Hadron background rejection for Very High Energy gamma ray astronomy with ARGO-YBJ

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On behalf of the ARGO-YBJ Collaboration

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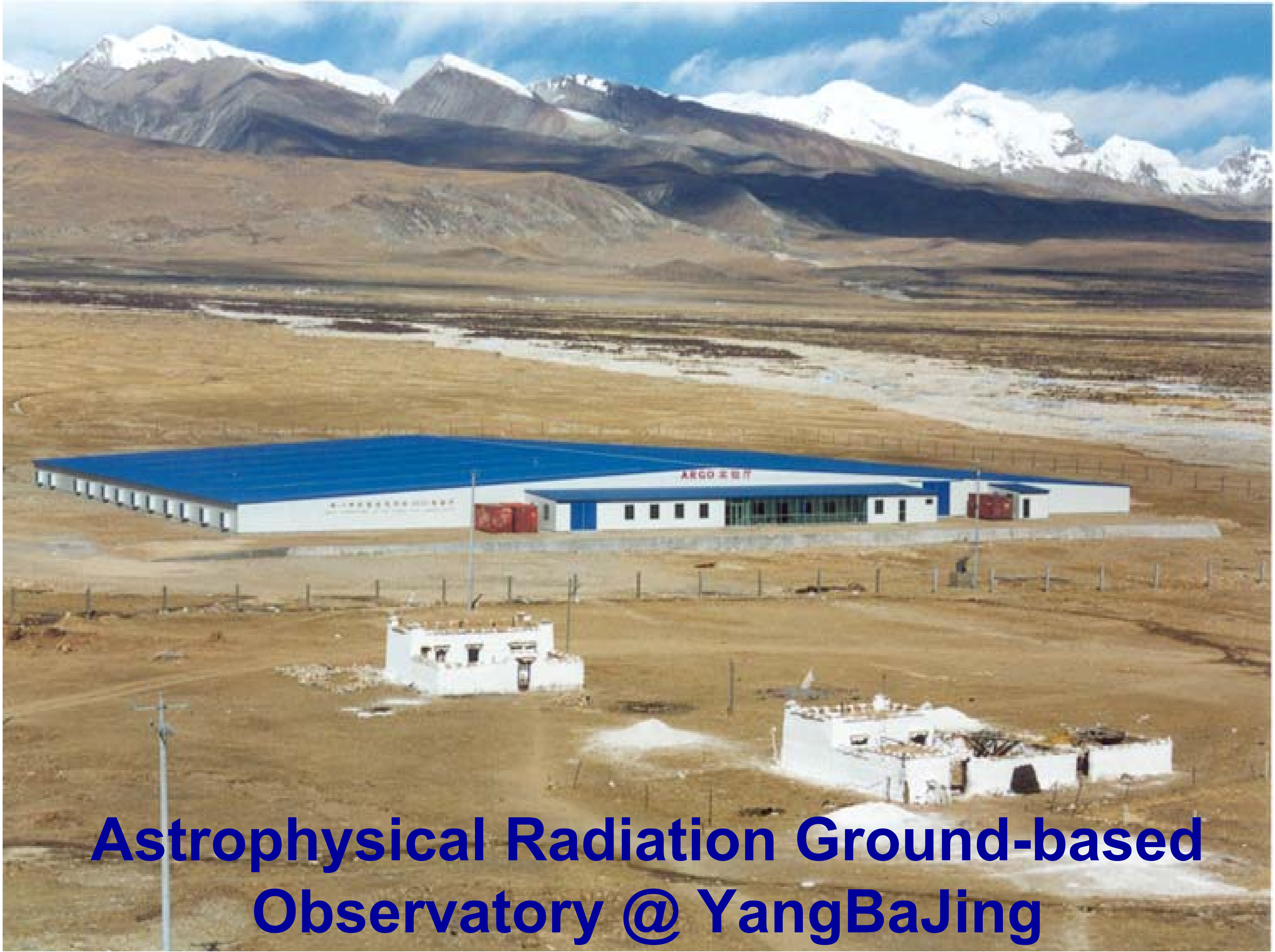
Physics goals

- **γ-Ray Astronomy**:
  Search for point-like galactic and extra-galactic sources at few hundreds GeV energy threshold
- **Diffuse γ-Rays**
  from the Galactic plane and SuperNova Remnants
- **Gamma Ray Burst physics** (full GeV / TeV energy range)
- **Cosmic ray physics**:
  - anti-p / p ratio at TeV energy
  - spectrum and composition around “knee” ($E_{th} \sim 10$ TeV)
- **Sun and Heliosphere physics** ($E_{th} \sim 10$ GeV)

through **the observation of *Extensive Air Showers* produced in the atmosphere by γ’s and primary nuclei**

The ARGO-YBJ experiment

- **Collaboration between:**
  - **Istituto Nazionale di Fisica Nucleare (INFN) – Italy**
  - **Chinese Academy of Science (CAS)**
- **Site: Cosmic Ray Observatory @ Yangbajing (Tibet), 4300 m a.s.l.**

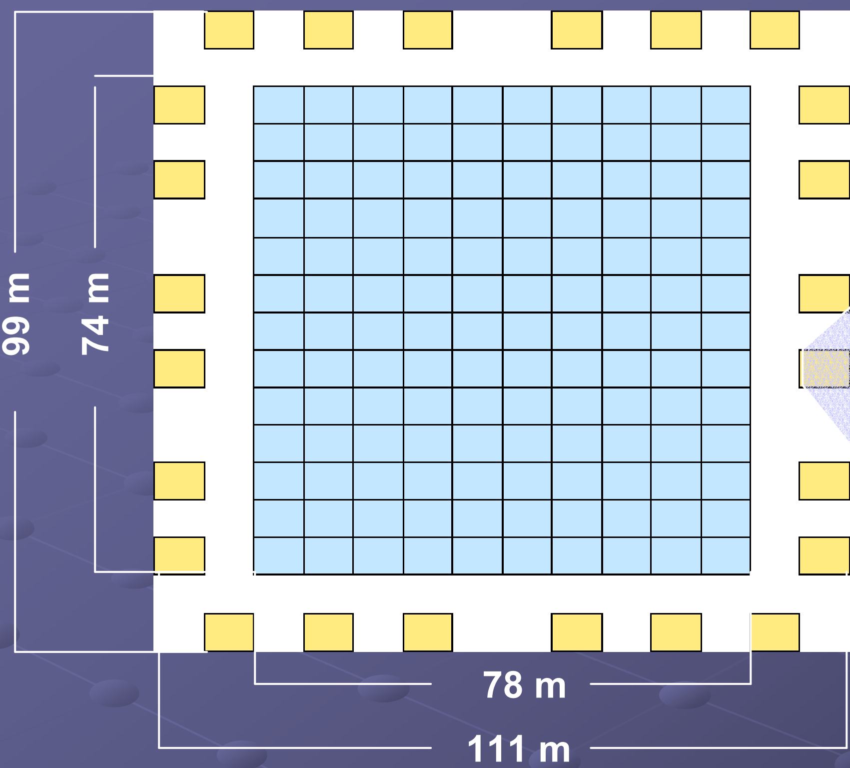

ARGO
Astrophysical Radiation Ground-based Observatory @ YangBaJing

High Altitude Cosmic Ray Laboratory @ YangBaJing

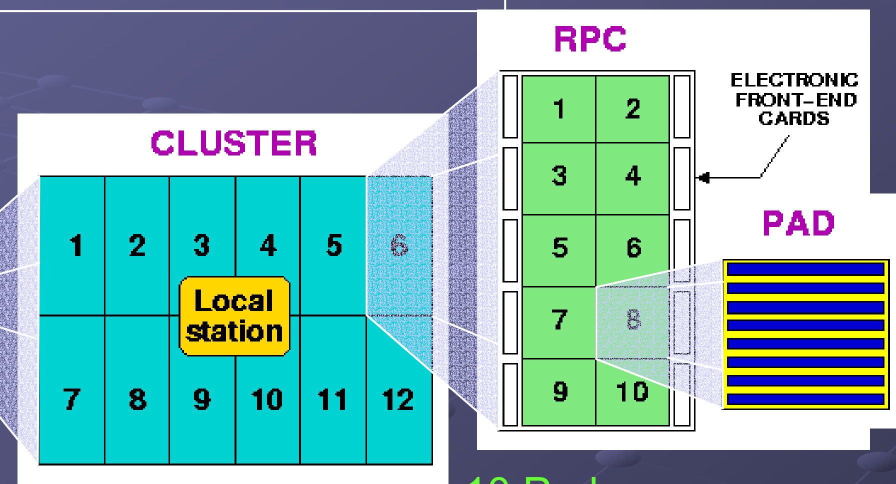
(Site Coordinates: longitude 90° 31’ 50” E, latitude 30° 06’ 38” N)

ARGO-YBJ layout

Detector layout



time resolution ~1 ns
space resolution = strip

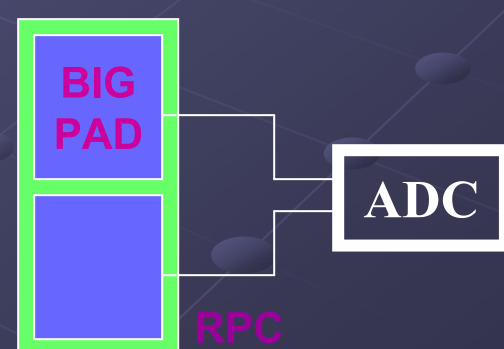


1 CLUSTER = 12 RPC
(~43 m^2)

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

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

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



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

Main detector features and performance

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

▼

- good pointing accuracy (≤1°)
- detailed space-time image of the shower front
- capability of small shower detection (⇒ low E threshold)
- large aperture (→2π) and high "duty-cycle" (→100%)

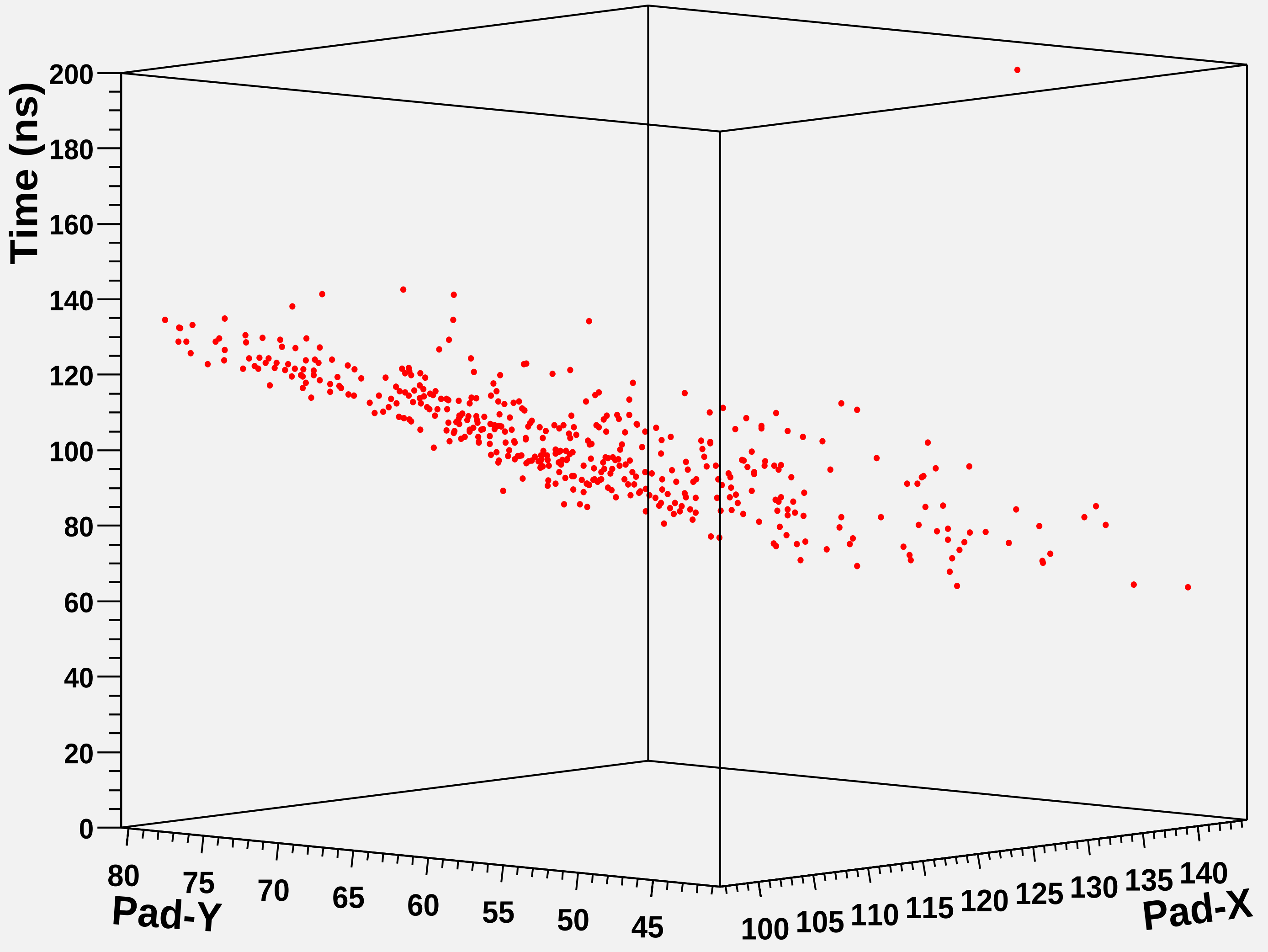
⇒ continuous monitoring of the sky ($-10° < \delta < 70°$)

