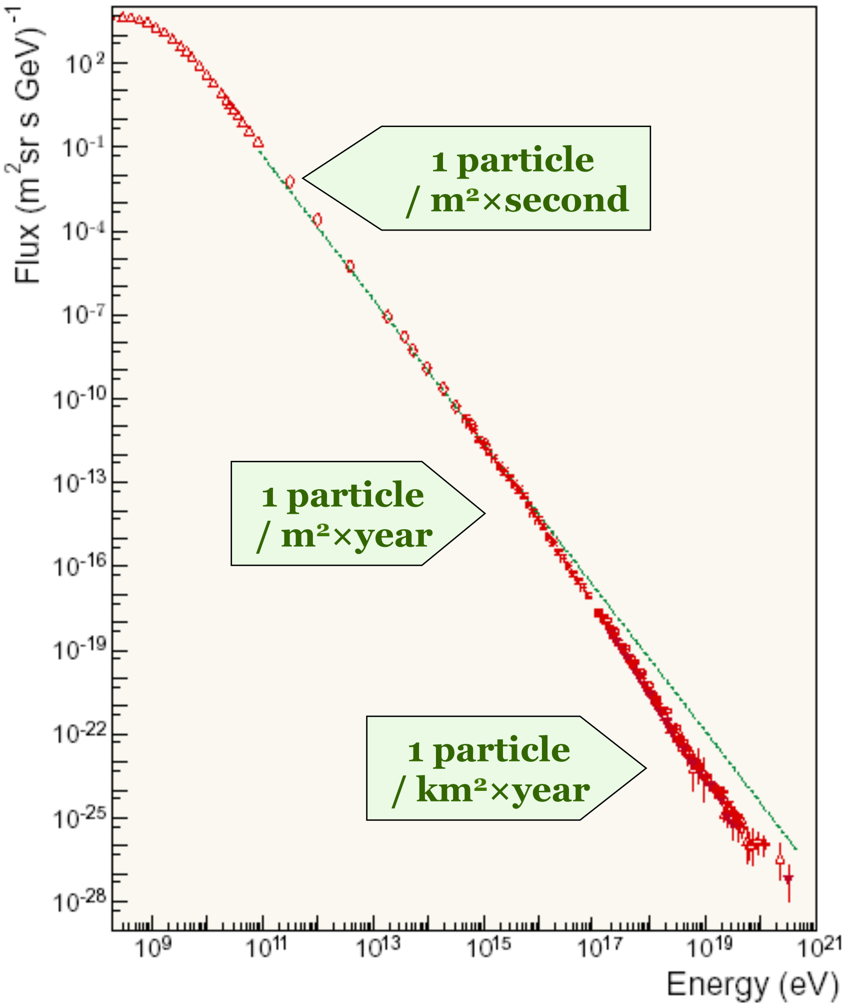
3-D CALORIMETRY FOR SPACE EXPERIMENTS

Oscar Adriani
INFN and University of Florence

Frascati, September 19th, 2013

Some of the Cosmic-Ray ‘mysteries’



High energy nuclei

- **“Knee” structure around ~ PeV**
  - Upper energy of galactic accelerators (?)
  - Energy-dependent composition
- **Structures in the GeV – TeV region recently discovered for p and He**
  - Composition at the knee may differ substantially from that at TeV
- **Spectral measurements in the knee region up to now are only indirect**
  - Ground-based atmospheric shower detectors
  - High uncertainties

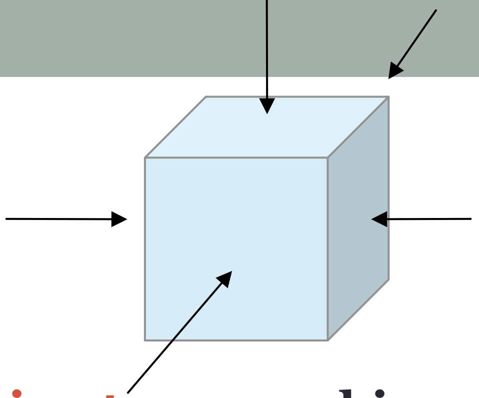
A direct spectral measurement in the PeV region requires great acceptance (few m^{2}sr) and good energy resolution for hadrons (at least 40%)

High energy Electrons+Positrons

- **Currently available measurements show some degree of disagreement in the 100 GeV – 1 TeV region**
- **Cutoff in the TeV region?**

Direct measurements require excellent energy resolution (~%), a high e/p rejection power (> 10^5) and large acceptance above 1 TeV

Our proposal for an ‘optimal’ CR detector



- **A 3-D, deep, homogeneous and isotropic calorimeter can achieve these design requirements:**
  - depth and homogeneity to achieve energy resolution
  - isotropy (3-D) to accept particles from all directions and increase GF
- **Proposal: a cubic calorimeter made of small cubic sensitive elements**
  - can accept events from 5 sides (mechanical support on bottom side) → GF * 5
  - segmentation in every direction gives e/p rejection power by means of topological shower analysis
  - cubic, small (~Moliére radius) scintillating crystals for homogeneity
  - gaps between crystals increase GF and can be used for signal readout
    - small degradation of energy resolution
  - must fulfill mass&power budget of a space experiment
    - modularity allows for easy resizing of the detector design
- Work going on since a couple of years

Additional details….

- Exercise made on the assumption that the detector's only weight is ~ 1600 kg
  - Mechanical support is not included in the weight estimation
- The optimal material is CsI(Tl)

Density:	4.51 g/cm^3
X_0:	1.85 cm
Moliere radius:	3.5 cm
λ_I:	37 cm
Light yield:	54.000 ph/MeV
τ_{decay}:	1.3 µs
λ_{max}:	560 nm

- Simulation and prototype beam tests used to characterize the detector

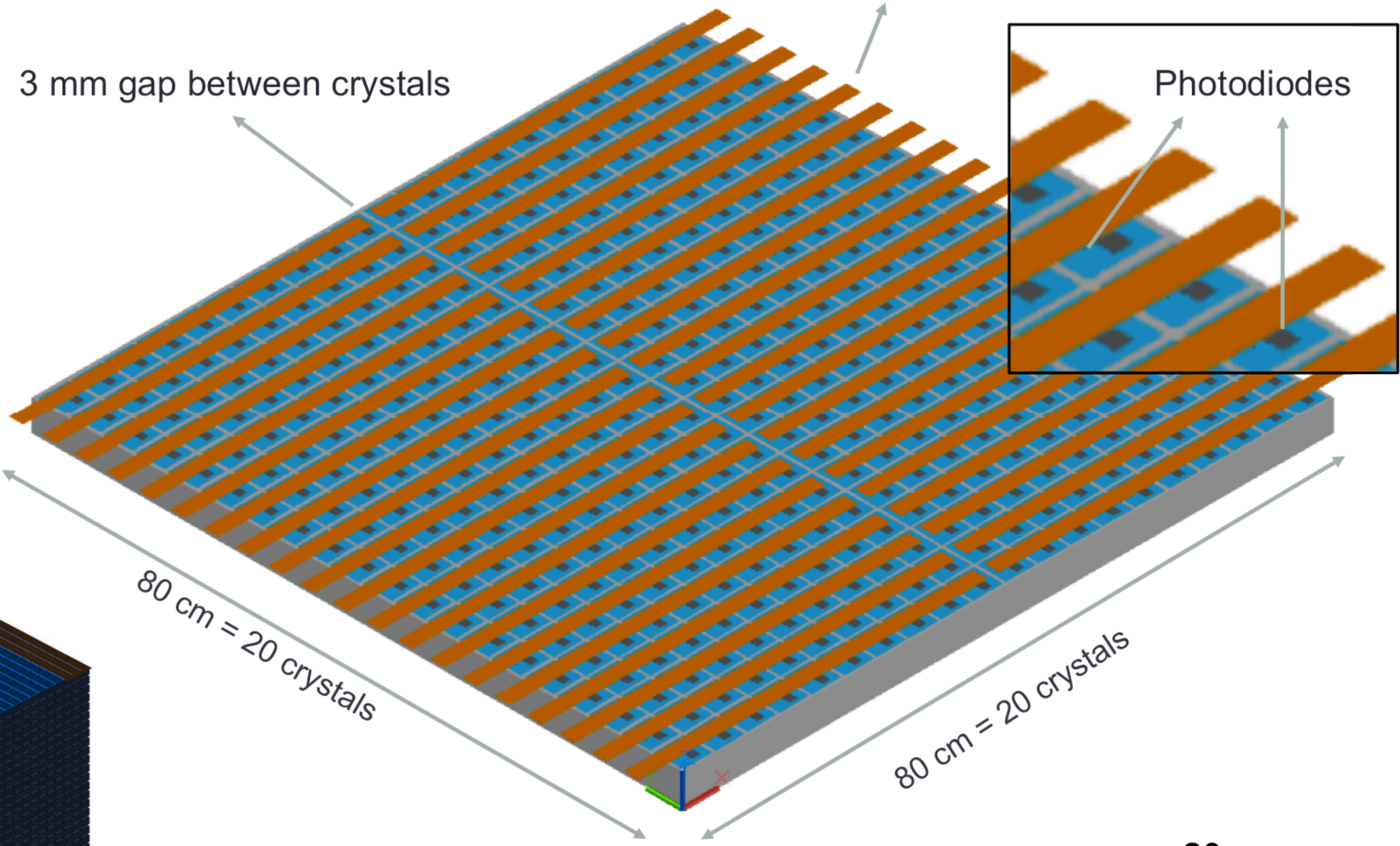
See for example:
N. Mori, et al.,
Homogeneous and isotropic calorimetry for space experiments
NIMA (2013)
http://dx.doi.org/10.1016/j.nima.2013.05.138i

N×N×N	**20×20×20**
L of small cube (cm)	3.6*
Crystal volume (cm^3)	46.7
Gap (cm)	**0.3**
Mass (Kg)	1683
N.Crystals	8000
Size (cm^3)	78.0×78.0×78.0
Depth (R.L.) " (I.L.)	39×39×39 1.8×1.8×1.8
Planar GF (m^{2}sr) **	1.91

(* one Moliere radius)
(** GF for only one face)

Mechanical idea

Single layer



Kapton cables for readout

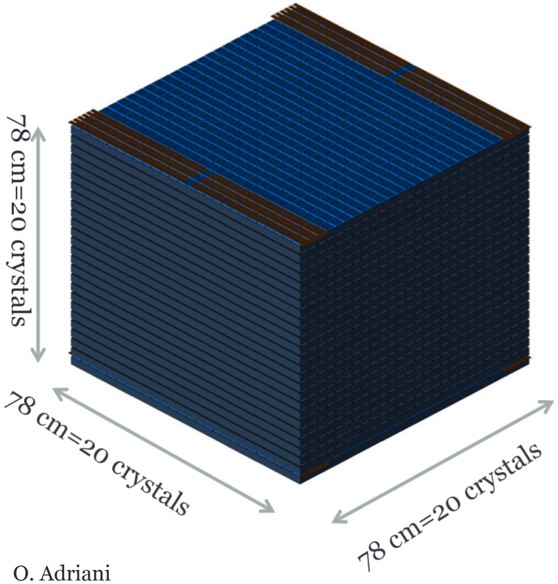
3 mm gap between crystals

Photodiodes

80 cm = 20 crystals

80 cm = 20 crystals

x 20 layers



78 cm=20 crystals

78 cm=20 crystals

78 cm=20 crystals

The readout sensors and the front-end chip

- Minimum 2 Photo Diodes are necessary on each crystal to cover the whole huge dynamic range 1 MIP→10^7 MIPS
  - Large Area Excelitas VTH2090 9.2 x 9.2 mm^2 for small signals
  - Small area 0.5 x 0.5 mm^2 for large signals

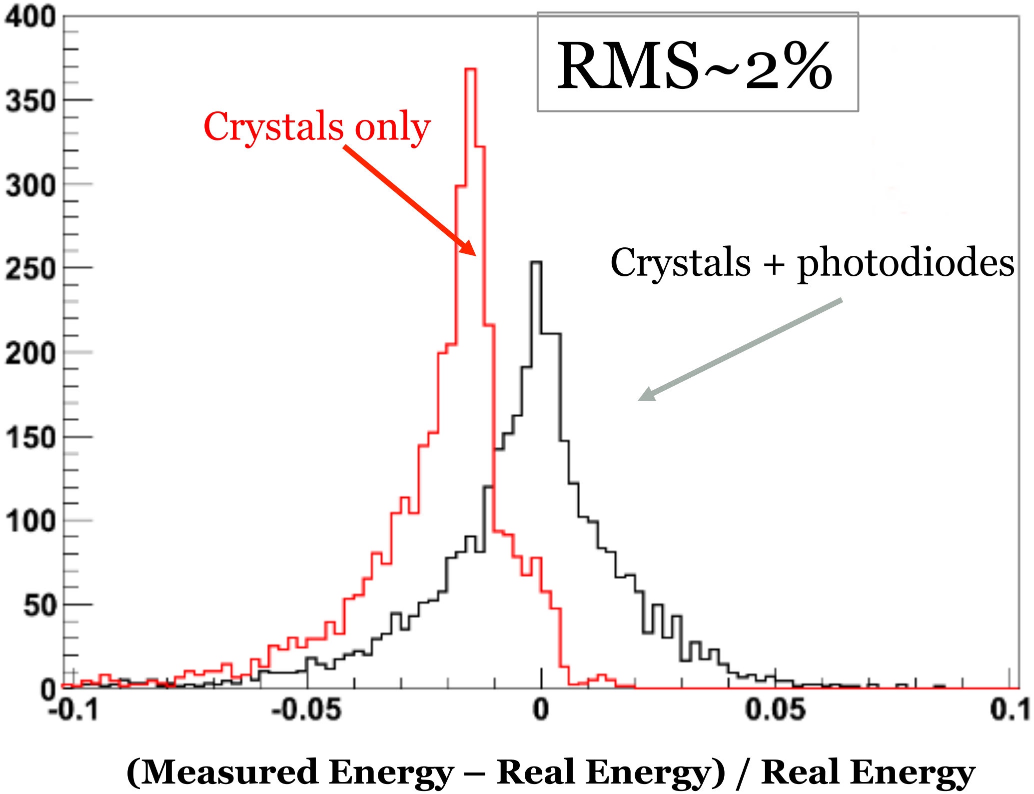
- Front-End electronics: a big challenge!
- The CASIS chip, developed in Italy by INFN-Trieste, is very well suited for this purpose
  - IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 57, NO. 5, OCTOBER 2010
- 16 channels CSA+CDS
- Automatic switching btw low and high gain mode
- 2.8 mW/channel
- 3.10^3 e^- noise for 100 pF input capacitance
- 53 pC maximum input charge

