Calocube - A highly segmented calorimeter for a space based experiment.

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for the Calocube Collaboration

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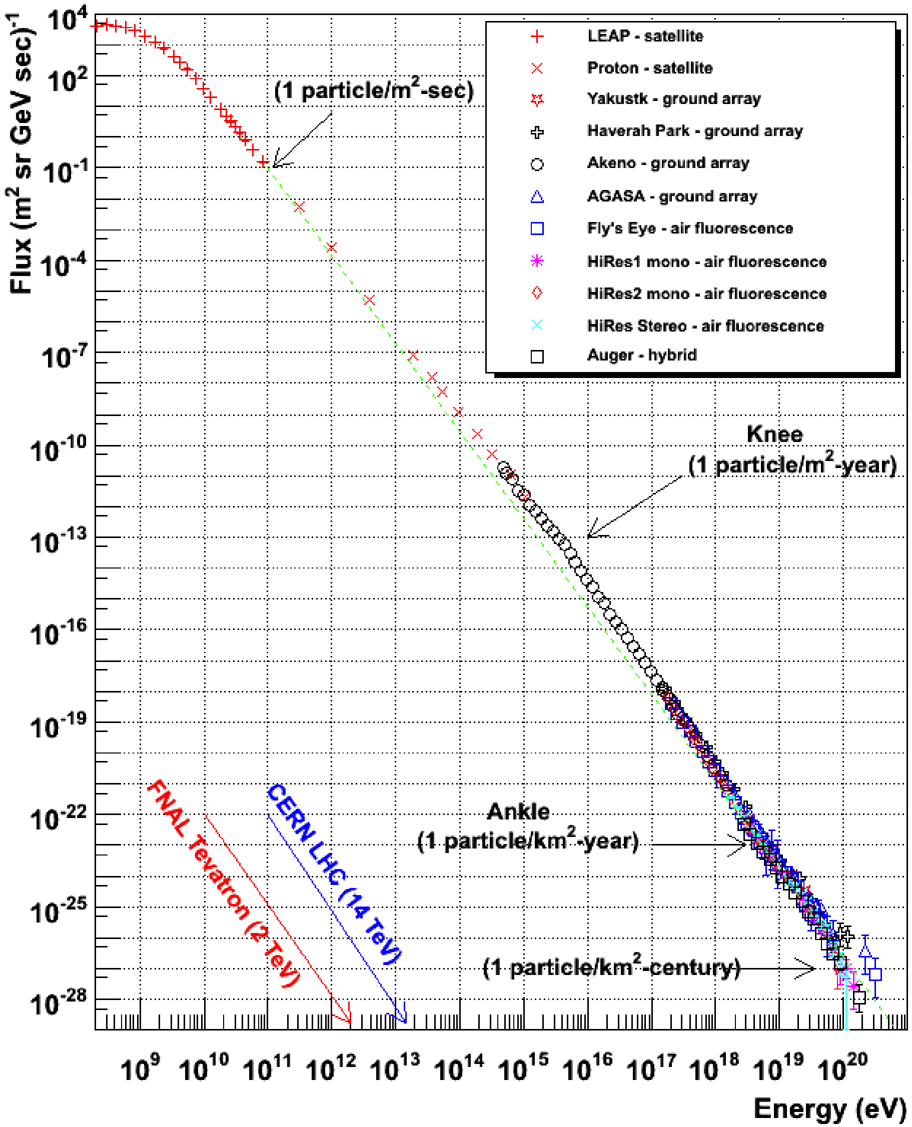
Background

- Future research in High Energy CR concerns fundamental questions on their origin, acceleration mechanism, and composition.
- Well known "features" of the energy spectra of cosmic rays such as the "knee" region can provide some of the answers to the above questions.
- Ground based observations rely on sophisticated models describing high energy interactions in the earth's atmosphere.
- These limitations can be overcome by direct measurements in space.

Open Questions (1)



High energy protons and nuclei

- “Knee” structure around ~ PeV
- Upper energy of galactic accelerators (?)