Experiment Hall

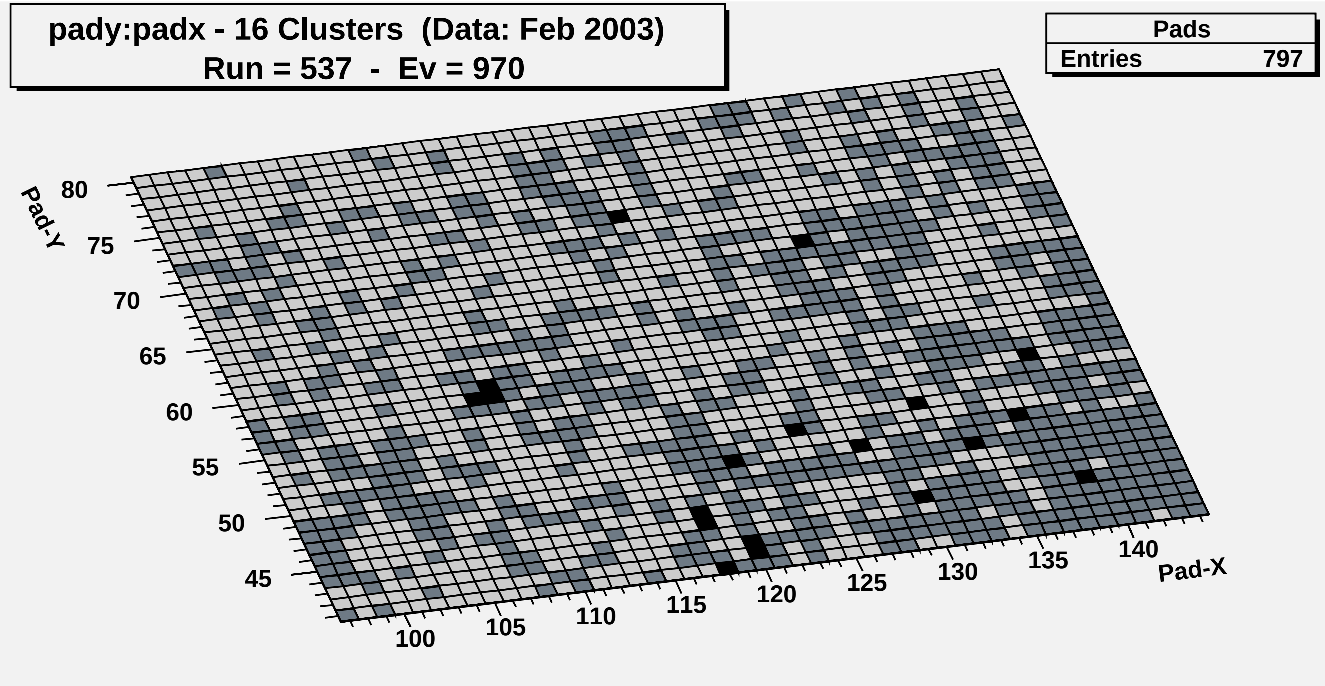
Space view of
event with 512
detected by
16 Clusters
(pixel ≡ Pad)

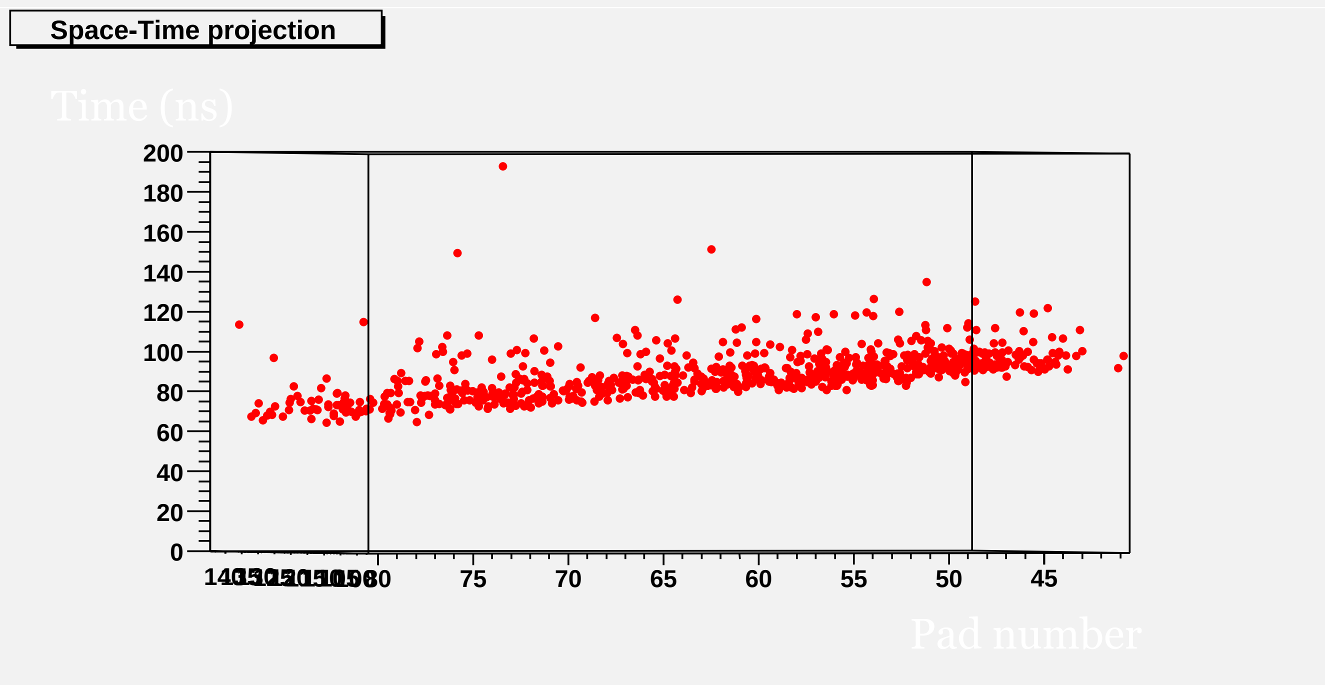
Projected
space-time vie
of the same ev

3D view of the same event

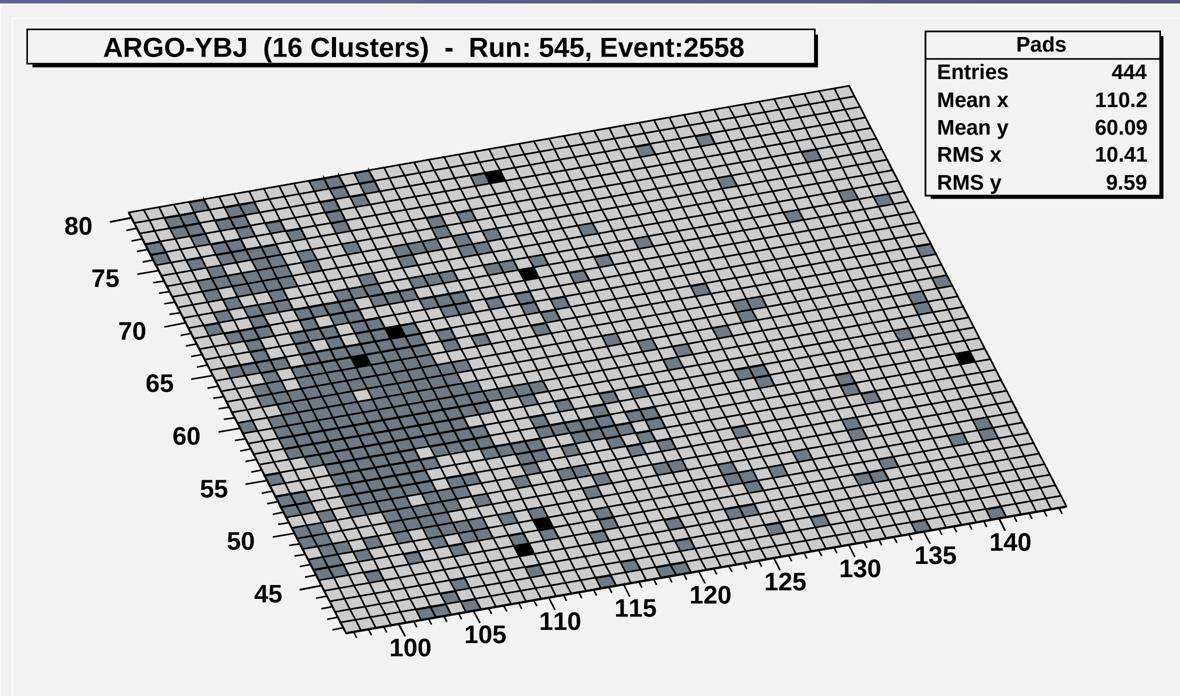


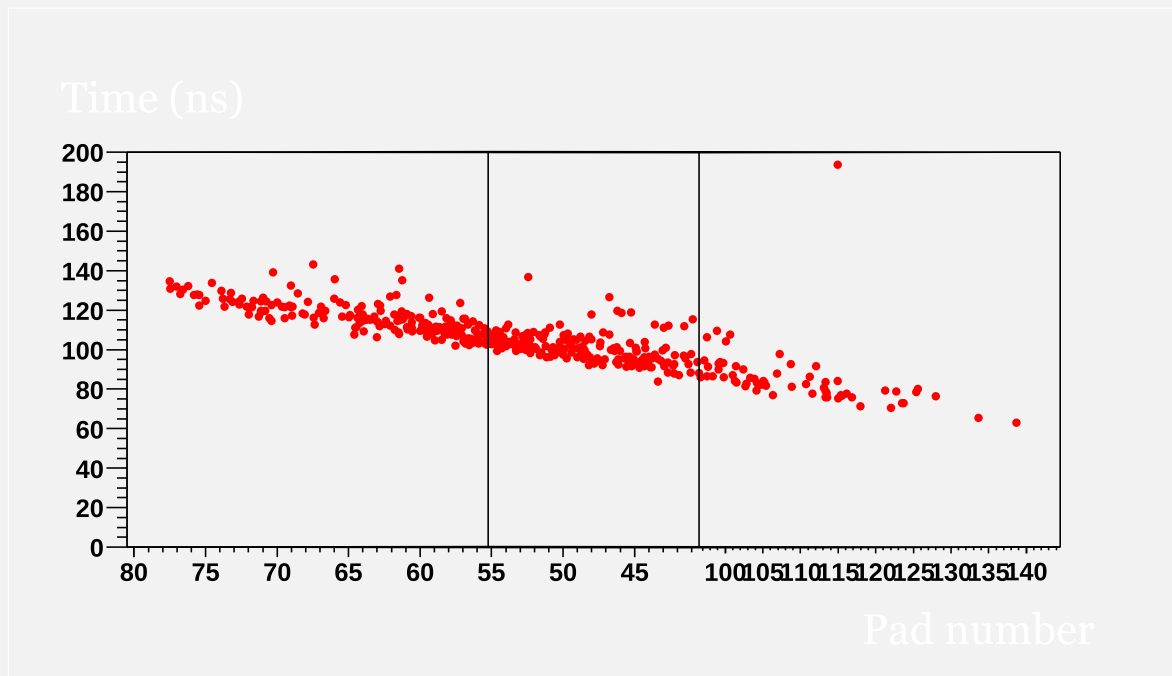
View of an event with ~ 800 hits detected by 16 Clusters





