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Multiple Shell Shower fronts in EAS with ARGO-YBJ

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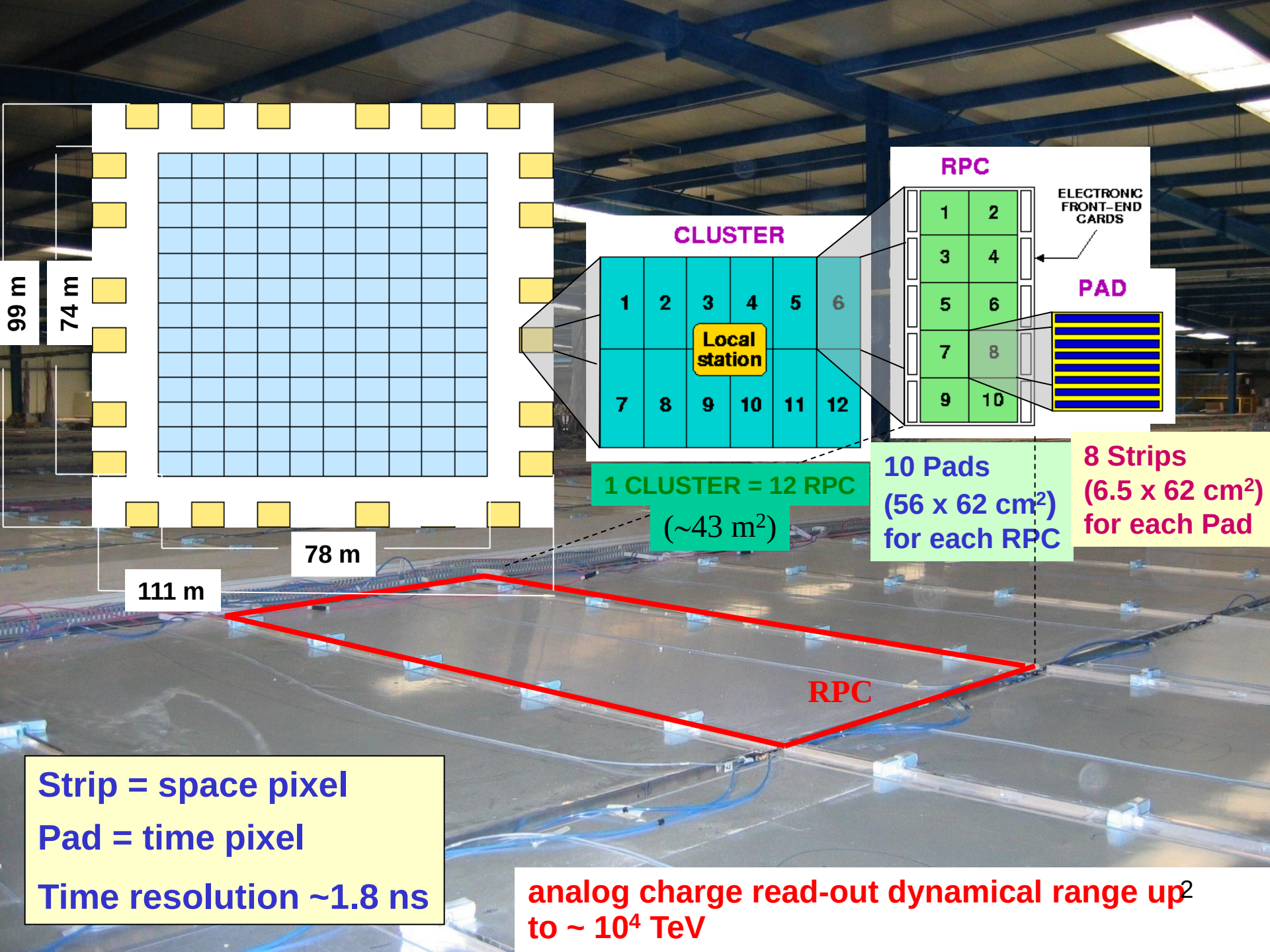
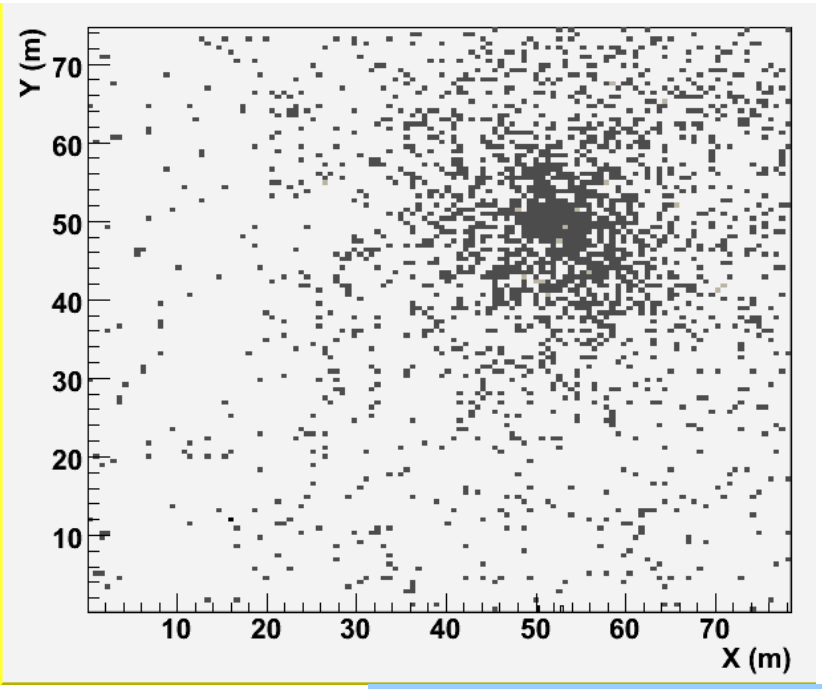
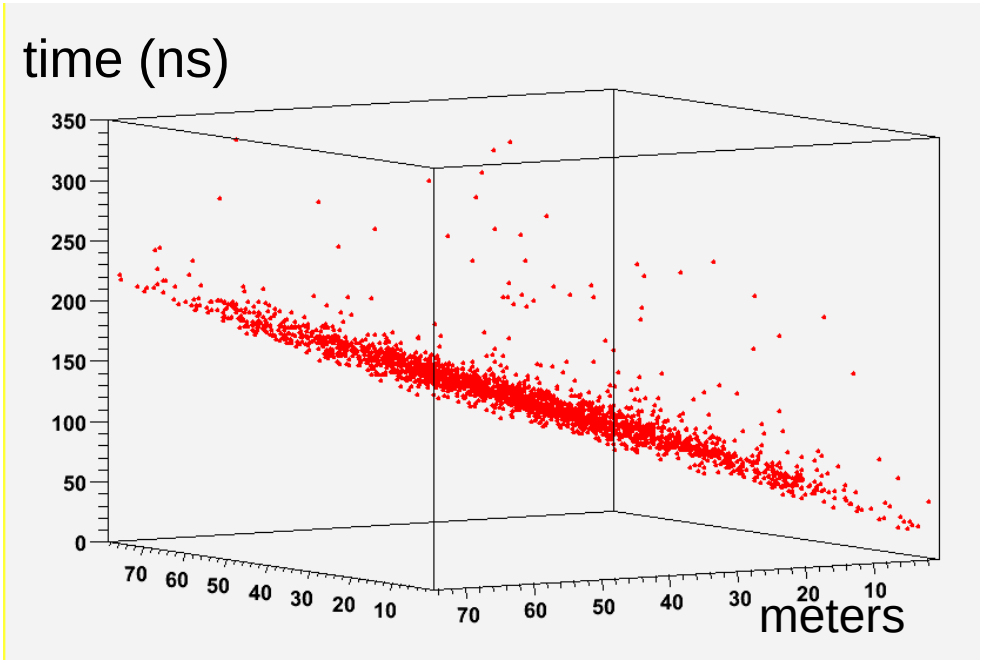

