CALOCUBE: an innovative 3-D calorimeter for experiments in space

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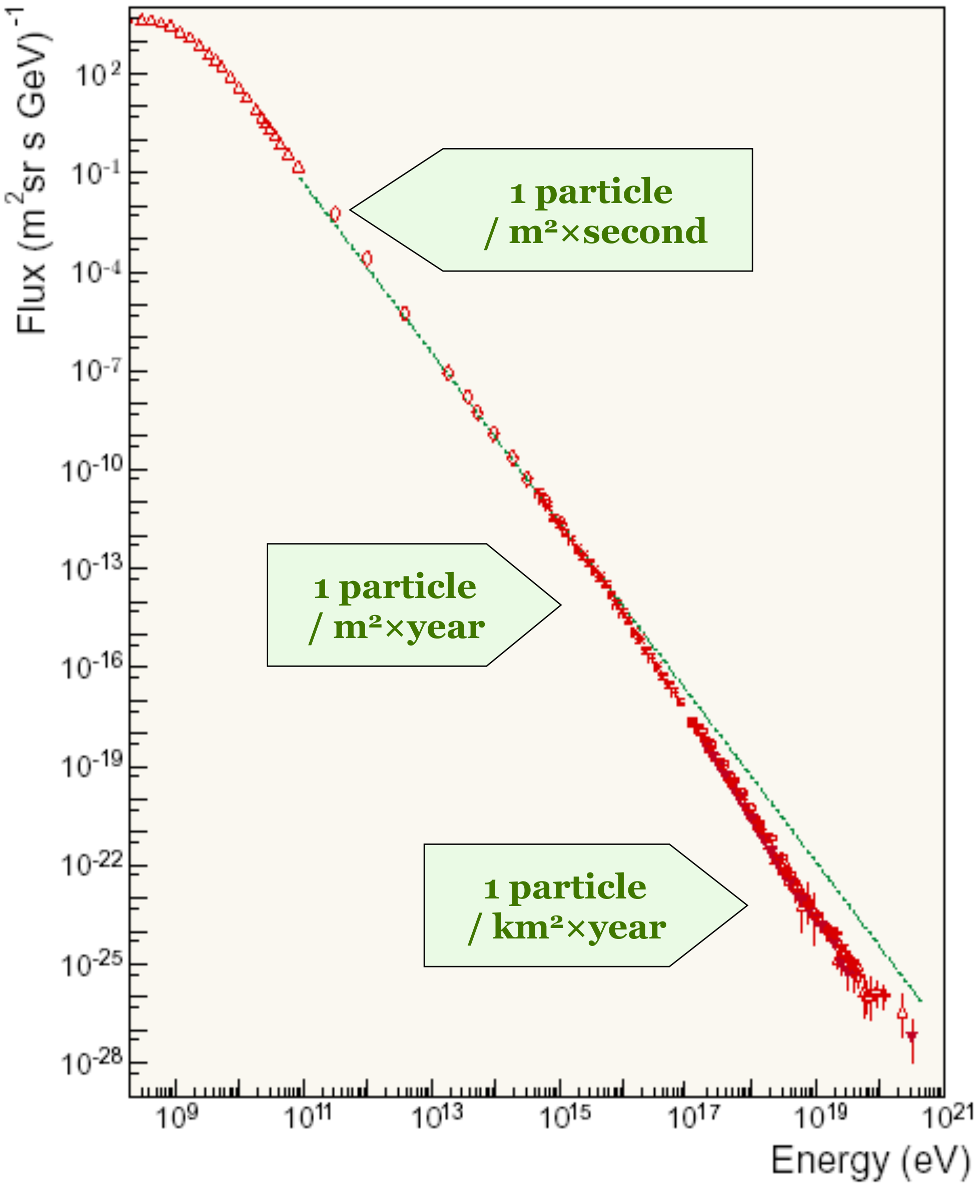
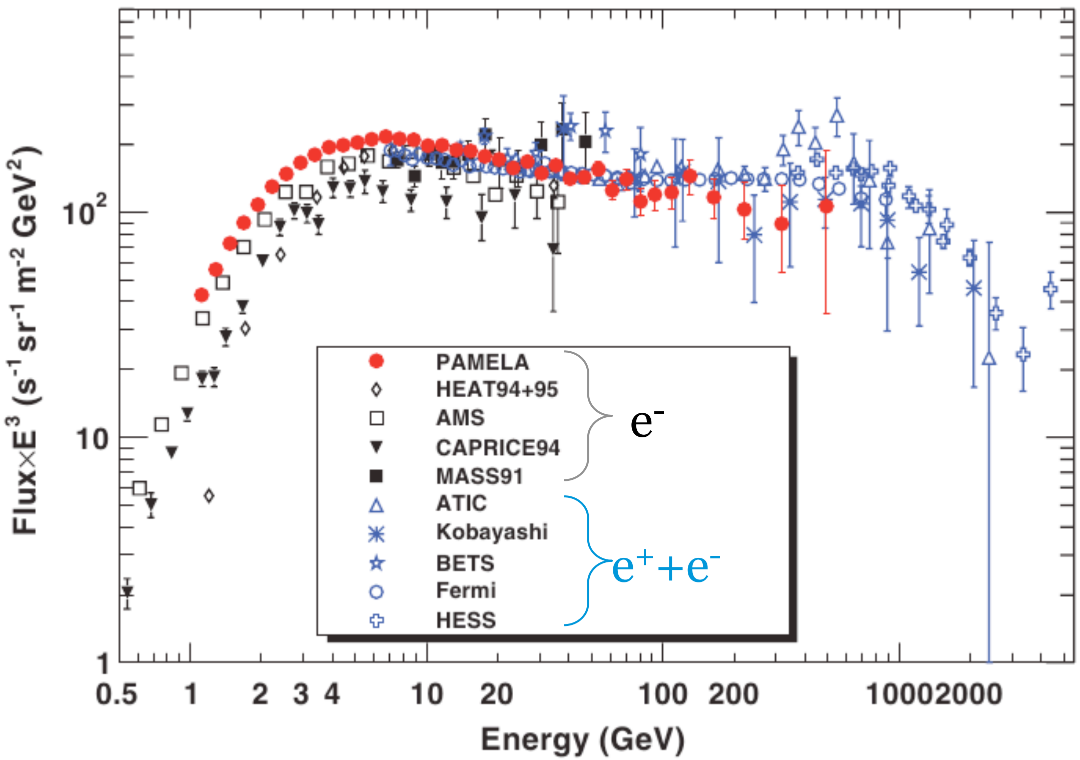
Gruppo V Pisa, 1/7/2013

Cosmic-ray spectrum



- **Composition**:
  ~90% p, He/p ~ 0.1, (Z>2)/p ~ 0.01
  e^-/p ~ 0.01 @ 10 GeV
- **"Knee" structure around ~ PeV**
  Upper energy of galactic accelerators ?
  Energy-dependent composition?
- **Direct measurements of spectral composition up to ~ 500 TeV**
- **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 are only indirect**
  Ground-based air shower detectors
  High uncertainties

Electron spectrum



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

Which are the most important aspects of a calorimeter for high-energy CR space-based experiment?

