DEVELOPMENT OF A 3-D CUBIC CRYSTAL CALORIMETER FOR SPACE

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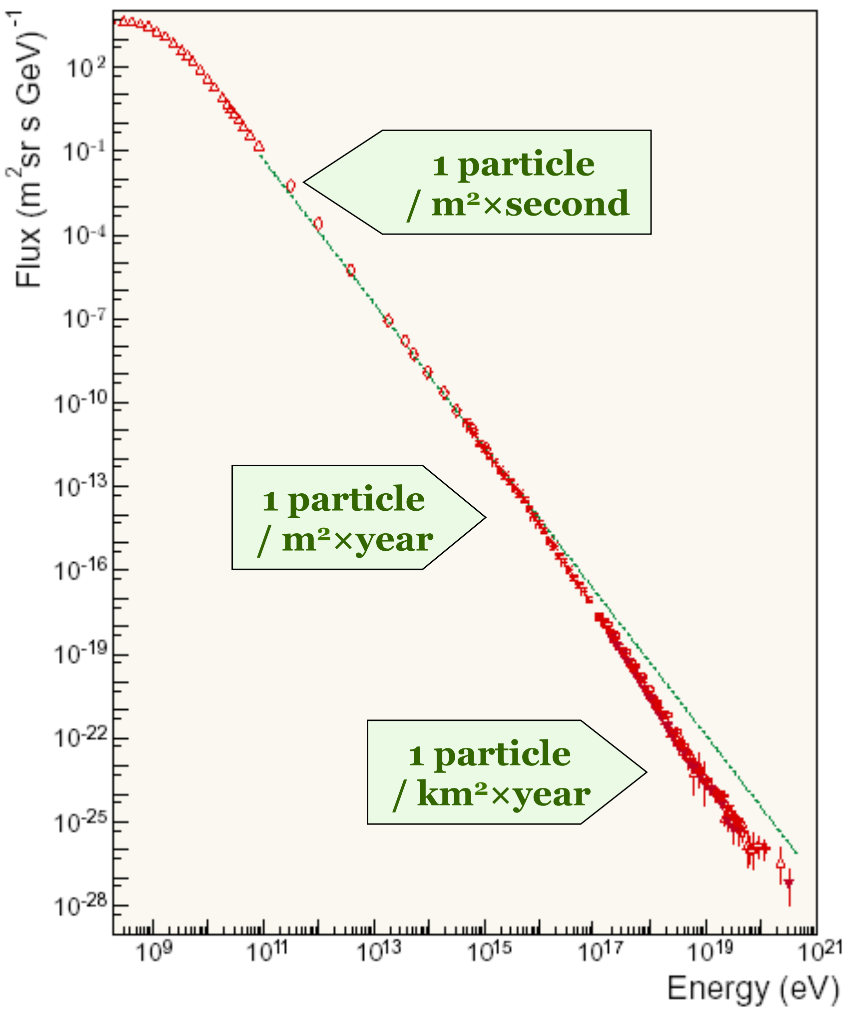
Paris, April 25th, 2013

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

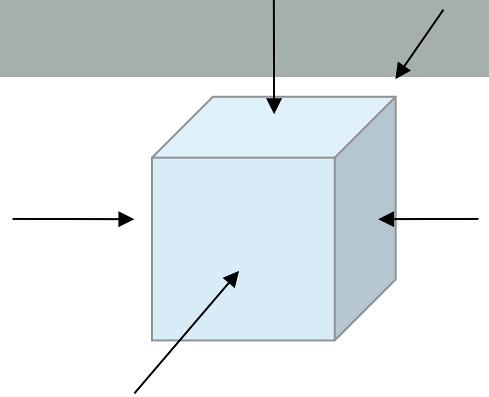
A direct spectral measurement in the PeV region requires great acceptance (few m^2sr) and good energy resolution for hadrons (at least 40%)

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 depending on the available mass&power

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)

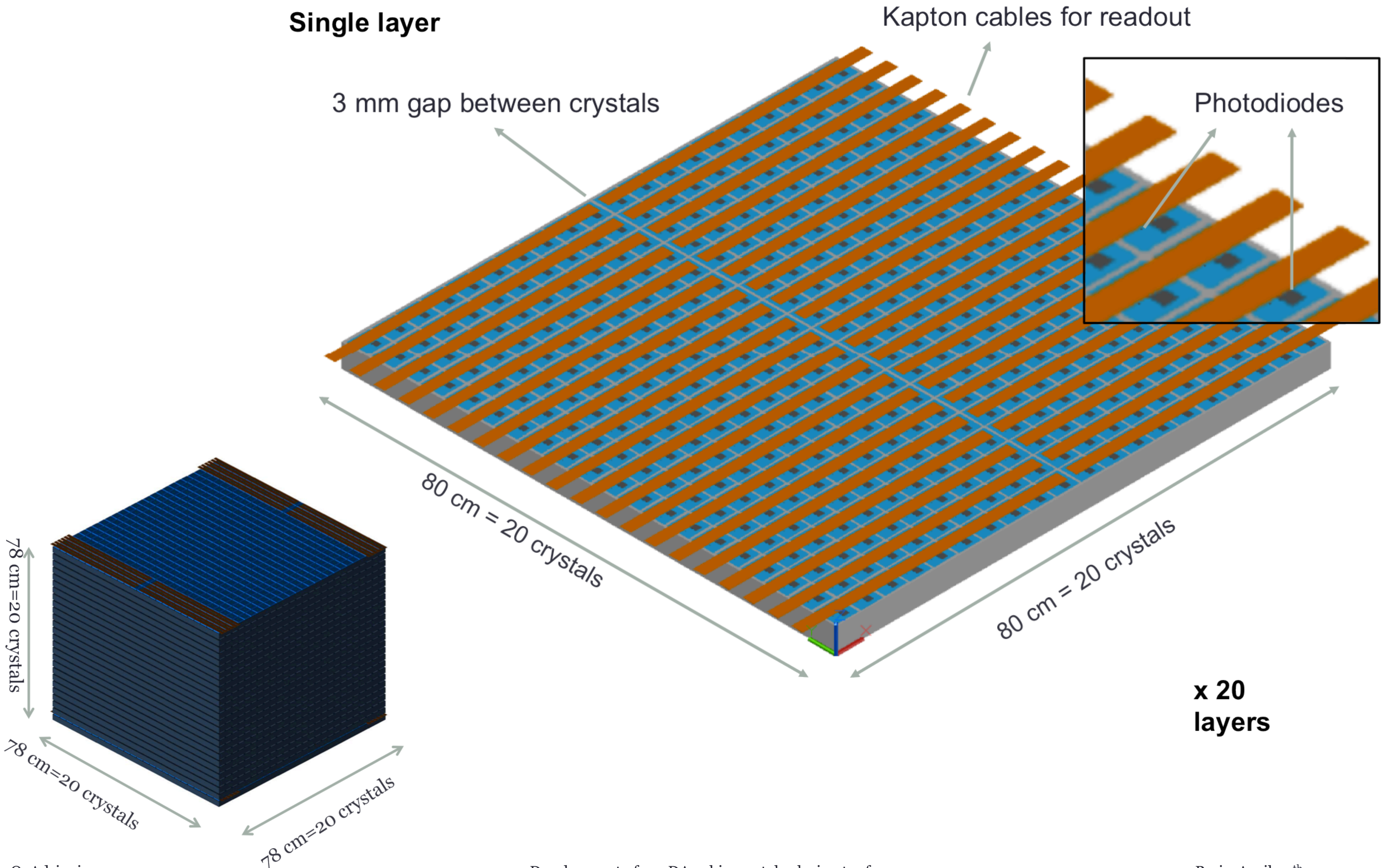
Density:	4.51 g/cm^3
X_0:	1.85 cm
Moliere radius:	3.5 cm
λ_I:	37 cm
Light yield:	54.000 ph/MeV
τ_{decay}:	1.3 μs
λ_{max}:	560 nm

- Simulation and prototype beam tests used to characterize the detector

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



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

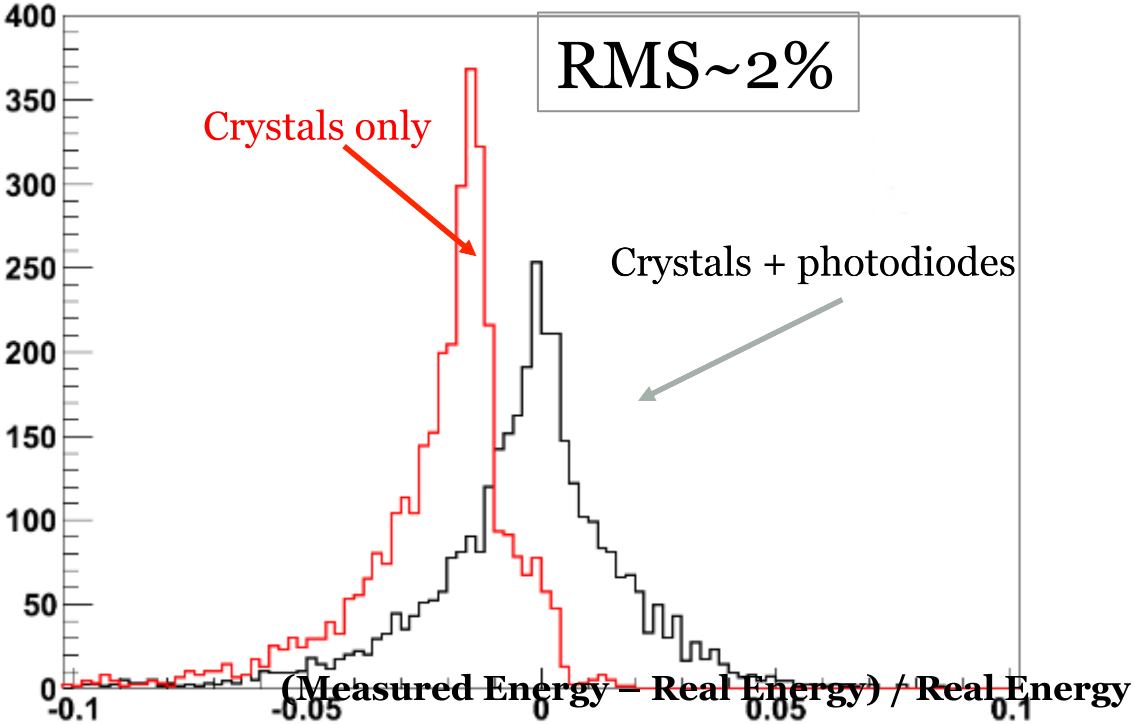
- Front-End electronics: a big challenge!
- The CASIS chip, developed in Italy by INFN-Trieste, is very well suited for this purpose
  - IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 57, NO. 5, OCTOBER 2010
- 16 channels CSA+CDS
- Automatic switching btw low and high gain mode
- 2.8 mW/channel
- 3.10^3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

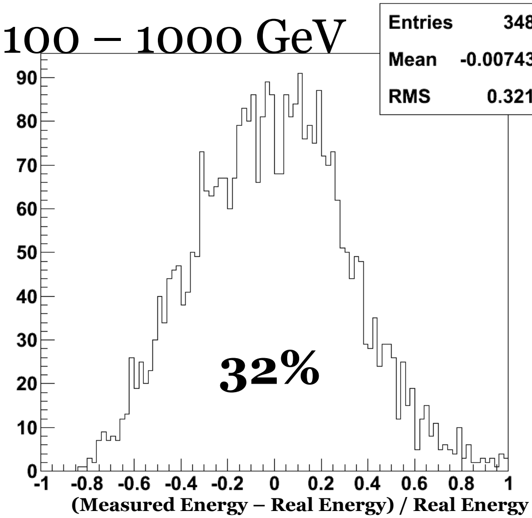
GF_{eff} ~ 3.4 m²sr

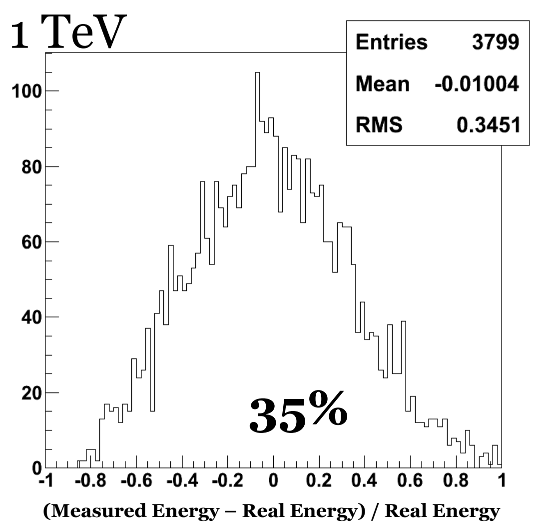
Non-gaussian tails due to leakages and to energy losses in carbon fiber material