99 m
74 m
78 m
111 m
CLUSTER
1 2 3 4 5 6
Local station
7 8 9 10 11 12
RPC
ELECTRONIC FRONT-END CARDS
PAD
1 2
3 4
5 6
7 8
9 10
1 CLUSTER = 12 RPC
(~43 m²)
10 Pads
(56 x 62 cm²)
for each RPC
8 Strips
(6.5 x 62 cm²)
for each Pad
RPC
Strip = space pixel
Pad = time pixel
Time resolution ~1.8 ns
analog charge read-out dynamical range up to ~ 10⁴ TeV

Shower reconstruction

Fired pads on the carpet



Arrival time vs position



7 yrs operation

- **duty cycle>85%**
- **event rate ±5%**

Arrival direction measurement:

- Core reconstruction: Maximum Likelihood Method applied to the lateral density profile of the shower
- Fit of the shower front with a conical shape

Full coverage, high time and space resolution provide a detailed view of shower front

$$S^2 = \frac{1}{W}\sum_{i=1}^{N_{hit}} w_i \left(t_i - t_0 - \frac{x_i}{c} l - \frac{y_i}{c} m - \frac{R_i}{c}\alpha \right)^2$$

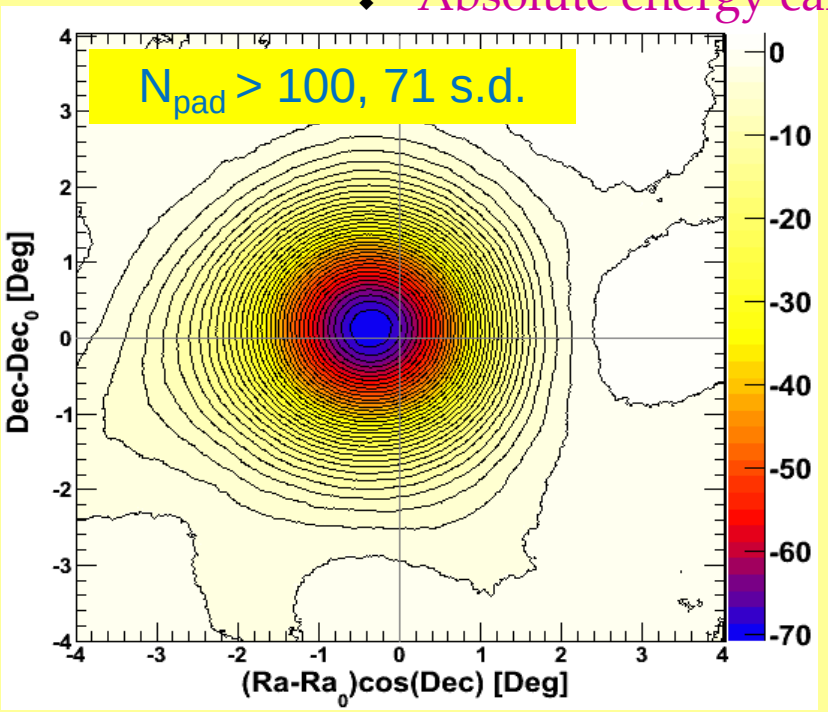
Energy Calibration

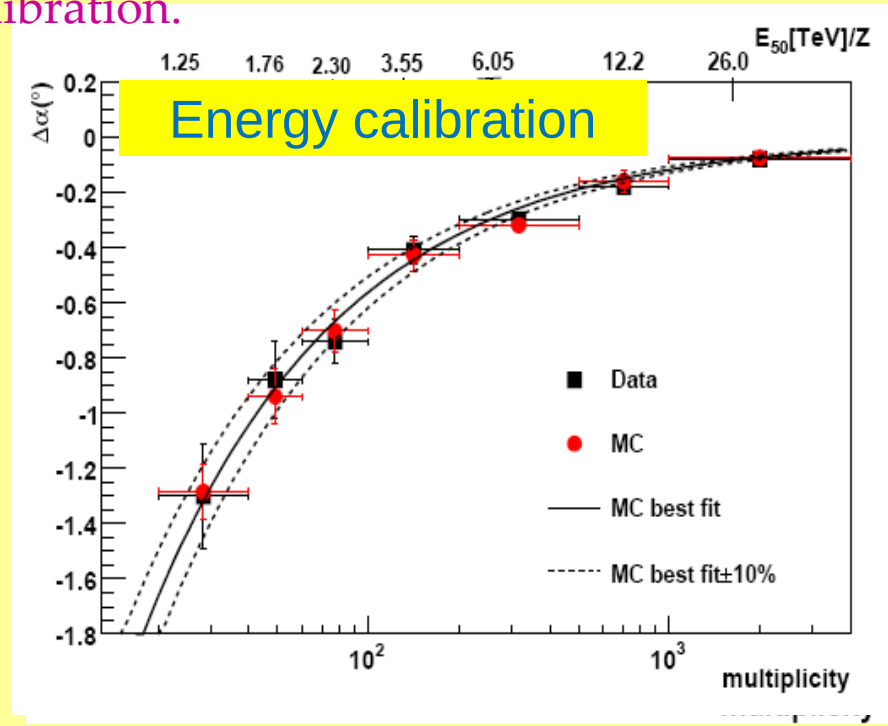
PRD 84 (2011) 022003

- A natural tool to evaluate the performance of the detector

The energy scale uncertainty is estimated to be smaller than 13% in the range 1 – 30 (TeV/Z).

❖ Absolute energy calibration.





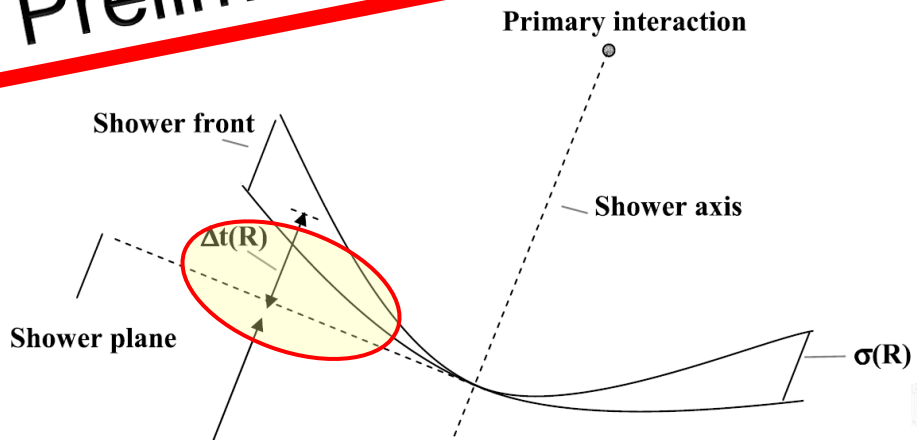
10 s.d./month

Preliminary

Time profile

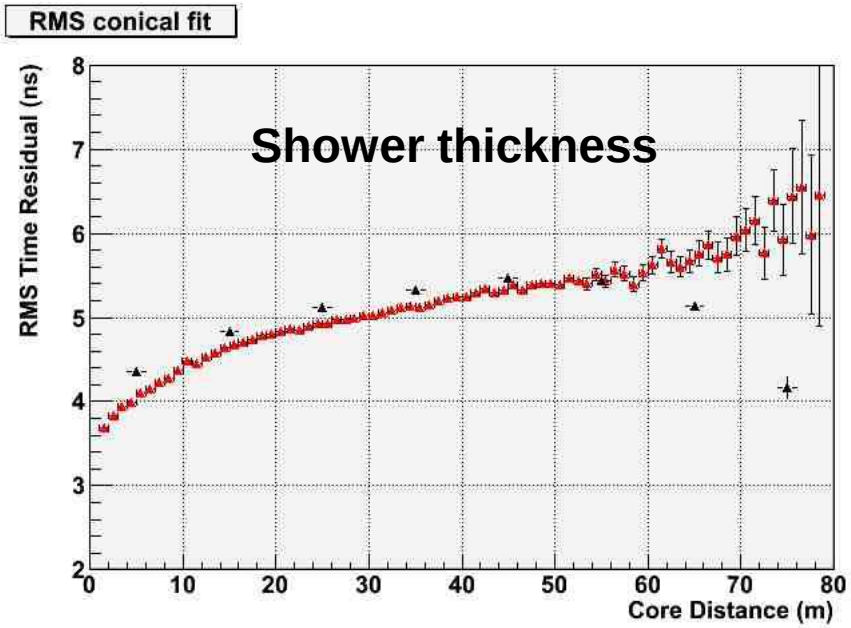
7.9 10^8 events

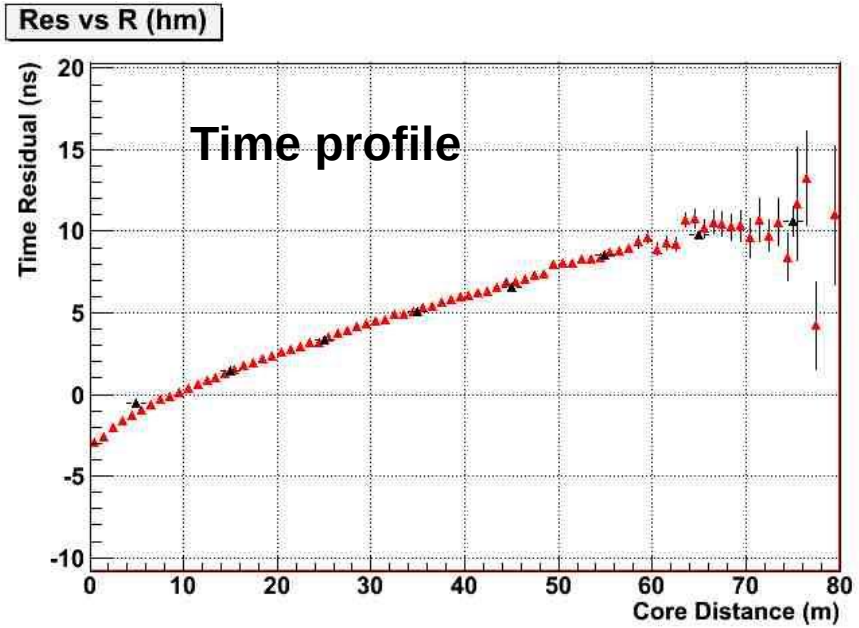
zenith < 15°



Average Curvature: the mean of time residuals **Δt(R)** with respect to a **plane fit**