Physics goal:

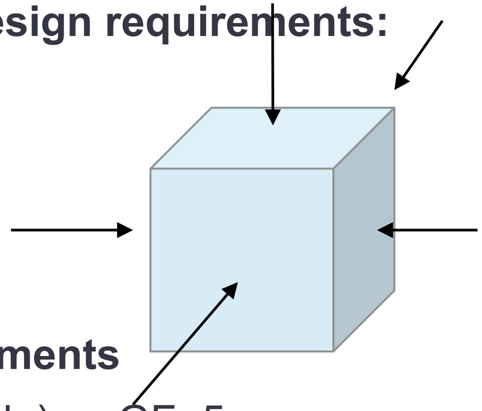
- High energy (~ TeV) electron to search for structures in the spectrum and to study close-by sources
- High energy ($>10^{14}$ eV) proton and nuclei to study the knee region

Requirements

1. Very large geometrical factor (few m^2 sr)
2. Good electron and hadron energy resolution (~1-2% for e, ~30% for hadrons)
3. Excellent electron/hadron separation ($>10^5$ rejection factor)
4. Reduced weight and power consumption (depend on the launch vehicle)

Proposal

- **A deep, homogeneous and isotropic calorimeter can achieve design requirements:**
  - depth and homogeneity to achieve energy resolution
  - isotropy to accept particles from all directions



- **Proposal: a cubic calorimeter made of small cubic sensitive elements**
  - can accept events from 5 sides (mechanical support on bottom side) → GF×5
  - Fine segmentation in every direction to achieve high e/p rejection
  - cubic, small (~ Moliére radius) scintillating crystals for homogeneity
  - gaps between crystals increase GF and can be used for signal readout, at the price of a small degradation of energy resolution
  - modularity allows for easy resizing of the detector design depending on the available mass and power budget

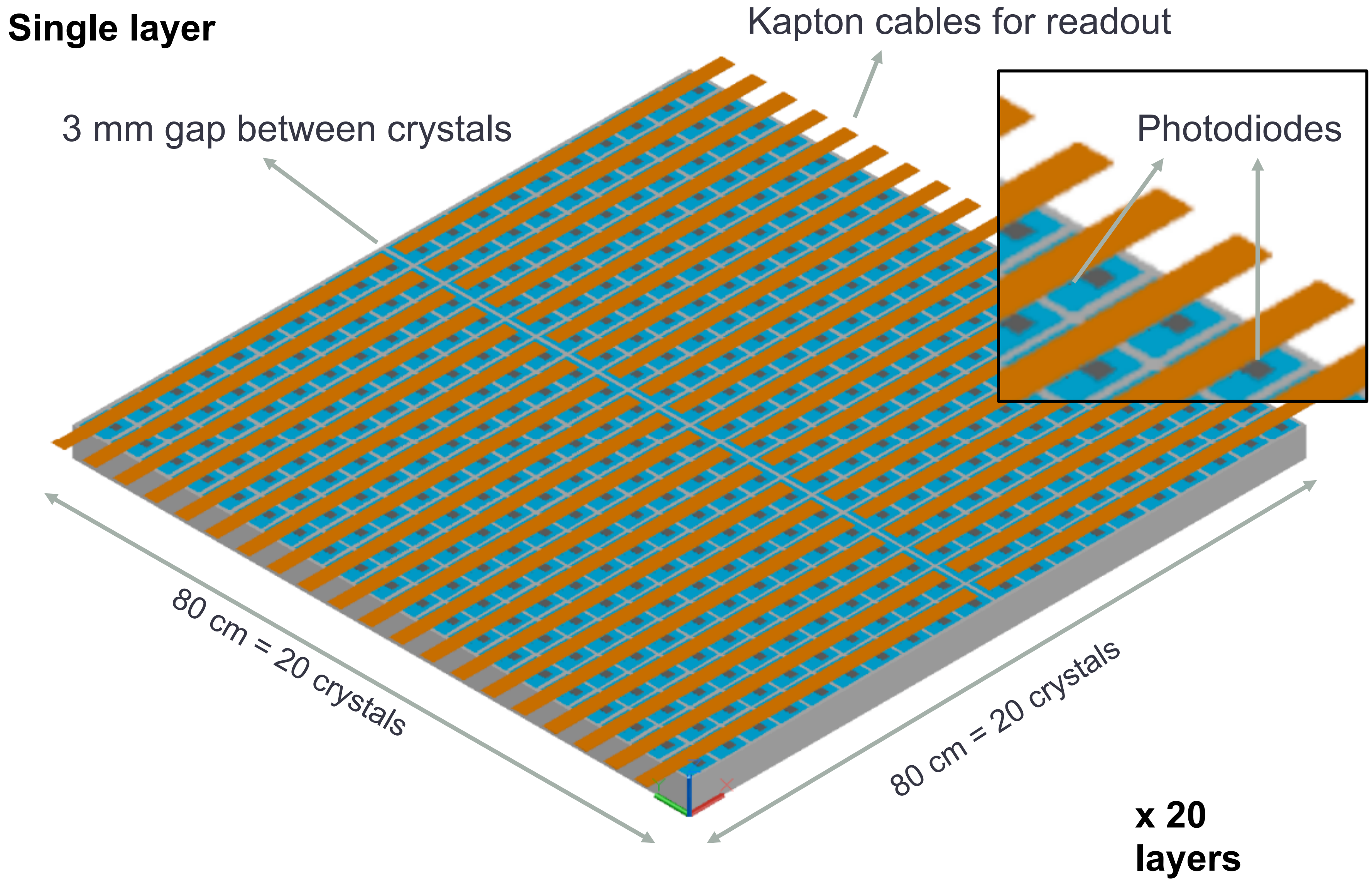
The proposed configuration

- **Mass budget of ~1600 Kg**
  - No constraints on power budget

- **Scintillating cubes: tallium-doped cesium iodide (CsI(Tl)) crystals**
  - Density: 4.51 g/cm³
  - X_0: 1.85 cm
  - Moliére radius: 3.5 cm
  - λ_I: 37 cm
  - Light yield: 54.000 photons/MeV
  - T_{decay}: 1.3 μs
  - λ_{max}: 560 nm

Parameters	
NxNxN	20x20x20
L of small cube (cm)	3.6
Crystal volume (cm^3)	46.7
Gap (cm)	0.3
Mass (Kg)	1683
No. of crystals	8000
Size (cm^3)	78.0x78.0x78.0
Depth (R.L.) **" (I.L.)**	**39x39x39** **1.8x1.8x1.8**
Planar GF (m^2sr)	**1.91**

Mechanical design



Readout sensors and dynamic range estimation

CsI(Tl)

