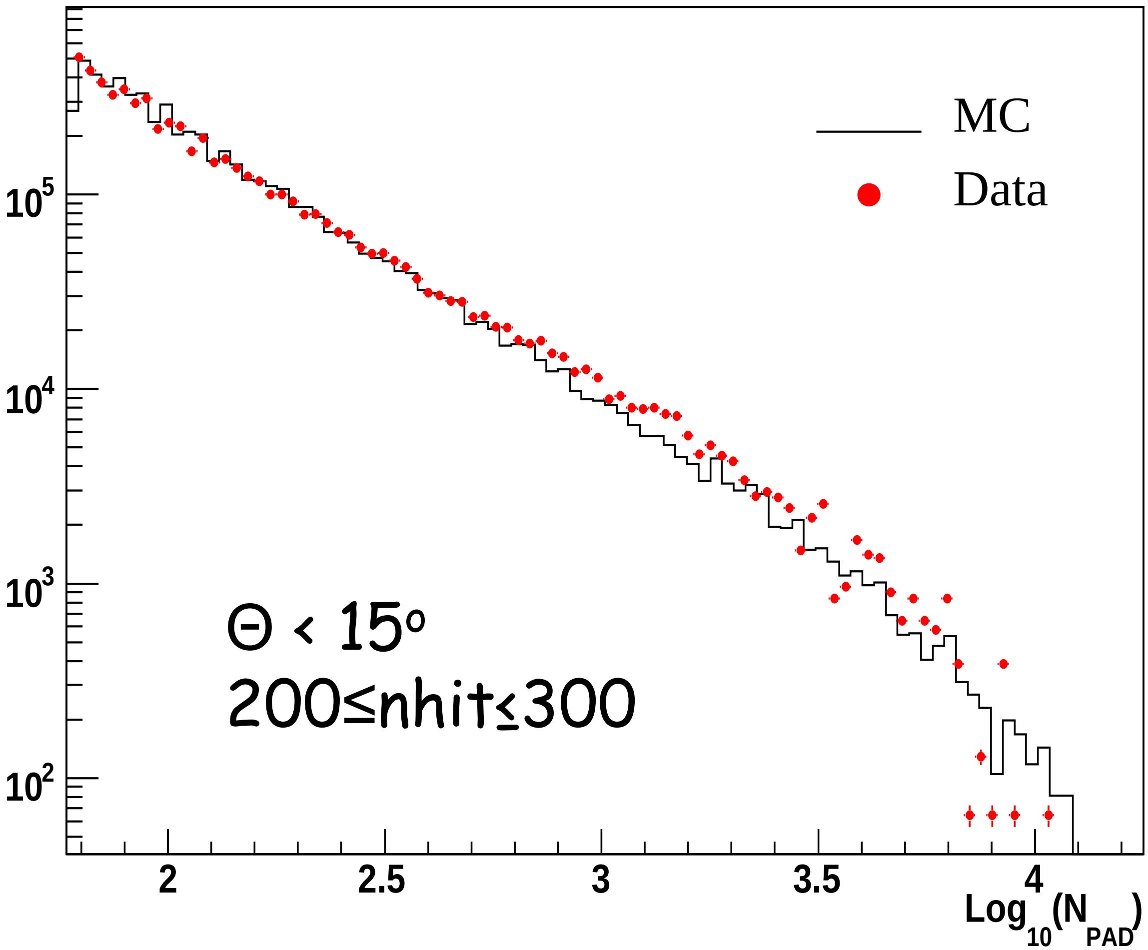
- RMS of time residuals with respect to a conical fit as a function of the distance to the shower axis for different pad multiplicities and for zenith angles <15°.

- The thickness of the shower front increases with distance (up to about 7 ns at 40 m) without any significant dependence on hit multiplicity in the considered energy range.