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



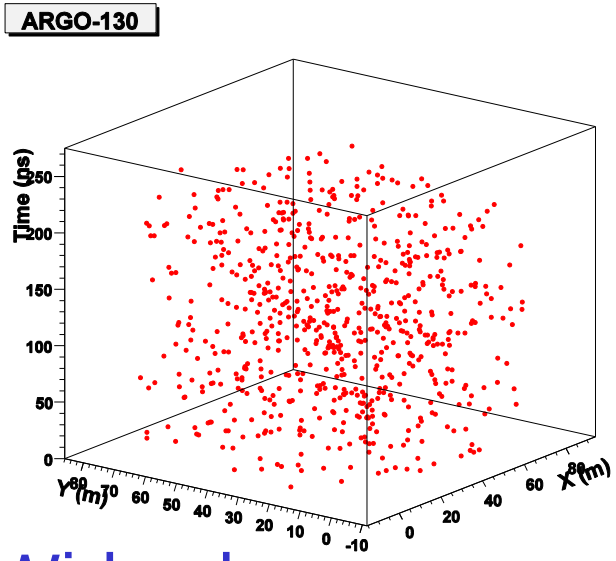


- **10 ns from 10m to 60 m from the core.**

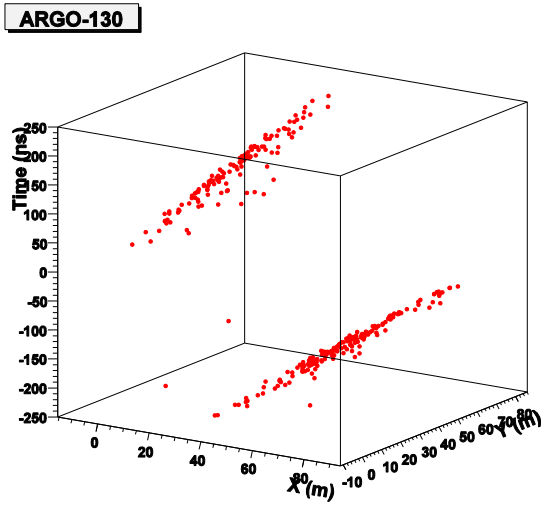
4 ns to 6ns from 10m to 60 m from the core.

Large RMS Shower fronts

- In order to exploit at maximum space-time information, we started a detailed study on the longitudinal time structures in data
- The idea is to study more in detail the shower structures to define selection criteria for particular analysis (gamma/hadron separation, composition, exotic physics)
- In particular we studied showers with large time residual with respect to the shower front
- Two Categories have been observed



Wide showers



Multiple Shell Front showers

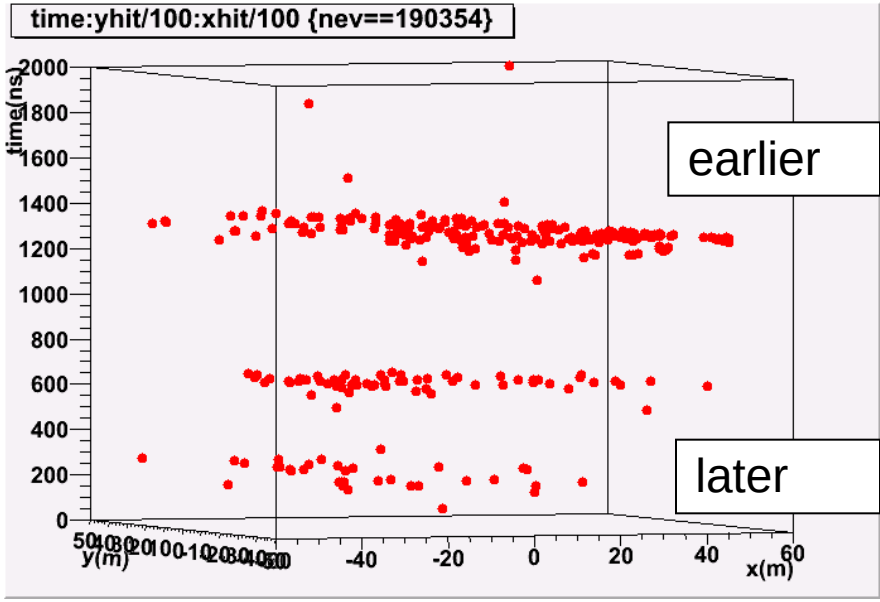
Multiple Shell Shower Fronts

- What are these showers?

accidental coincidences and

possible delayed showers

- How many events?
- How many are compatible with accidental coincidences?



  - Angular difference distribution
  - Nhit Distribution
  - Time delay
  - Observed vs Expected events

Double Shell Shower fronts

Short (not complete) list of references….

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- G. Damgaard et al., Phys. Lett. 17 (1965) 152.
- B.K. Chatterjee et al., Proc. 9th ICRC (1965).
- L. W. Jones et al., Phys. Rev. 164 (1967) 1584.
- G. Feinberg, Phys. Rev. 159 (1967) 1089.
- L. W. Jones et al., Rev. of Mod. Phys. 49 (1977) 717.
- N. Sakuyama et al., Il Nuovo Cimento vol. 6 C (1983) 371
- M. Yoshida et al., J. of the Phys. Soc. of Jap. 53 (1984) 1983.
- M. Ambrosio et al., Astrop. Phys. 11 (1999) 437
- V. I. Yakovlev et al., Yadernaya Fizika 73 (2010) 816..