1 MIP (for cube 3.6 cm) = 1.25 MeV/(g/cm^2)*4.5 g/cm ^{3} *3.6 = 20 MeV

Light yield = 54 000 ph/MeV

Light yield for cube = 54 000*20 ~ 10^6 photons/MIP

Photodiode Excelitas VTH2090 (9.2 x 9.2 mm^2) for small signals

Geometry factor * Light collection efficiency = 0.045 QE = 0.6

$Signal_{MIP}$ (CsI) = Light yield* Geometry factor* QE = 28.10^3 e$^-$

Small Photodiode (0.5 x 0.5 mm^2) for large signals

Geometry factor * Light collection efficiency = 1.3x10^{-4} QE = 0.6

$Signal_{MIP}$ (CsI) = Light yield* Geometry factor* QE = 80 e$^-$

Requirements on the preamplifier input signal:

Minimum: **1/3 MIP**=10^4 e$^-$ = 2 fC (Large area PD)

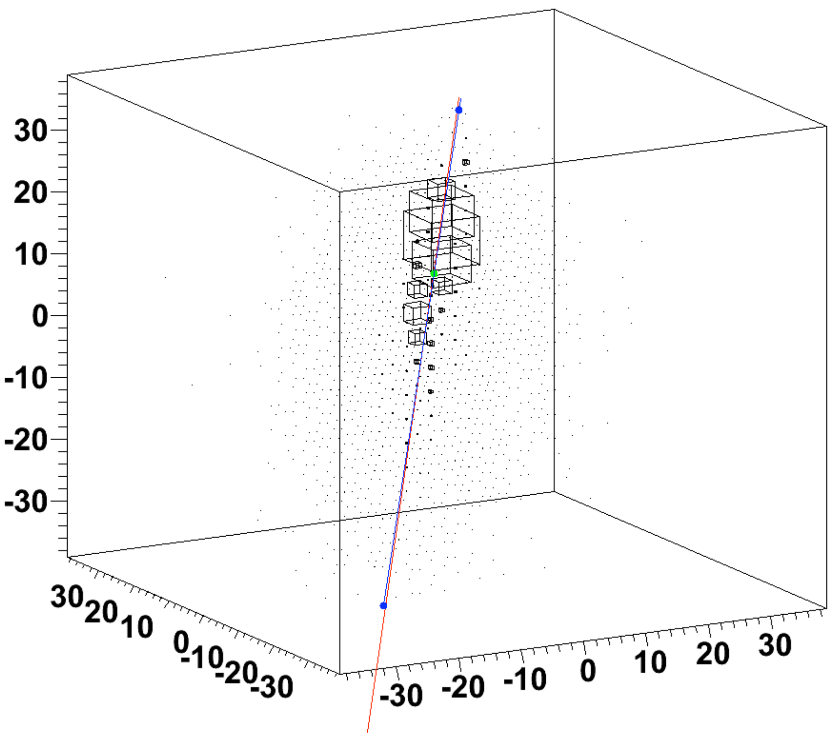
Maximum: 0.1xE_{part}= 100 TeV=**5.10^6 MIP**=4.10^8 e$^-$ = 64 pC (Small area PD)

By using two different PD we could well see MIP, and we could avoid saturation in one crystal provided we can find a suitable preamplifier chip (64pC/2fC=3.10^4 dynamic range)

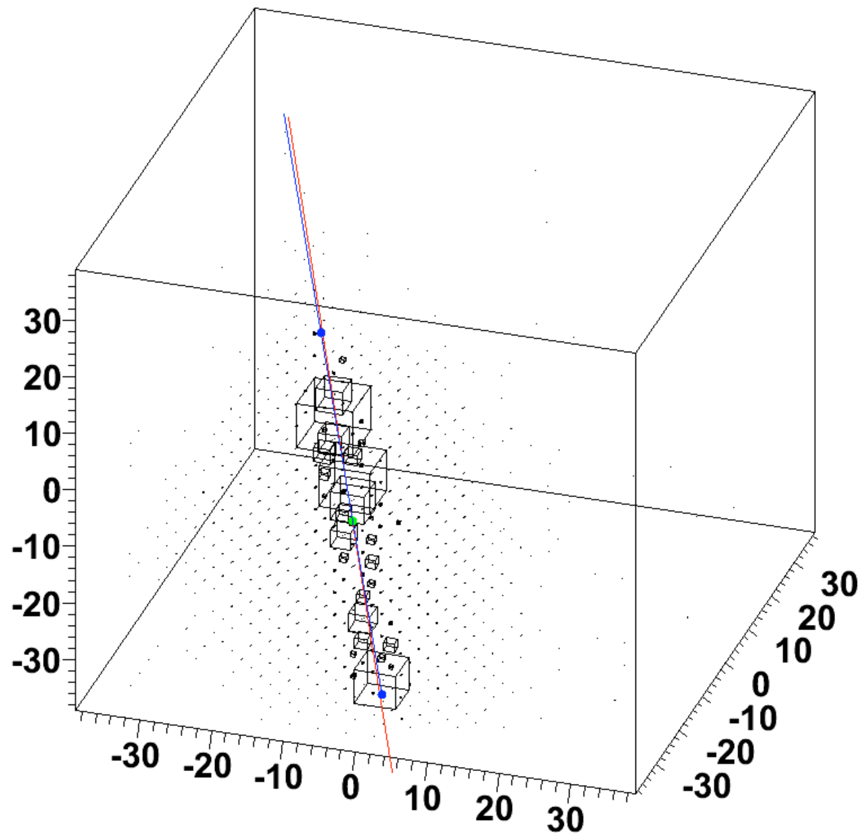
MC simulations

- **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: $(0.78*0.78*\pi)*5*\varepsilon\ m^2sr = 9.55*\varepsilon\ m^2sr$