Comparison of simulation to data

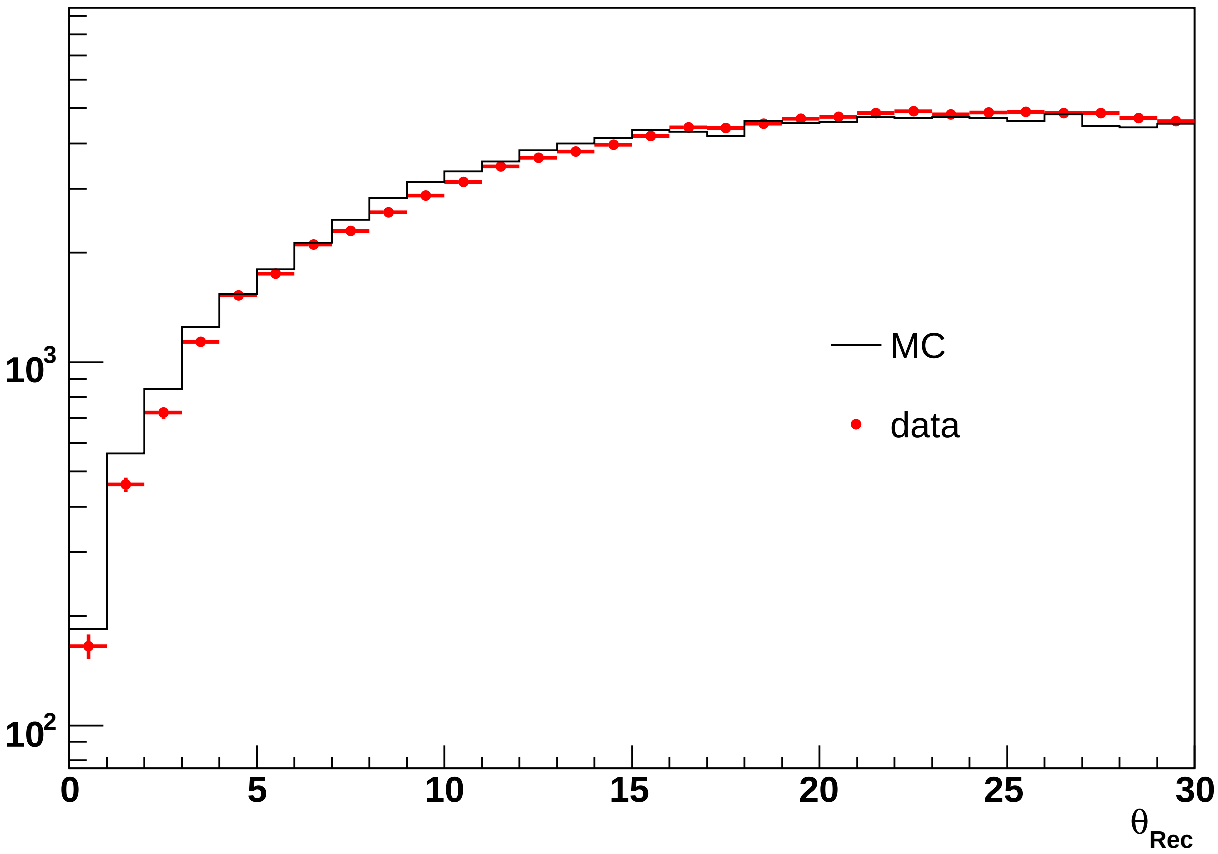
- 6×10^6 CORSIKA proton showers
- Zenith angle < 45°
- Spectral index -2.7
- Energy range 100 GeV – 1000 TeV
- Detector simulation based on GEANT3