MC simulations

- **Fluka-based MC simulation**
  - Scintillating crystals
  - Photodiodes
    - Energy deposits in the photodiodes due to ionization are taken into account
  - Carbon fiber support structure (filling the 3mm gap)
- **Isotropic generation on the top surface**
  - Results are valid also for other sides
- **Simulated particles:**
  - Electrons: 100 GeV → 1 TeV
  - Protons: 100 GeV → 100 TeV
  - about $10^2 - 10^5$ events per energy value
- **Geometry factor, light collection and quantum efficiency of PD are taken into account**
- **Requirements on shower containment (fiducial volume, length of reconstructed track, minimum energy deposit)**
  - Nominal GF: $(0.78*0.78*\pi)*5*\varepsilon\ m^2sr = 9.55*\varepsilon\ m^2sr$

Electrons

Electrons 100 – 1000 GeV



Selection efficiency:
ε ~ 36%

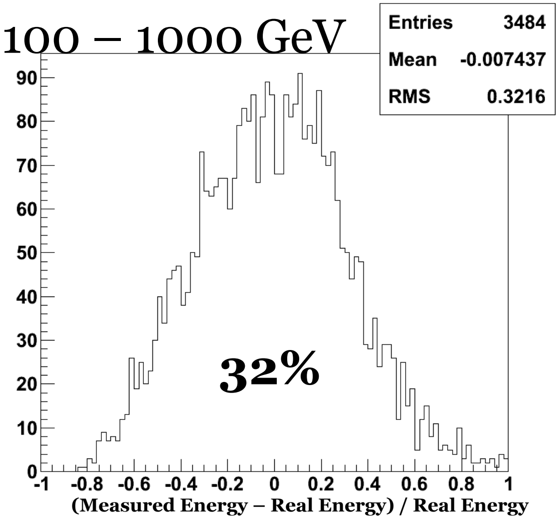
GF$_{\text{eff}}$ ~ 3.4 m^{2}sr

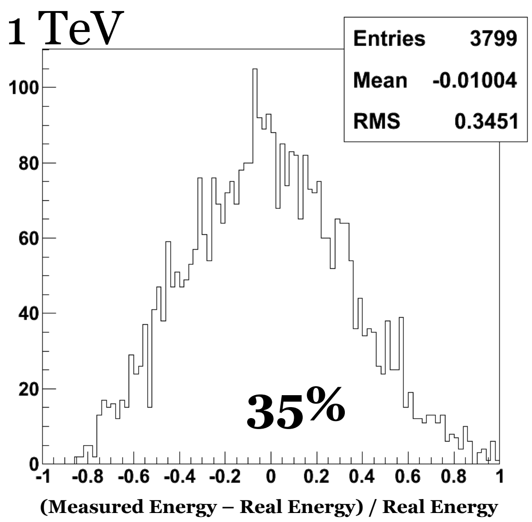
Non-gaussian tails due to leakages and to energy losses in carbon fiber material

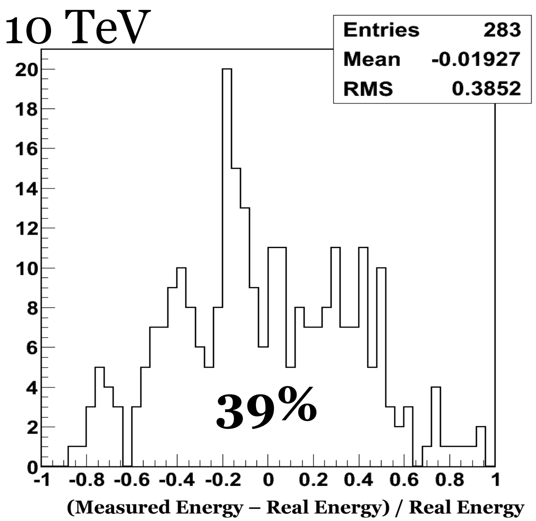
Ionization effect on PD: 1.7%

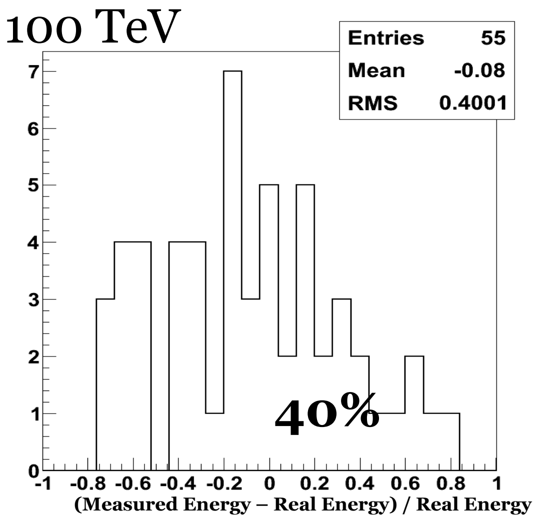
Protons

Energy resolution (correction for leakage by looking at the shower starting point)









Selection efficiencies:

$\varepsilon^{0.1\text{-}1TeV} \sim 35\%$

$\varepsilon^{1TeV} \sim 41\%$

$\varepsilon^{10TeV} \sim 47\%$

$GF_{eff}^{0.1\text{-}1TeV} \sim 3.3\ m^2sr$

$Gf_{eff}^{1TeV} \sim 3.9\ m^2sr$

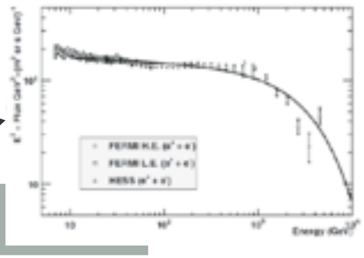
$Gf_{eff}^{10TeV} \sim 4.5\ m^2sr$

Proton rejection factor with simple topological cuts:
2.10^5-5.10^5 up to 10 TeV

Expected number of events

Assumptions:

- 10 years exposure
- p/e rejection factor ~ 10^5
- Depth: 39 X_0 – 1.8 λ



Electrons

Effective GF (m² sr)	σ(E)/E	E>0.5 TeV	E>1 TeV	E>2 TeV	E>4 TeV
3.4	~1%	181.10^3	35.10^3	5.10^3	6.10^2

Knee

Protons and Helium – Polygonato Model

Effective GF (m² sr)	σ(E)/E	E>0.1 PeV		E>0.5 PeV		E>1 PeV		E>2 PeV		E>4 PeV	
		P	He	P	He	P	He	P	He	P	He
~4.0	35%	$7.8.10^3$	$7.4.10^3$	$4.6.10^2$	$5.1.10^2$	$1.2.10^2$	$1.5.10^2$	28	43	5	10

Heavier Nuclei (2<Z<25)– Polygonato Model

Effective GF (m² sr)	σ(E)/E	E>0.1 PeV		E>0.5 PeV		E>1 PeV		E>2 PeV		E>4 PeV	
		P	He	P	He	P	He	P	He	P	He
~4.8	32%	$4.3.10^3$	$4.5.10^3$	$3.0.10^2$	$3.2.10^2$	$1.0.10^2$	$1.0.10^2$	29	34	8	10

The prototypes and the test beams

- Two prototypes have been built at INFN Florence, with the help of INFN Trieste, INFN Pisa and University of Siena.

- A small, so called "pre-prototype", made of 4 layers with 3 crystals each
  - 12 CsI(Tl) crystals, 2.5x2.5x2.5 cm^3

- A bigger, properly called "prototype", made of 14 layers with 9 crystals each
  - 126 CsI(Tl) crystals, 3.6x3.6x3.6 cm^3

- Both devices have been tested at CERN SPS (pre-prototype in October 2012 and prototype in January-February 2013)

The prototype

14 Layers

9x9 crystals in each layer

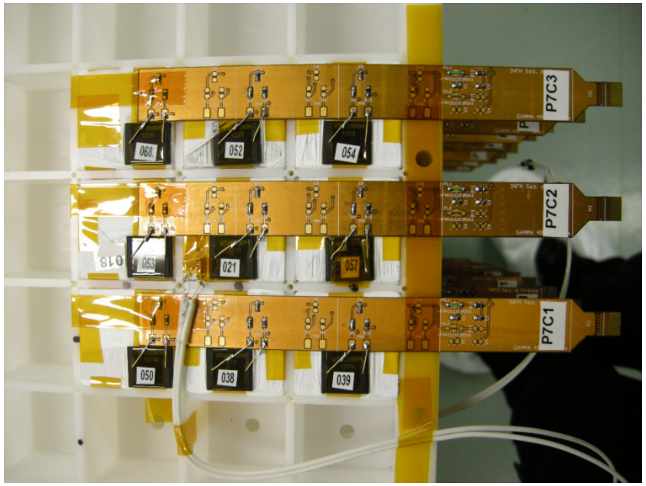
126 Crystals in total

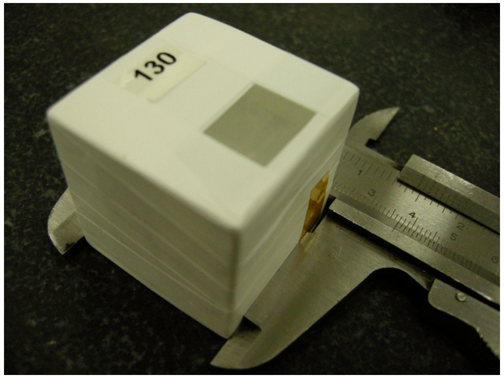
126 Photo Diodes

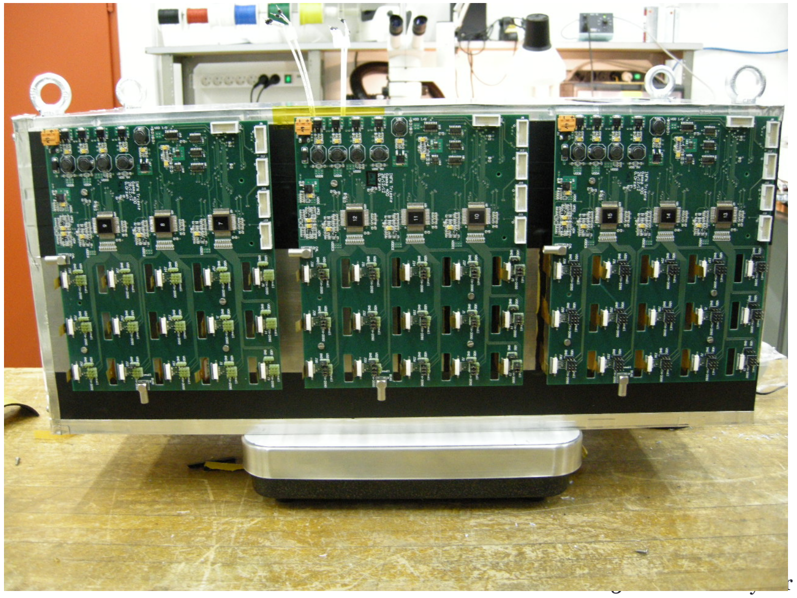
50.4 cm of CsI(Tl)