Electron image



Proton image

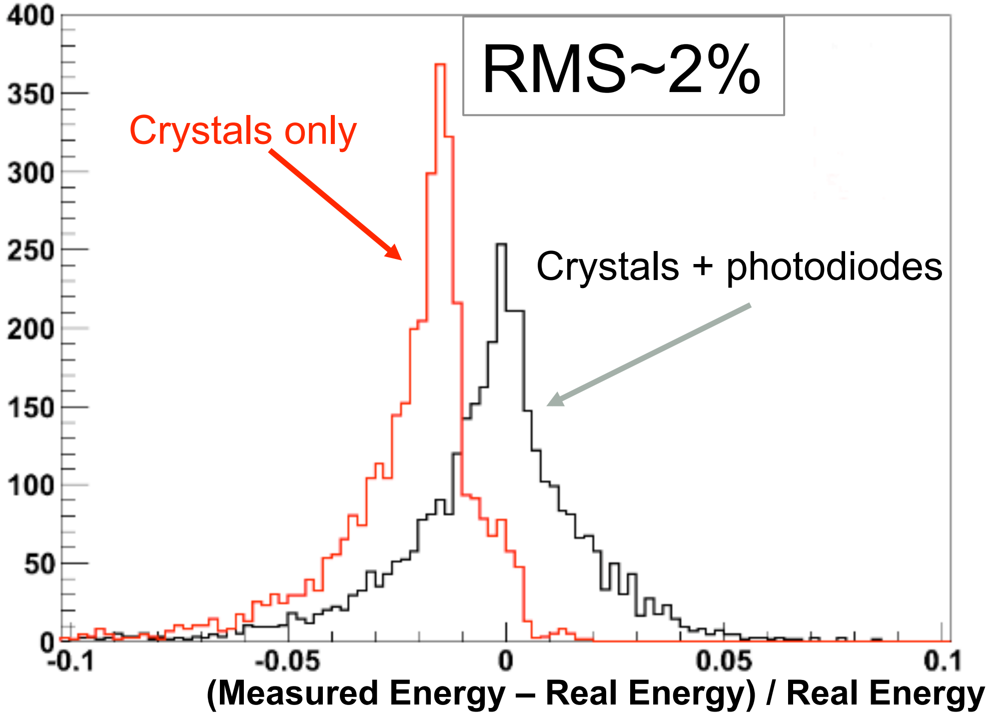


Electrons

Very simple geometrical cuts:

- The track should point to a fiducial surface (excluding 2 crystals on the side)
- The maximum of the shower should be well contained in the fiducial volume
- The length of the shower should be at least 40 cm (~21 X_0)

Electrons 100 – 1000 GeV



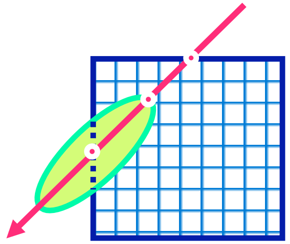
Selection efficiency: ε ~ 36%

GF_{eff} ~ 3.4 m^2sr

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

Ionization effect on PD: 1.7%

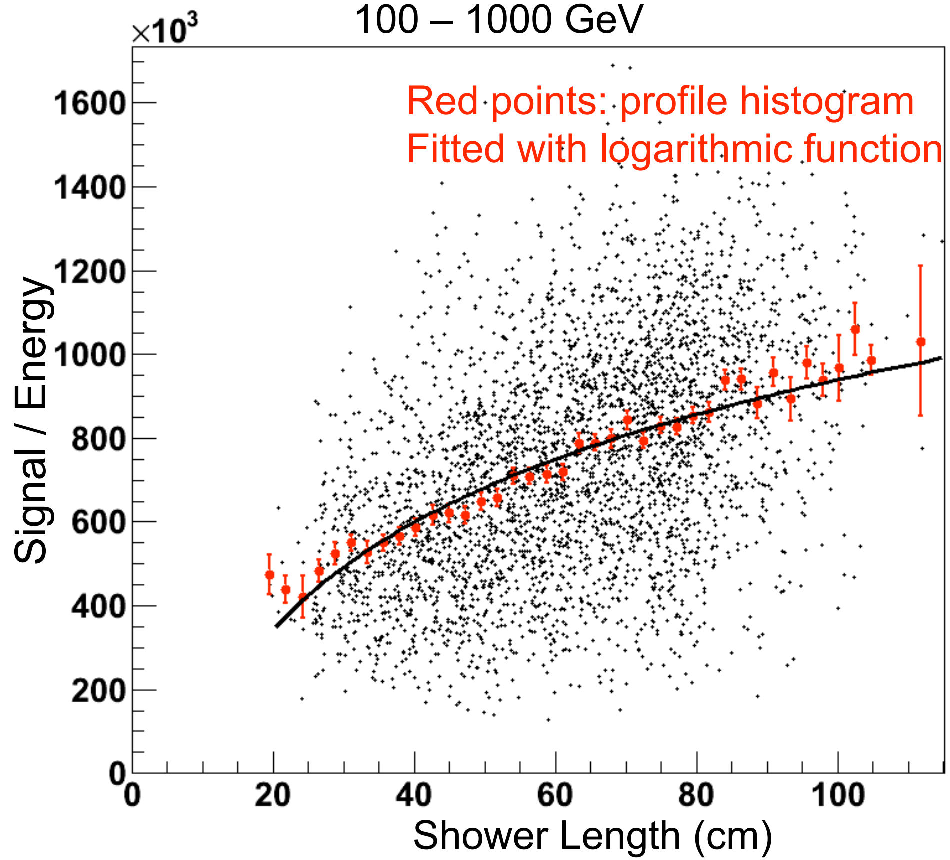
Protons



Very simple geometrical cuts:

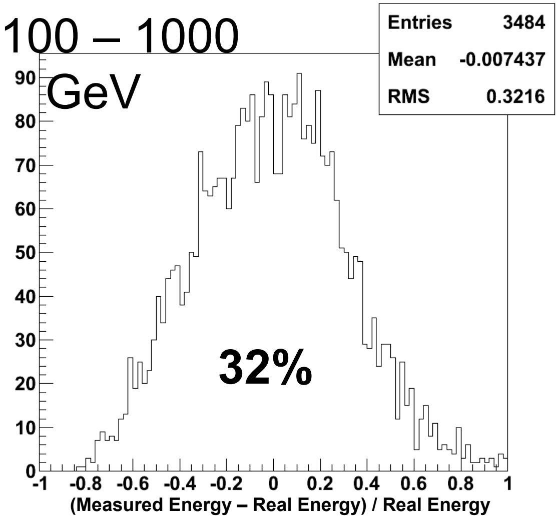
- good reconstruction of the shower axis
- At least 50 crystals with >25 MIP signal

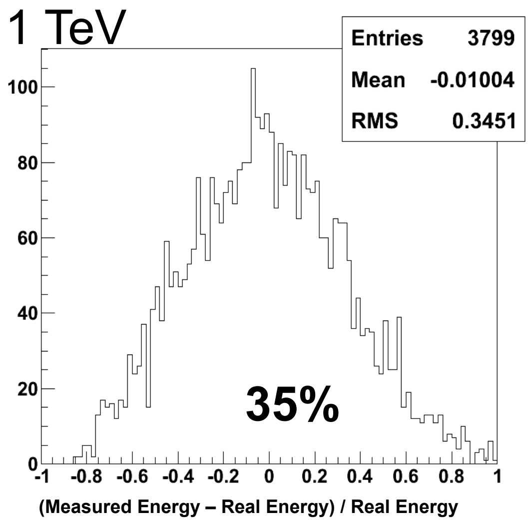
Shower length can be used to reconstruct the correct energy, since leakage important.