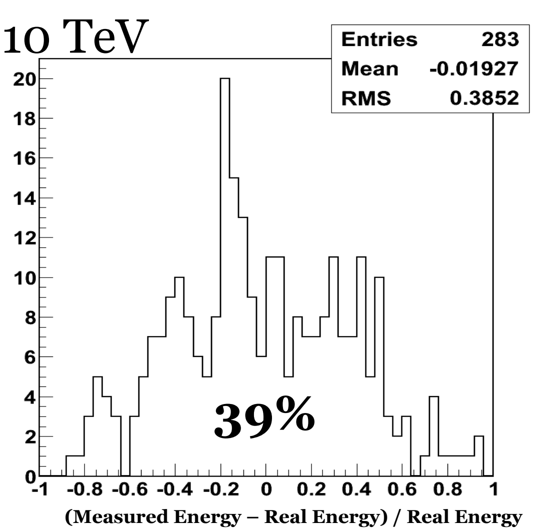
Ionization effect on PD: 1.7%

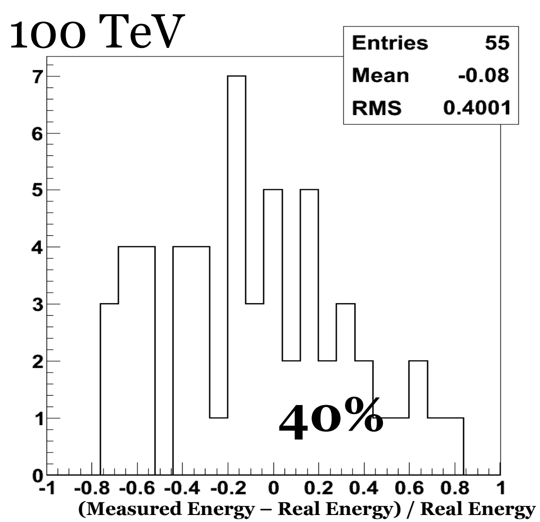
Protons

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

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.

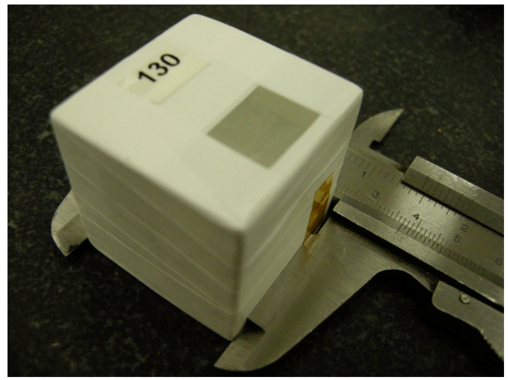
- A small, so called "pre-prototype", made of 4 layers with 3 crystals each
  - 12 CsI(Tl) crystals, 2.5x2.5x2.5 cm^3

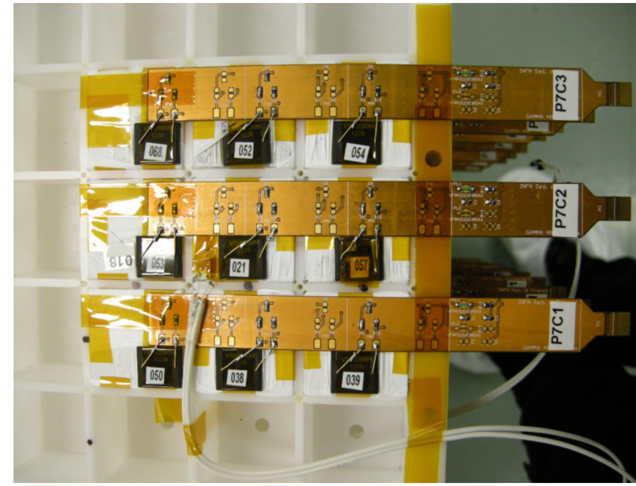
- A bigger, properly called "prototype", made of 14 layers with 9 crystals each
  - 126 CsI(Tl) crystals, 3.6x3.6x3.6 cm^3

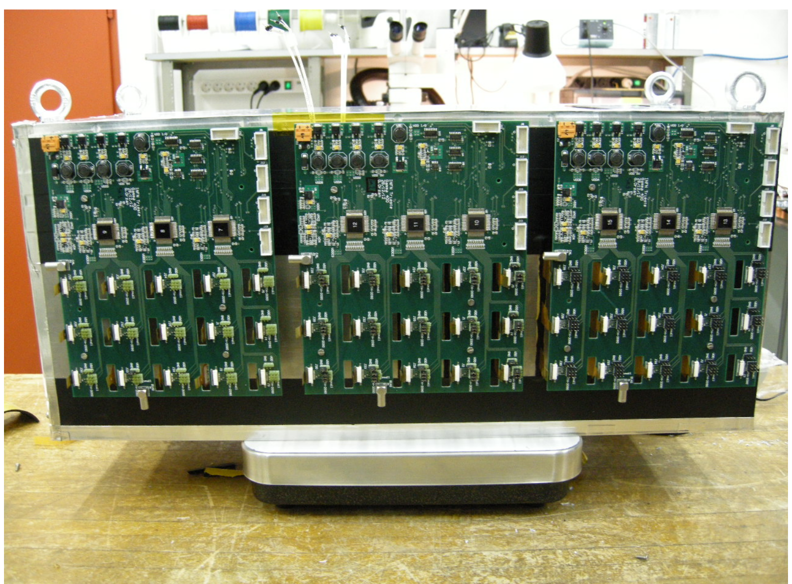
- Both devices have been tested at CERN SPS (pre-prototype in October 2012 and prototype in January-February 2013)