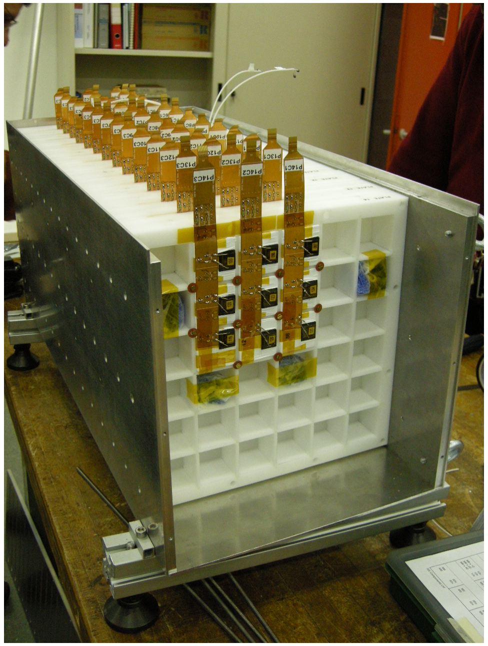
27 X_0

1.44 λ_I





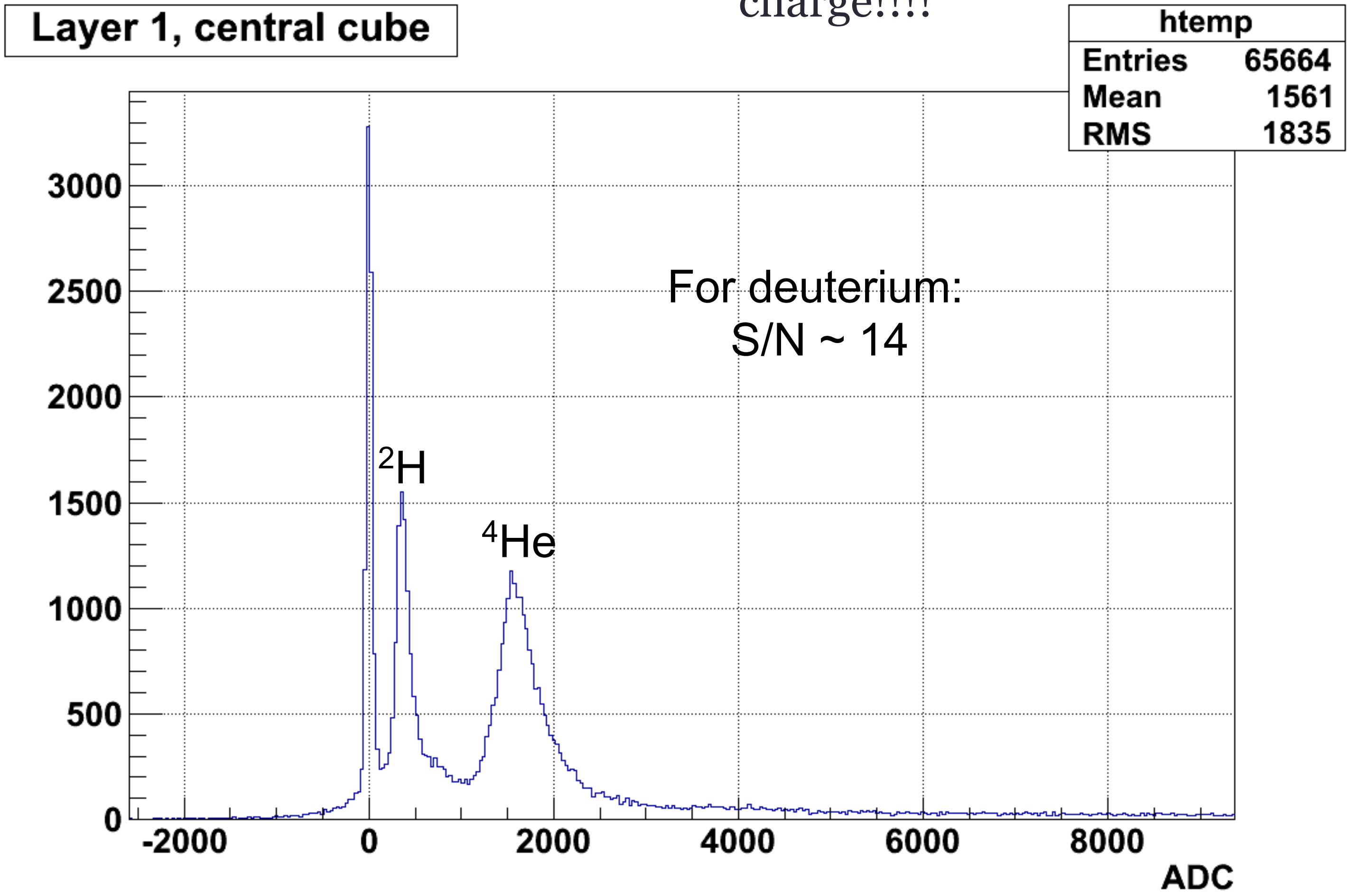




A glance at prototype's TB data

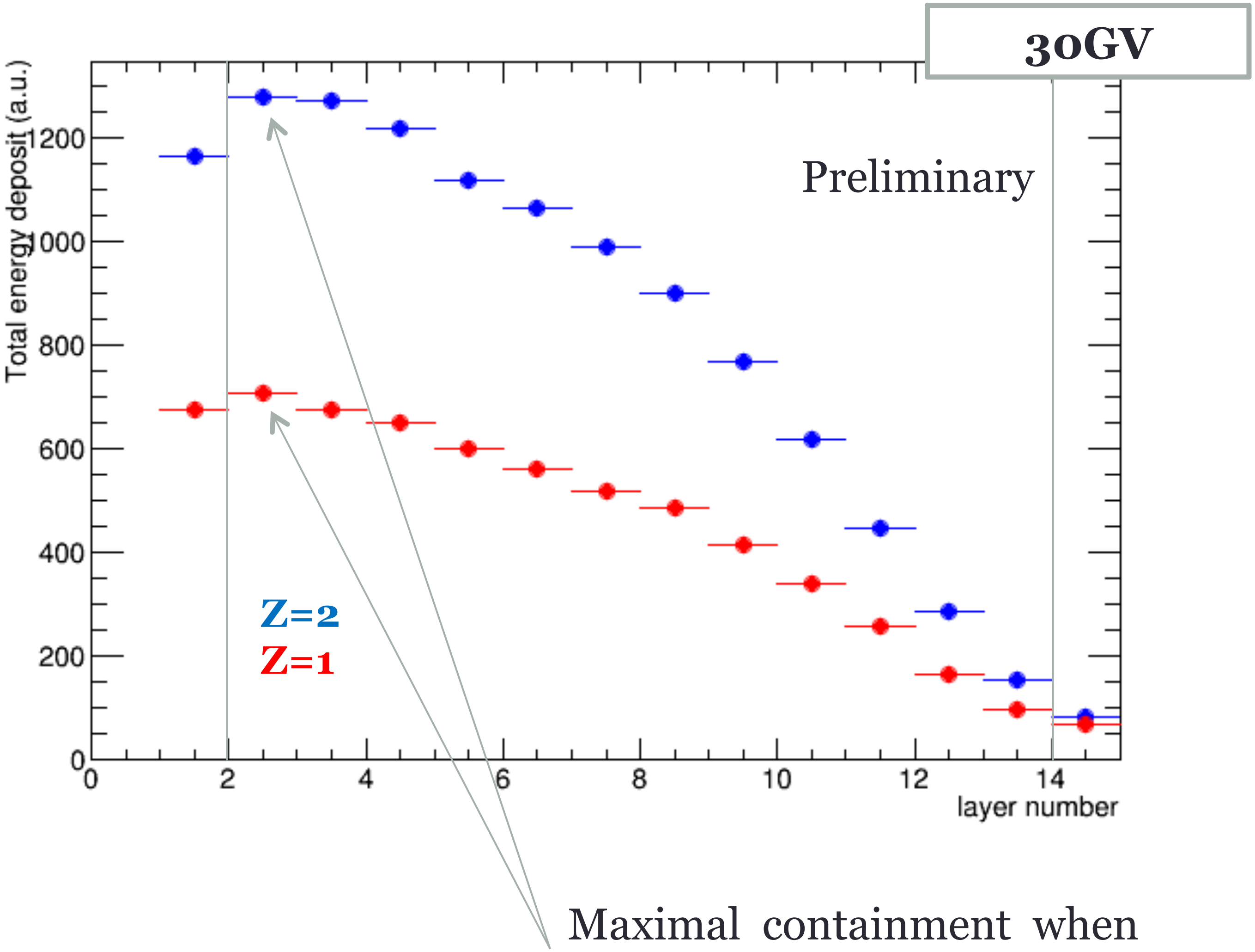
SPS H8 Ion Beam: Z/A = 1/2, 12.8 GV/c and 30 GV/c

Please note: we can use the data from a precise silicon Z measuring system located in front of the prototype to have an exact identification of the nucleus charge!!!!



For deuterium:
S/N ~ 14

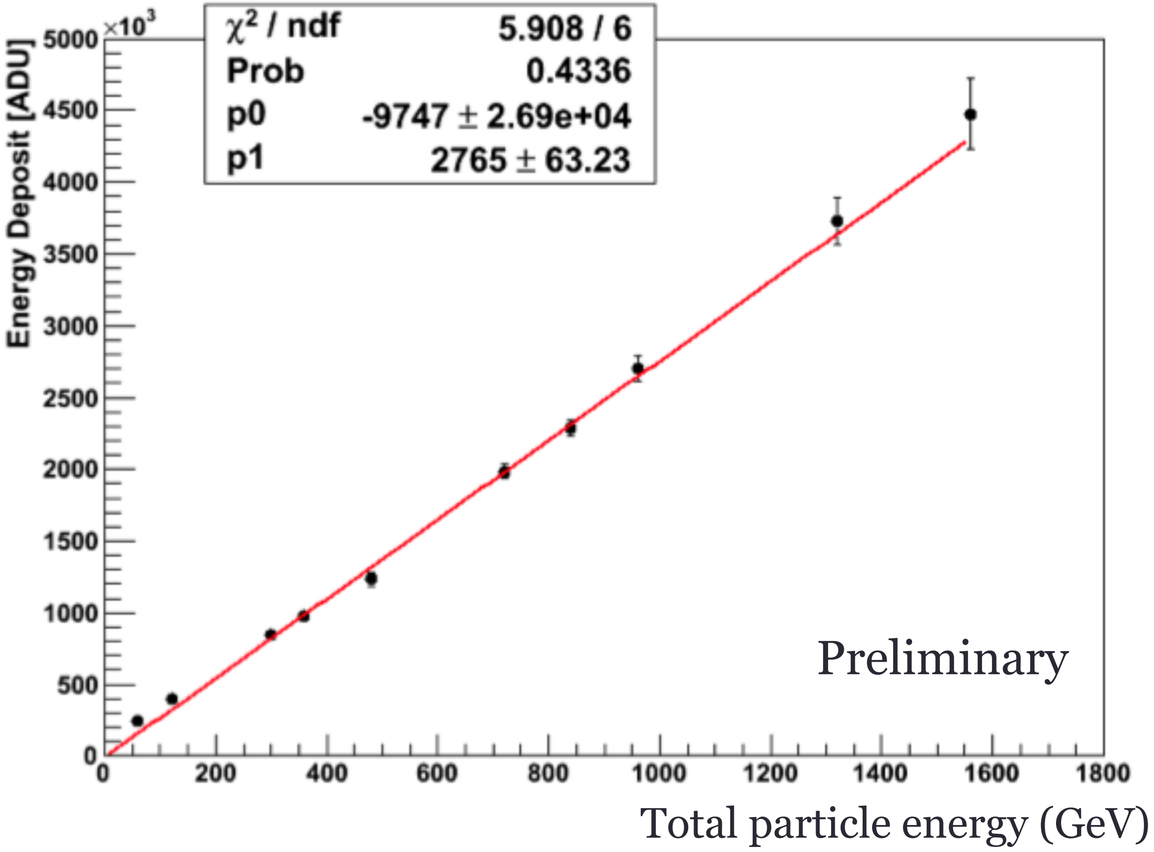
Total energy deposit VS shower-starting layer



Maximal containment when starting-layer == 2

Energy deposit for various nuclei

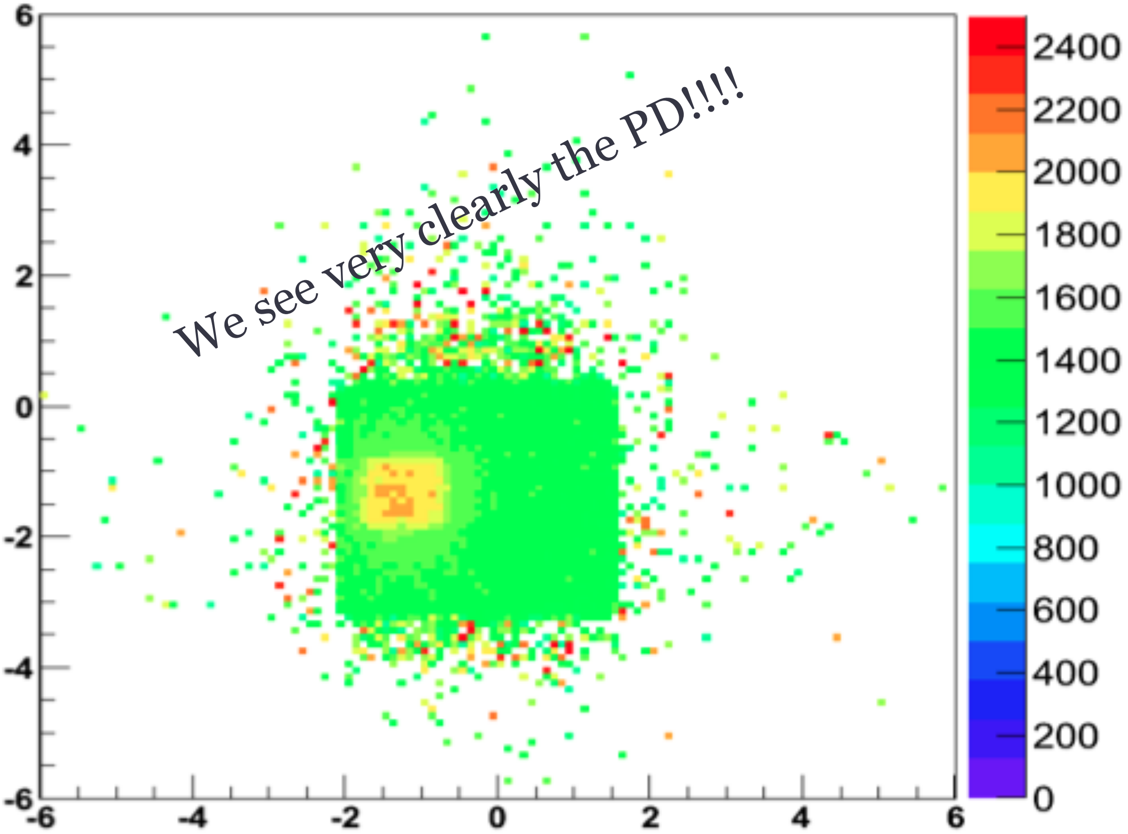
Energy Deposit Vs Beam Energy (D,He,B,C,O,Mg,Si,S,Ti,Fe)



Charge is selected with the placed-in-front tracking system

Good Linearity even with the large area PD!