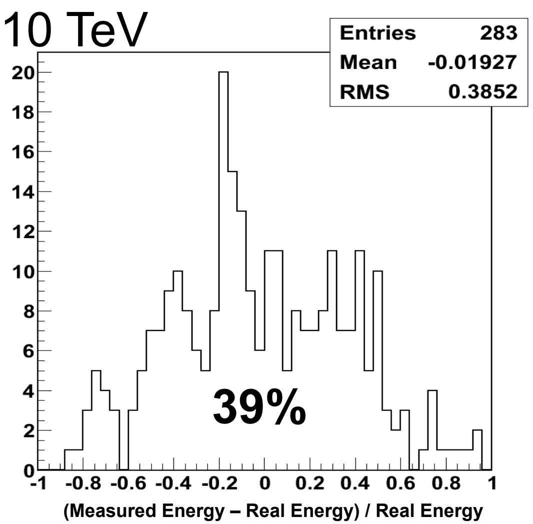


Protons - energy resolution

Energy resolution







Selection efficiencies:

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

$\varepsilon^{1\text{TeV}}$ ~ 41%

$\varepsilon^{10\text{TeV}}$ ~ 47%

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

$GF_{eff}^{1\text{TeV}}$ ~ 3.9 m^2sr

$GF_{eff}^{10\text{TeV}}$ ~ 4.5 m^2sr

The prototypes

- **Two prototypes have been built at INFN Florence, with the help of INFN Trieste, University of Siena/INFN-gruppo collegato**

- **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 with beams of e, p and muons
  - prototype in January-February 2013 with fragmented ion beam

Sensors and readout

- **Excelitas VTH2090 photodiodes have been used**

  9.2x9.2 mm^2 area

  Only one PD per crystal for both the prototypes

- **Readout is done by means of the CASIS chip developed by INFN Trieste**

  V. Bonvicini *et al.,* IEEE transactions on nuclear science, vol. 57(5) 2010

  16 channels, charge sensitive ampl. and correlated double sampling

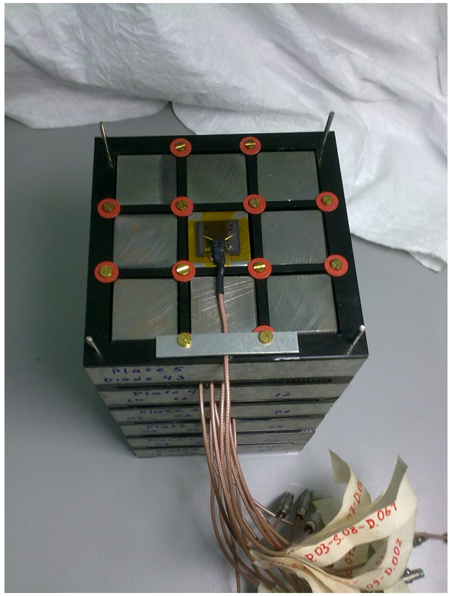
  Automatic switching between high and low gain mode

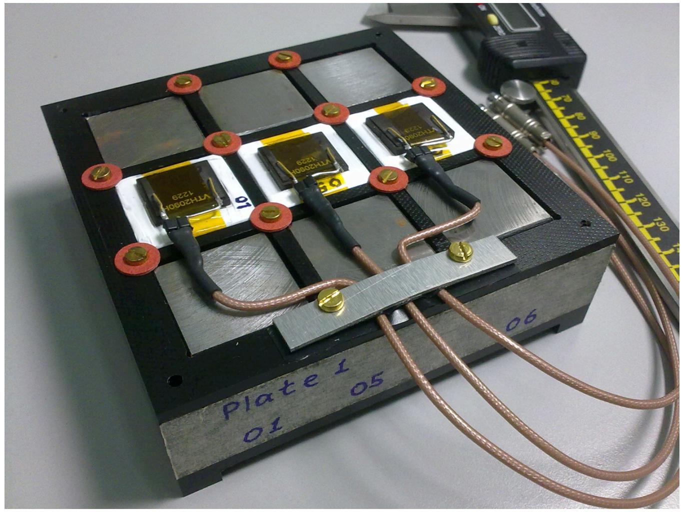
  2.8 mW/channel

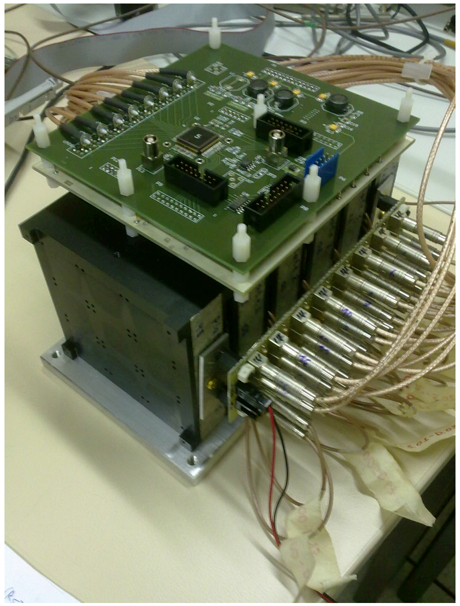
  3000 e^- noise for 100 pF input capacitance