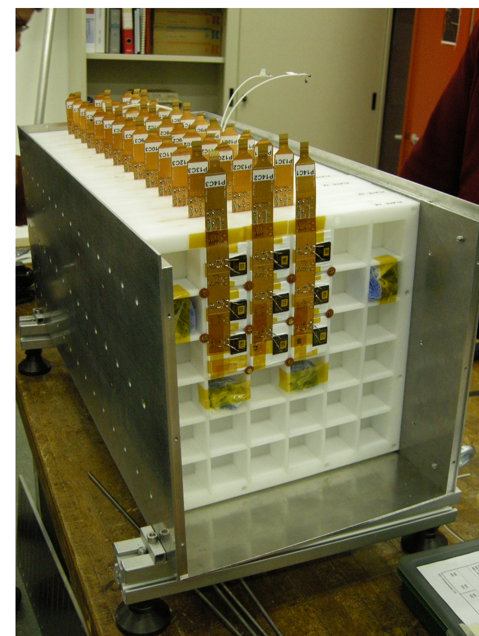
The prototype

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





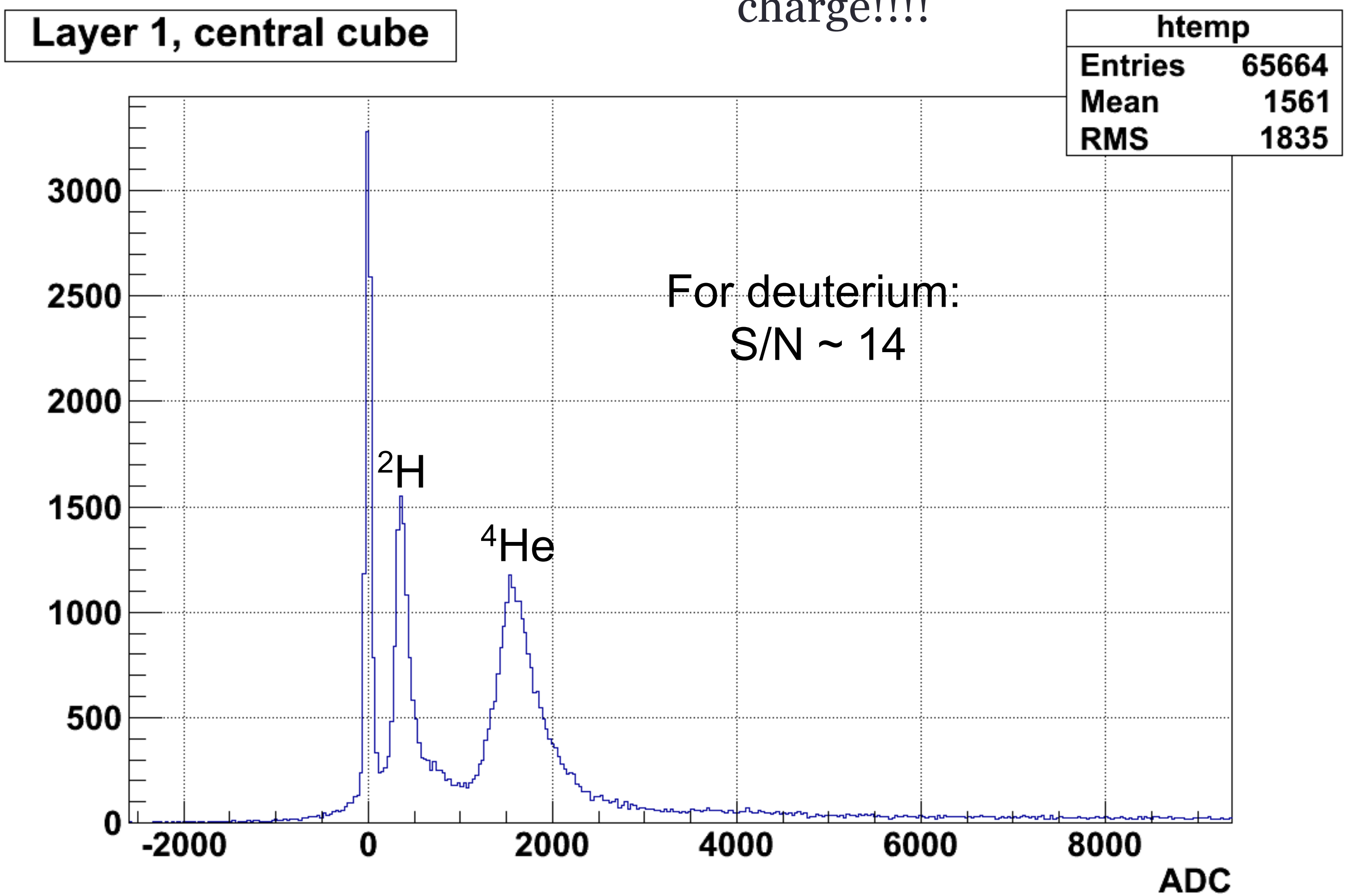




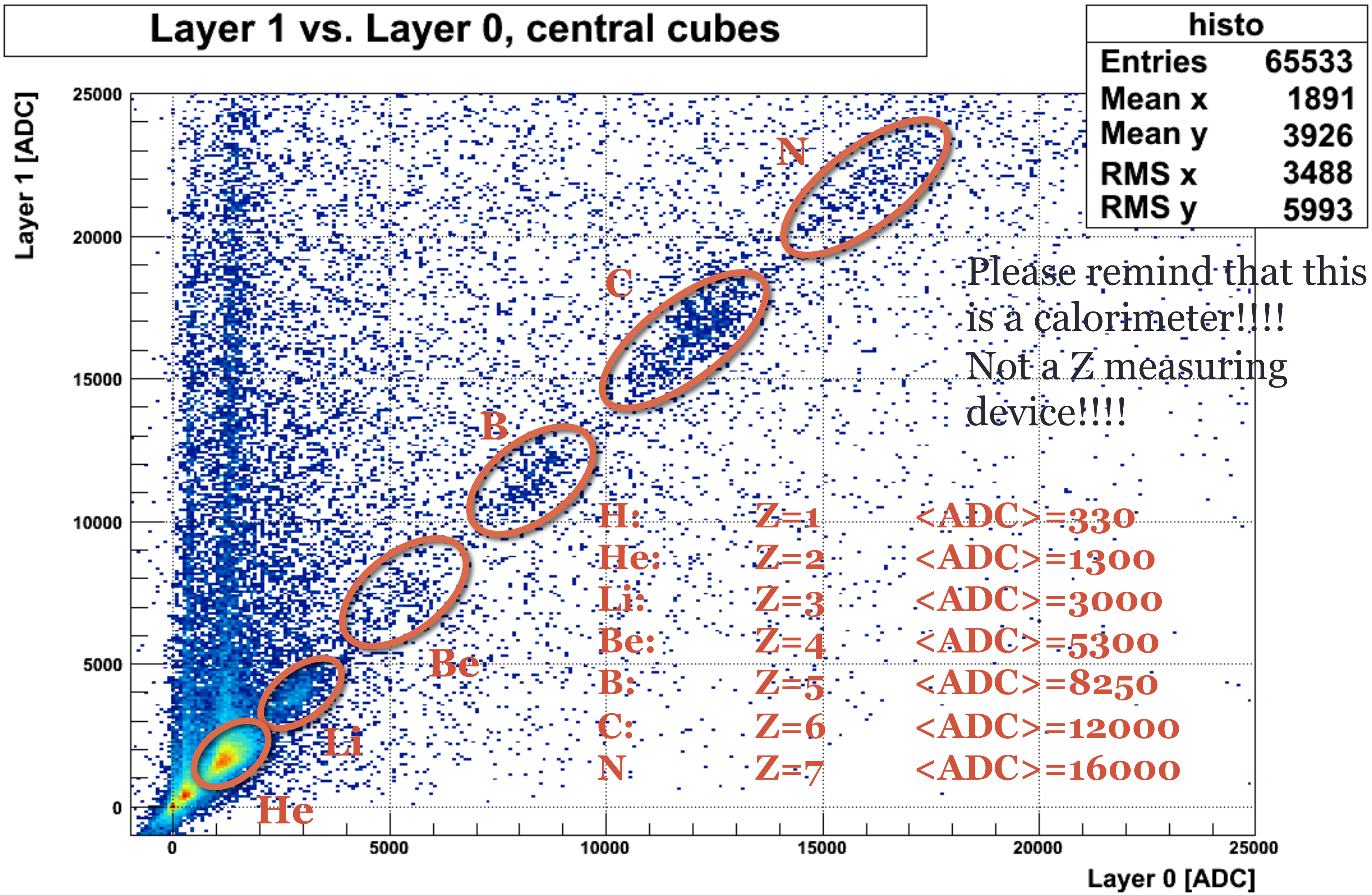
A glance at prototype's TB data

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

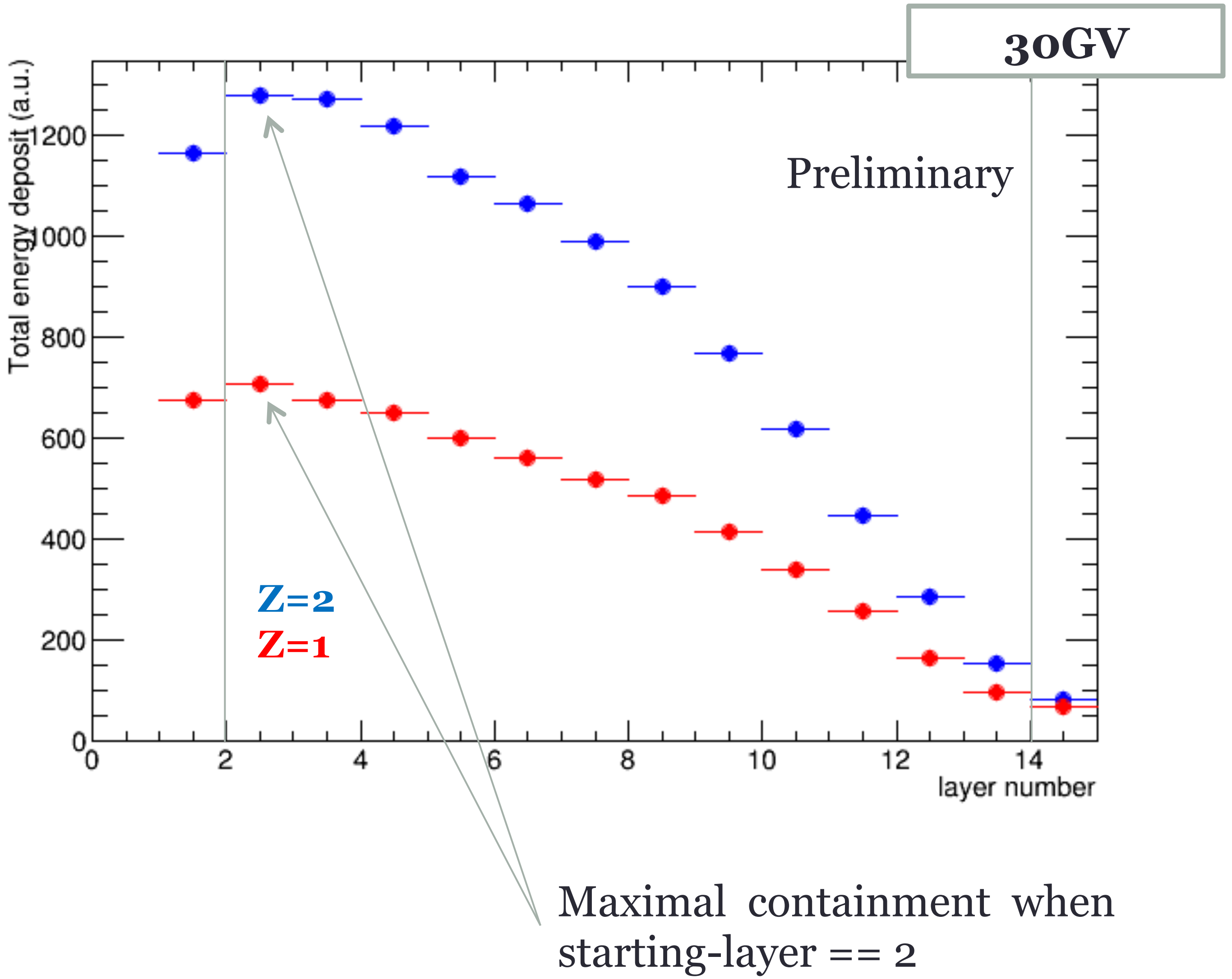
Please note: we can use the data from a precise silicon Z measuring system located in front of the prototype to have an exact identification of the nucleus charge!!!!