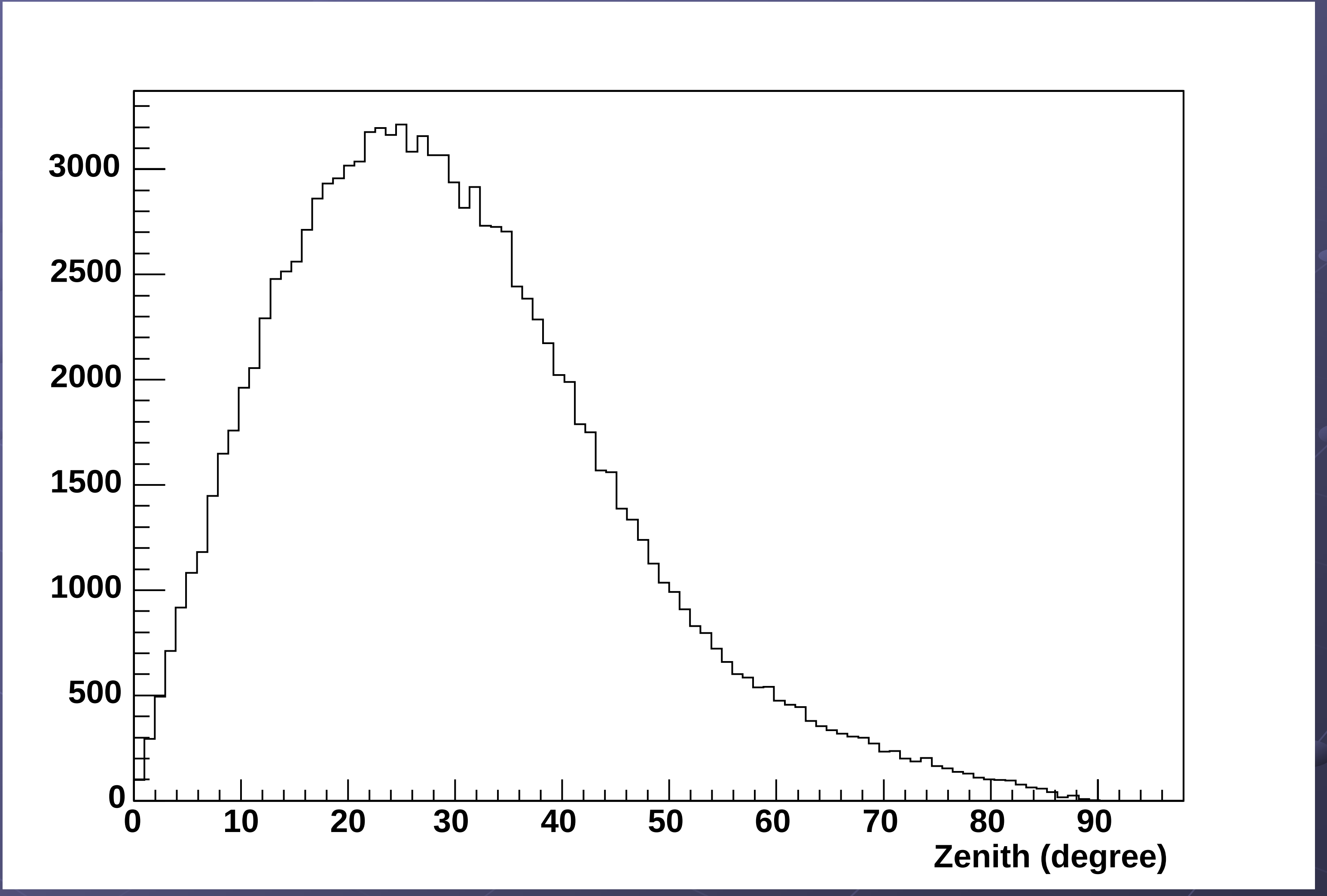
A shower giving 444 hits on 16 Clusters.
The shower *core* is well contained into the detector area.



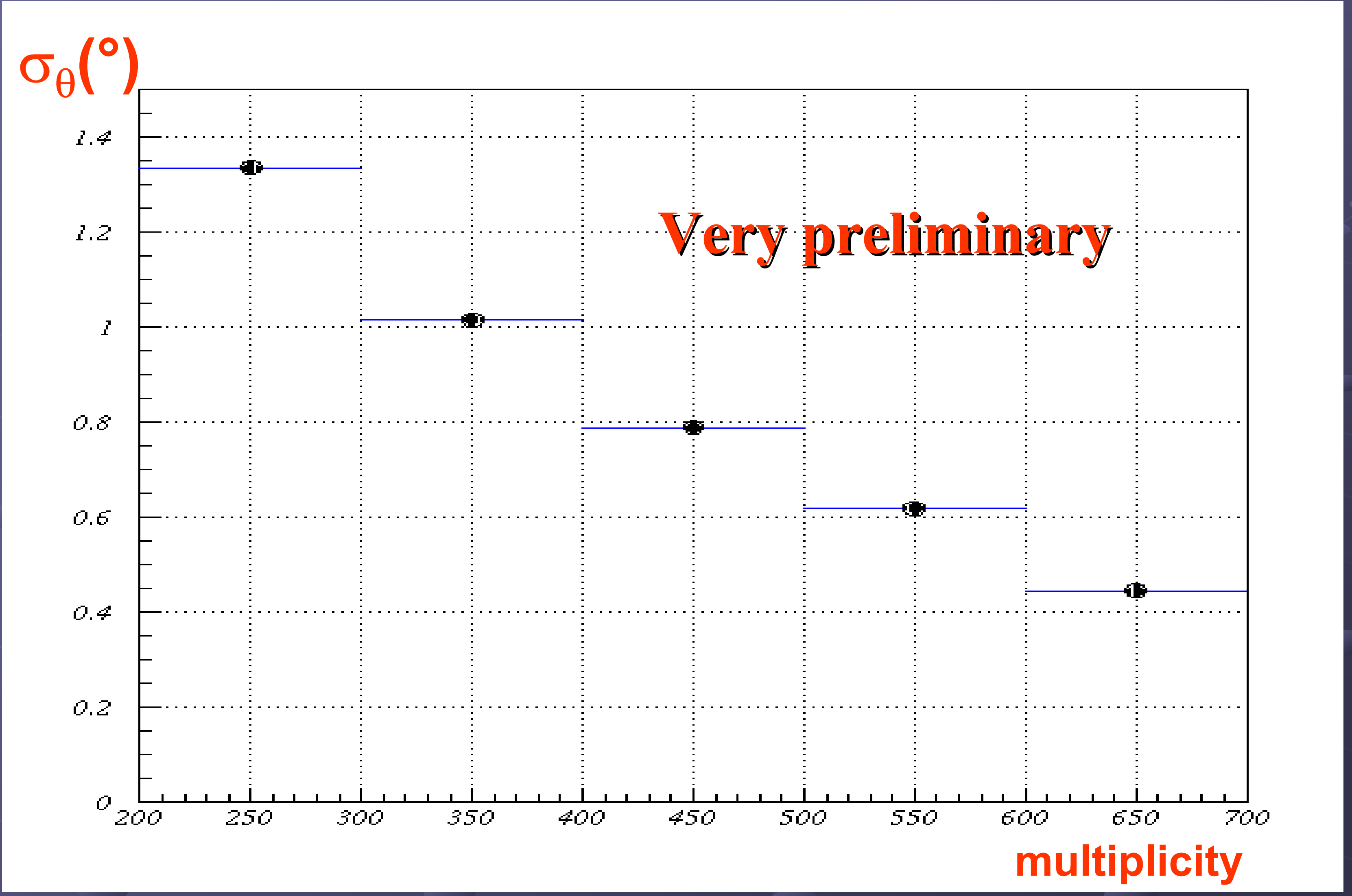


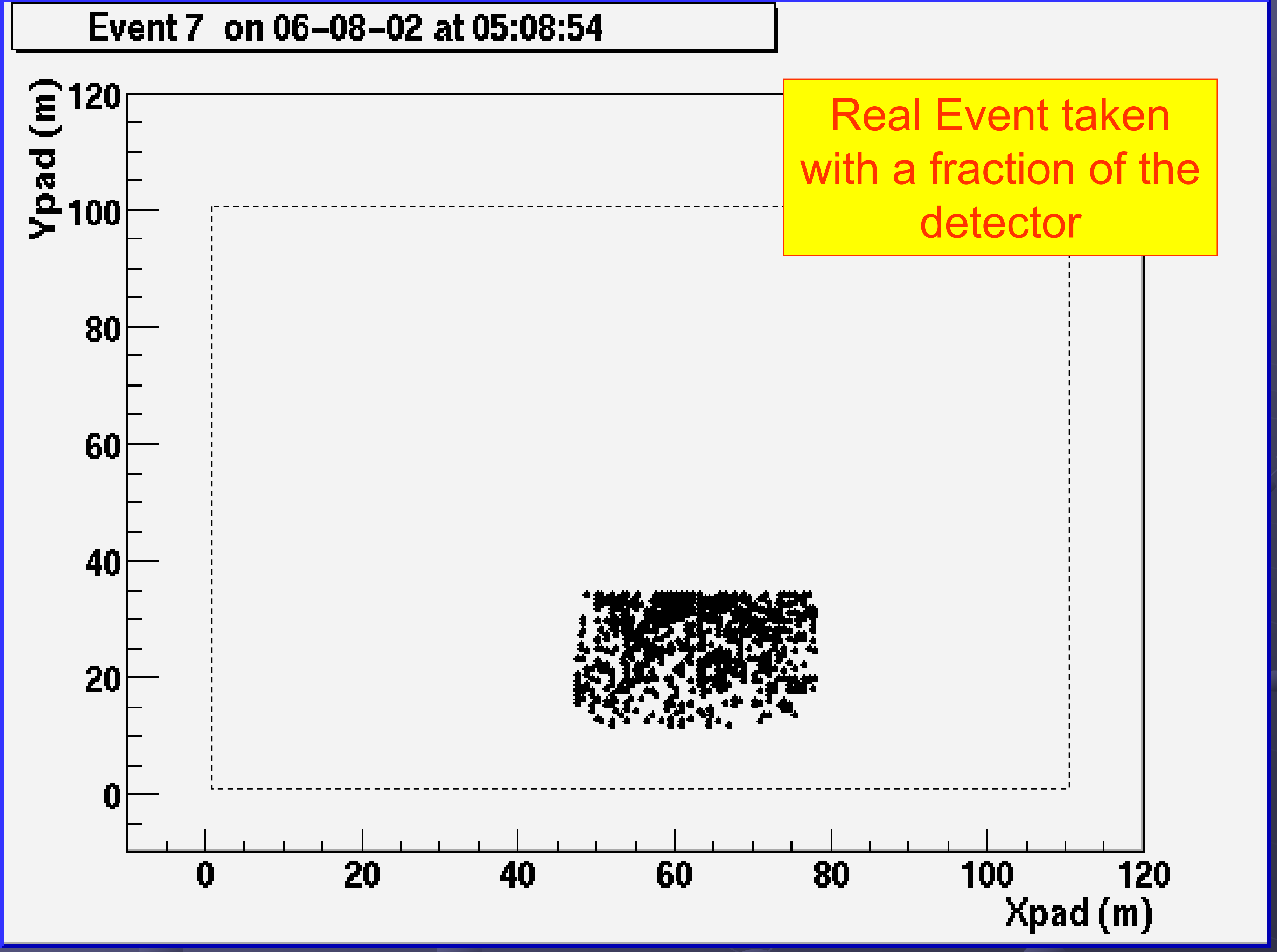
Distribution of reconstructed zenith angle