  53 pC maximum input charge

The pre-prototype

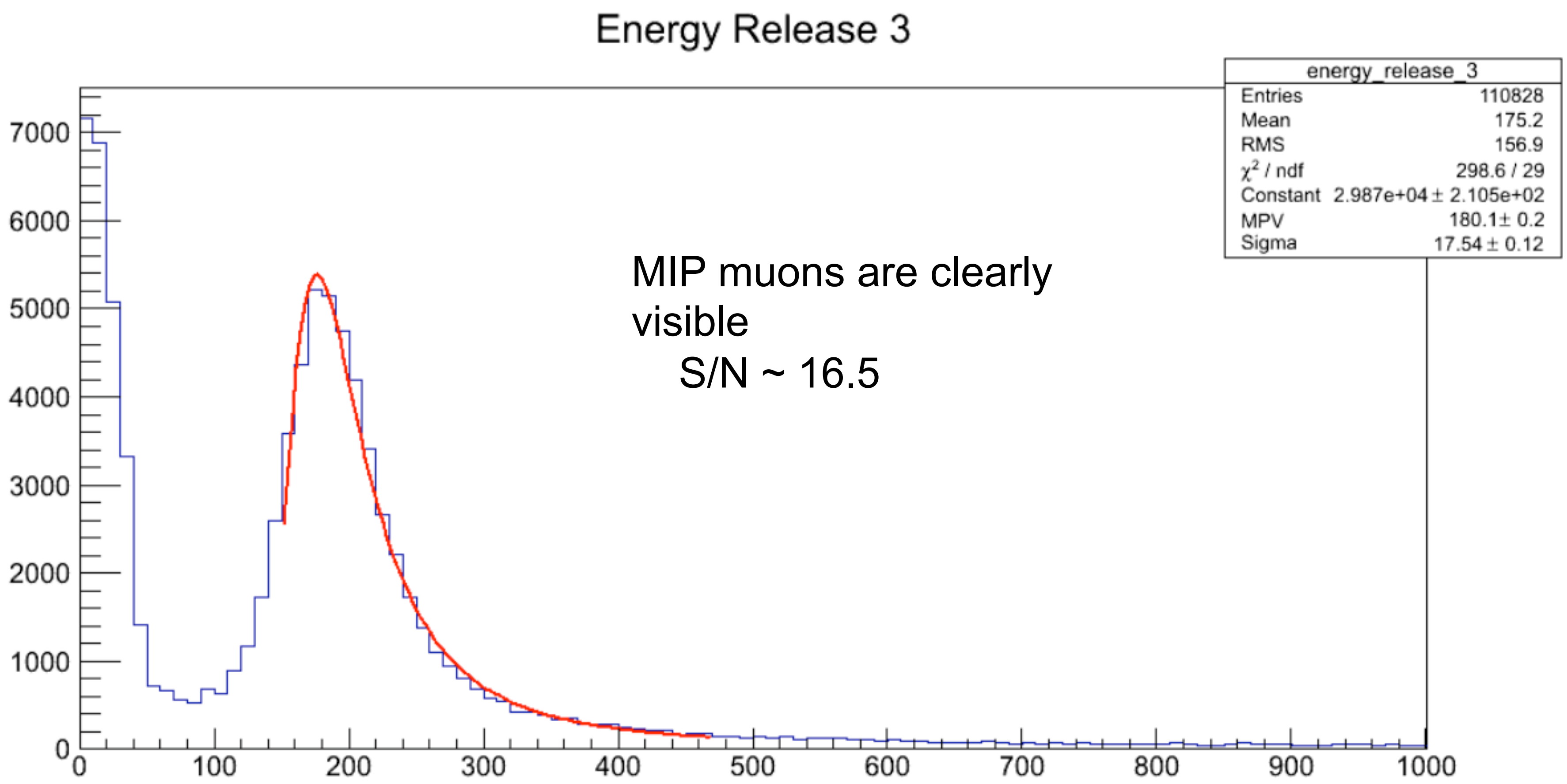






Pre-prototype test

Muon beam

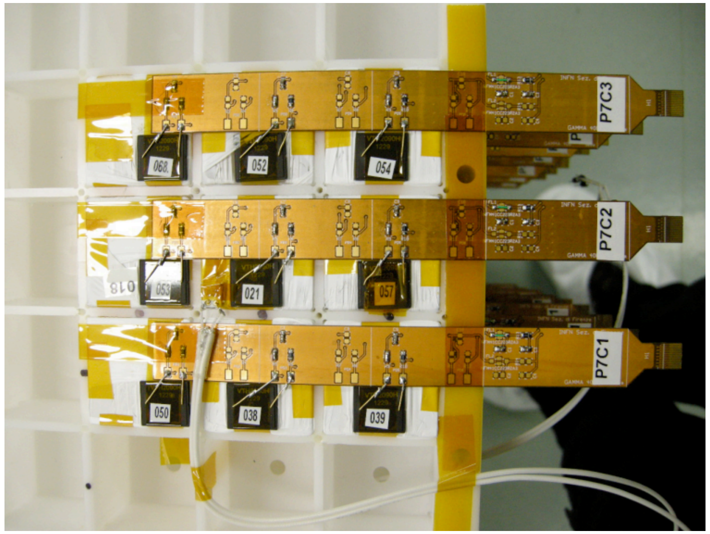


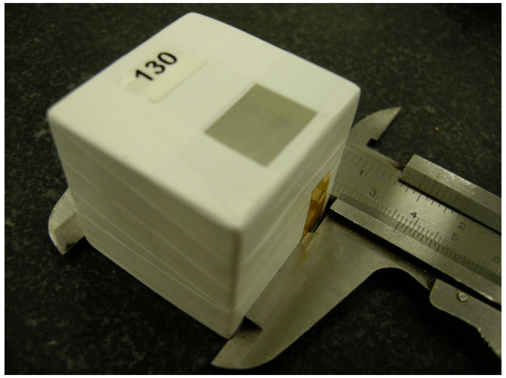
MIP muons are clearly visible

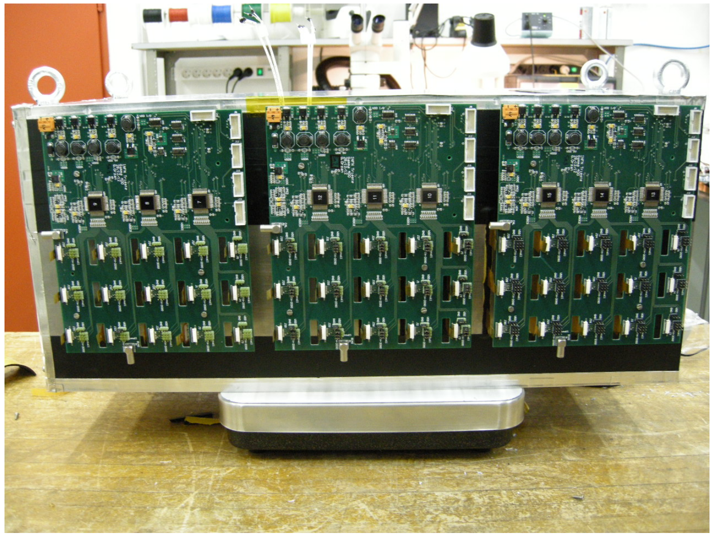
S/N ~ 16.5

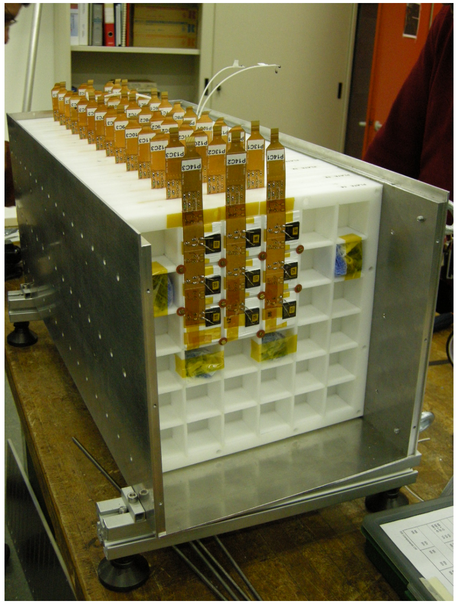
The prototype

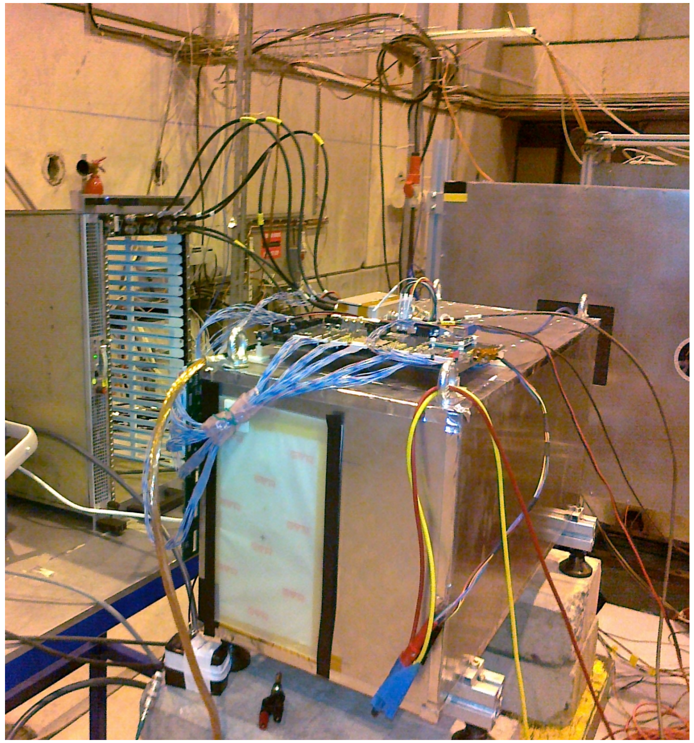
14 Layers
9x9 crystals in each layer
126 Crystals in total
126 Photo Diodes
50.4 cm of CsI(Tl)
27 X_0
1.44 l_I