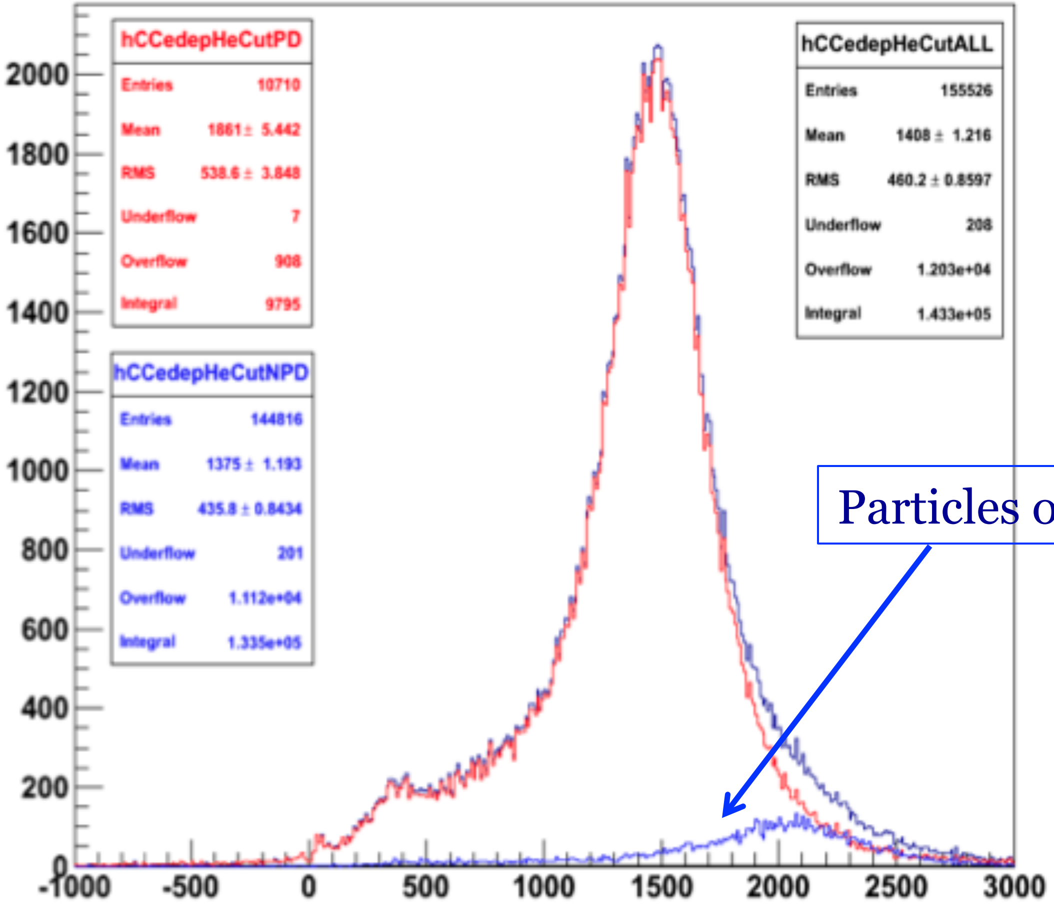
Response as function of impact point



We see very clearly the PD!!!!

Mean PH in central cube vs particle (He) entry point coordinates (using Si strips tracking)

Signals for different impact points



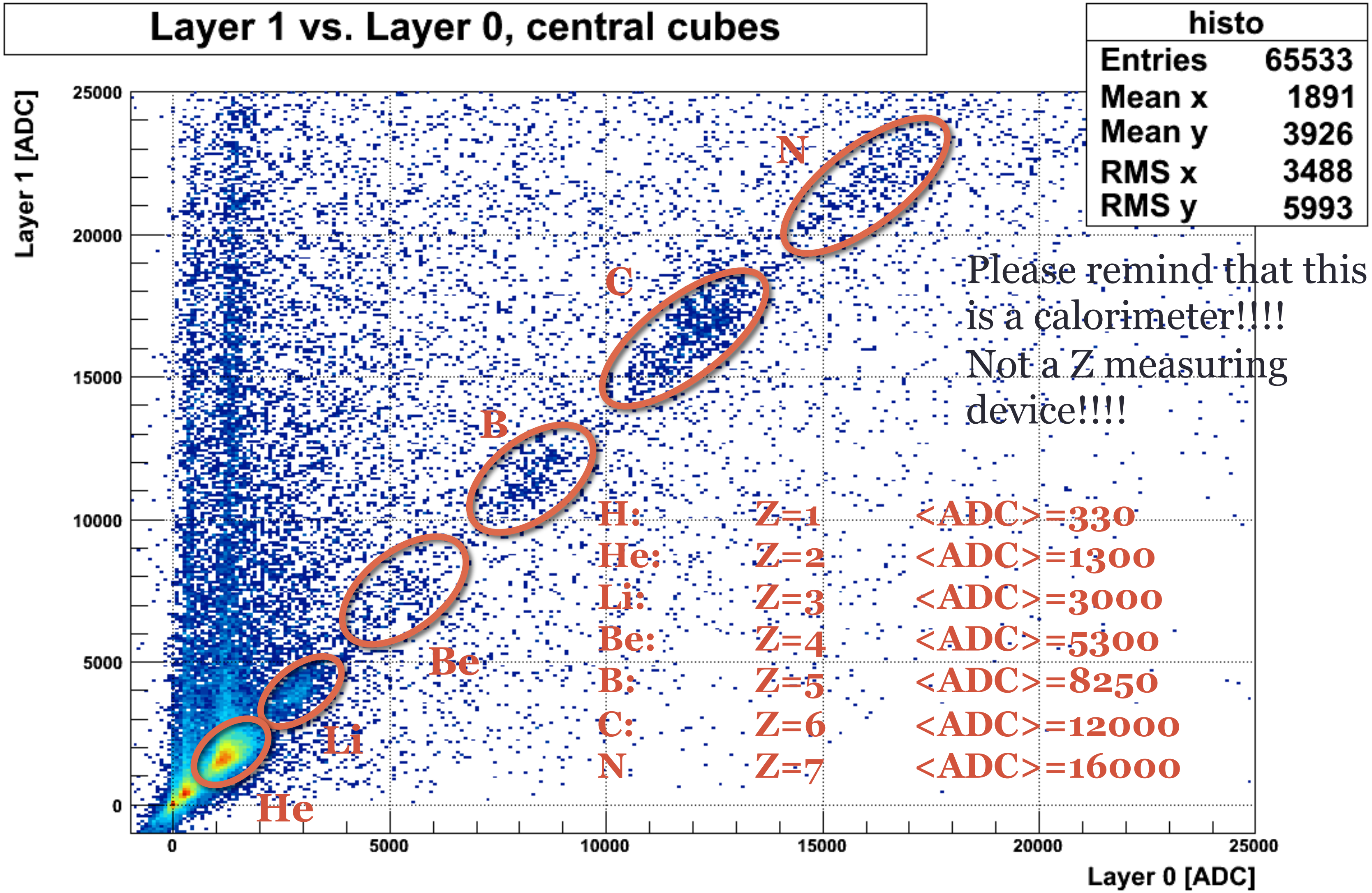
Particles on the PD

PD contribution is compatible with the expectations!

PD Signal

PH cube energy distributions:
- Black line: all signals
- Red line: tracks not crossing the phodiode
- Blue line: tracks crossing the photodiode

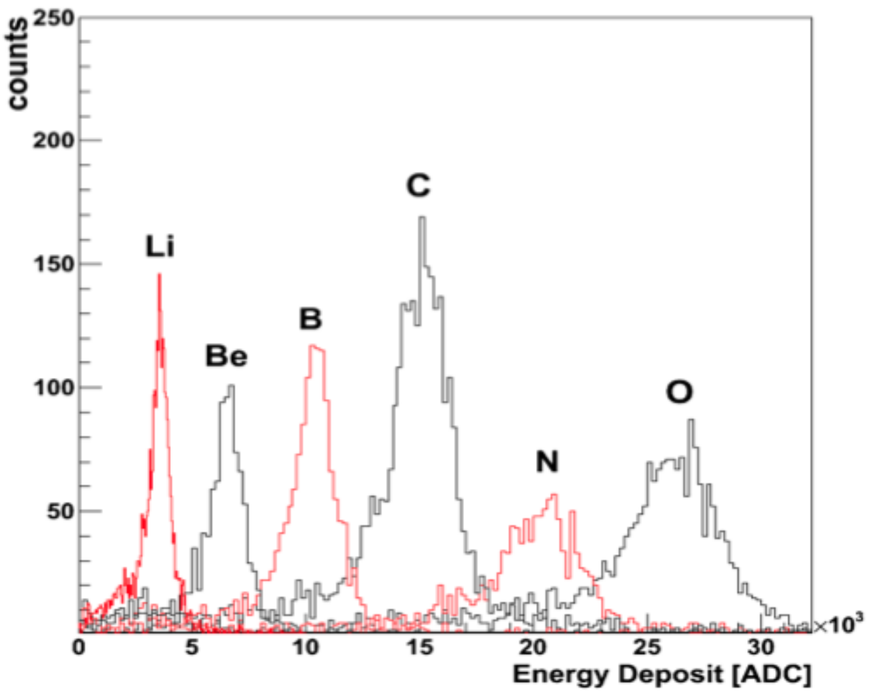
Non interacting ions

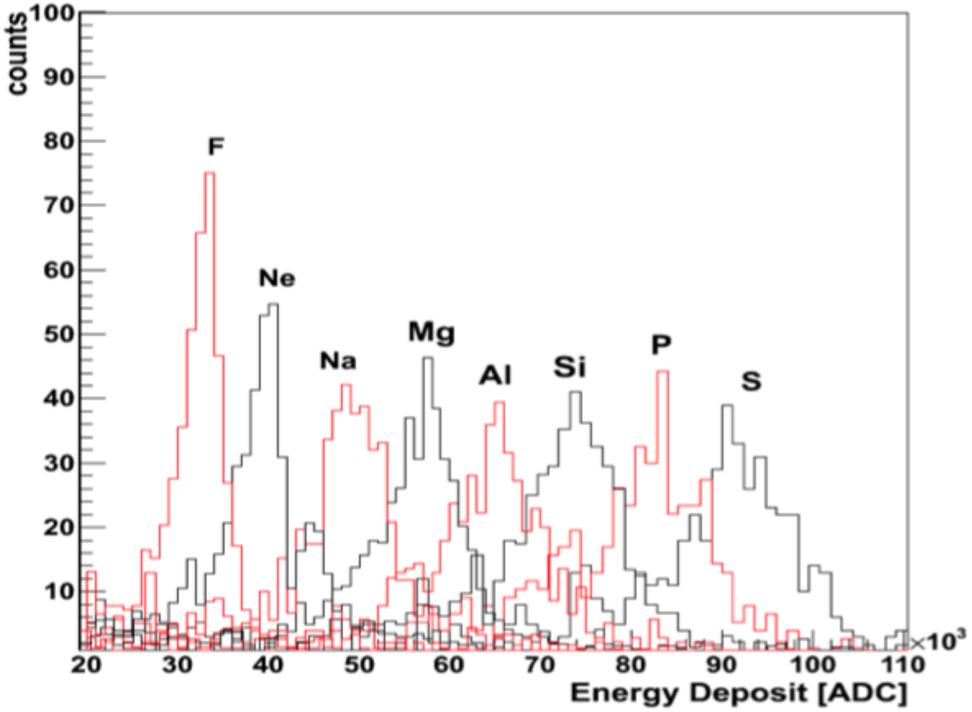


Please remind that this is a calorimeter!!!! Not a Z measuring device!!!!

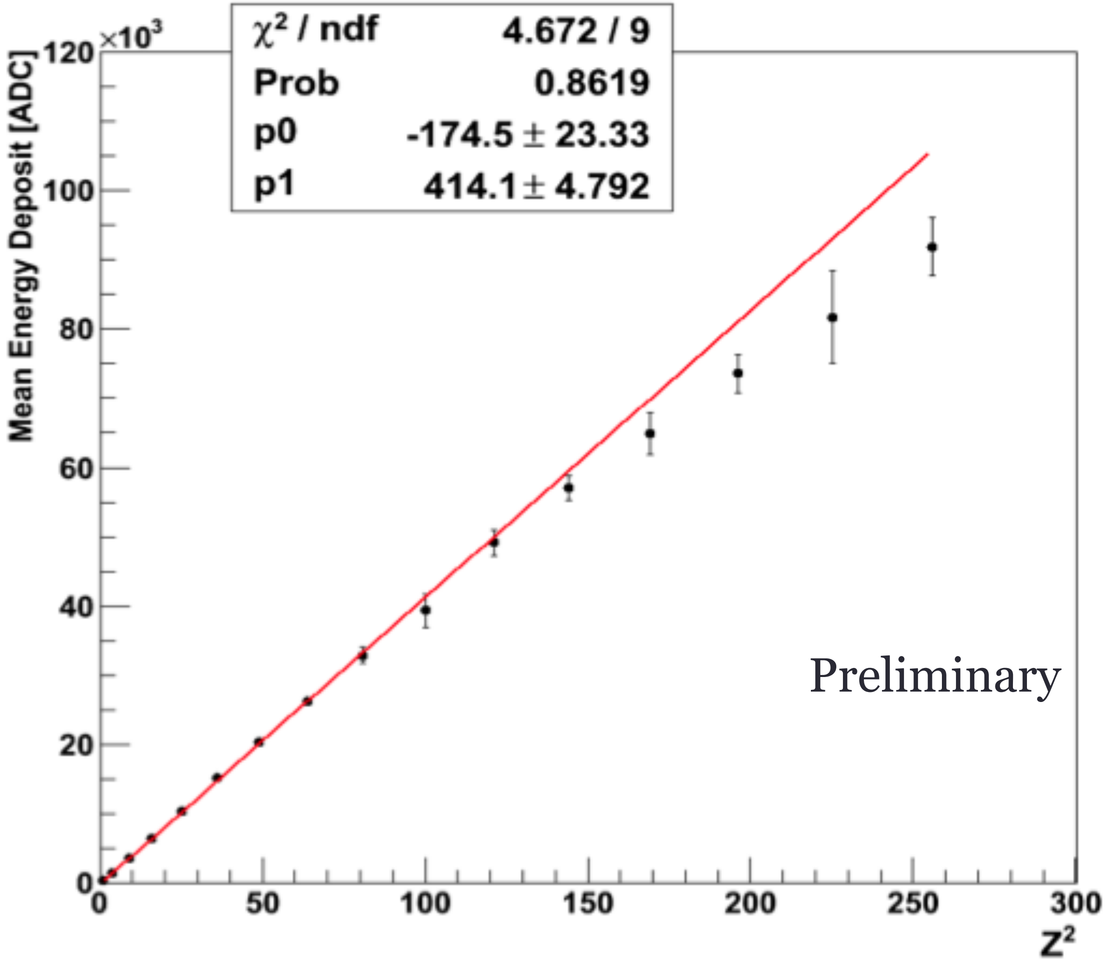
H:	Z=1	<ADC>=330
He:	Z=2	<ADC>=1300
Li:	Z=3	<ADC>=3000
Be:	Z=4	<ADC>=5300
B:	Z=5	<ADC>=8250
C:	Z=6	<ADC>=12000
N:	Z=7	<ADC>=16000

Charge selected with the Pisa-Siena tracker located in front (non interacting ions)





Charge linearity on the single crystal (non interacting ions)



Please note: fit function calculated using data from Helium up to Magnesium

HOW TO IMPROVE THE CALORIMETER PERFORMANCES?