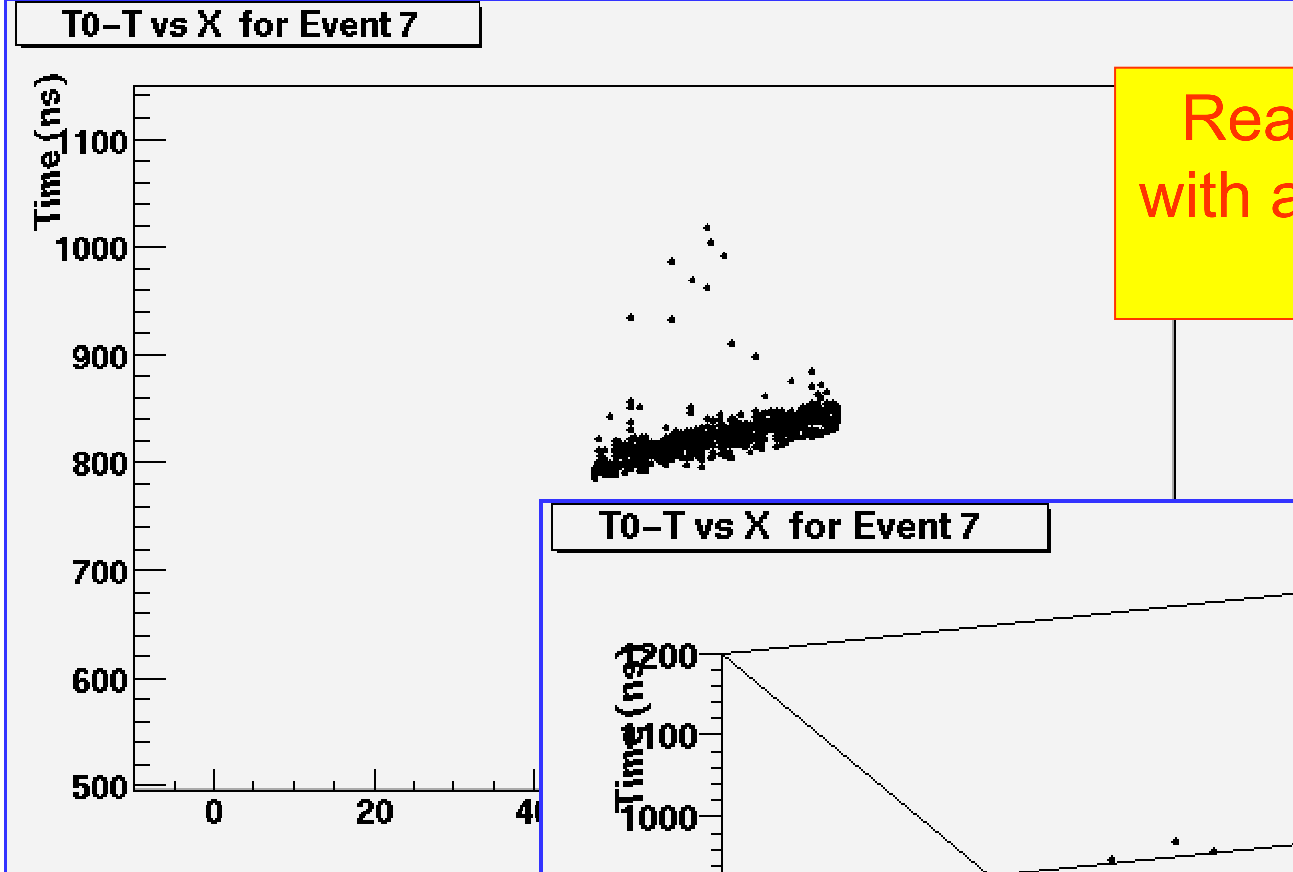
Sample of 122,000 events on 16 Clusters (Trigger: N_pad ≥ 20)



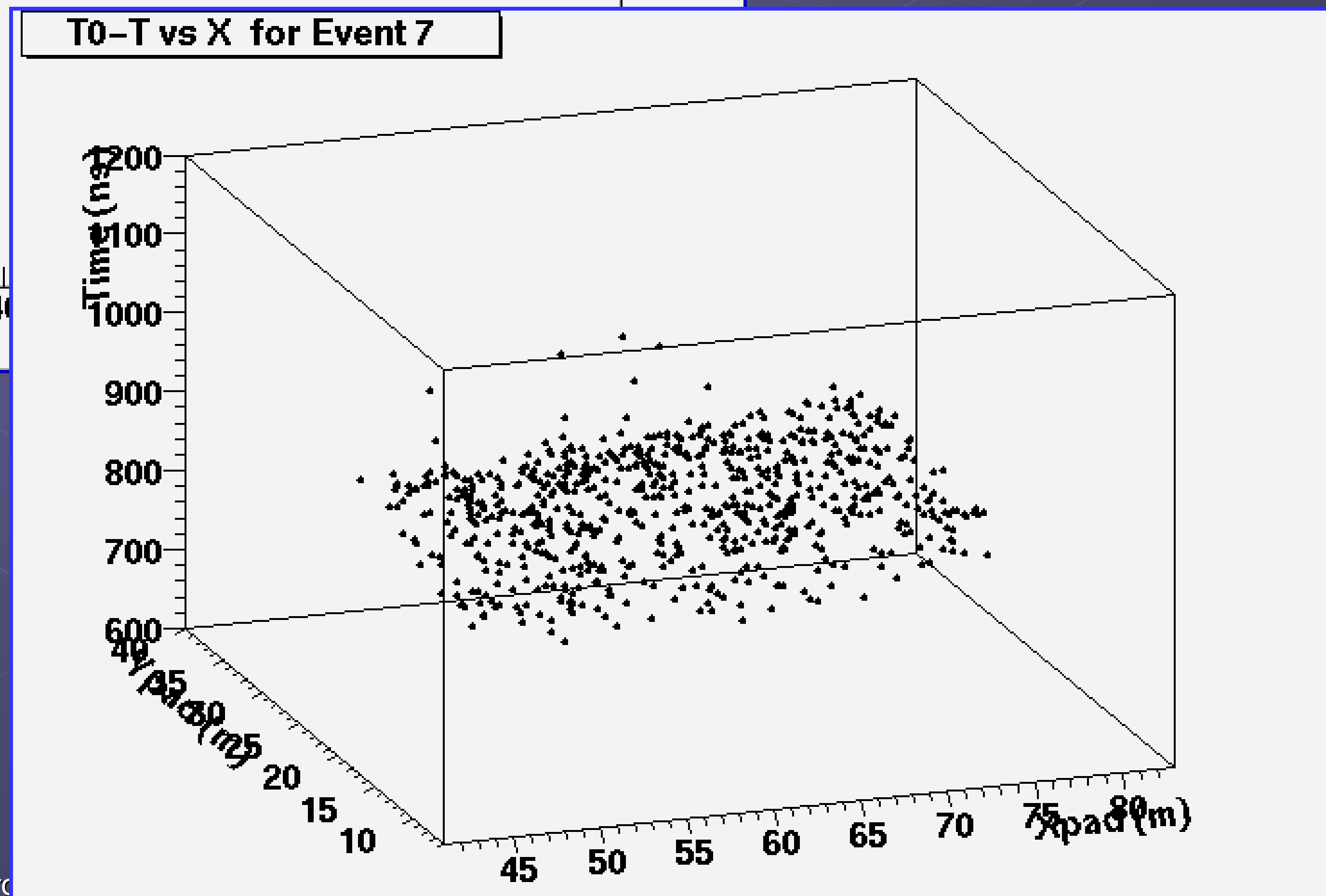
Even-odd angle difference vs pad multiplicity
(run on 6 Clusters)

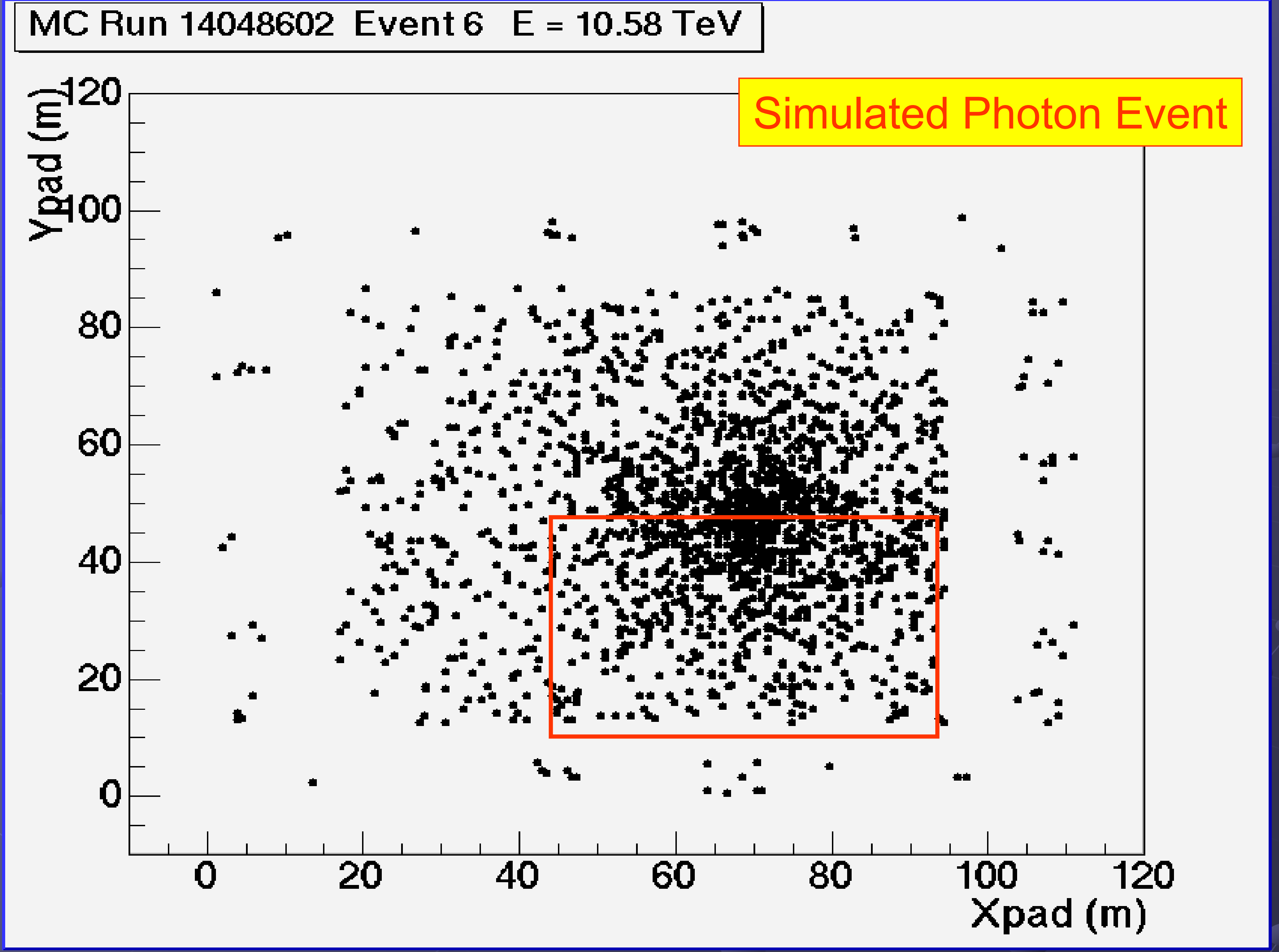



Event 7 on 06-08-02 at 05:08:54
Real Event taken with a fraction of the detector
Ypad (m)
Xpad (m)
0
20
40
60
80
100
120