A glance at prototype's TB data

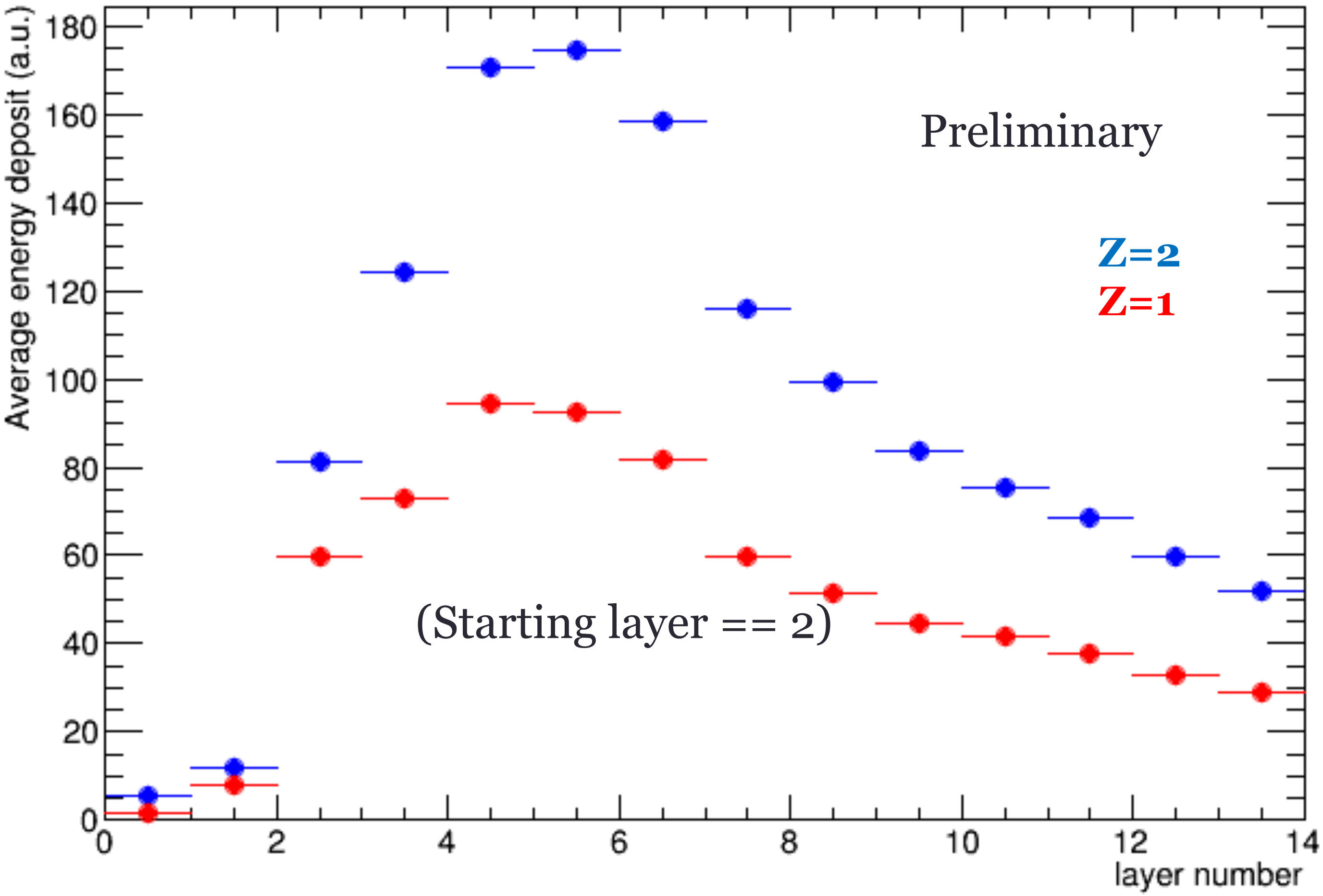


Total energy deposit VS shower-starting layer

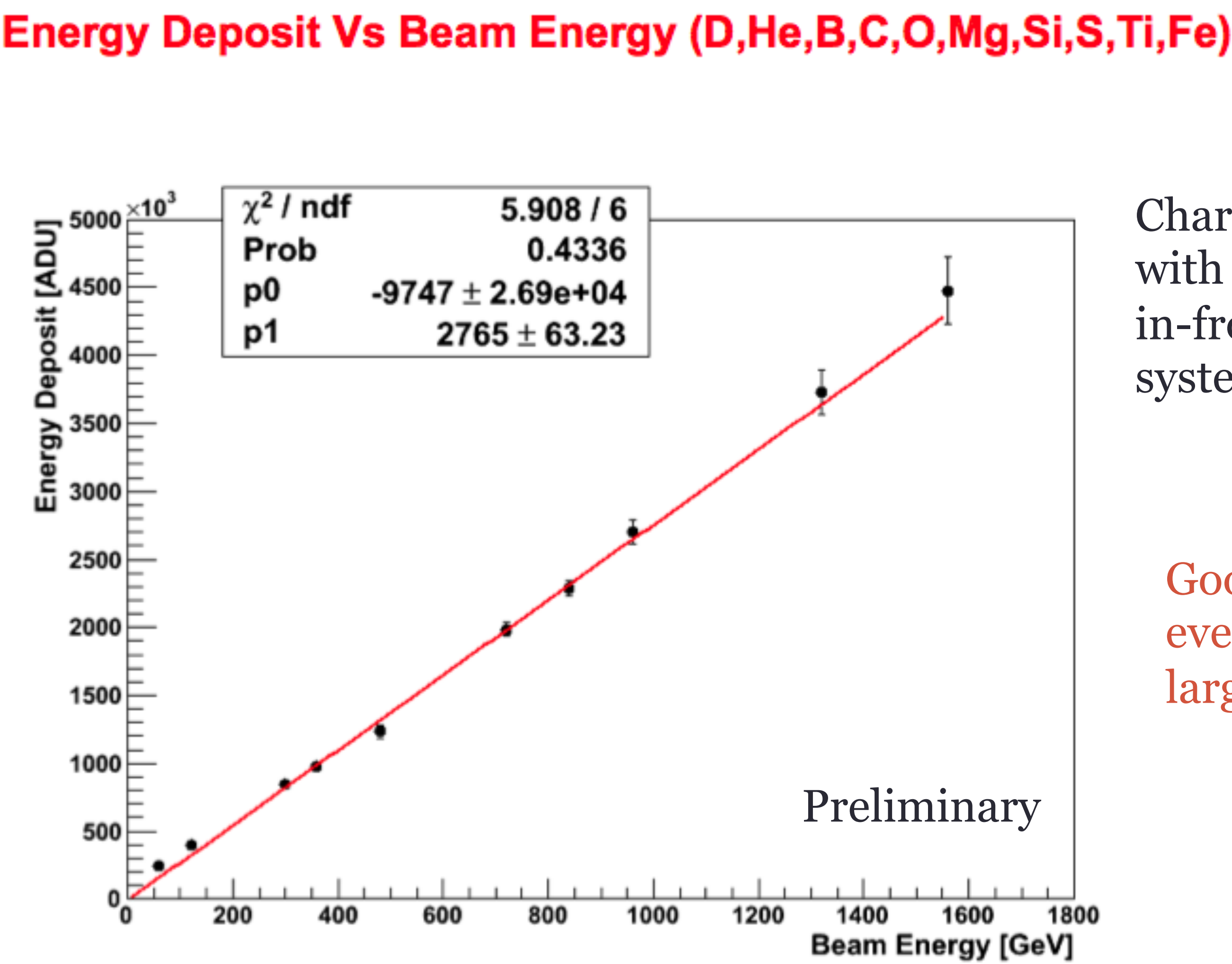


Average longitudinal profile (1.44 λ_I)

30GV/c



Energy deposit for various nuclei



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

Good Linearity even with the large area PD!

How to improve the calorimeter performances?

- We could try to see the Cherenkov light produced in the crystals by the electromagnetic component of the shower
  1. Improvement of the e/p rejection factor
  2. Improvement of the hadronic energy resolution (DREAM project)

☺ Possibility to use the timing information to discriminate btw scintillation (slow) and Cherenkov (fast) component

☹ Cherenkov light is a small fraction of the scintillaton light, compatible with the direct energy release in the PD….

Some ideas for the Cherenkov light

- Use of SiPM to detect Cherenkov light
  - Discrimination btw Fast Cherenkov light and Slow Scintillation light possible with dedicated fast sampling electronics
  - Use of SiPM highly sensitive in the UV region
- Use of 'UV transmitting' filters on the SiPM face
  - to block the largely dominant scintillation light
- Possible use of ≥3 SiPM for each crystal on orthogonal faces
  - to have a good uniformity in the response for particles hitting the different calorimeter's faces

- R&D is under way…. More news at the end of the year!

Conclusion

- An homogeneous, isotropic calorimeter looks to be an optimal tool for the direct detection of High Energy CR

- The status of the project is quite advanced:
  - Simulation
  - Prototypes
  - Test beams

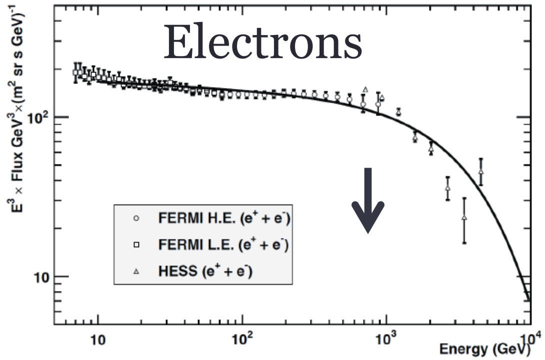
- Next steps:
  - R&D on the Cherenkov light during 2013
  - Low energy electron test beam in INFN Frascati in autumn 2013 for Cherenkov light studies
  - Possibly enlarge the prototype's dimensions
  - R&D for the Calibration system of every crystal is certainly necessary to optimize the whole calorimeter's performances

BACKUP

What we can reach with this calorimeter?

Assumptions:

- 10 years exposure
- No direct closeby sources for electrons
- Polygonato model for protons/nuclei



Electrons

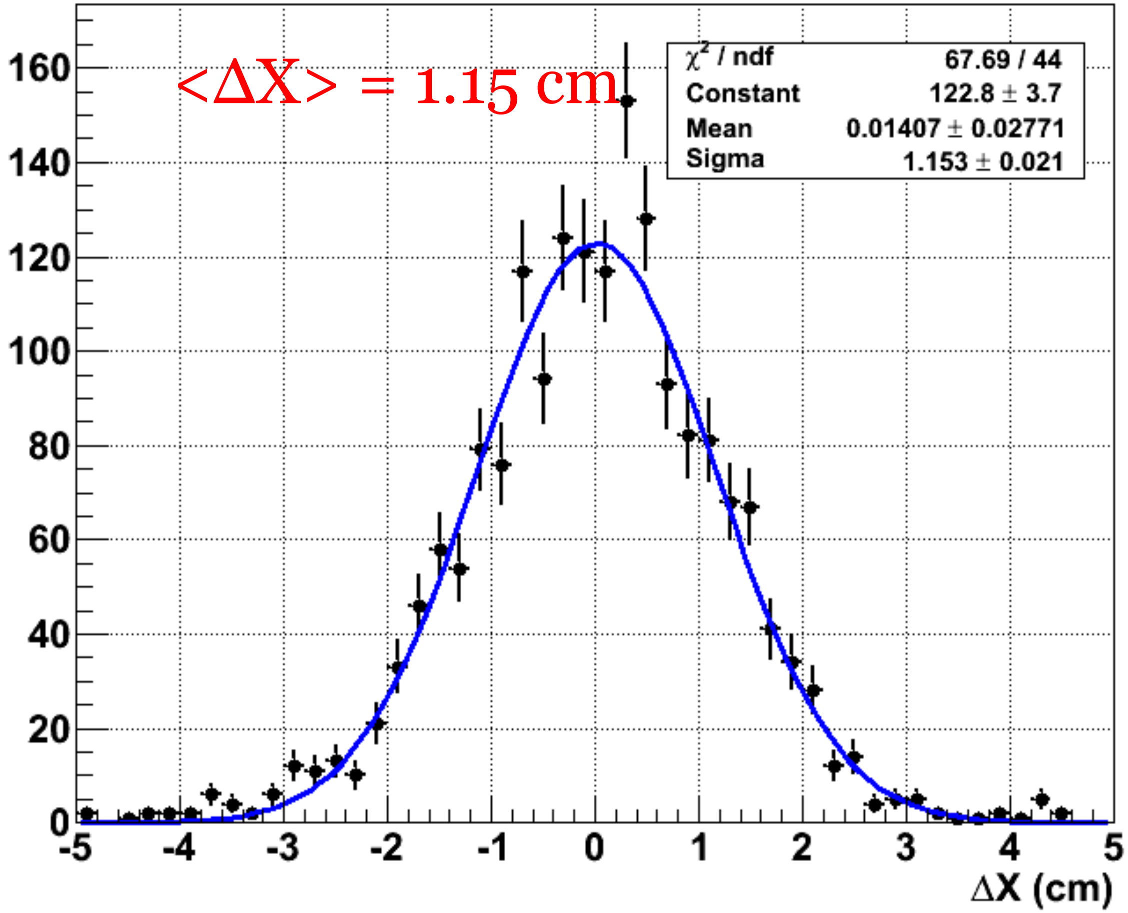
Gf_{eff} (m^2sr)	ΔE/E	Depth (X_0)	e/p rej. factor	E>0.5 TeV	E>1 TeV	E>2 TeV	E>4 TeV
3.4	2%	39	$>10^5$	~2.10⁵	~4.10⁴	~6.10³	~7.10²

~ knee

Protons and Helium

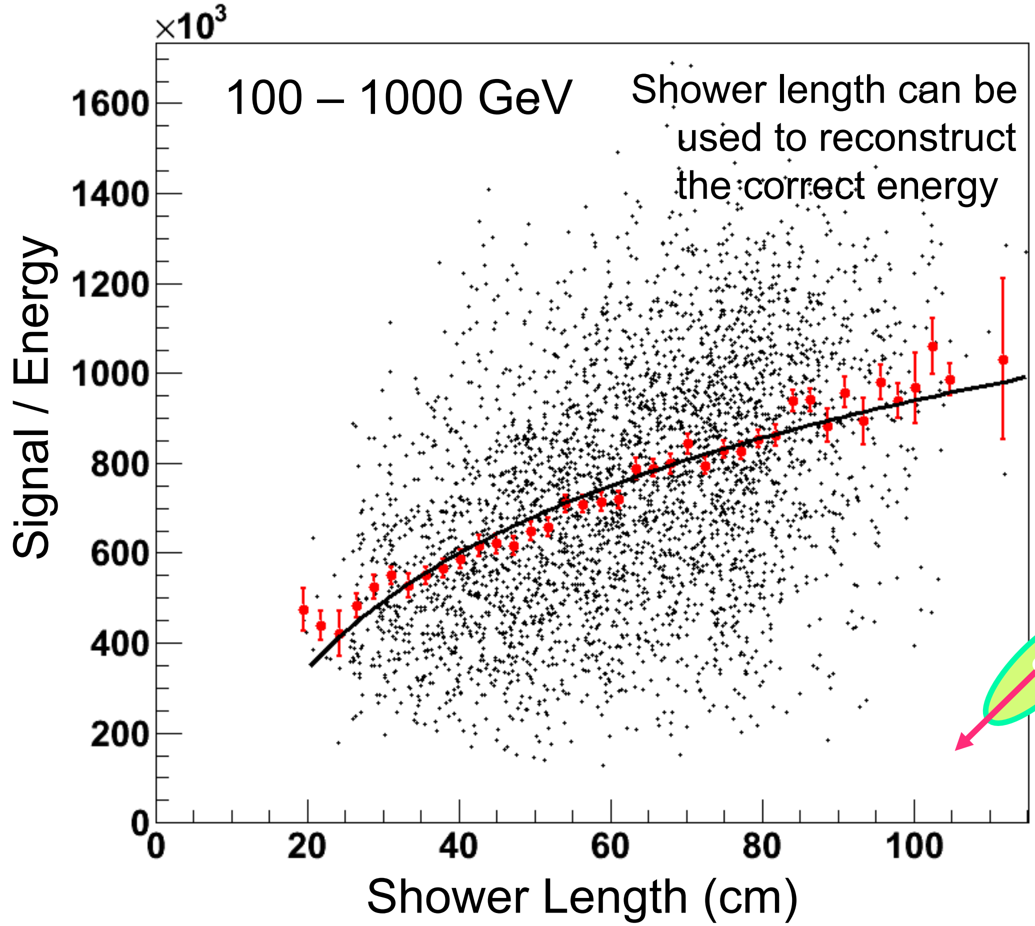
Gf_{eff} (m^2sr)	ΔE/E	Depth (λ_I)	E>100 TeV		E>500 TeV		E>1000 TeV		E>2000 TeV		E>4000 TeV	
			p	He	p	He	p	He	p	He	p	He
~4	40%	1.8	2.8×10^4	2.7×10^4	1.7×10^3	1.8×10^3	4.4×10^2	5.5×10^2	1.0×10^2	1.6×10^2	1.7×10^1	3.6×10^1