Pad multiplicity



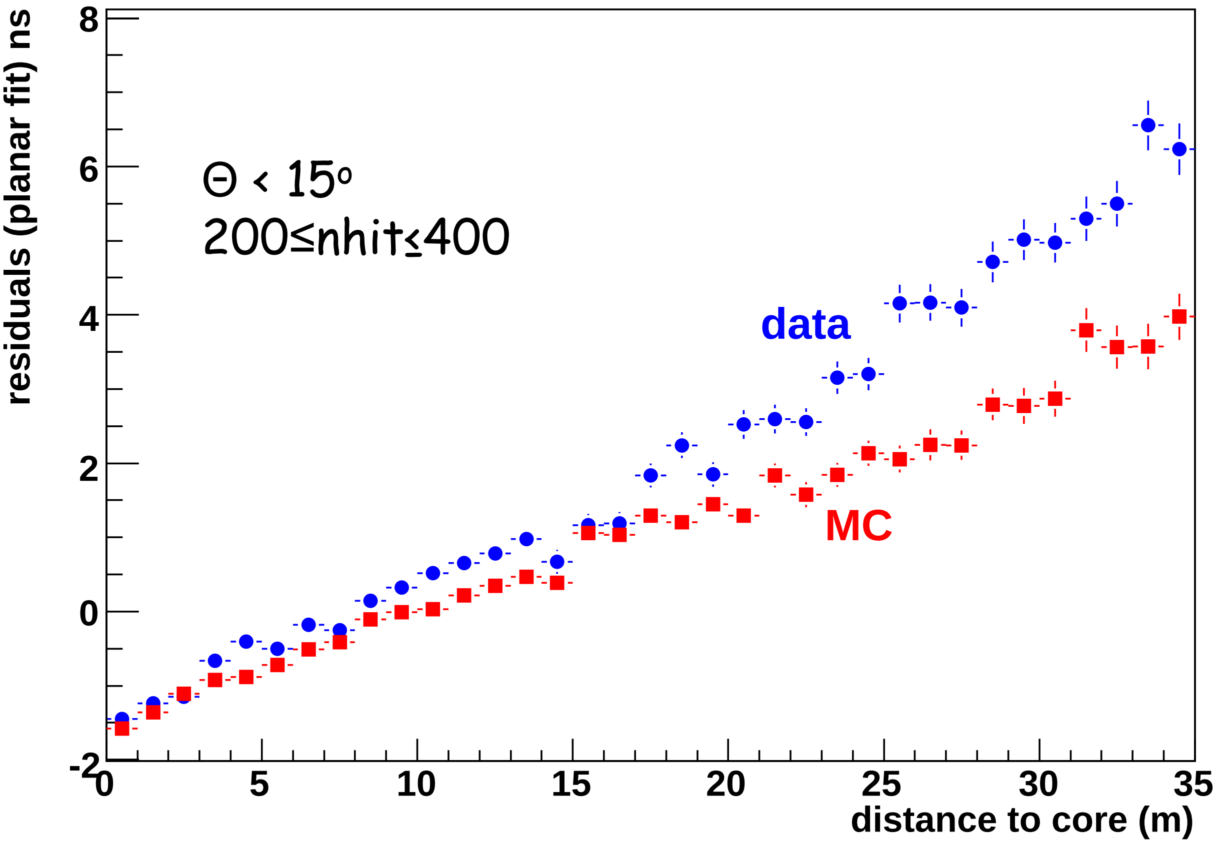
Distribution of pad multiplicity from simulation (solid line) in comparison with data (bullets), for zenith angle <15°.

Reconstructed zenith angle



Distribution of reconstructed θ from simulation (solid line) in comparison with data (bullets).