Calocube

Sviluppo di calorimetria omogenea ad alta accettanza per esperimenti di Raggi Cosmici nello spazio

Call nell'ambito della CSN5 dell'INFN

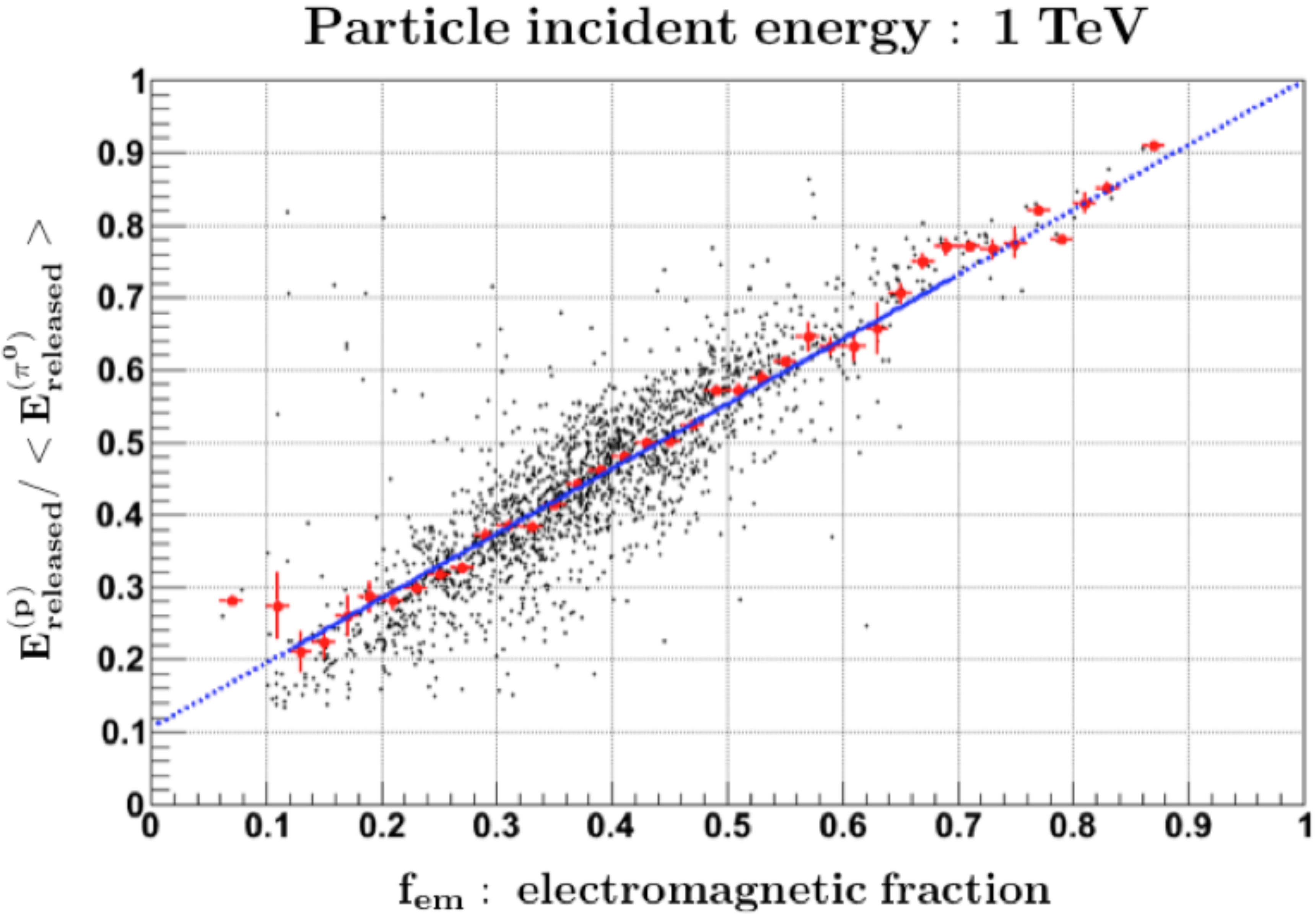
Oscar Adriani, Responsabile Nazionale

Basic ideas - A

Optimization of the overall calorimetric performances

- Optimize the hadronic energy resolution by means of the dual - or multiple - readout techniques (Compensation techniques)
  - Scintillation light, Cherenkov light, neutron related signals
- Innovative analysis techniques (software compensation)
  - Possible, due to the very fine granularity
- Development of innovative light collection and detection systems
  - Optical surface treatments directly on crystals, to collect/convert the UV Cherenkov light
    - Dichroic filters
    - WLS thin layers
  - UV sensitive SiPM and small/large area – twin - Photo Diodes
- New development of front end and readout electronics
  - Huge required dynamic range ($>10^7$)
  - Fast, medium and slow (delayed) signals together
  - New CASIS chip ASIC with integrated ADC

Principle of compensation



Basic ideas – B and C

Optimization of the charge identifier system - CIS

- The integration of the charge identifier system inside the calorimeter is a real break through for a space experiment
  - Huge reduction of mass, power and cost, simplification of the structure
- Thinner size scintillators crystals/Cherenkov radiators
- Pixel structure
- Multiple readouts in the ion track
- Back scattering problem to be carefully studied

Space qualification

- Demonstrate that such a complex device can be built with space qualified technologies
  - Necessary step for a real proposal for space
  - Production of a space qualified medium size prototype (~700 crystals)
  - Composite materials mechanics
  - Thermal aspects
    - Microcooling technologies to cool down sensors and/or electronics
  - Radiation damage issues

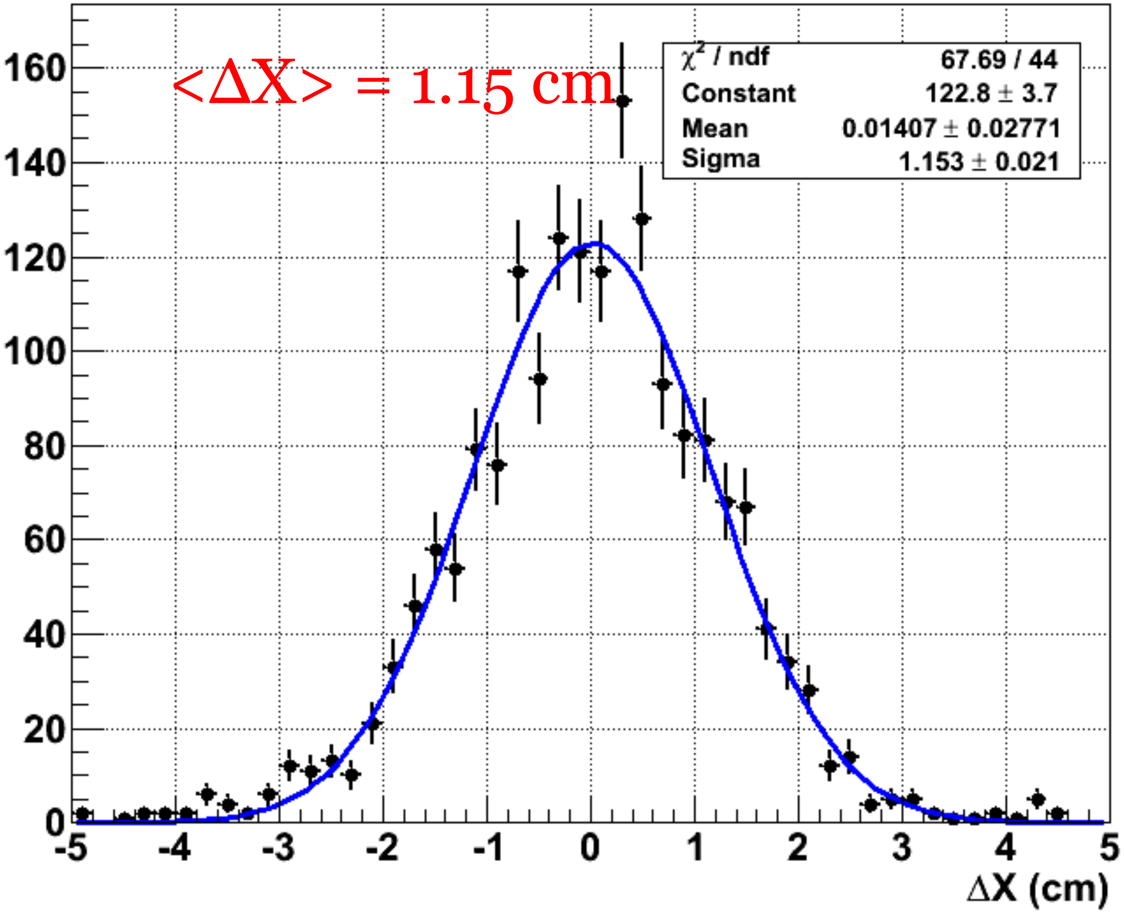
Conclusion

- An homogeneous, 3-D isotropic calorimeter looks to be an optimal tool for the direct detection of High Energy CR
  - Possible applications: GAMMA-400, HERD, …..

- The status of the project is quite advanced:
  - Simulation
  - Prototypes
  - Test beams
- Next steps:
  - Improve the overall performances of the system
    - Compensation techniques
    - High Dynamic range electronics
    - Deposition of optical filters on the crystals
    - Charge Measuring System optimization
    - Space qualification
- Thanks to INFN-Space!!!!!!!!!!
- Joint activities are really useful, necessaries and welcome