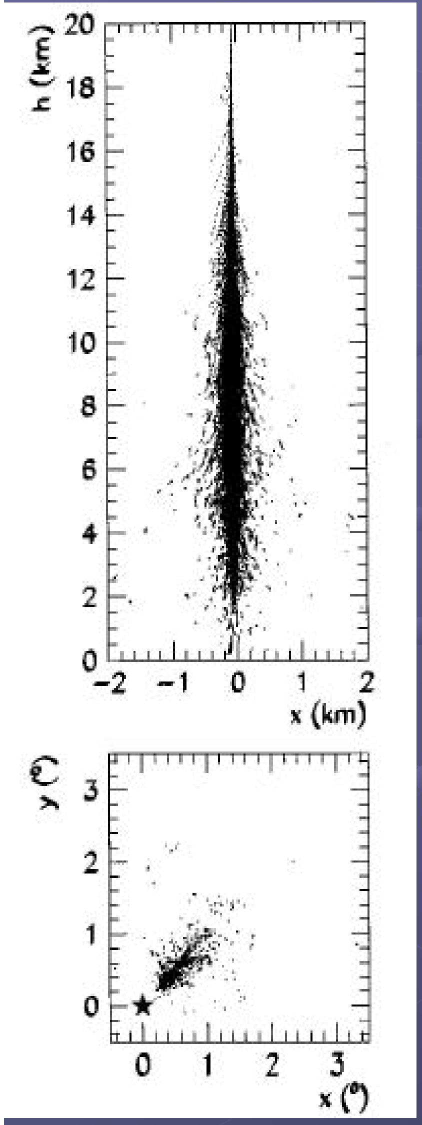
Real Event taken with a fraction of the detector



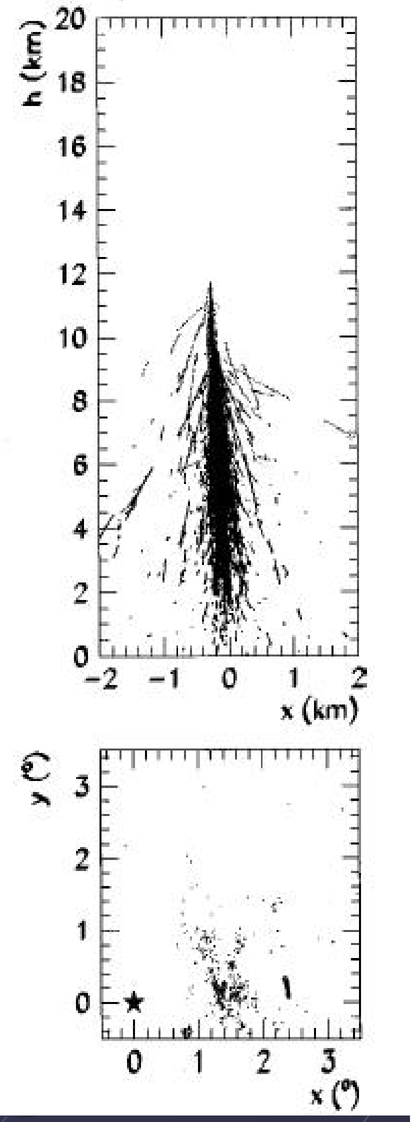

MC Run 14048602 Event 6 E = 10.58 TeV
Simulated Photon Event
Ypad (m)
120
100
80
60
40
20
0
0
20
40
60
80
100
120
Xpad (m)

Gamma/hadron discrimination

Photon Shower



Proton Shower



The photon signal is statistically identified by looking for an excess, coming from a given direction, over the isotropic background due to charged cosmic rays (H, He, Li, .. nuclei)

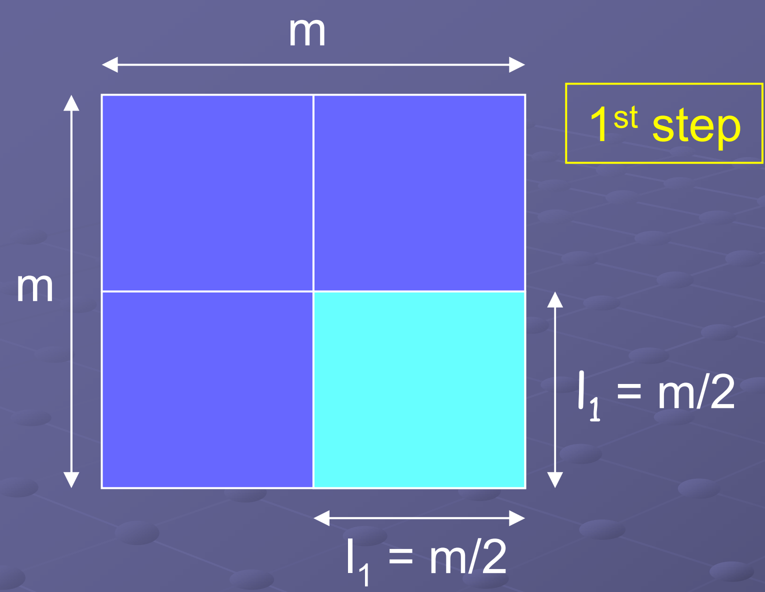
In addition to this tool the study of the shower

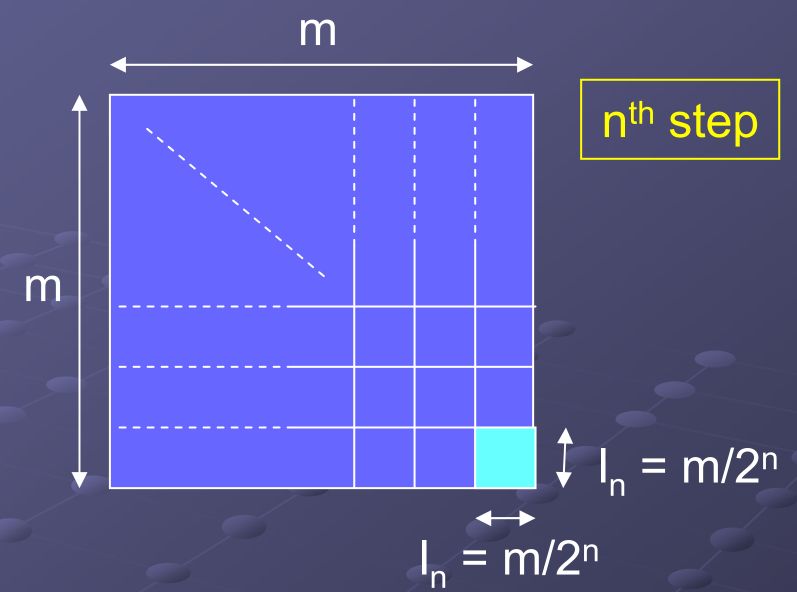
1) space (and time) patterns

2) muon content

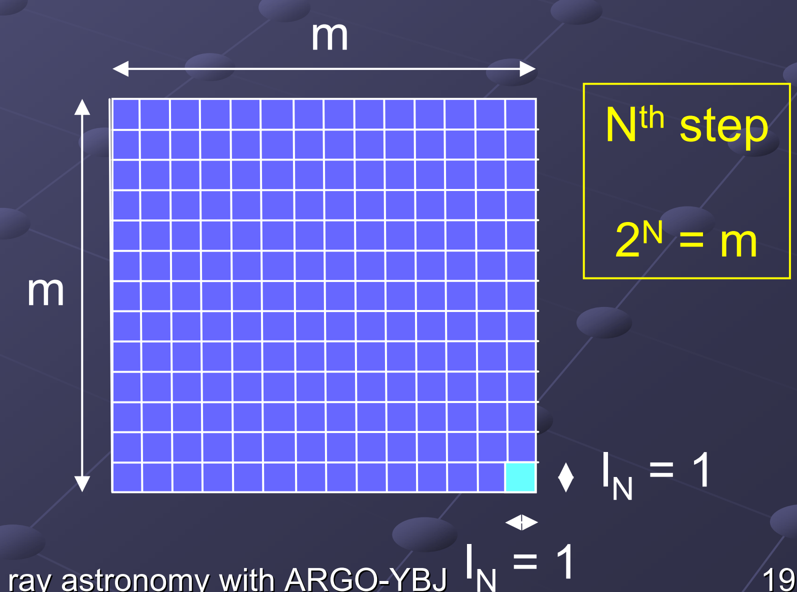
can be useful to have higher discrimination power and then a larger sensitivity

The multiscale approach





$$p(x,y,l) = \frac{\phi(x,y,l)}{N_{tot}}$$



$\phi(x,y,l) =$ content of the cell at position (x,y) as seen at scale length l

N_{tot} = total map content

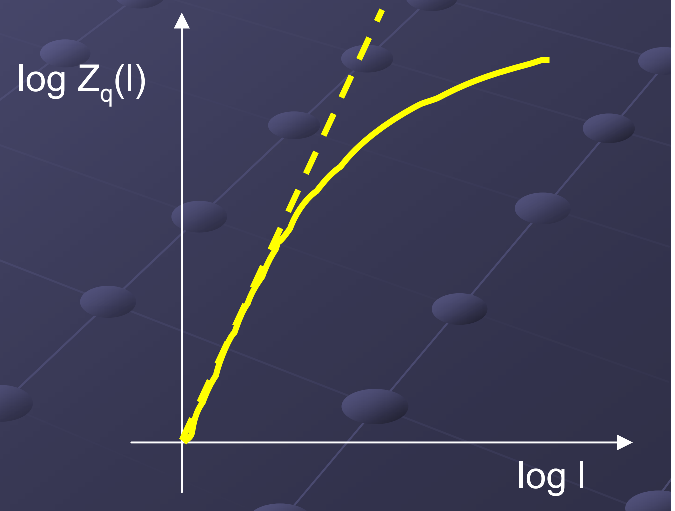
The multifractal analysis (MFA)

Structures displaying self-similar properties are called fractals.
They can be quantitatively described by their **fractal dimension**.
To fully characterize self-similar distributions an infinite number of fractal dimensions is required.
Multifractals can be analyzed with the box-counting method.

The MFA moment of order q at length scale l is defined by:

$$Z_q(l) = \sum_{\{x,y\}} \left| p(x,y,l) \right|^q$$

When scaling is observed $Z_q(l) \xrightarrow{l \to 1} \sim l^{\tau(q)}$

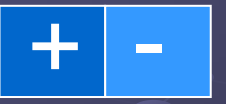


The dependence of the MFA scaling exponent τ(q) on the order q, gives the main information on the image.