Shower starting point resolution

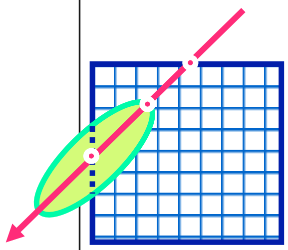


Protons

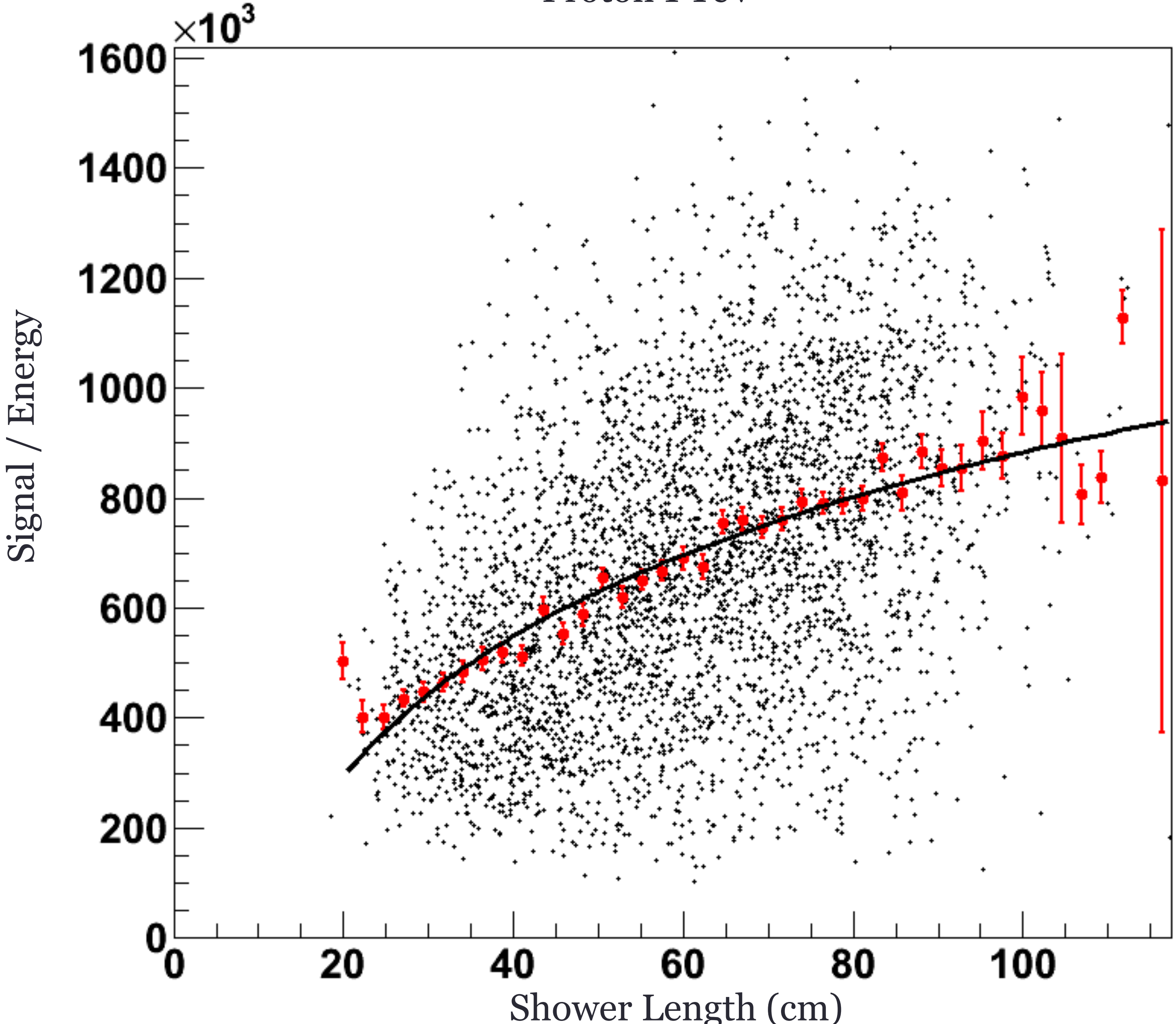
Energy estimation



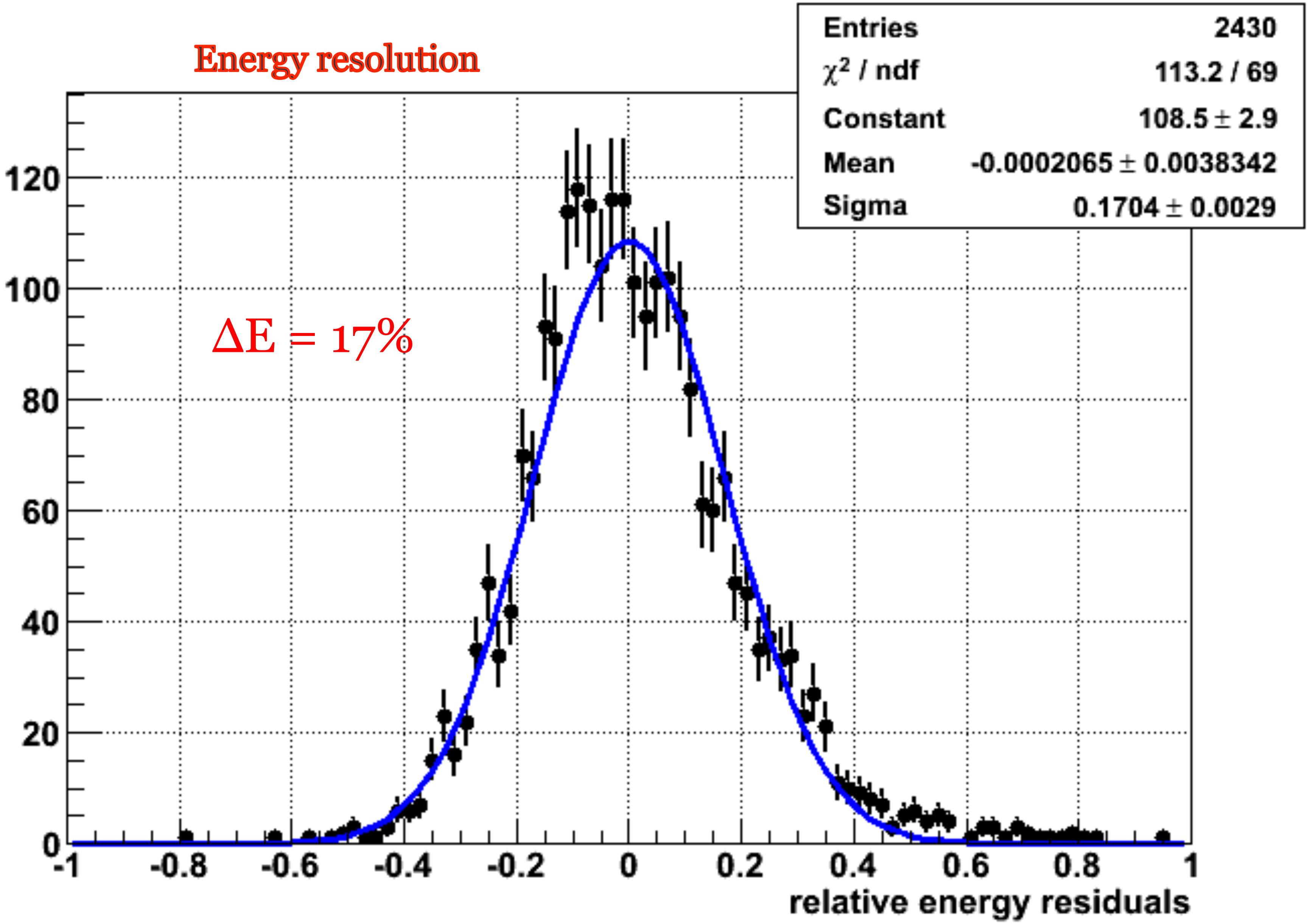
Red points: profile histogram
Fitted with logarithmic function



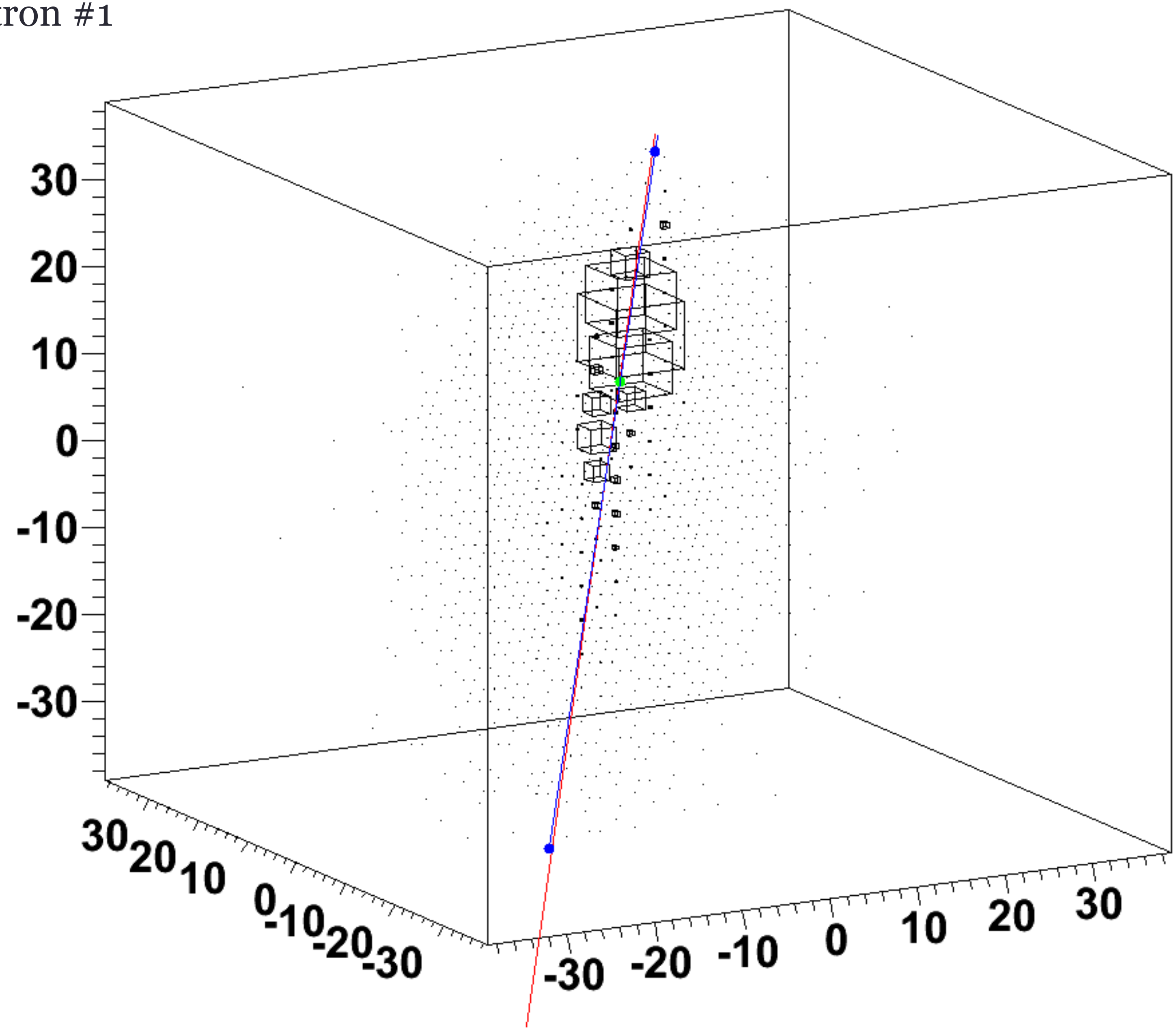
Proton 1 TeV



×10³
1600
1400
1200
1000
800
600
400
200
0
Signal / Energy
0
20
40
60
80
100
Shower Length (cm)


Energy resolution
Entries 2430
χ² / ndf 113.2 / 69
Constant 108.5 ± 2.9
Mean -0.0002065 ± 0.0038342
Sigma 0.1704 ± 0.0029
ΔE = 17%
120
100
80
60
40
20
0
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
relative energy residuals