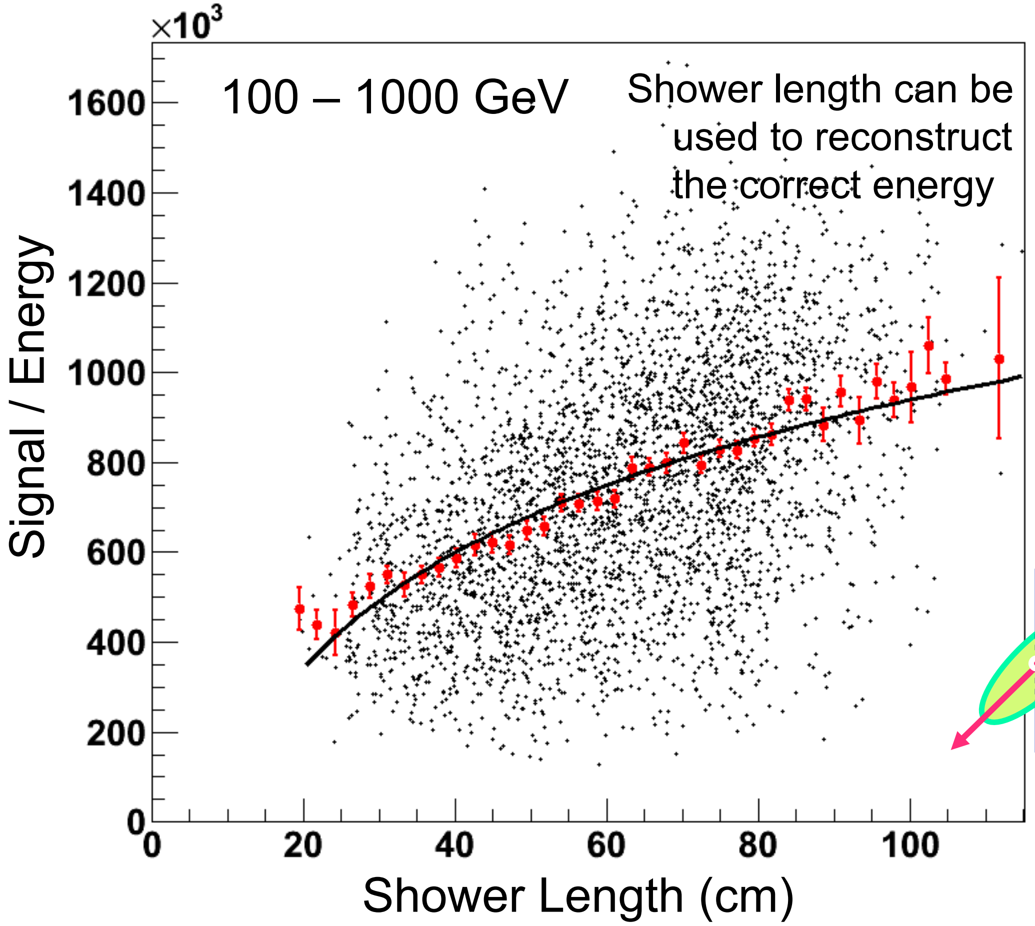
BACKUP

Shower starting point resolution



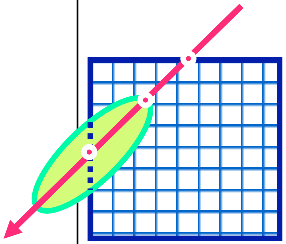
Protons

Energy estimation

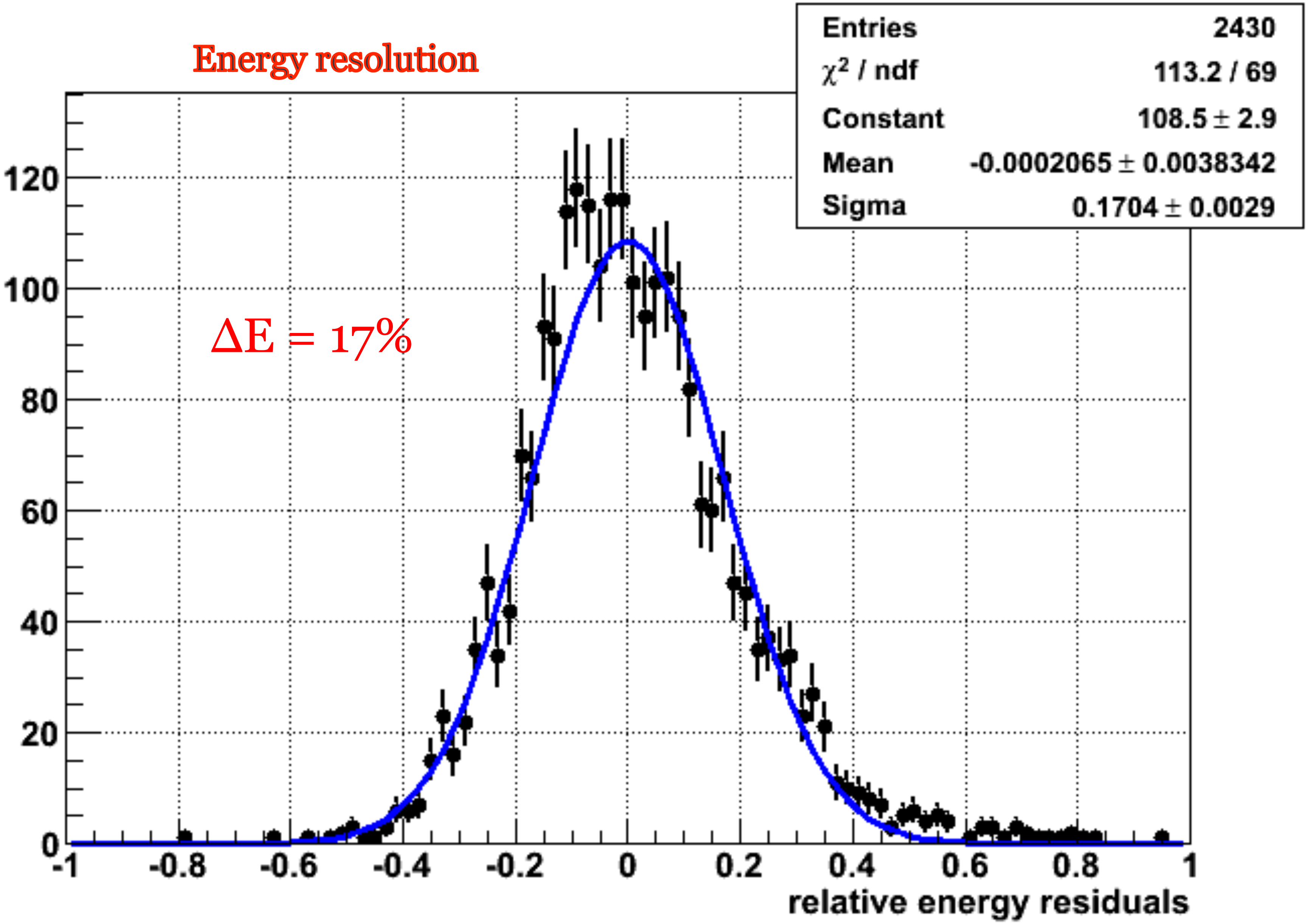


Shower length can be used to reconstruct the correct energy

Red points: profile histogram
Fitted with logarithmic function

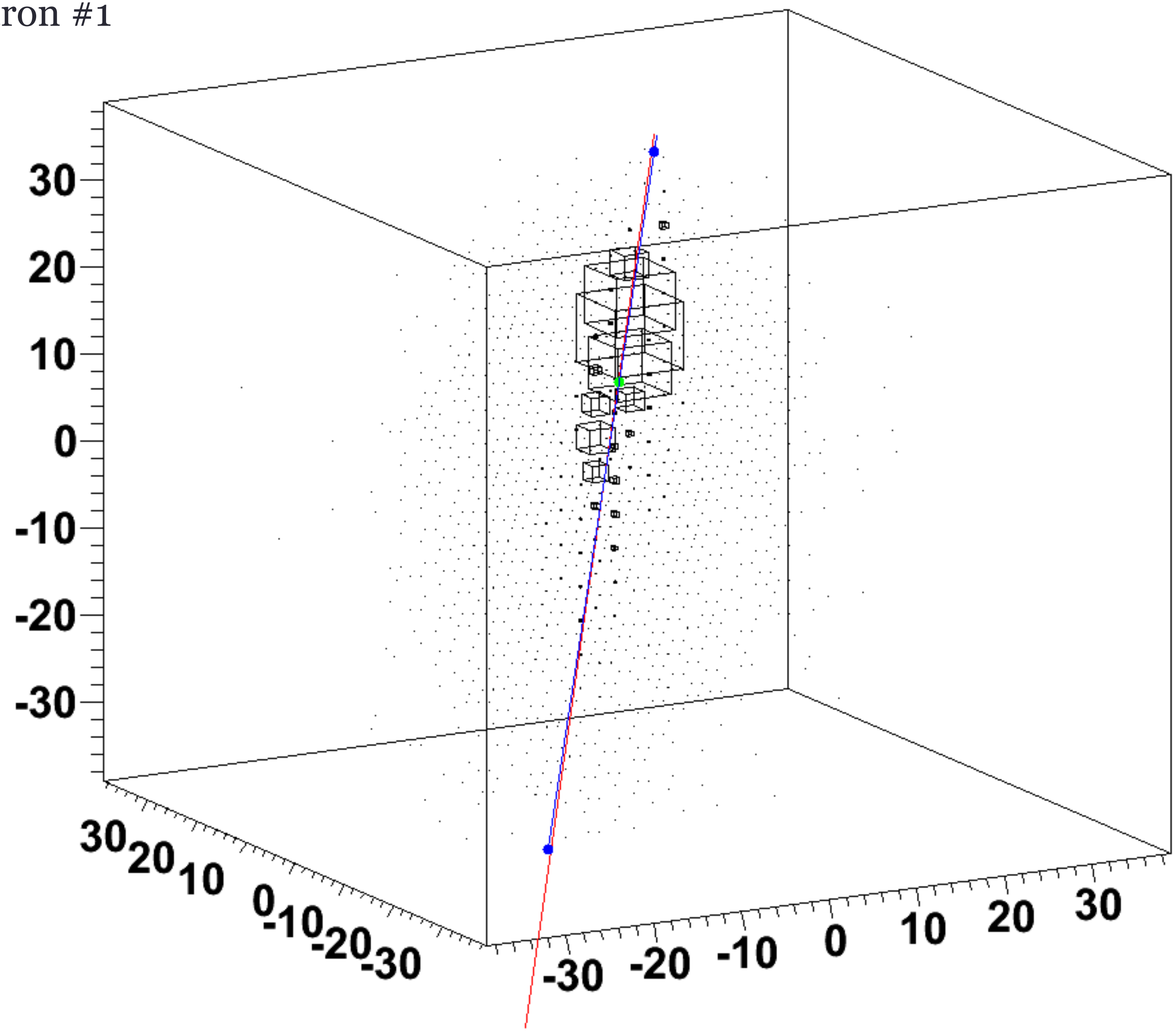


Energy resolution



$\Delta E = 17\%$

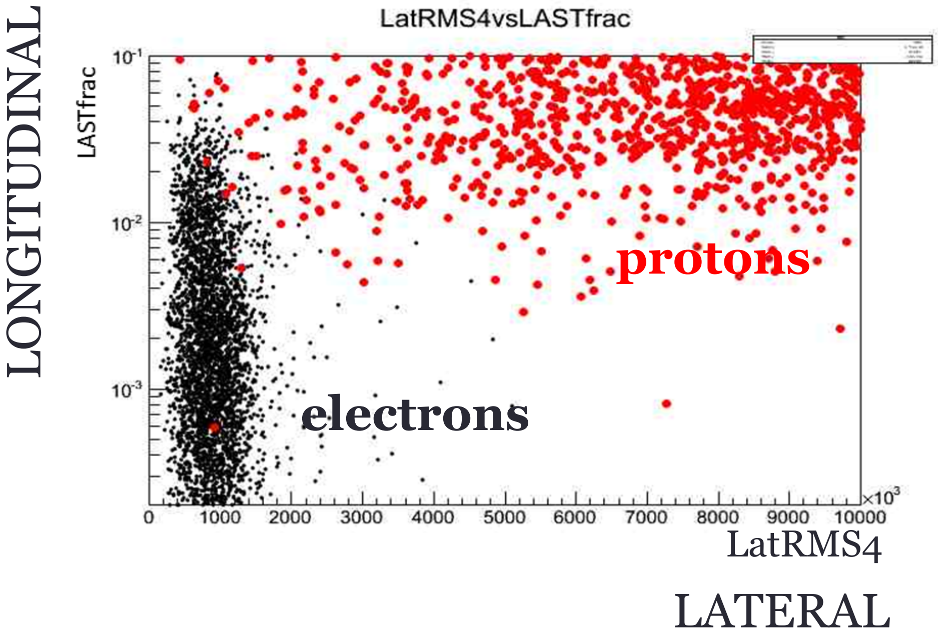
Electron #1



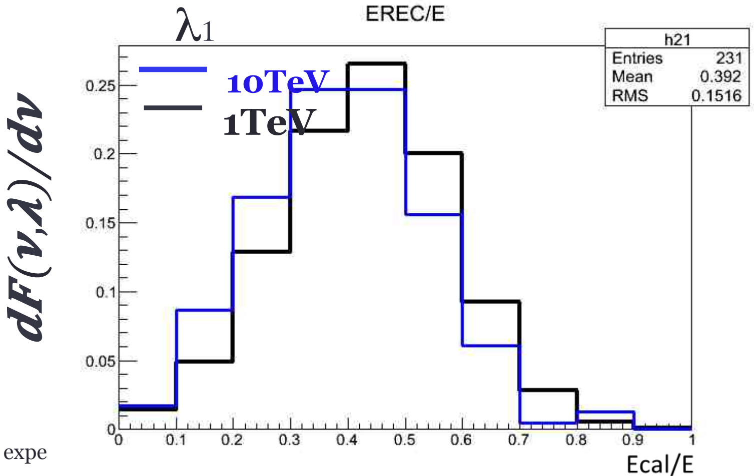
Proton rejection factor

Montecarlo study of proton contamination
using CALORIMETER INFORMATIONS ONLY

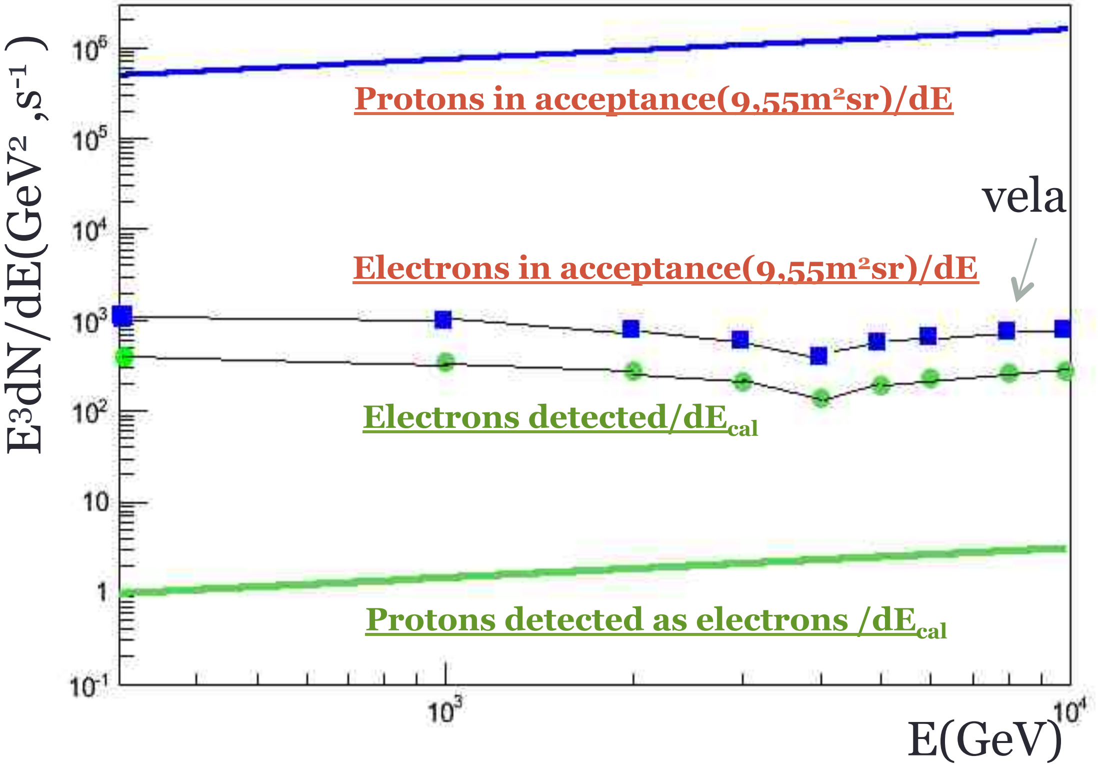
- **PARTICLES propagation & detector response simulated with FLUKA**
- **Geometrical cuts for shower containment**
- **Cuts based on longitudinal and lateral development**