Double Shell Shower fronts

- Long story of observation of delayed events associated to EAS

A possible origin is the production of heavy particles. Assuming a production distance (or decay length) L from the detector the expected delay is:

$$\Delta t = L\,(1/v - 1/c) \approx L/2c\gamma^2$$

Assuming L ~ 20 km, with a useful time window 50 ns – 1400 ns, we can probe γ ranging from 5 to 26

- Define constraint on Heavy Mass particle $\gamma = E/M$
- Evaluate lifetime

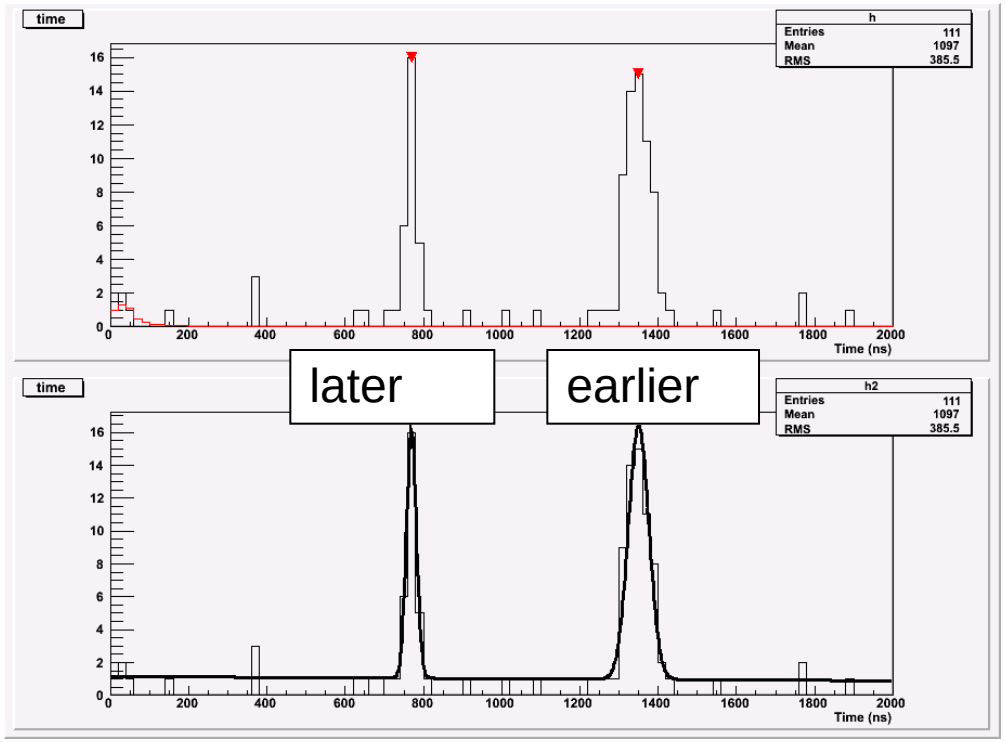
$$f(\Delta t) = C \times exp\,[-\Delta t/\Delta t_0]$$

$$\Delta t_0 = \tau/2\gamma. \qquad \tau = 2\gamma\Delta t_0$$

Multiple Shell Shower Fronts

Selection

- Hit Number >100 (10% of Ev.)
- Fit on time distribution
  - **Used TSpectrum class of root**



Reconstruction

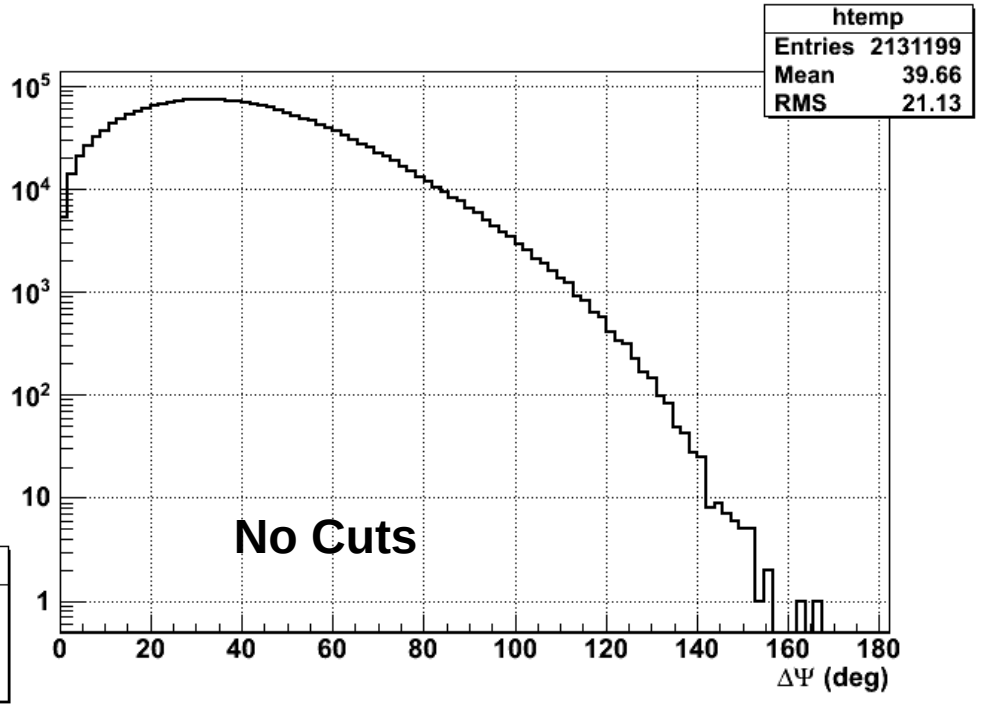
- Separation of subshowers
- Planar Fit on subshowers
- Quality cuts on reconstructed subshowers