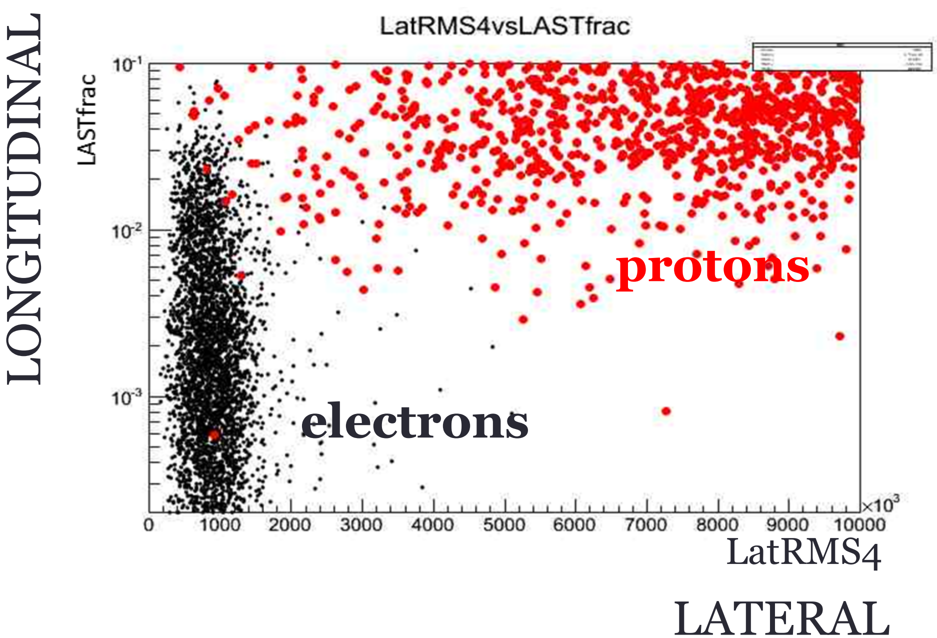
Electron #1



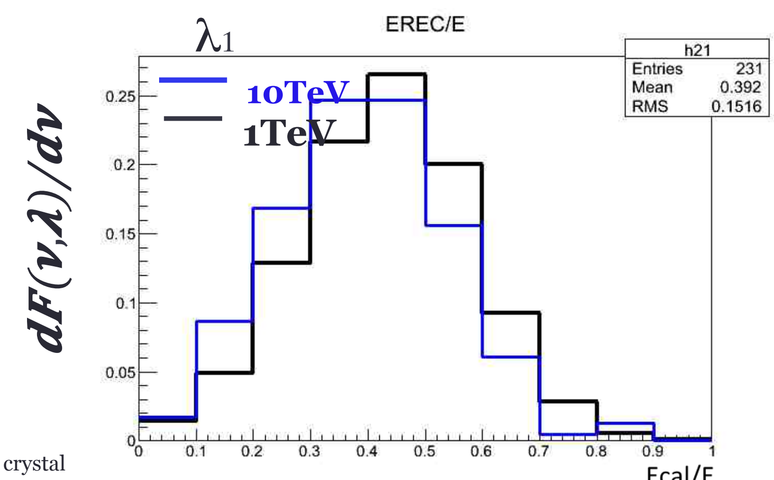
Proton rejection factor

Montecarlo study of proton contamination
using CALORIMETER INFORMATIONS ONLY

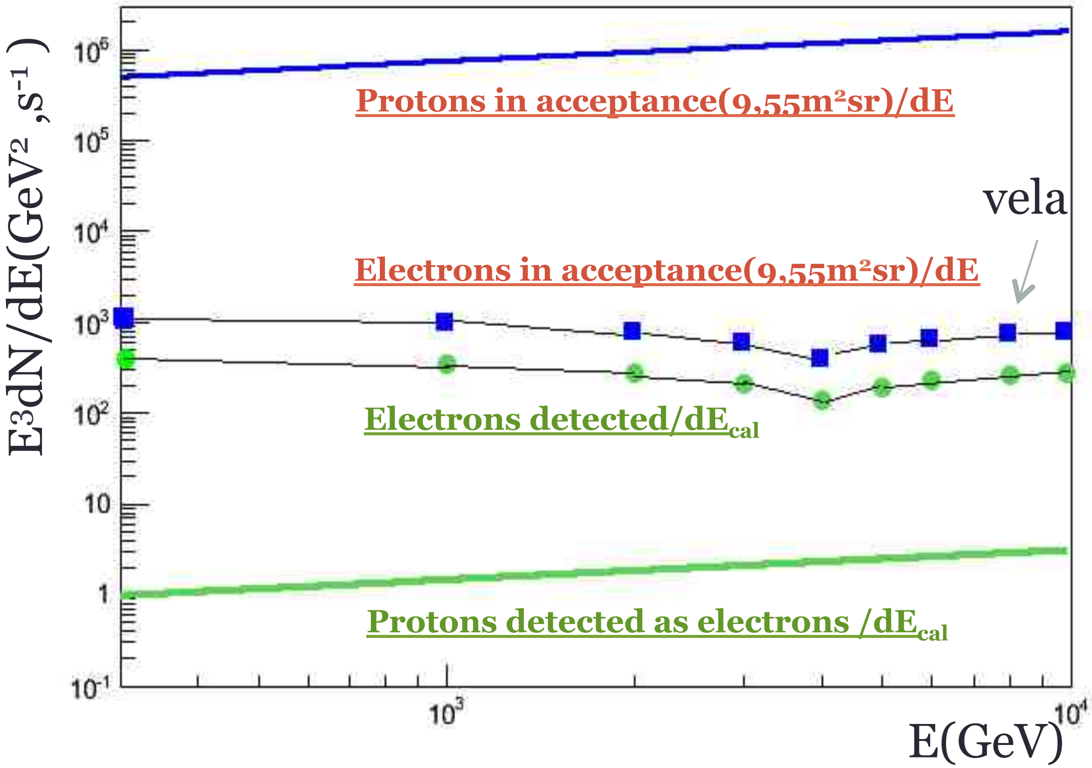
- **PARTICLES propagation & detector response simulated with FLUKA**
- **Geometrical cuts for shower containment**
- **Cuts based on longitudinal and lateral development**



- **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



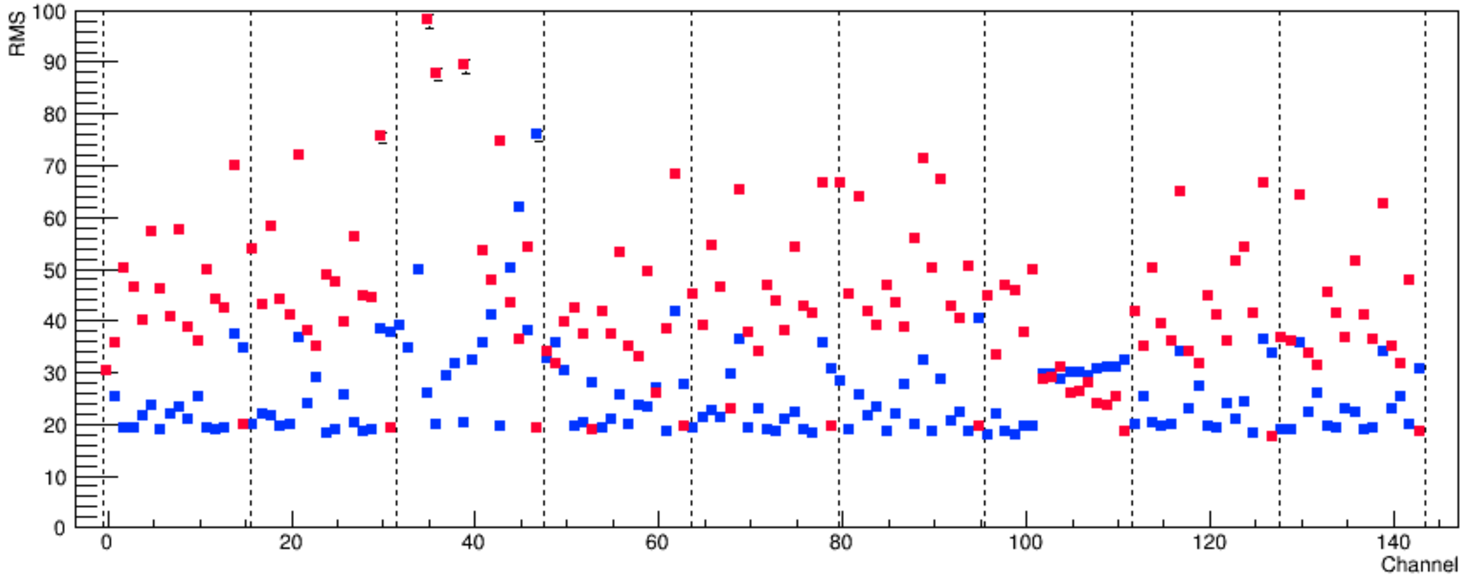
Contamination :
0,5% at 1TeV
2% at 4 TeV

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

Protons in acceptance/dE/Protons detected as electrons/dEcal (E=Ecal) = **1/6,4 10↑−6 ·0,3** =
0,5 x 10^6
Protons in acceptance/dE/Protons detected as electrons/dEcal (E=Ecal) **X Electron Eff.** ~ 2 x 10^5