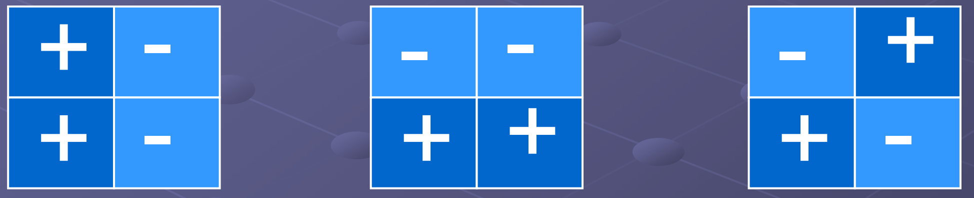
The discrete wavelet analysis (DWA)

The DWA moment of order q at length scale l is directly related to the coefficients of the DW transform of φ(x). It is defined by:

$$W_q(l) = \sum_{\{x\}} \left| p(x,l) - p(x+l,l) \right|^q \xrightarrow{l \to 1} \sim l^{\beta(q)}$$



In the 2-D case, three Haar mother wavelets can be used:



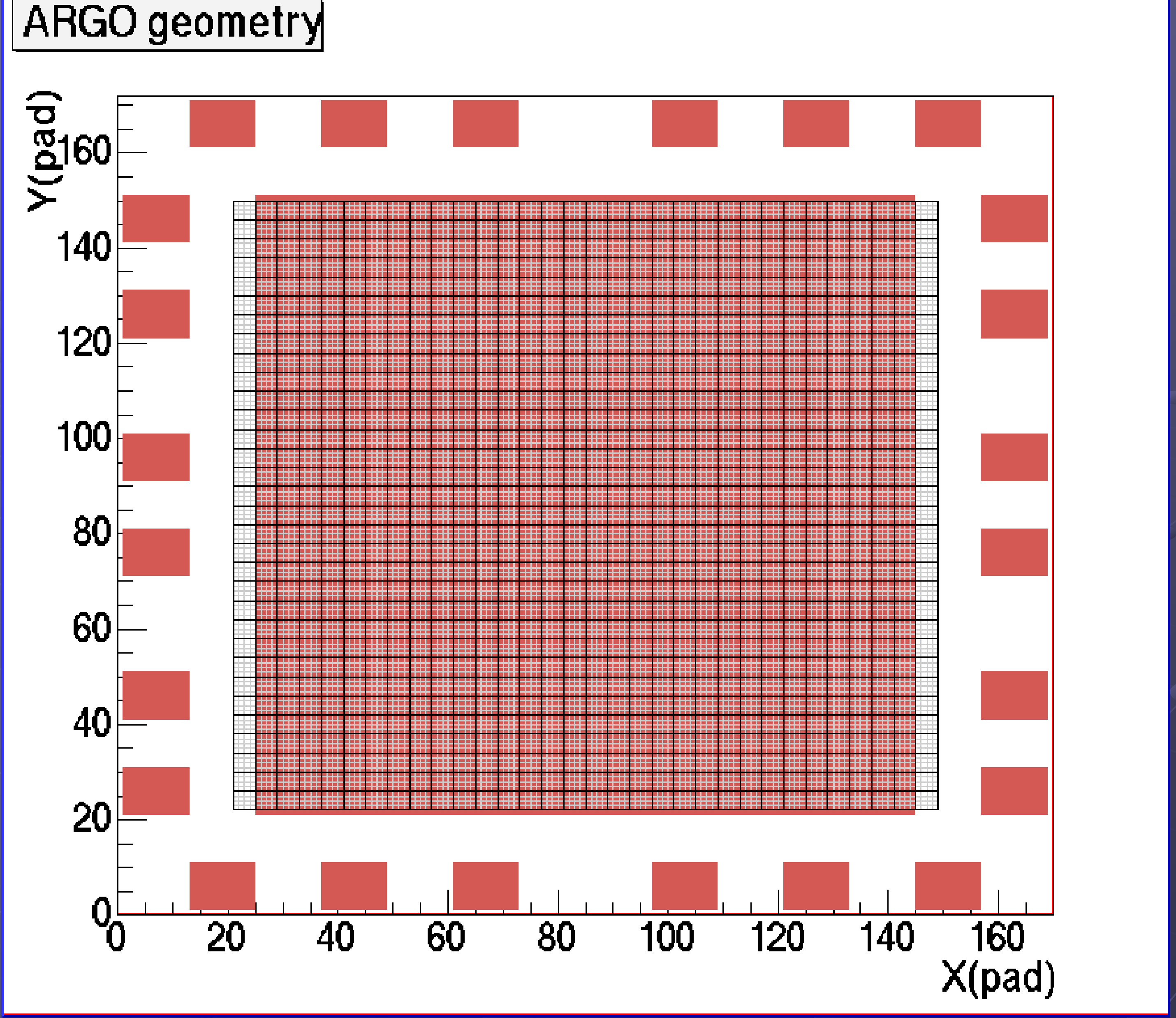
$$W_q^{(1)}(l) \xrightarrow{l \to 1} \sim l^{\beta^{(1)}(q)}$$

$$W_q^{(2)}(l) \xrightarrow{l \to 1} \sim l^{\beta^{(2)}(q)}$$

$$W_q^{(3)}(l) \xrightarrow{l \to 1} \sim l^{\beta^{(3)}(q)}$$

For *isotropic* cases $\beta^{(1)}(q) = \beta^{(2)}(q) = \beta^{(3)}(q) \equiv \beta(q)$

The dependence of the DWA scaling exponent β(q) on the order q, gives the main information on the image.



The smallest pixel is taken at (2 ×2) pad ~ 1m^2

Simulated data sample

Gamma and proton induced showers have been simulated with CORSIKA + ARGOG

with the following characteristics:

- power spectrum between 10GeV and 300TeV with a spectral index γ = -2.5 and -2.7 for photons and protons respectively
- azimuth between 0 and 15 degrees
- core at the detector center

Since the photons and hadrons of the same energy produce different pad multiplicities, the data sample has been divided into five multiplicity windows

N_{pad}	$<E_\gamma>$ (TeV)	N_γ	$<E_p>$ (TeV)	N_p
50 – 100	0.5	6955	0.8	4160
100 - 500	1.1	11902	1.7	7601
500 - 800	2.9	2885	4.9	1951
800 - 1500	4.6	3397	7.7	2770
1500 - 6000	11.3	5145	18.0	3367

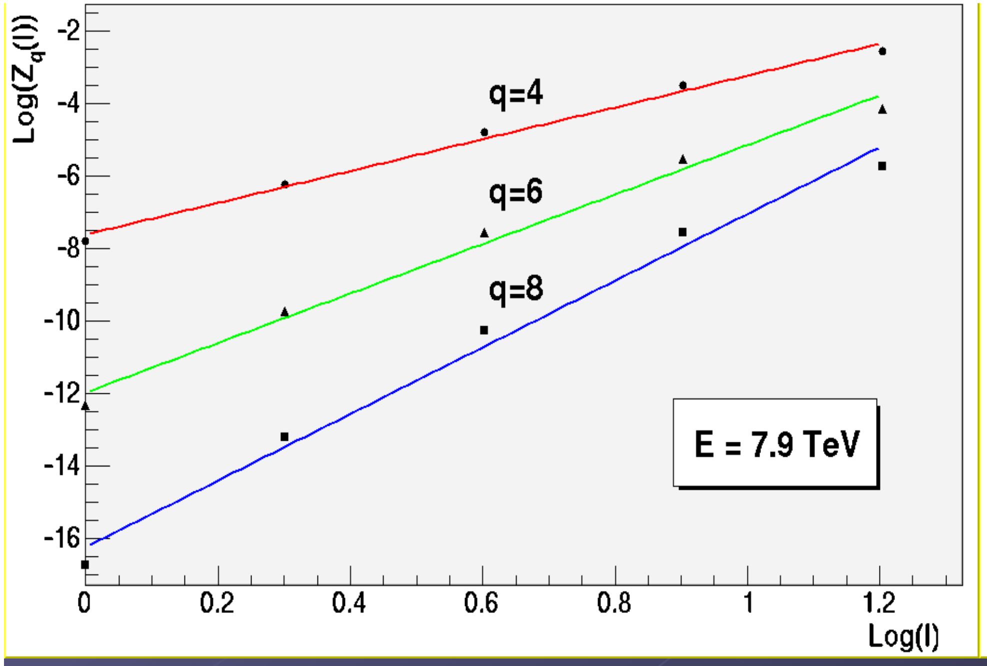
Single Event Analysis

Compute the MFA and DWA moments as a function of the scale length for different values of the order q.

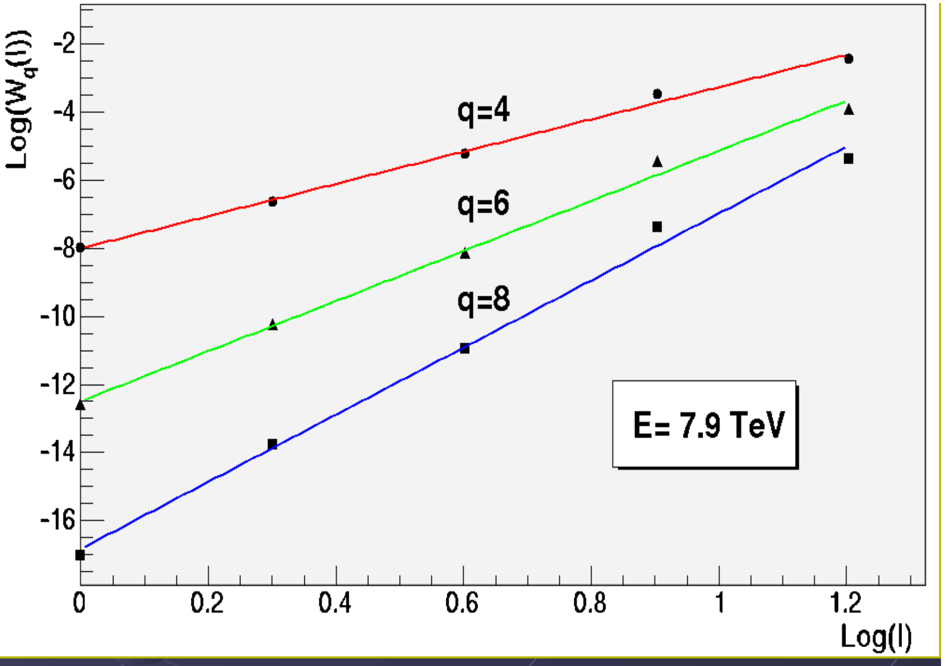
Fit these curves and get the scaling exponents τ and β