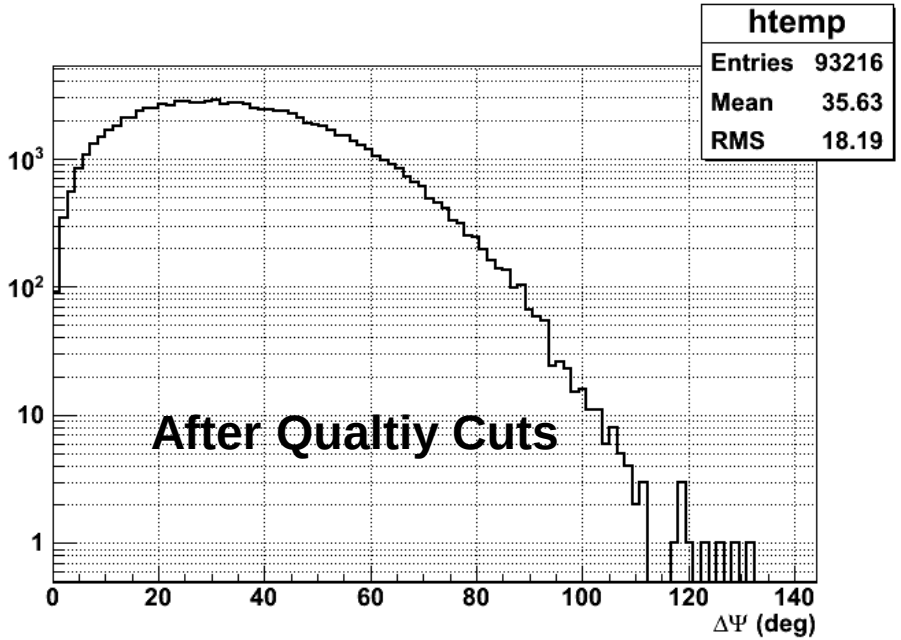
Distance of two peaks > σ1+σ2

Angular difference Distribution

Angular difference between the reconstructed subshower directions

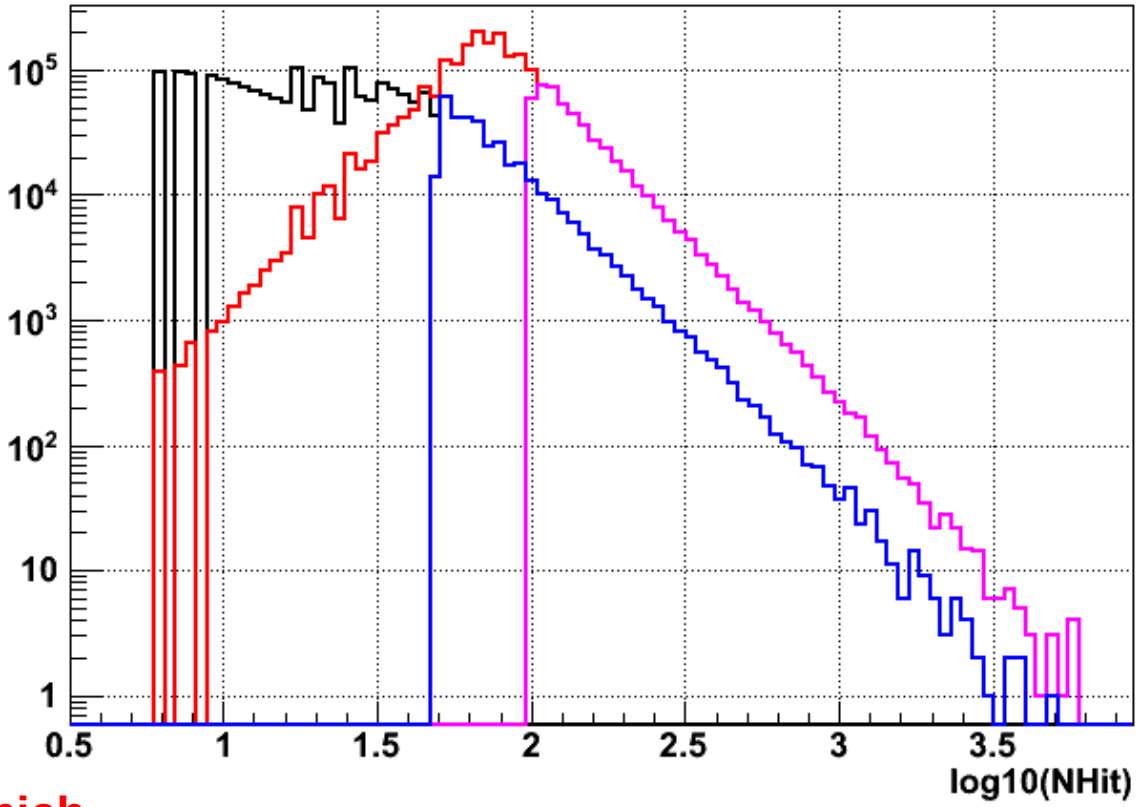
In agreement with CR distribution of consecutive events





Multiplicity Distribution

Multiplicity distribution of the reconstructed subshowers



Shower 1 (red) is the one which triggers the detector!