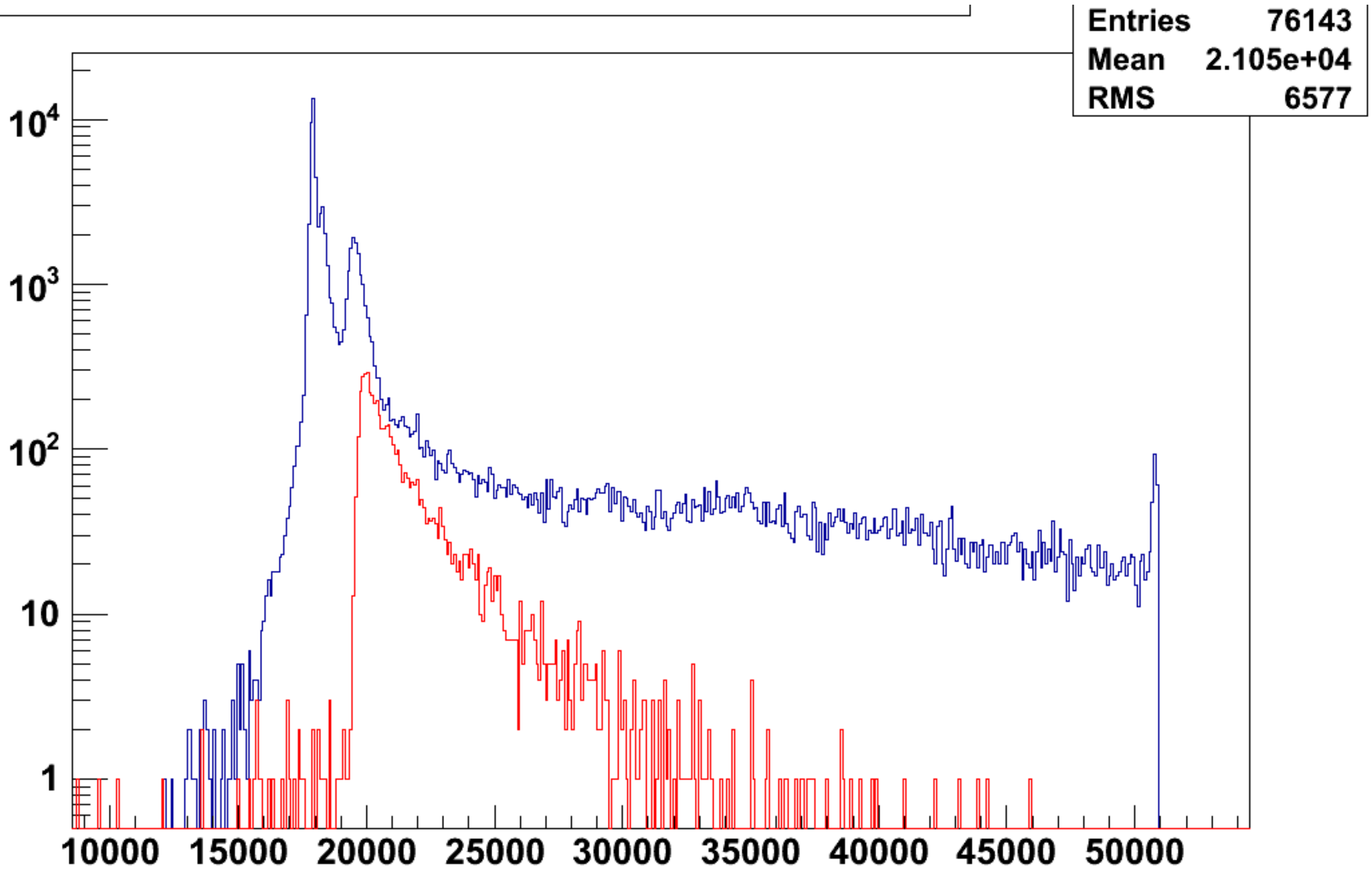
Noise

WITH and WITHOUT CN subtraction

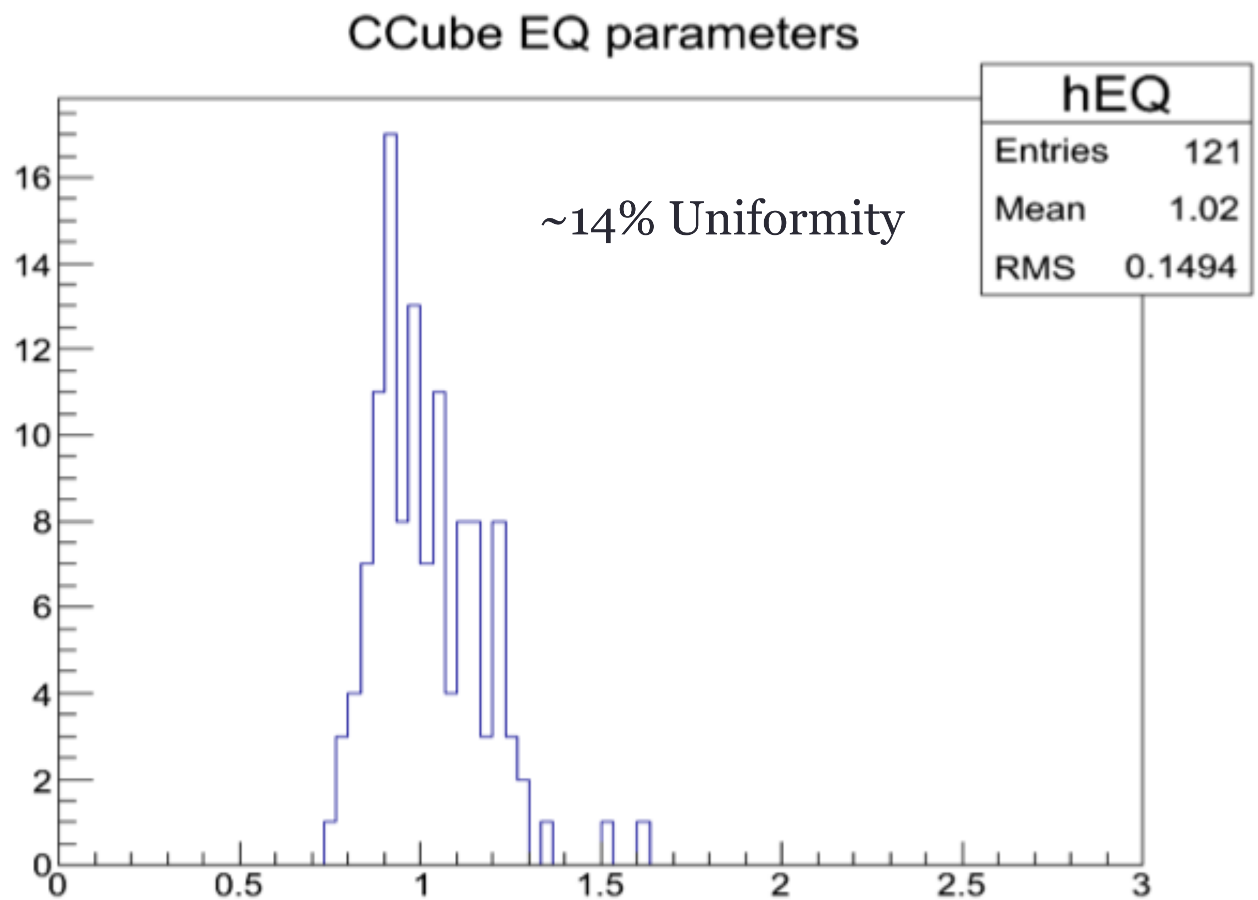


CN evaluated **without** disconnected channels

Signal in the central cube in High Gain (Blu) and Low Gain (Red)