Example for a 7.9TeV photon initiated shower……

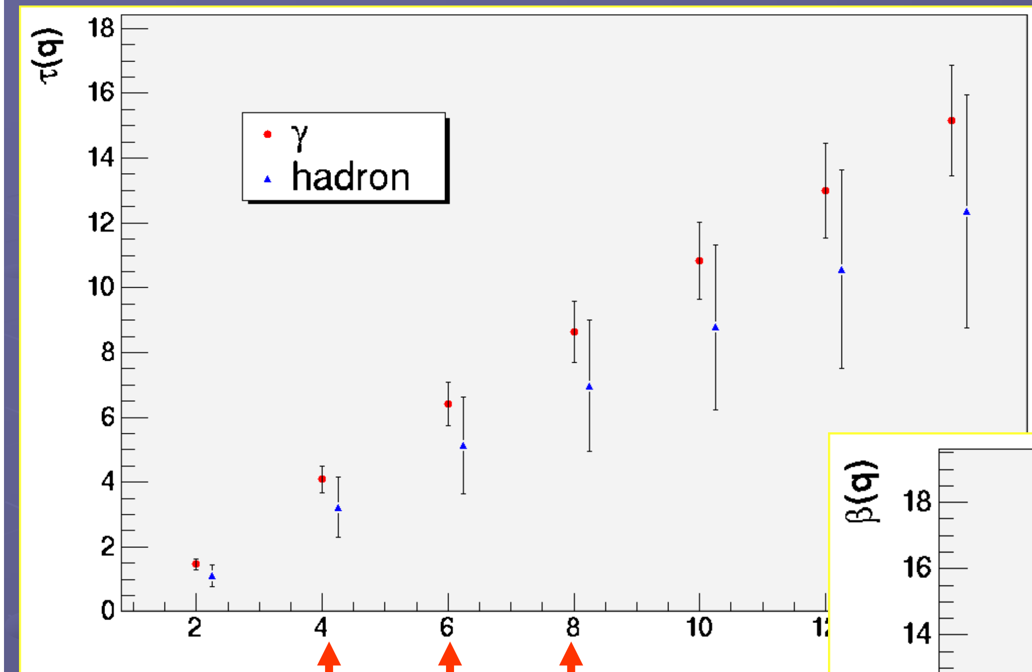
Z_q vs the scale length l



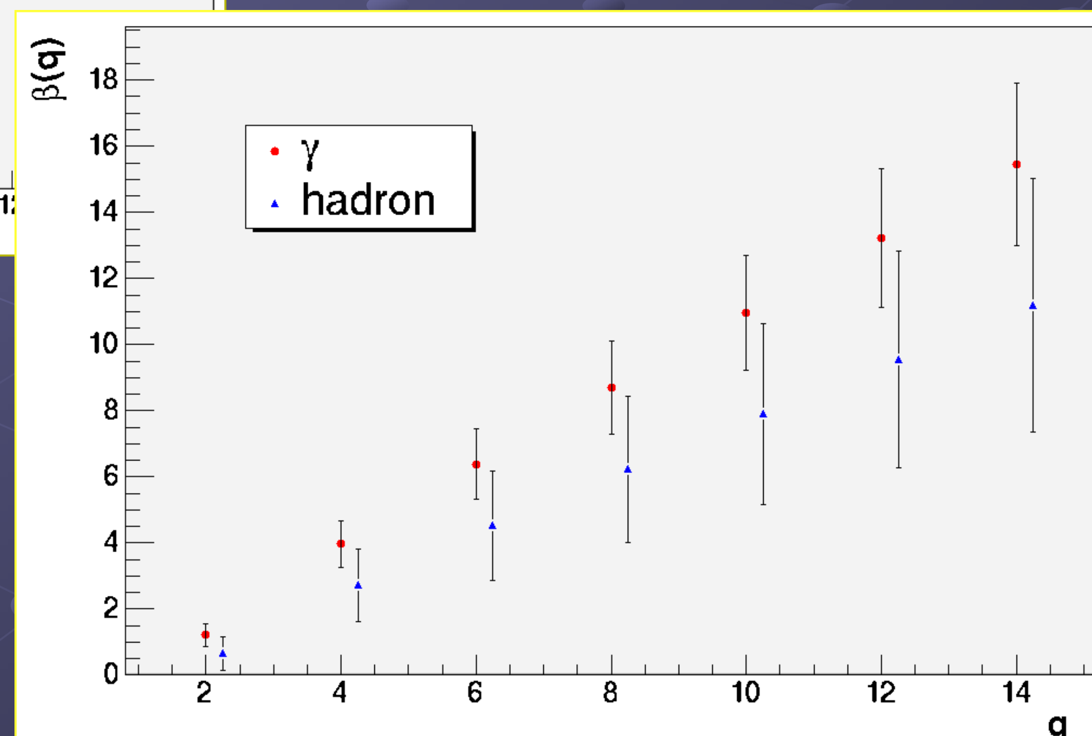
W_q vs the scale length l



Study of the scaling exponents



The linear dependence of τ and β on q allows the analysis just for three sample values.

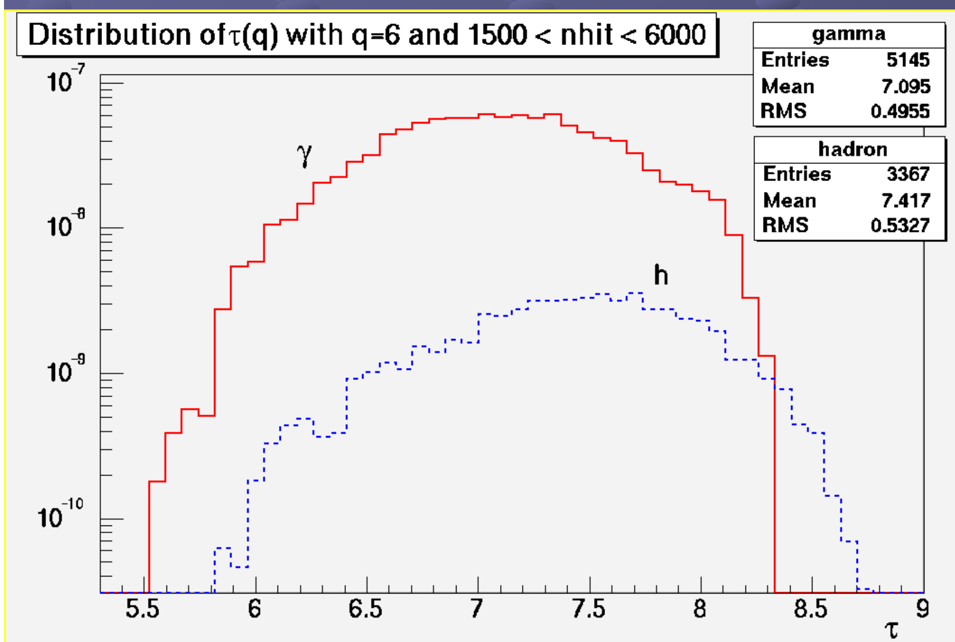


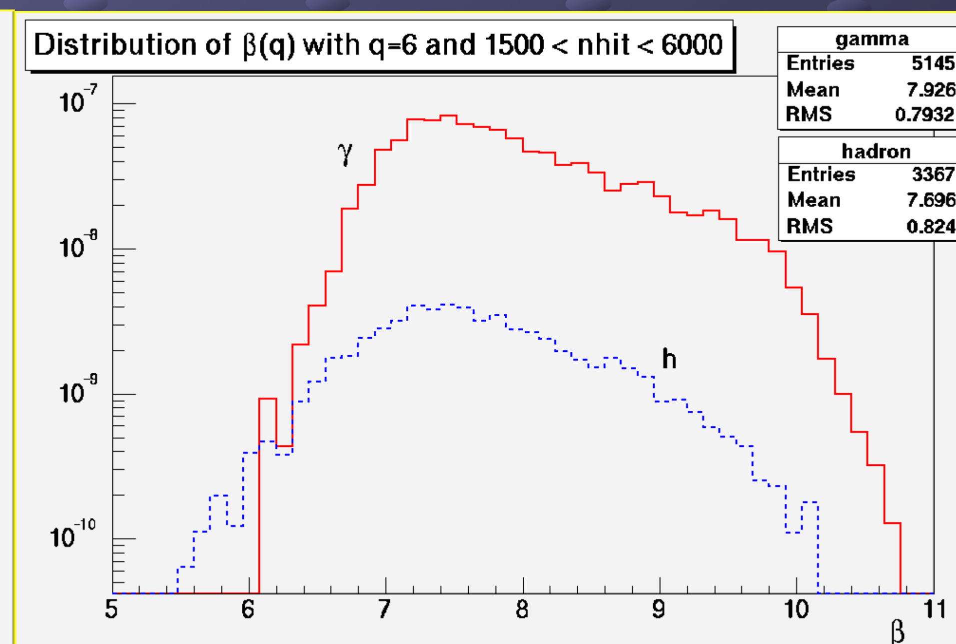
q = 4, 6, 8

Scaling exponents distributions

As expected from the previous graphs, the values of τ and β for different q's give similar but different distributions.

The scaling exponents are very good candidates to be the input values for an Artificial Neural Network able to discriminate between photon and hadron induced showers.

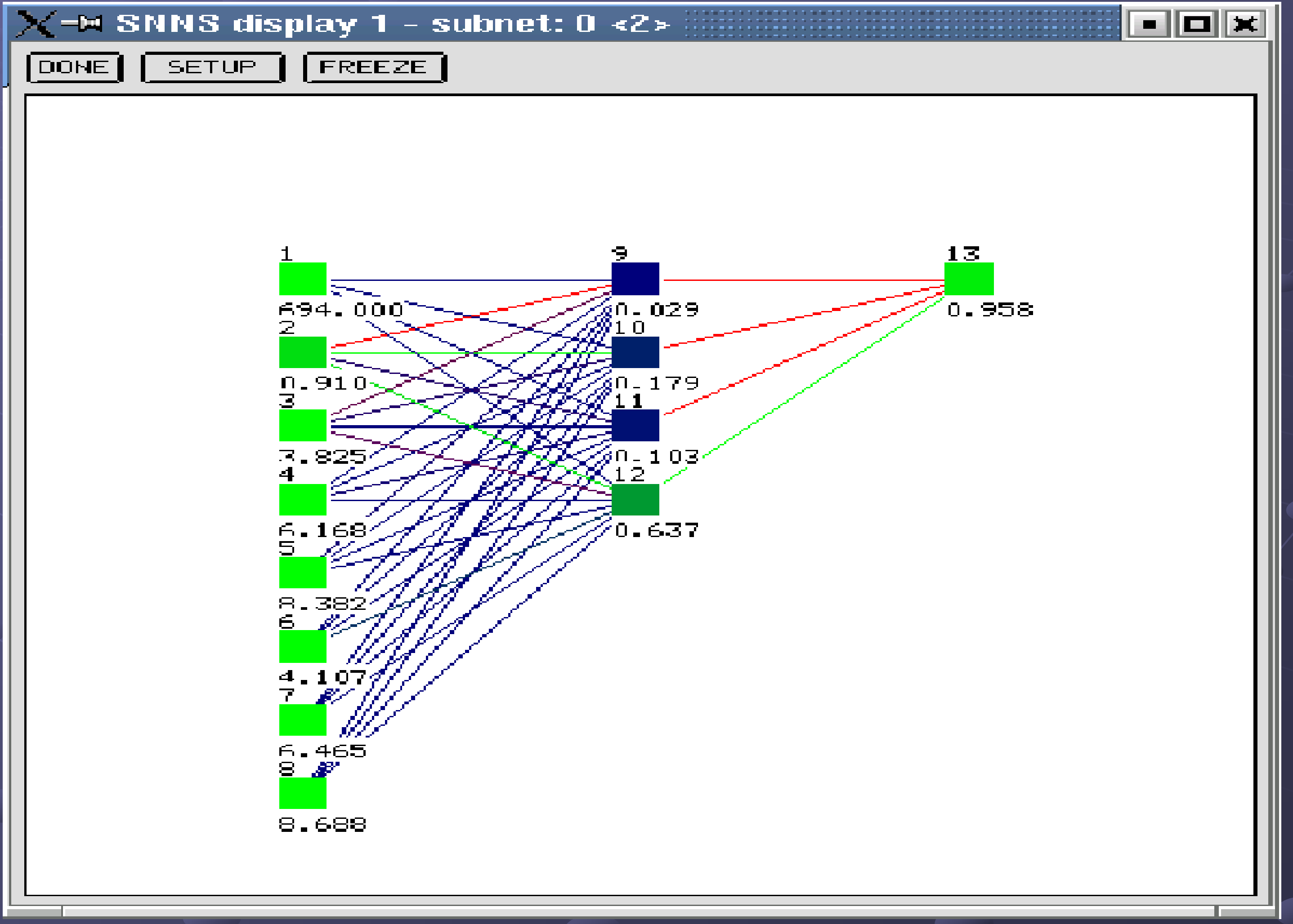




Artificial Neural Network

Eight parameters have been identified and used as input for an (8,4,1) ANN.

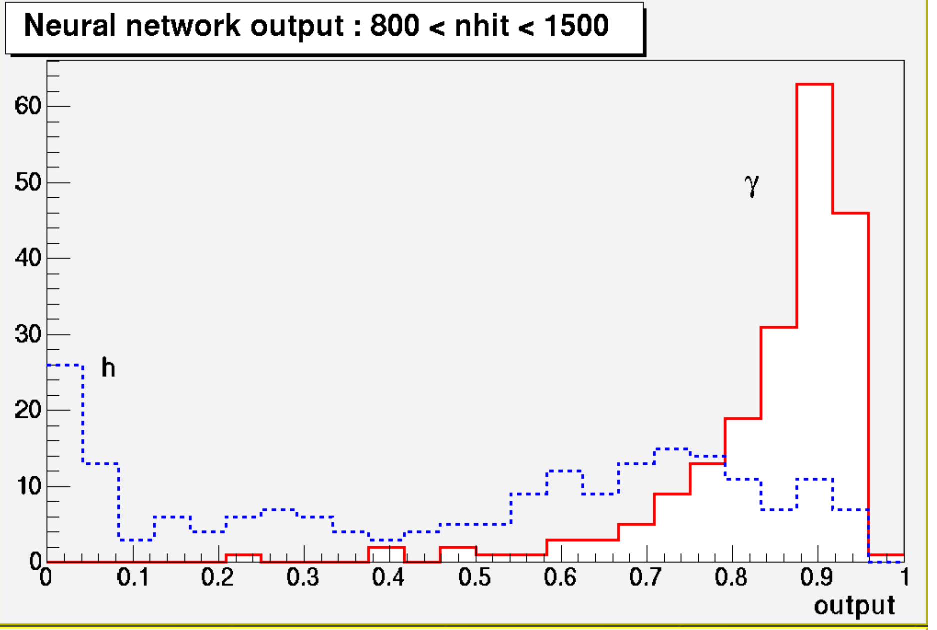
- ✓ N_{hit}
- ✓ $\tau(q=4)$
- ✓ $\tau(q=6)$
- ✓ $\tau(q=8)$
- ✓ $\beta(q=4)$
- ✓ $\beta(q=6)$
- ✓ $\beta(q=8)$
- ✓ $<x^3>/<y^3>$