Shower2 (black) is expected to have a lower multiplicity distribution because no more trigger condition is required

Shower 1 Nhit >100

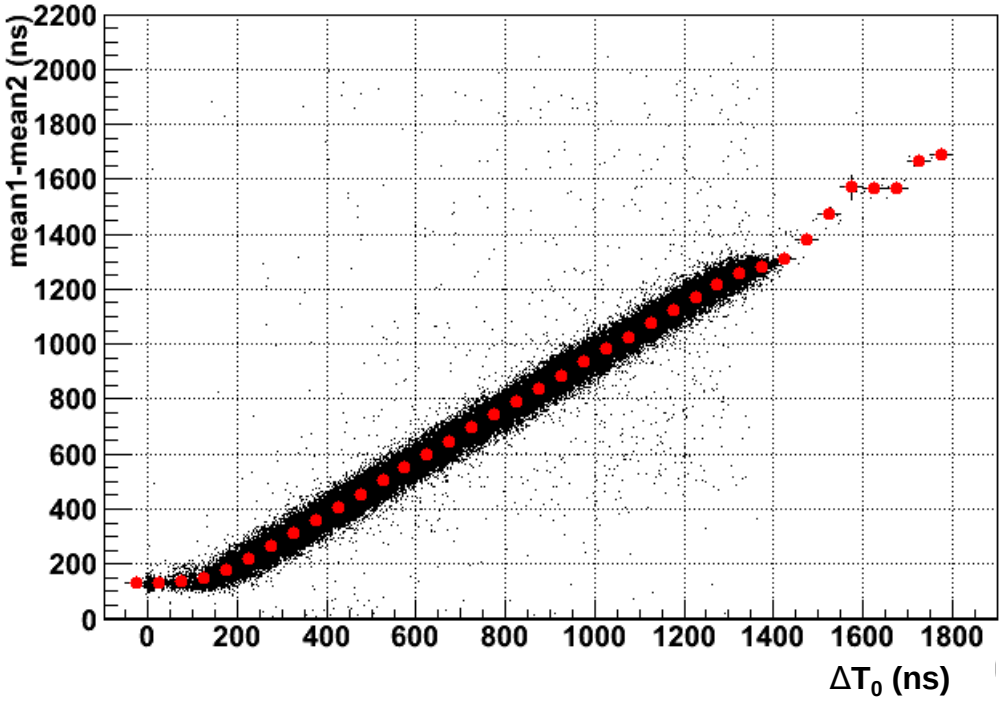
Shower2 Nhit >50

Time Distance

How to define time distance between two subshowers?

At least 2 variables:

- **Peak mean value**
- **T_0 from the shower plane Fit**

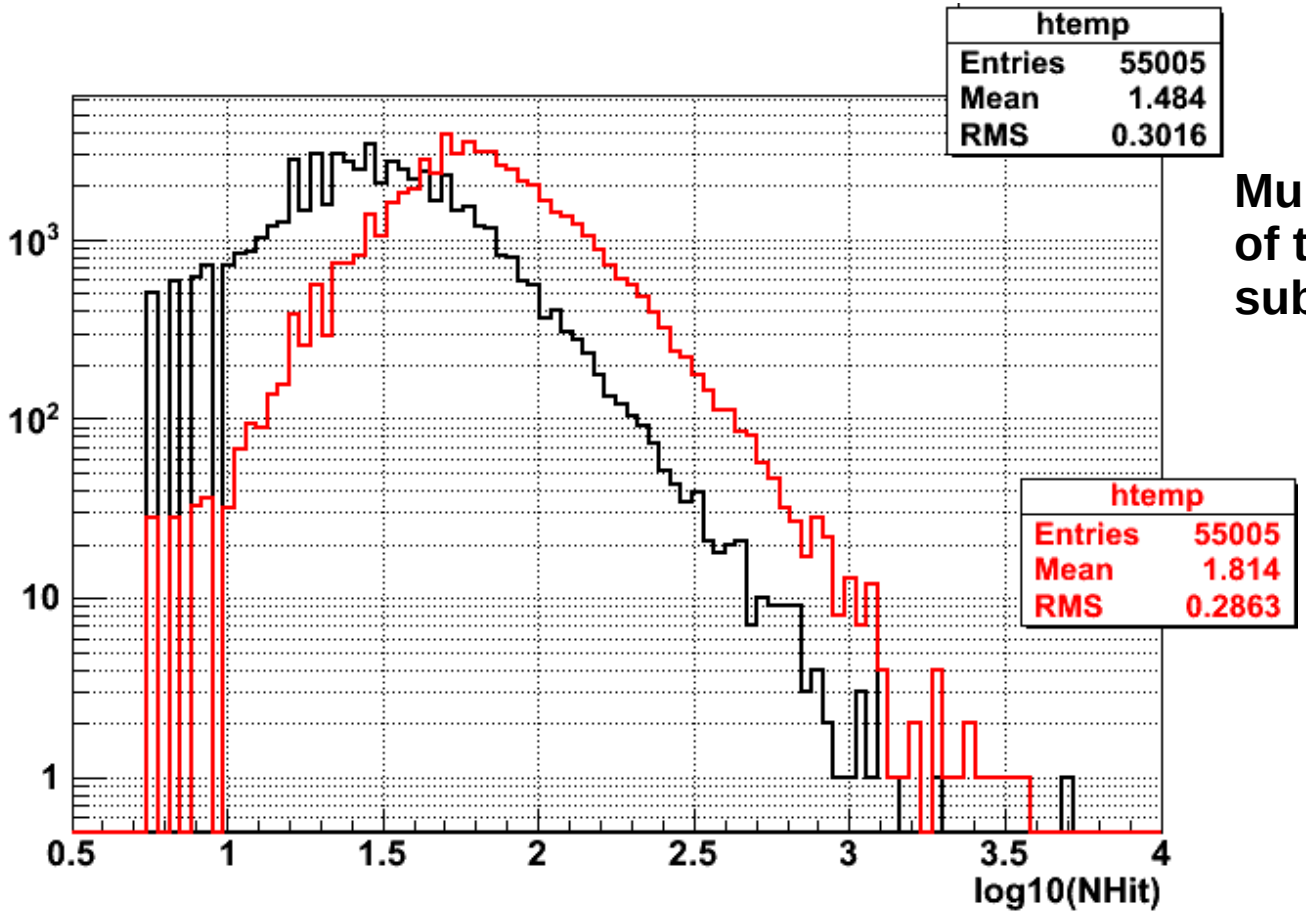


Analysis

Simulated double events

- “Artificial” double Events have been generated from real data
- Merged two consecutive events shifting the time of each hit of the second event by a randomly extracted ΔT by poissonian distribution compatible with the 2μs trigger window
- Verified the random double shower distributions (Angle, Multiplicity, relative time distribution)