Curvature



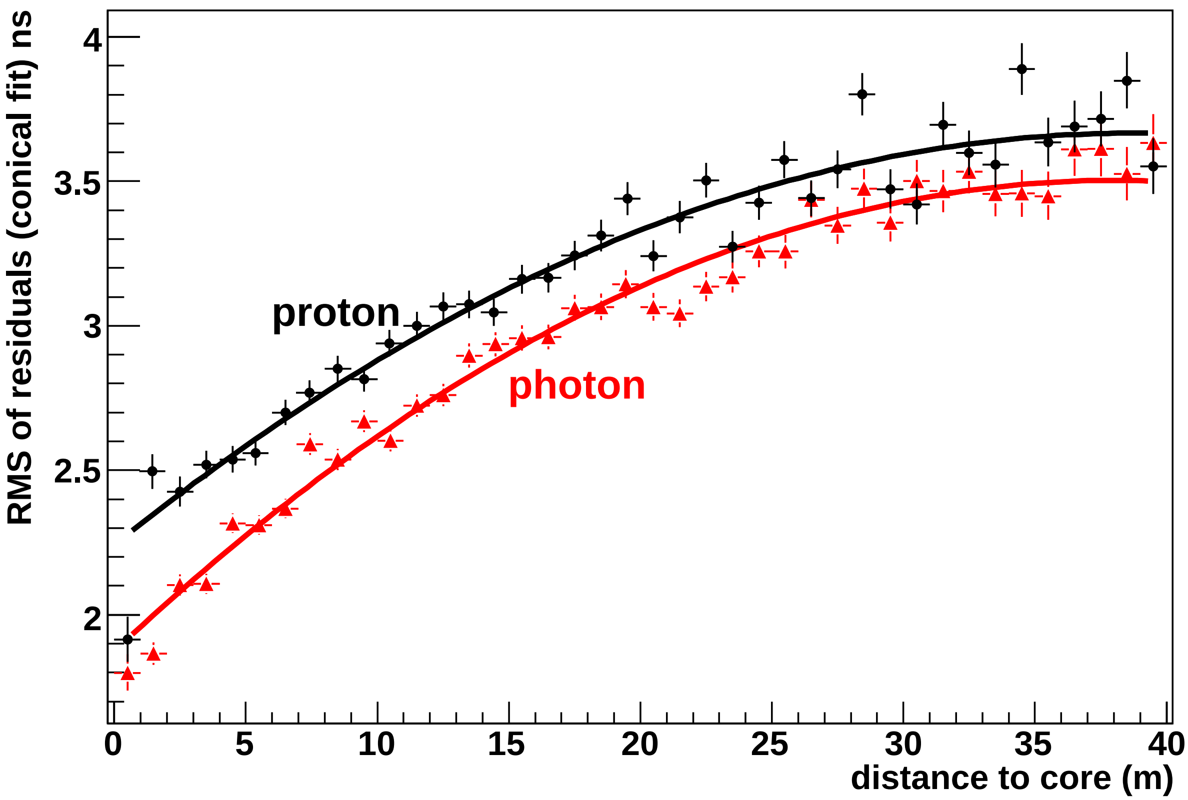
time residuals with respect to a planar fit for data (blue bullets) and simulatio (red boxes).

An agreement is foun up to a distance of 15 m. At larger distance the measured front curvature tends to be larger than predicted by simulation.

Photons and protons comparison

- 5000 photons and 5000 proton showers
- Zenith angle < 15°
- Energy range 3 - 10 TeV
- Core in 40 x 40 m^2
- Hit multiplicity > 200