- **155.000 protons simulated at 1 tev : only 1 survive the cuts**
- **The corresponding electron efficiency is 37% and almost constant with energy above 500gev**
- **Mc study of energy dependence of selection efficiency and calo energy distribution of misreconstructed events**



Proton rejection factor



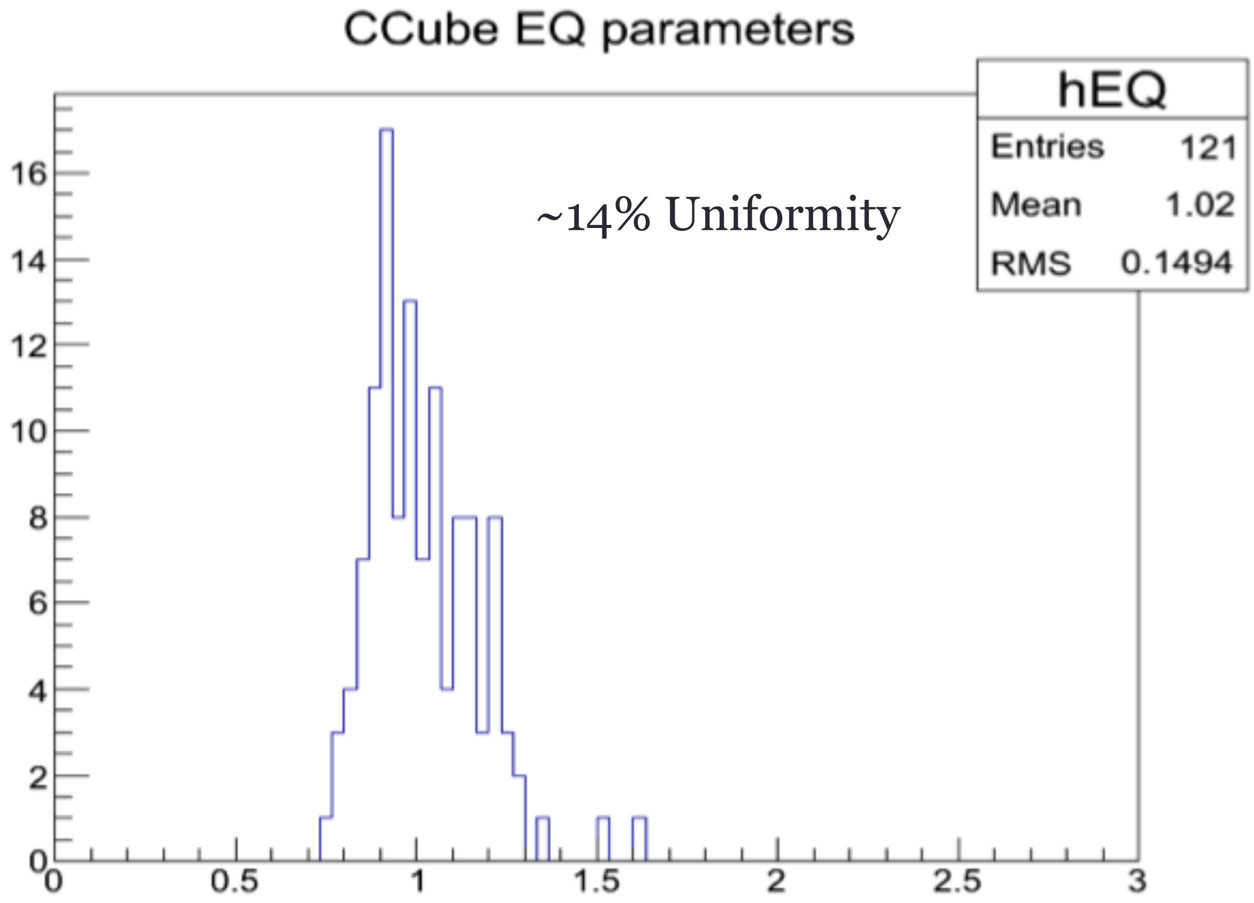
Contamination :
0,5% at 1TeV
2% at 4 TeV

An upper limit
90% CL is obtained
using a factor X 3,89

= = 0,5 x 10^6

X Electron Eff. ~ 2 x 10^5

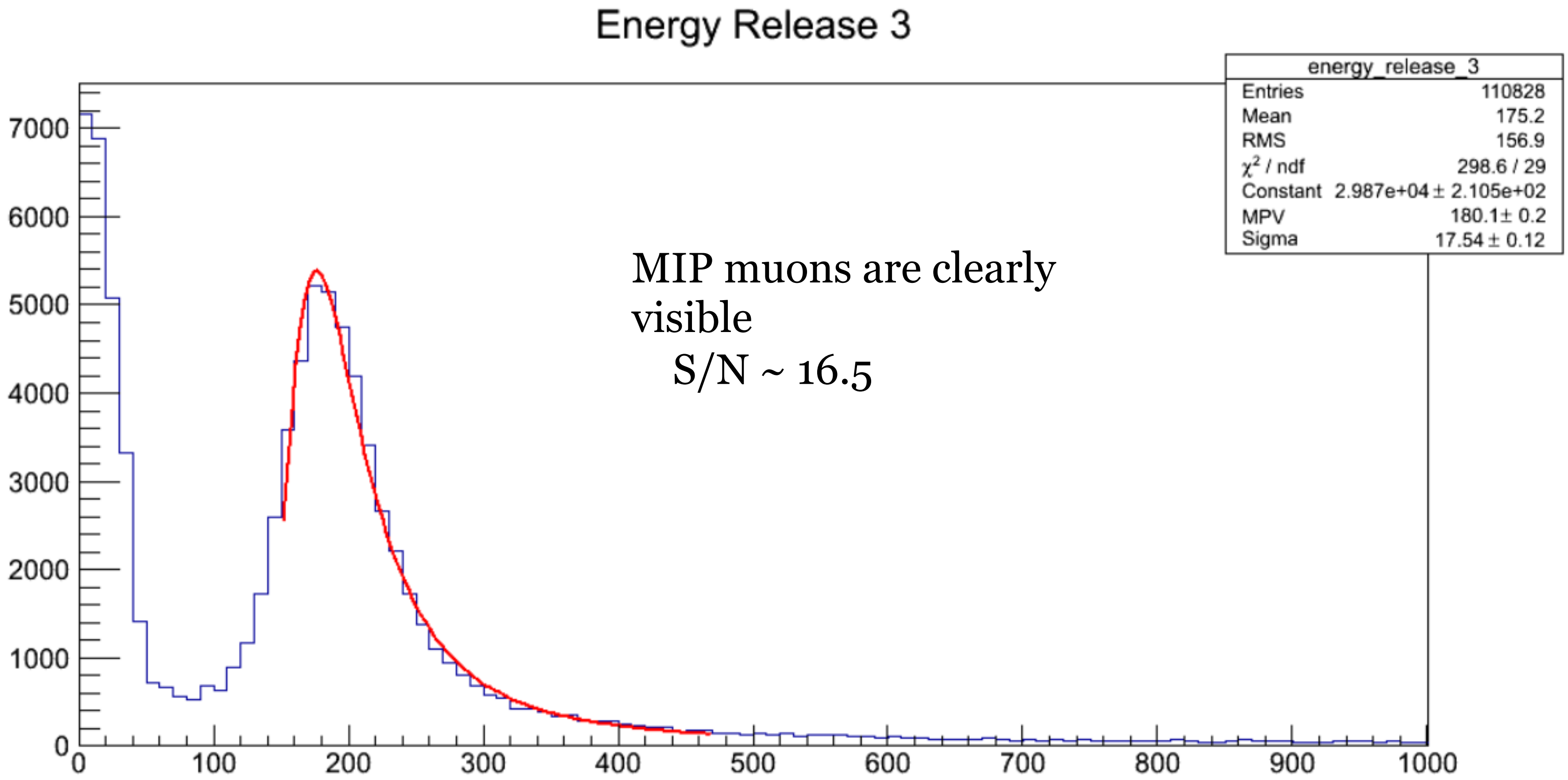
Response uniformity of the crystals



~14% Uniformity

Pre-prototype test

Muon beam



MIP muons are clearly visible

S/N ~ 16.5

Dual-readout calorimetry with a full-size BGO electromagnetic section

N. Akchurin [a], F. Bedeschi [b], A. Cardini [c], R. Carosi [b], G. Ciapetti [d], R. Ferrari [e], S. Franchino [f], M. Fraternali [f], G. Gaudio [e], J. Hauptman [g], M. Incagli [b], F. Lacava [d], L. La Rotonda [h], T. Libeiro [a], M. Livan [f], E. Meoni [h], D. Pinci [d], A. Policicchio [h,1], S. Popescu [a], F. Scuri [b], A. Sill [a], W. Vandelli [i], T. Venturelli [h], C. Voena [d], I. Volobouev [a], R. Wigmans [a,*]

Dual readout –> BGO: scintillation + Cherenkov

Filter: 250 ÷ 400 nm for Cherenkow light

>450 nm for Scintillator light

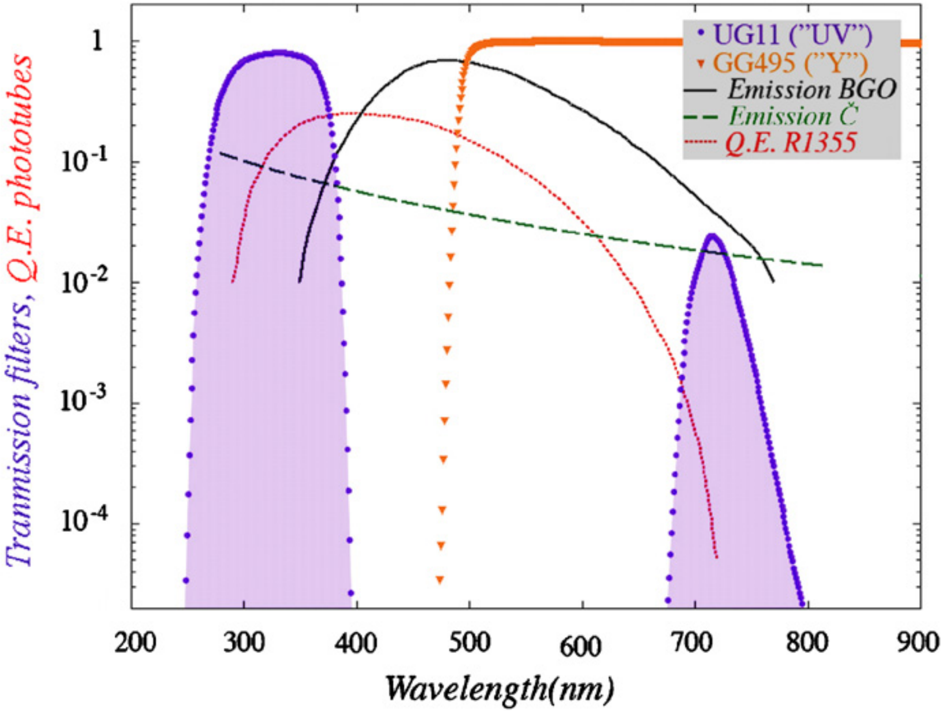
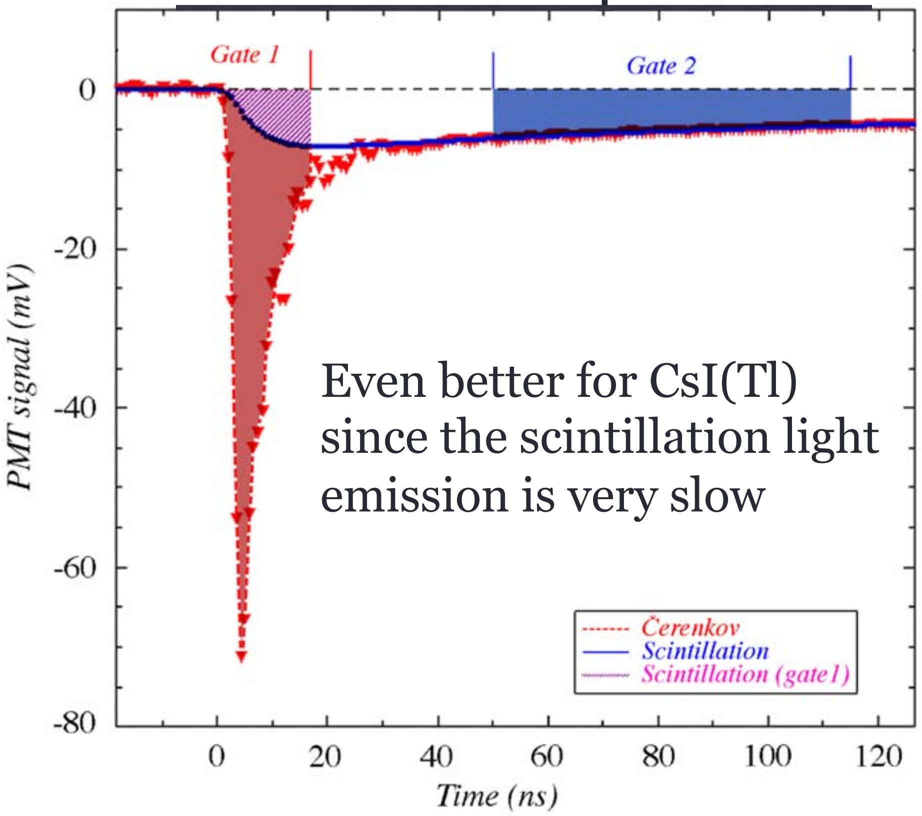