Multiplicity Distribution



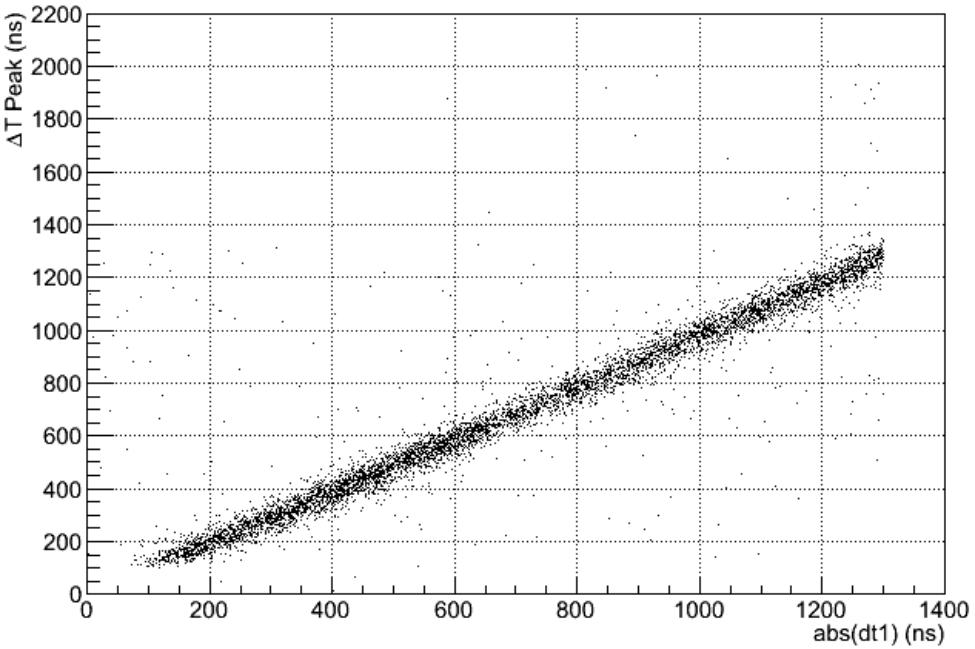
Multiplicity distribution of the reconstructed subshowers

Time Distance

Correlation between the reconstructed time distance and the generated time dt distance in “artificial” double shell shower fronts

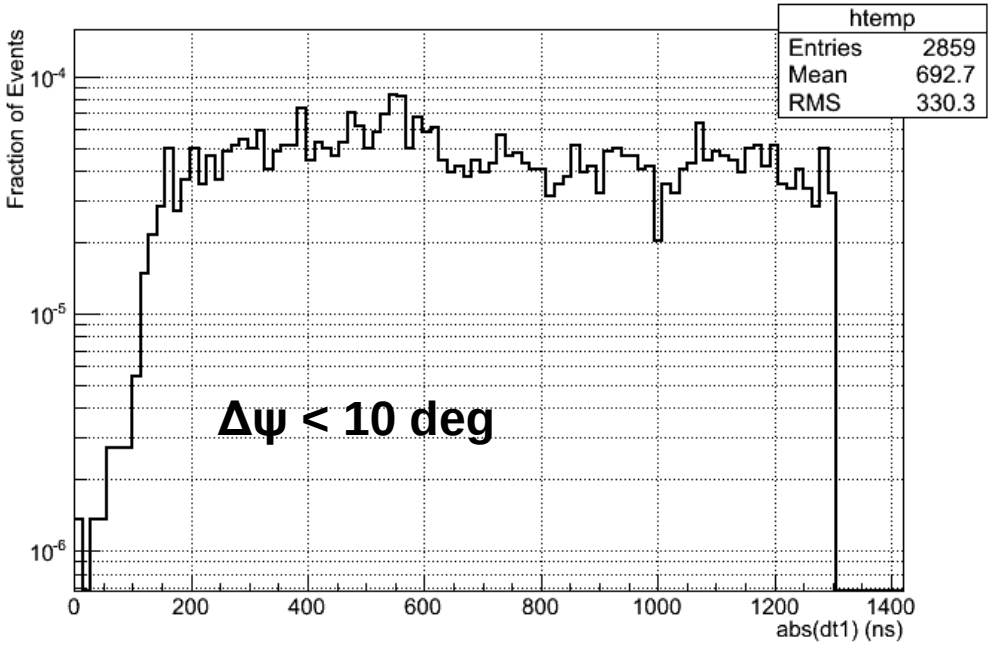
Time Peak distance is the good time distance observable

Peak Time vs dt Correlation



Selection Efficiency

Selection efficiency of the algorithm in function of the generated time dt distance in "artificial" double shell shower front has been tested



The total efficiency η is
10.94±0.05%

Analysis

Preliminary

Expected rates

- DAQ rate = 3266.03±0.03 Hz (multiplicity of Events Nhit > 20 in a time window τ = 2.048±0.001 μs)
- Rate of observed showers with

  $S^2 < 100\ ns^2$:

  1) Nhit >100 λ_1= 419±1 Hz
  2) Nhit > 50 λ_2= 1152±2 Hz

- **λ_{exp} = (0.957±0.003) Hz**

Observed rates

- 3.05 x10^9 events have been processed
- 2.1 x10^6 events selected as double coincidences
- 99 x10^3 events selected as double coincidences with quality cuts on subshowers (no angular aperture selection)
- Taking in account the efficiency of the selection algorithm the observed rate is:

λ_{obs} =(0.974±0.008) Hz

Summary

- **ARGO-YBJ allows detailed studies of EAS space-time features. Multiple Shell Shower fronts have been detected quite efficiently. They are mainly accidental coincidences due to the very high trigger rate.**

- **An upper limit on the fraction of double shell shower fronts, as a flag of possible 'exotic' physic events in CR, is on the way.**

- **Small angular aperture (< 10 deg) between the two sub-showers events and more geometrical parameters are under study in order to reduce the "accidental" coincidences.**