Thickness of shower front

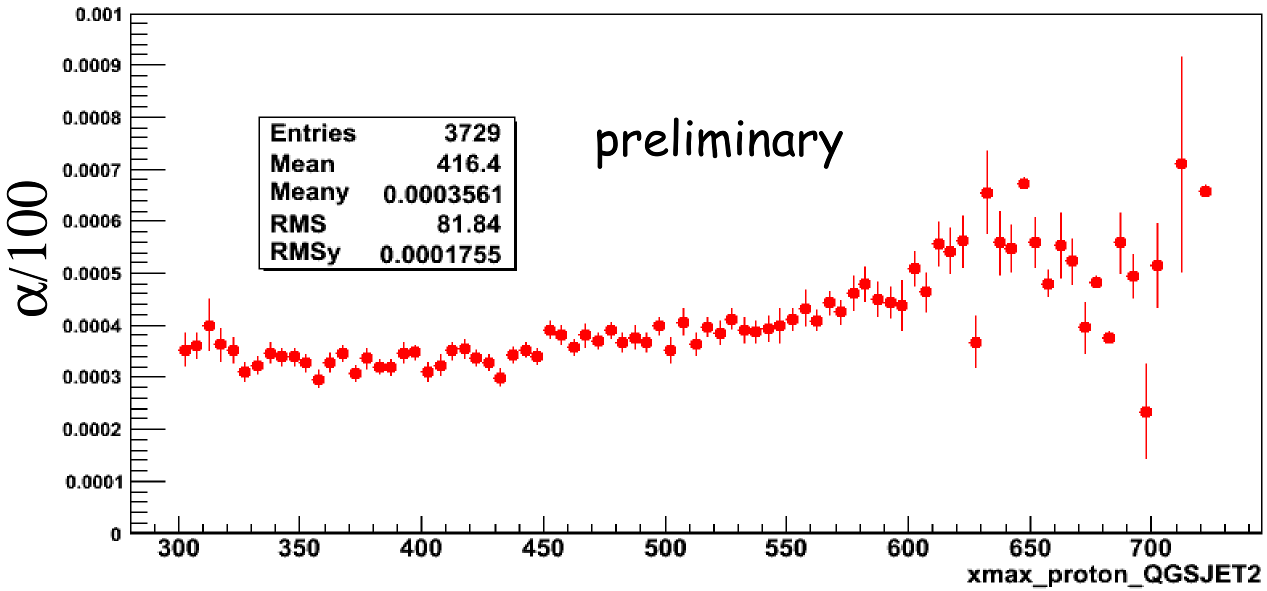


Hint for composition studies

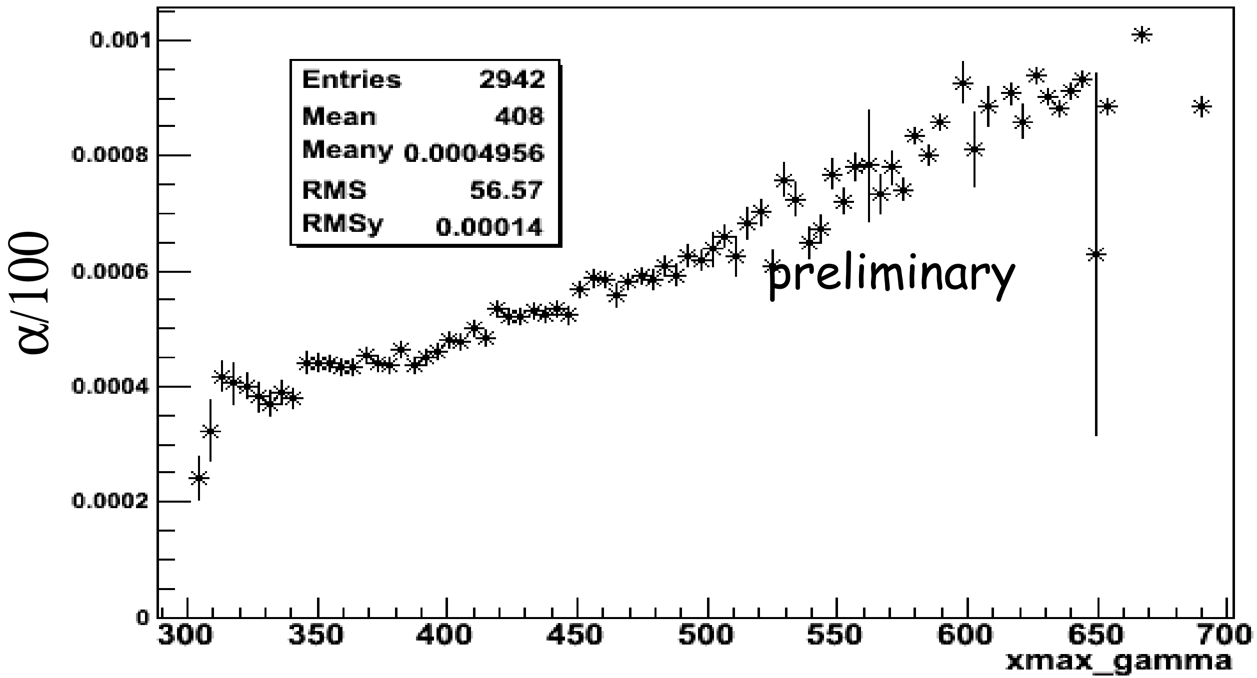
Though the measured difference is very small (at the level of the time resolution of the detector), this observable could be investigated in order to provide, on statistical basis, a clue to γ/hadron separation and mass composition studies.

Further studies and an extended simulation with heavier primaries are planned.

Conicity vs Xmax



Conicity vs Xmax



Conclusions

- Space-time granularity -> powerful tool for the study of time structure in cosmic ray showers
- A measure of the curvature and thickness of the shower front has been presented
- The impact of these observables on mass composition studies has been discussed and the potentialities of the method investigated