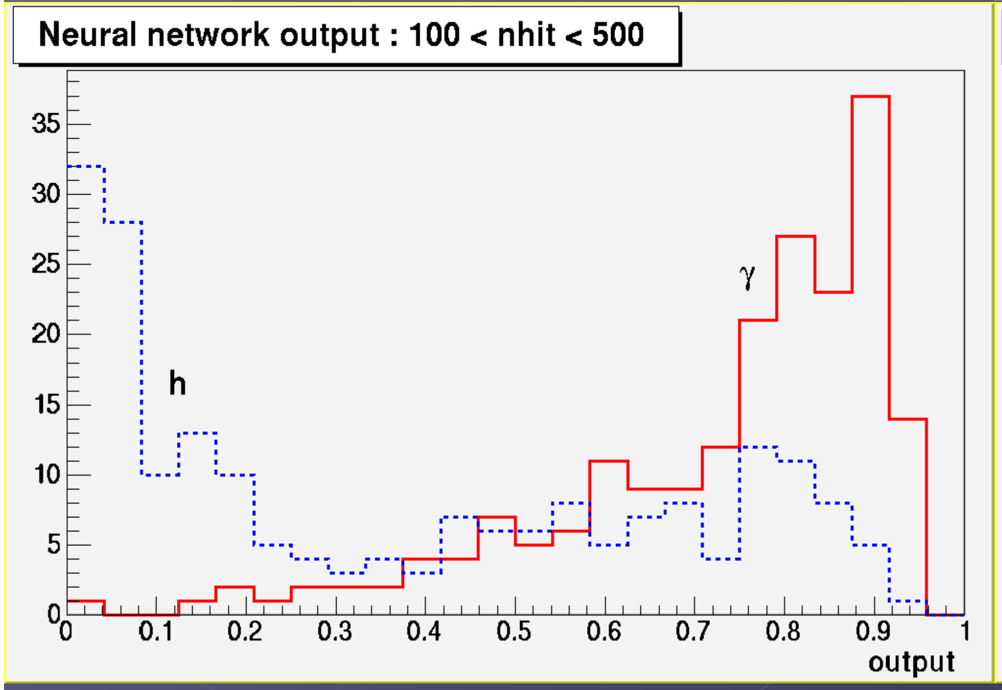


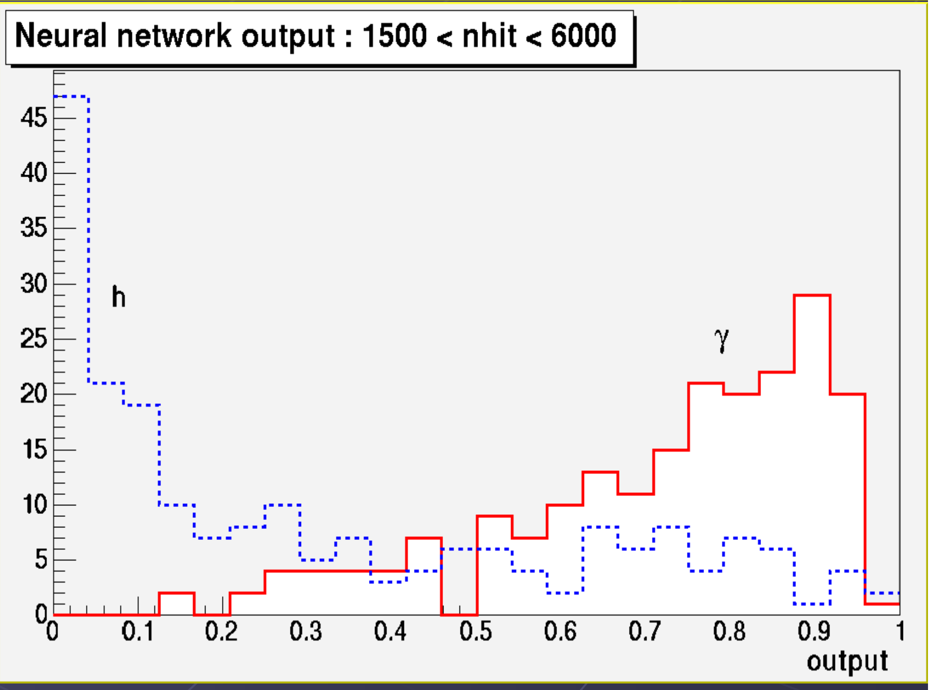
ANN results

Results have been obtained by using, in each multiplicity window, 400 events (200 γ + 200 p).

Fluctuations here are essentially due to this limited statistics.

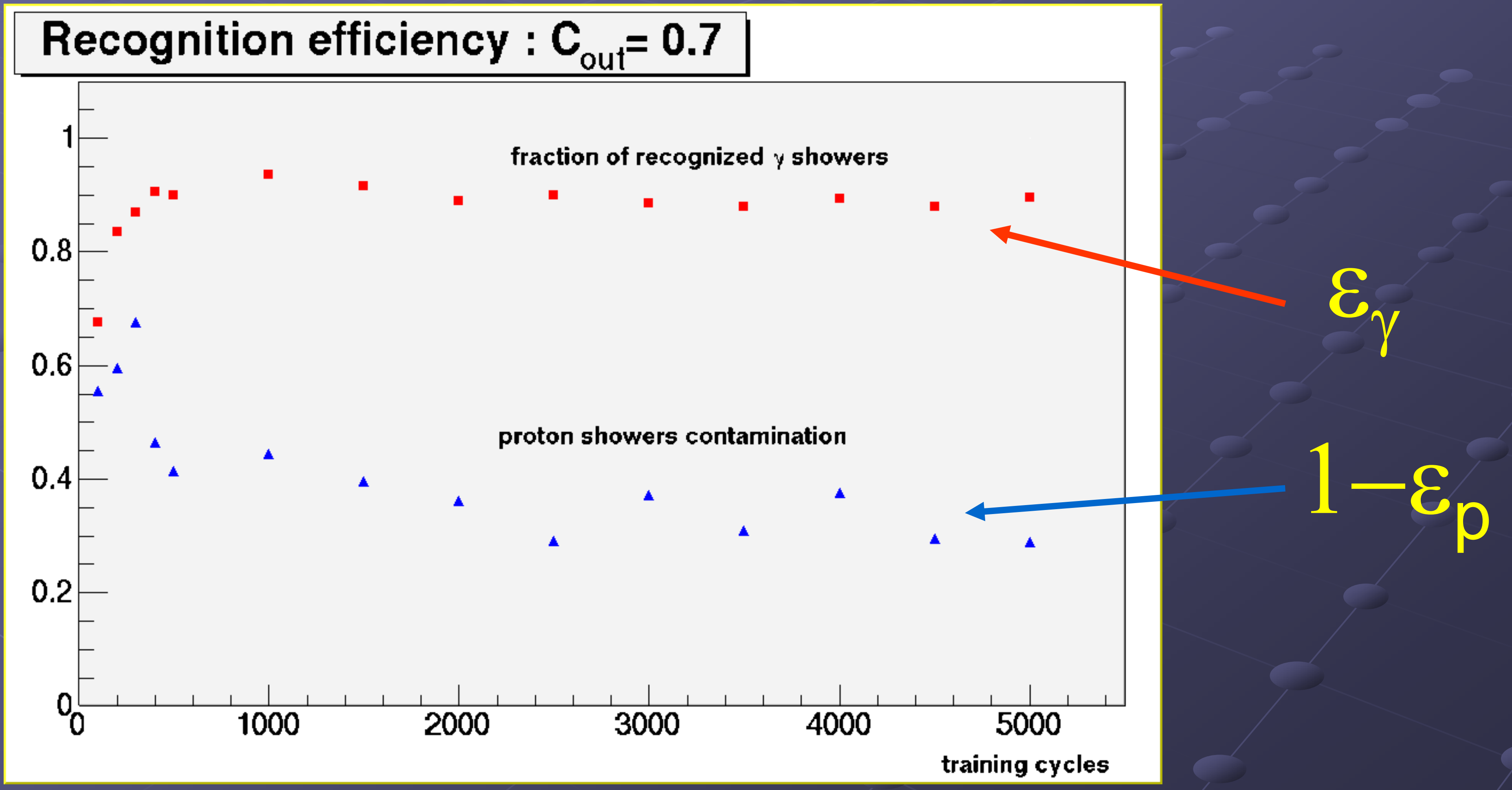






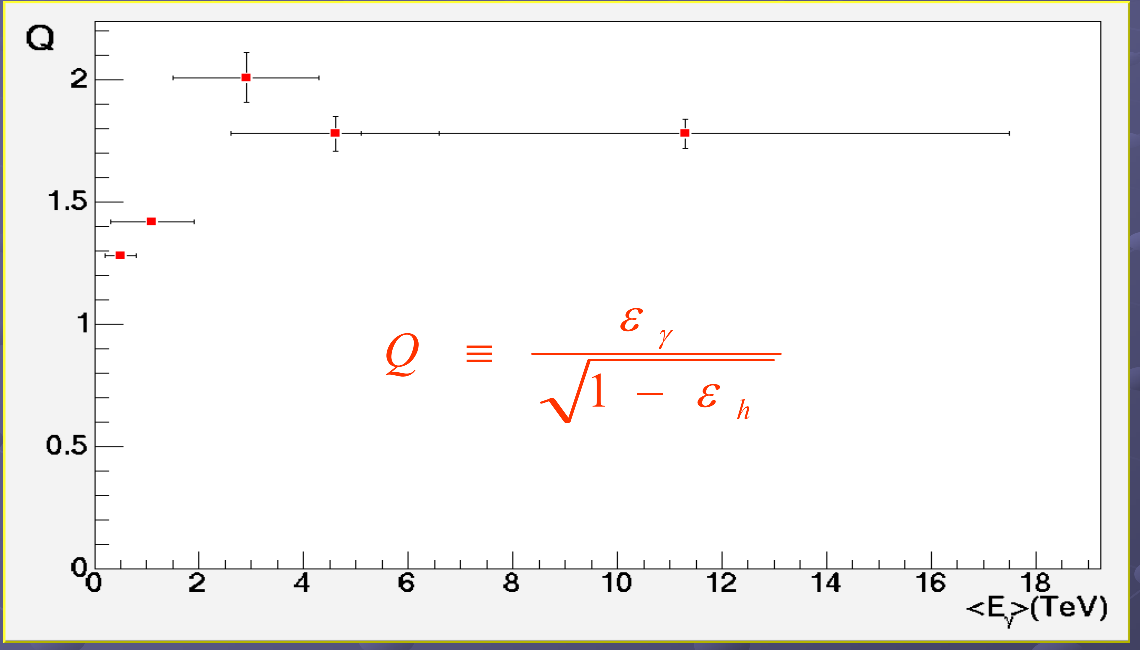
Artificial Neural Network training

Different ANN's (with the same topology) have been trained in the different multiplicity windows. The number of training epochs has been optimized in order to maximize the efficiencies and minimize the processing times.



ANN results

$$S \equiv \frac{N_\gamma}{\sqrt{N_h}} \times \frac{\varepsilon_\gamma}{\sqrt{1-\varepsilon_h}} \qquad Q \equiv \frac{\varepsilon_\gamma}{\sqrt{1-\varepsilon_h}}$$



$$T^{5\sigma}_{Crab}(Q=1) = 120 days$$

$$T^{5\sigma}_{Crab}(Q=2) = 30 days$$

- ✓ Reduced time interval needed to identify sources
  - ✓ Larger equivalent effective area
    - ✓ Sensitivity to smaller fluxes

Conclusions

- Multiscale image analysis has been showed to provide an efficient tool for gamma/hadron discrimination
- Results are encouraging and allow to nearly double the detector sensitivity.
- The best response is obtained in the *few TeV* range.
- The study is now being extended to all event categories
- The measurement of the muon content of the shower allows hadron background rejection at higher energies

… see next talk