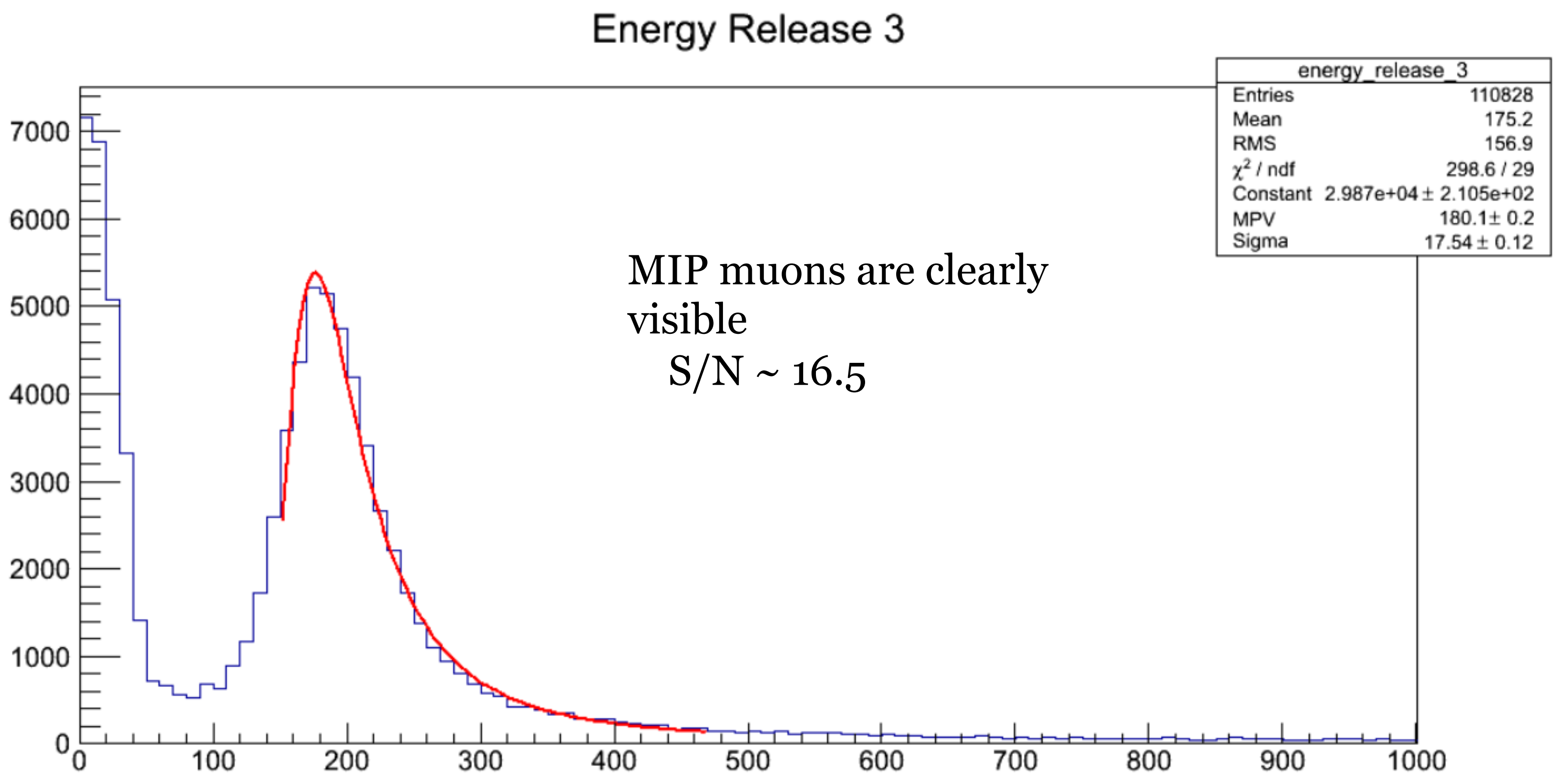


Response uniformity of the crystals



Pre-prototype test

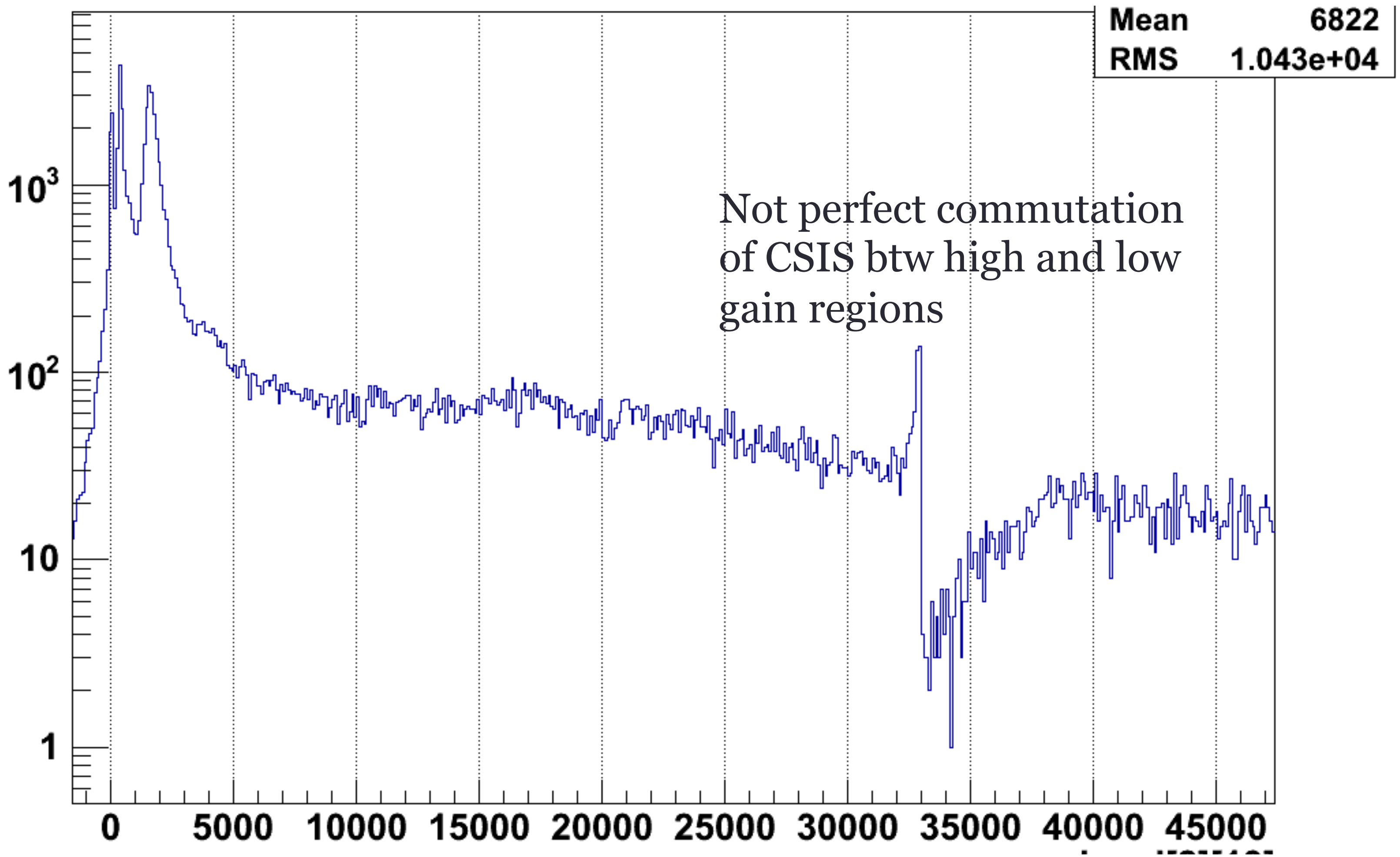
Muon beam



MIP muons are clearly visible

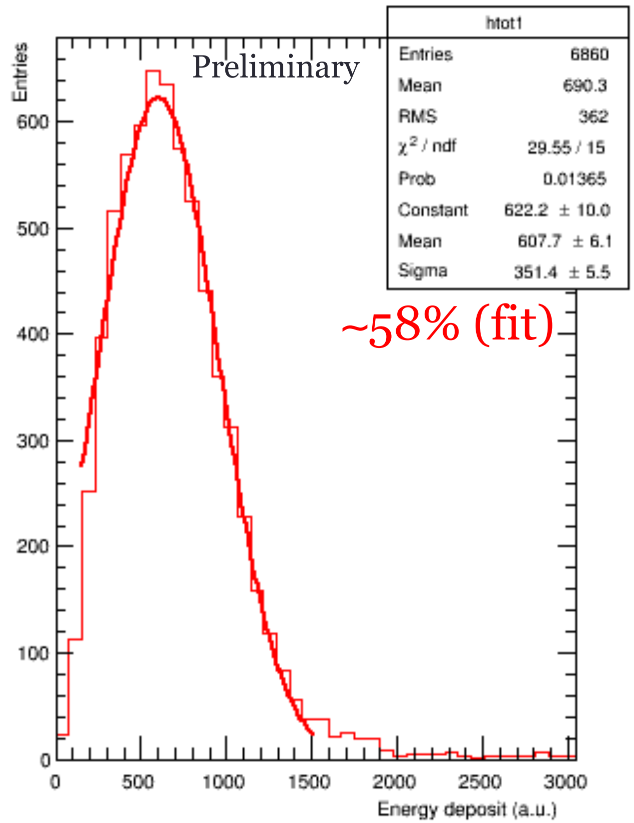
S/N ~ 16.5

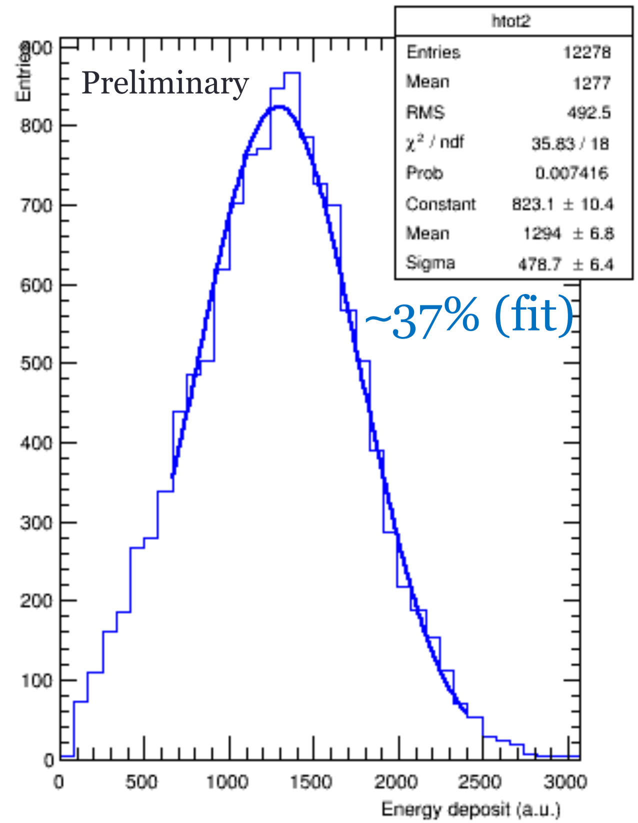
Matching region btw high and low gain



Not perfect commutation of CSIS btw high and low gain regions

Energy resolution (very rough)





Z=2

Z=1

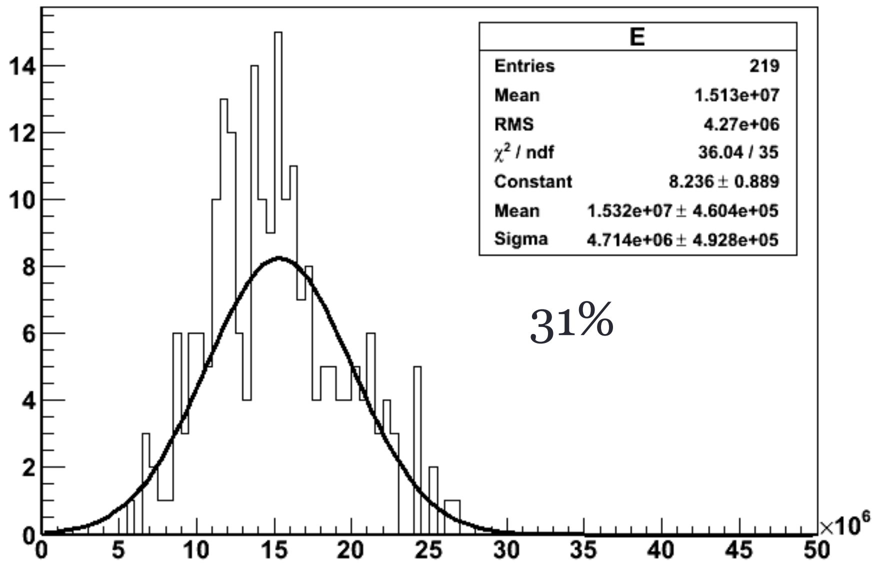
30 GV/c

Starting-layer ==2

No cuts and no corrections on the incident position

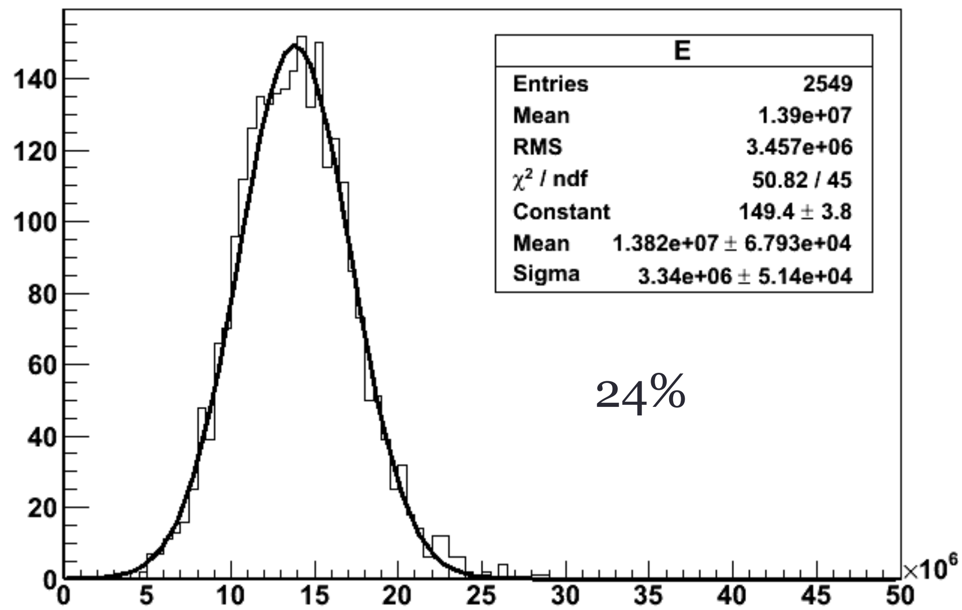
Expected resolution from simulation

Deuterium: 30 GeV kinetic energy



Particle hitting the center of the crystals

Helium: 30 GeV kinetic energy



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

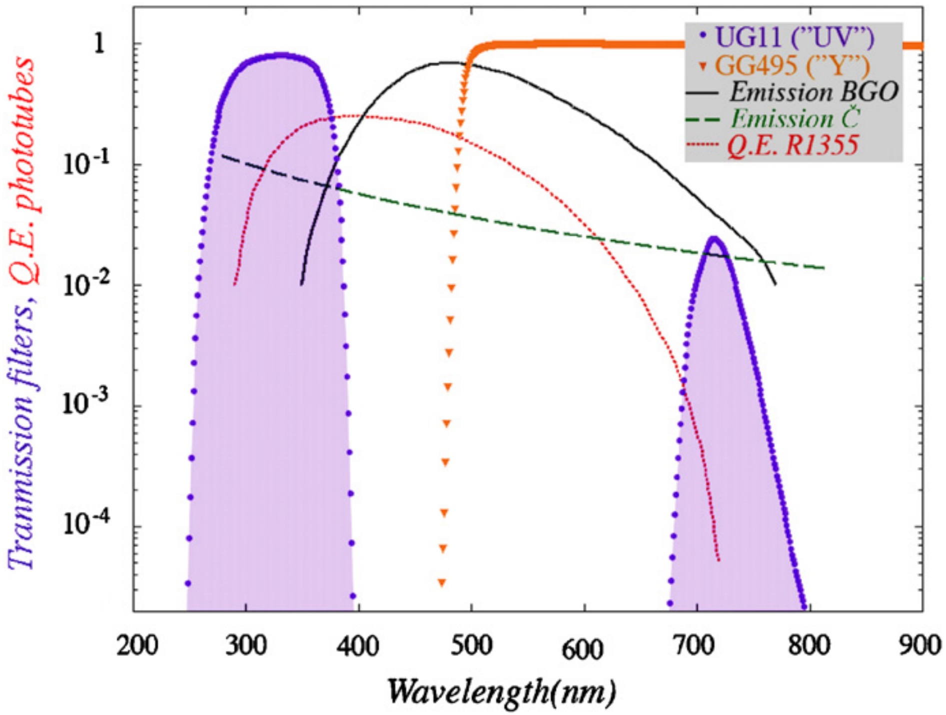
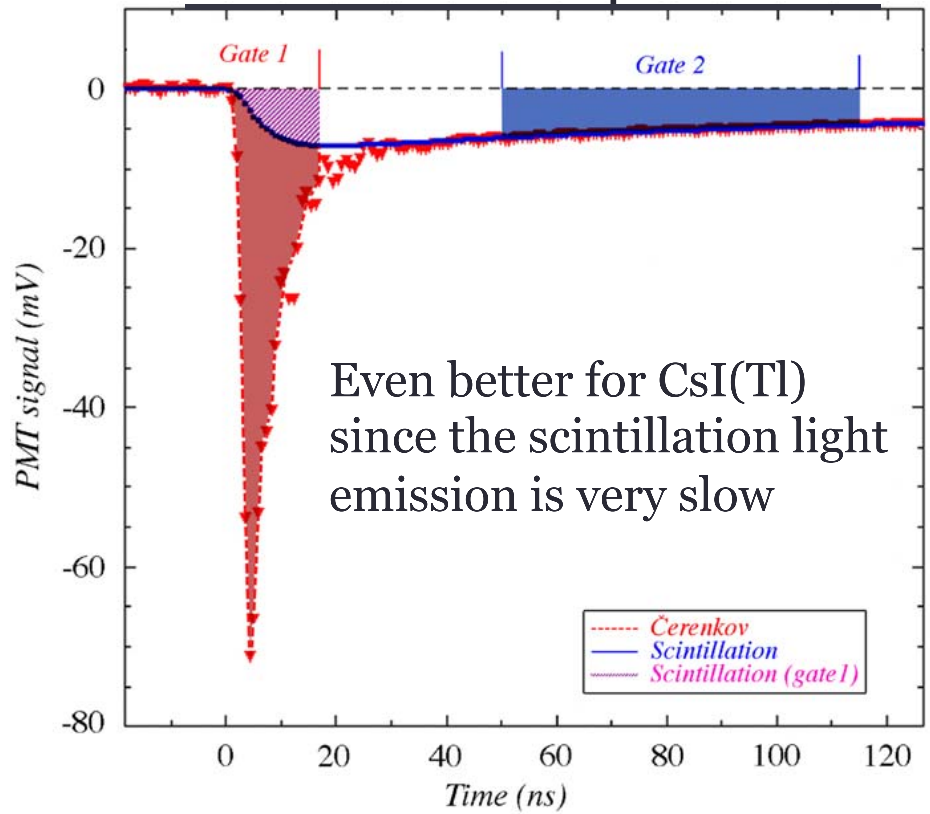


Fig. 14. Light transmission as a function of wavelength for the two filters used to read out the BGO crystal. The light emission spectrum of the crystal, the spectrum of the Cherenkov light generated in it and the quantum efficiency of the PMTs used to detect this light are shown as well. The vertical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