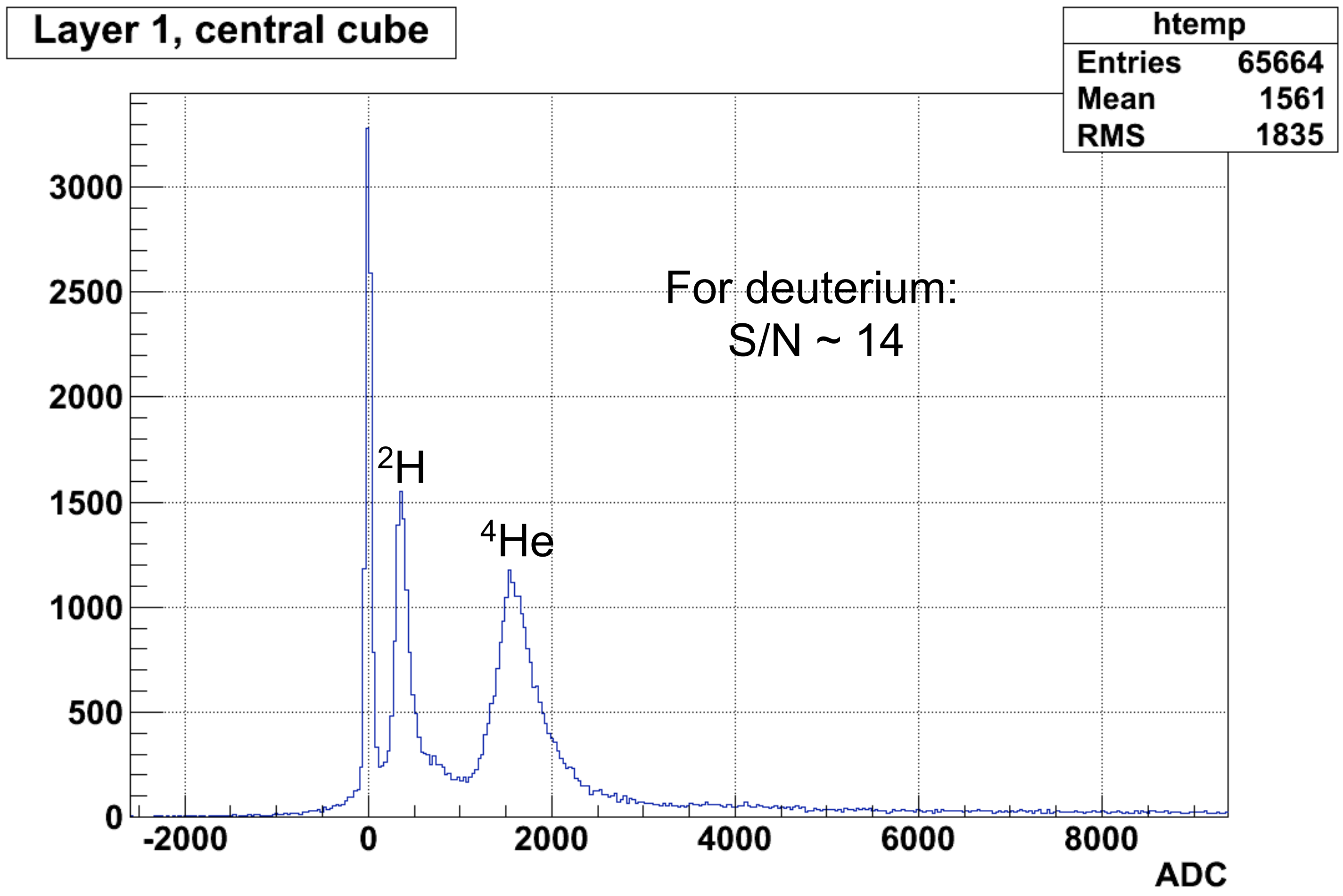




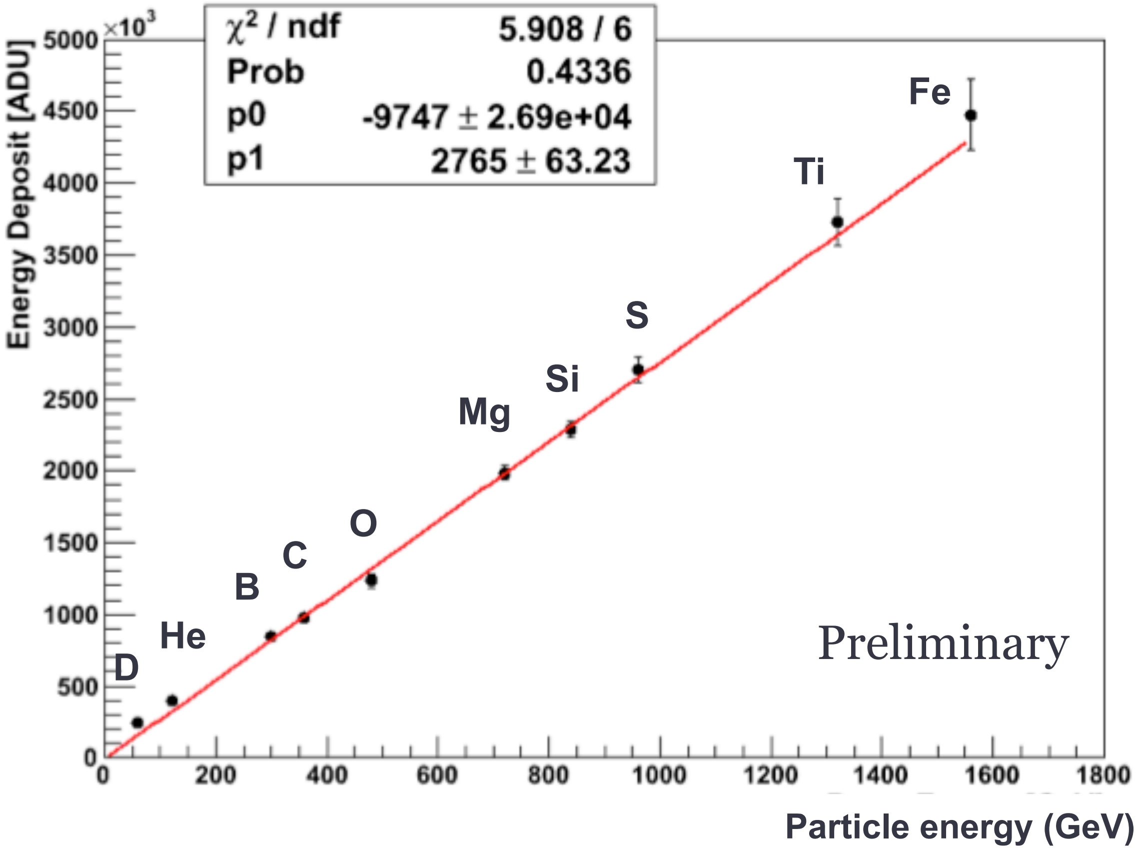


Pulse height spectrum in a crystal

Beam: A/Z = 2, 30 GeV/n



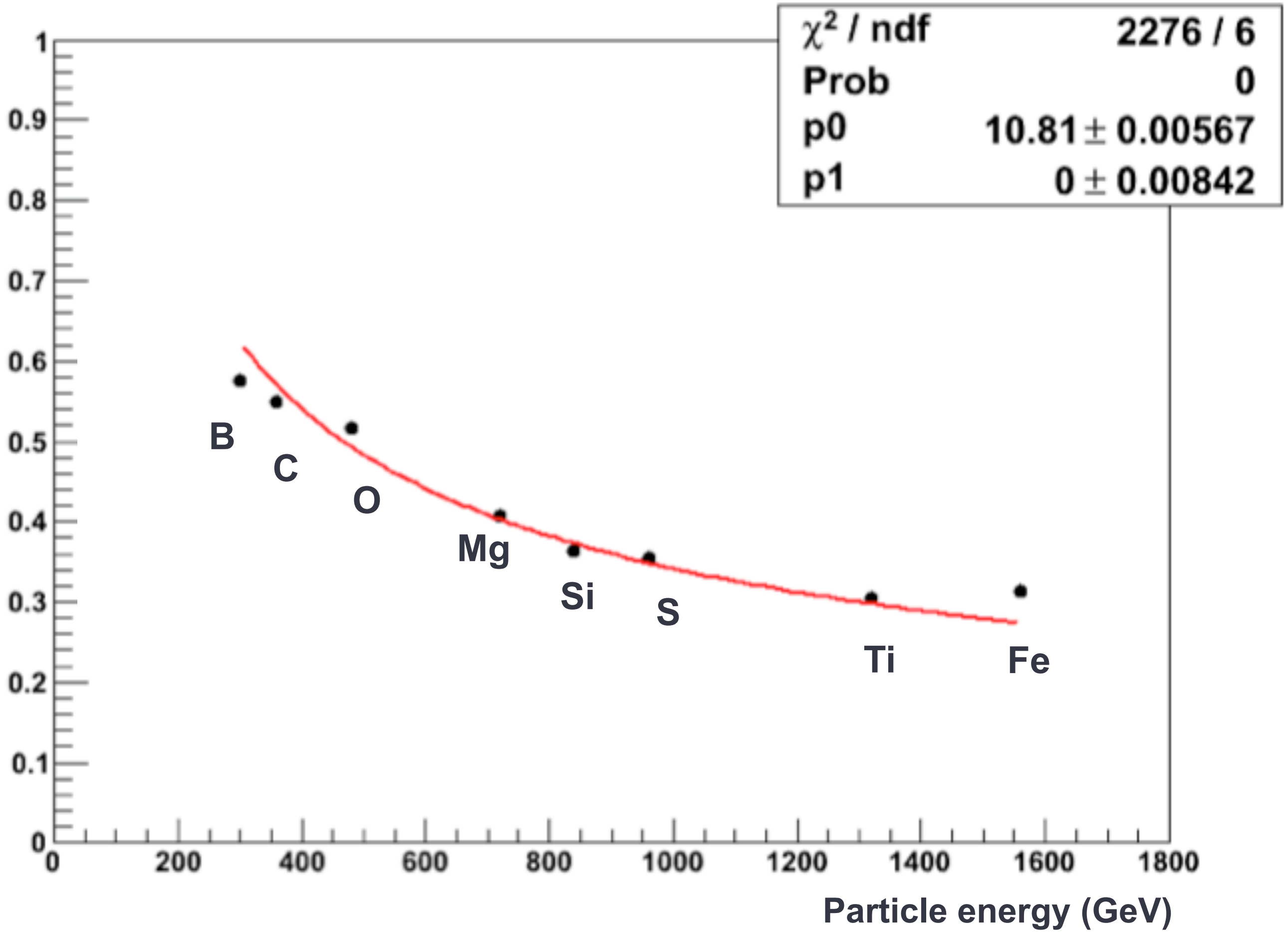
Energy deposit for various nuclei



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

Good Linearity even with the large area PD!

Energy resolution for various nuclei



Summary

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

Attivita' di Pisa/Siena nella "call" di CSN5 con capofila INFN-Firenze

- Studio di fattibilita' di un Particle-ID integrato nel calorimetro CALOCUBE rimpiazzando i cristalli sulle facce esterne del calorimetro con una serie di cristalli, della stessa superficie e dello stesso tipo, ma ciascuno di spessore pari a pochi mm. Misure multiple di dE/dx forniscono l'identificazione in carica della particella incidente prima che essa interagisca. La segmentazione fine di CALOCUBE permette di ridurre gli effetti di back-scattering.

- Studio della meccanica e analisi strutturale agli elementi finiti di un prototipo di CALOCUBE per uso in una missione spaziale

- Partecipazione allo sviluppo dei prototipi del progetto CALOCUBE con particolare riguardo alla meccanica e tests di qualificazione

- Upgrade dell'attuale beam tracker (tracking con Si-strips e PID con silici a pixel) per tests su fascio

CALOCUBE - Richieste di servizi in sezione per il 2014

- Officina Meccanica (4 weeks/uomo) meccanica per test articles/prototipi
- Progettazione meccanica e studi strutturali
- Supporto per beam test al CERN alla riapertura dei fasci di test (2015)

	2014 INFN sez. di Pisa + Siena GC	CALOCUBE
P.S. Marrocchesi	PO Univ.Siena + INFN Gruppo Collegato	0.3
P.Maestro	RC Univ.Siena + INFN Gruppo Collegato	0.3
JungEun Suh	Dottoranda Univ. di Siena	
S. Bonechi	Dottorando Univ. di Siena	
Arta Sulaj	Assegno di ricerca - Siena	1
Paolo Brogi	Dottorando Univ. di Siena	
Totale FTE		**1.6**