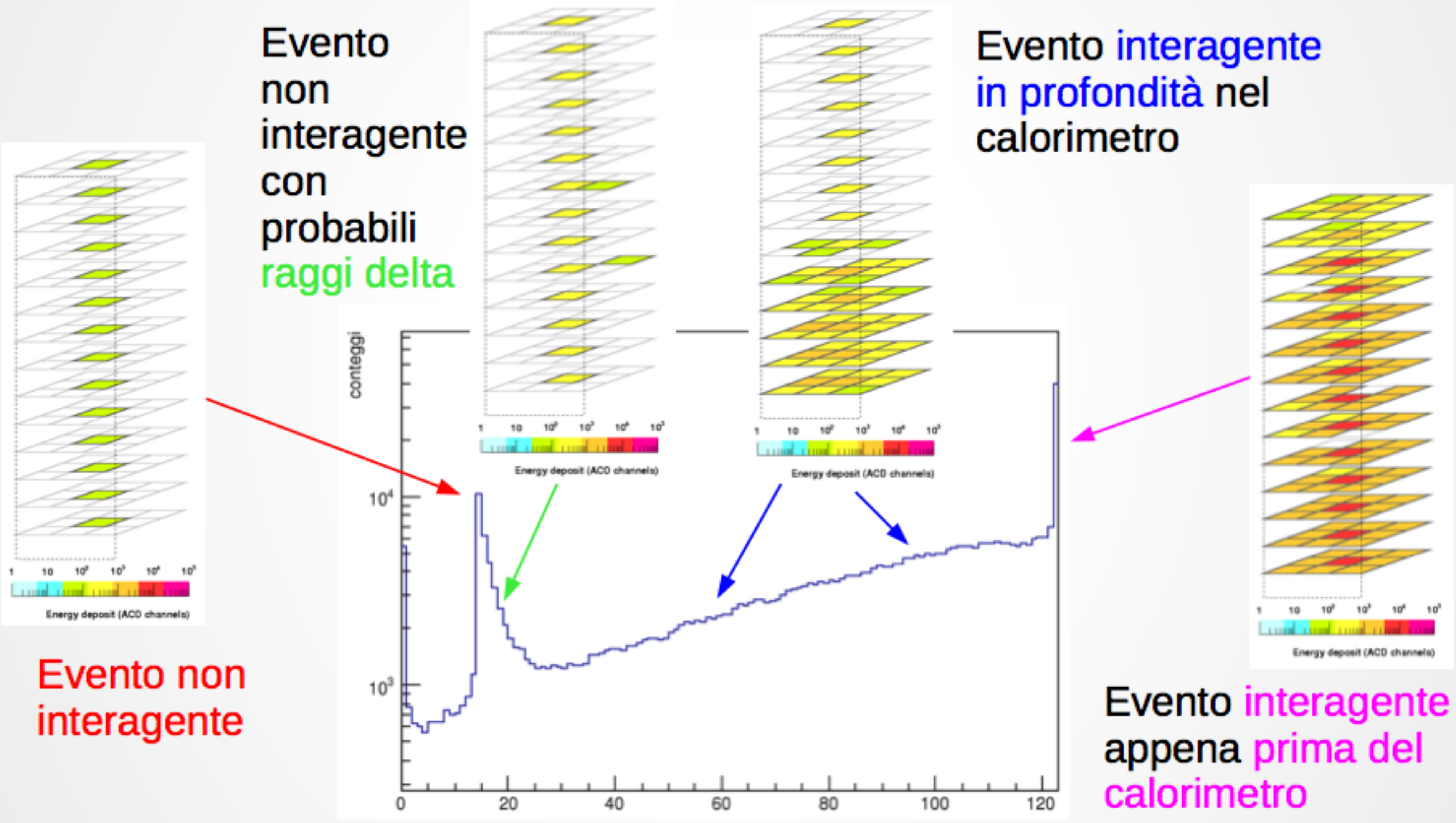
Fig. 14. Light transmission as a function of wavelength for the two filters used to read out the BGO crystal. The light emission spectrum of the crystal, the spectrum of the Cherenkov light generated in it and the quantum efficiency of the PMTs used to detect this light are shown as well. The vertical scale is absolute for the transmission coefficients and the quantum efficiency, and constitutes arbitrary units for the light spectra.

Hardware compensation



Even better for CsI(Tl) since the scintillation light emission is very slow

Fig. 5. The time structure of a typical shower signal measured in the BGO em calorimeter equipped with a UV filter. These signals were measured with a sampling oscilloscope, which took a sample every 0.8 ns. The UV BGO signals were used to measure the relative contributions of scintillation light (gate 2) and Cherenkov light (gate 1).



Evento non interagente con probabili raggi delta

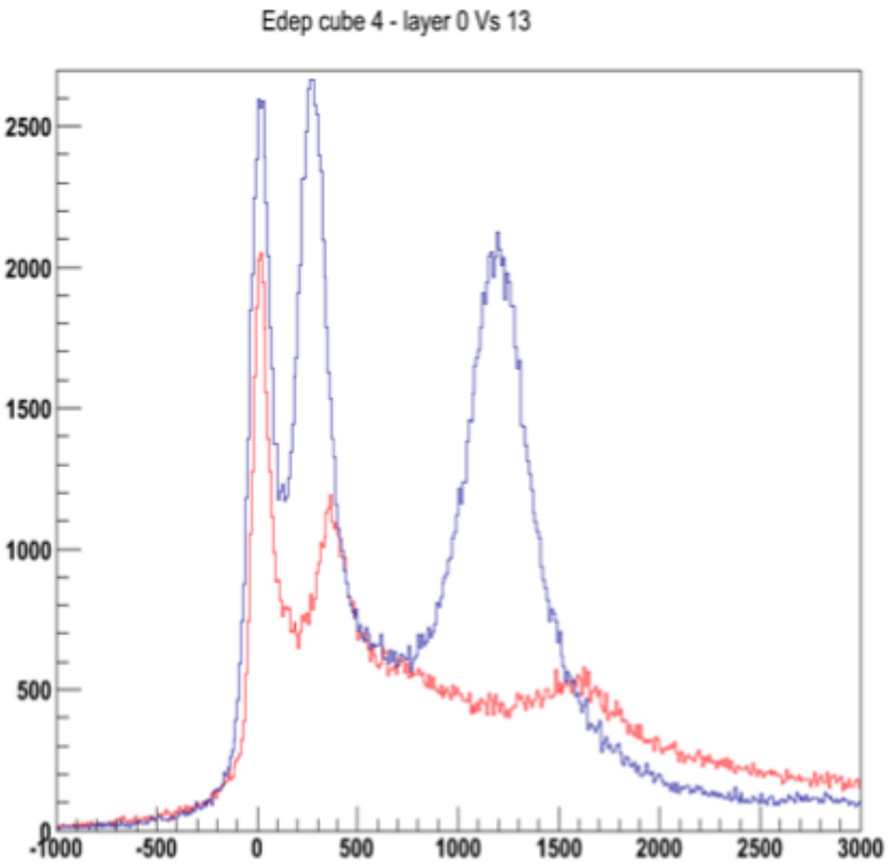
Evento interagente in profondità nel calorimetro

Evento non interagente

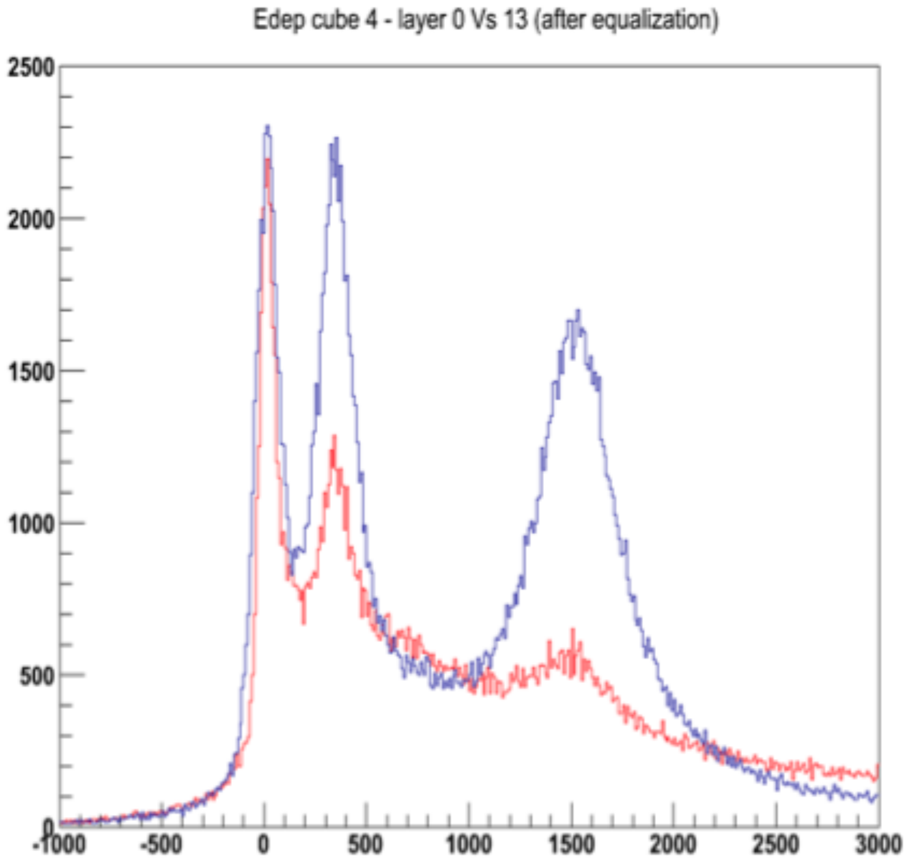
Evento interagente appena prima del calorimetro

Distribuzione del numero di cristalli che evento

Channel equalization

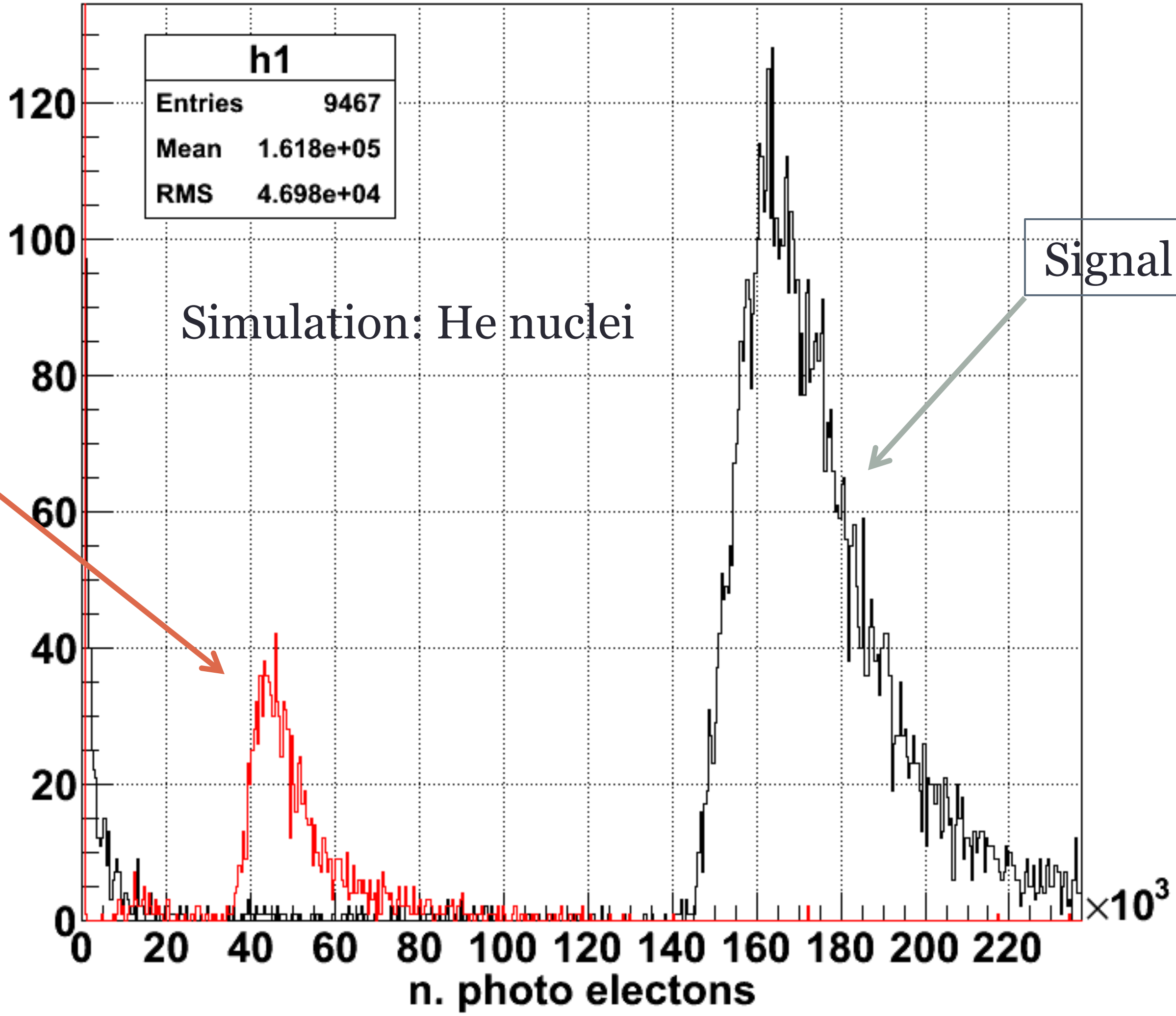


Edep cube 4 - layer 0 Vs 13



Edep cube 4 - layer 0 Vs 13 (after equalization)

Not interacting He nuclei on 1st layer



Simulation: He nuclei

Signal from crystal

Signal from PD