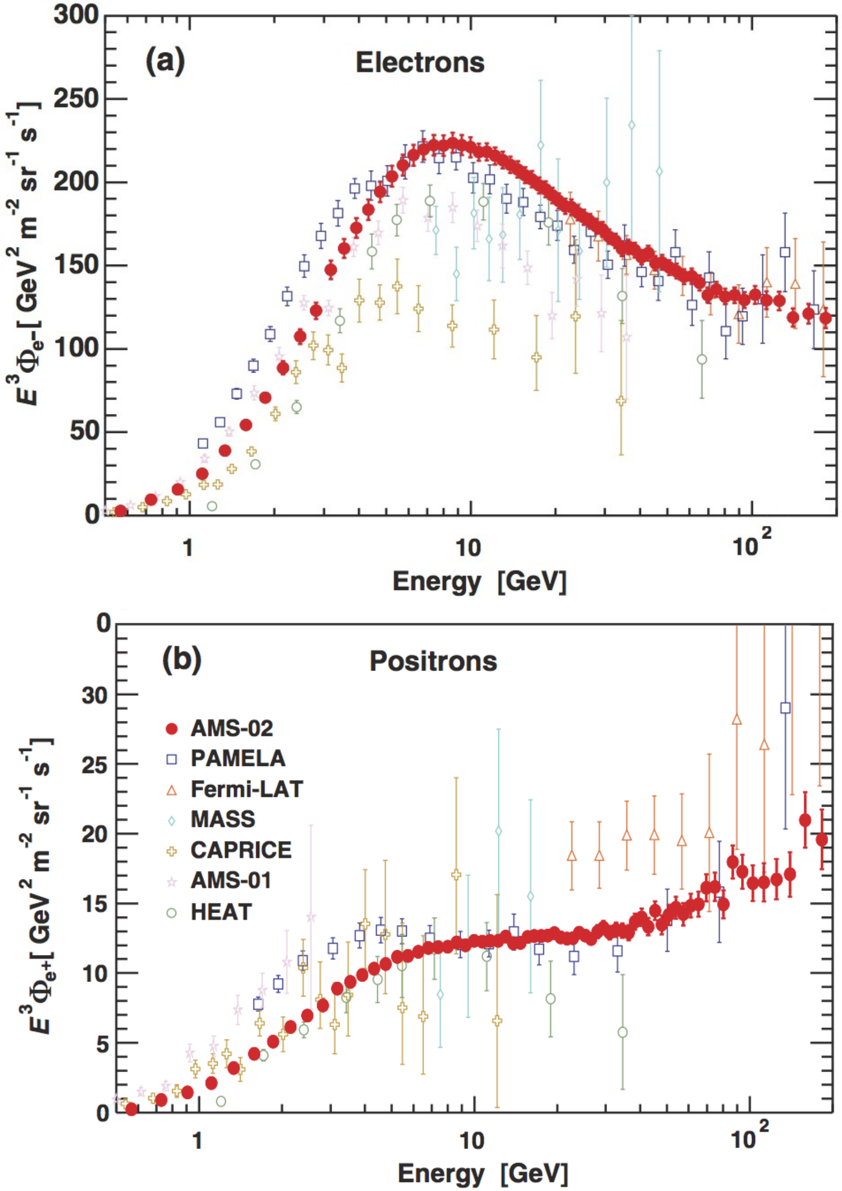
Composition

- Energy dependent
- High uncertainties , indirect measurement
- Spectral measurements in the knee are from ground-based shower detectors

For a direct measurement in the PeV region

- great acceptance (few m^{2}sr),
- charge measurement
- energy resolution for hadrons (< 40%)

Open Questions(2)



Aguilar et al . PRL 113: 121102, 2014 ;

- **High energy Electrons+Positrons**
  - Currently available measurements show disagreement with standard propagation models
  - Dark Matter, Pulsars, Acceleration in SNRs ?
- **Cutoff in the TeV region** *(HESS., ATIC ?)***?**
  - Direct measurements require excellent energy resolution (~2%),
  - high e/p rejection power (> 10^5)
  - large acceptance above 1 TeV

Why Calocube ?

- The scientific goal is the measurement of the energy spectrum of the nuclear component of cosmic rays in the region of the knee (10^{15} eV), where the spectral index shows a significant change, and of the electromagnetic component above the TeV region.
- A calorimeter based space experiment can provide not only flux measurements but also energy spectra and particle ID, especially when coupled to a dE/dx measuring detector.

Obstacles

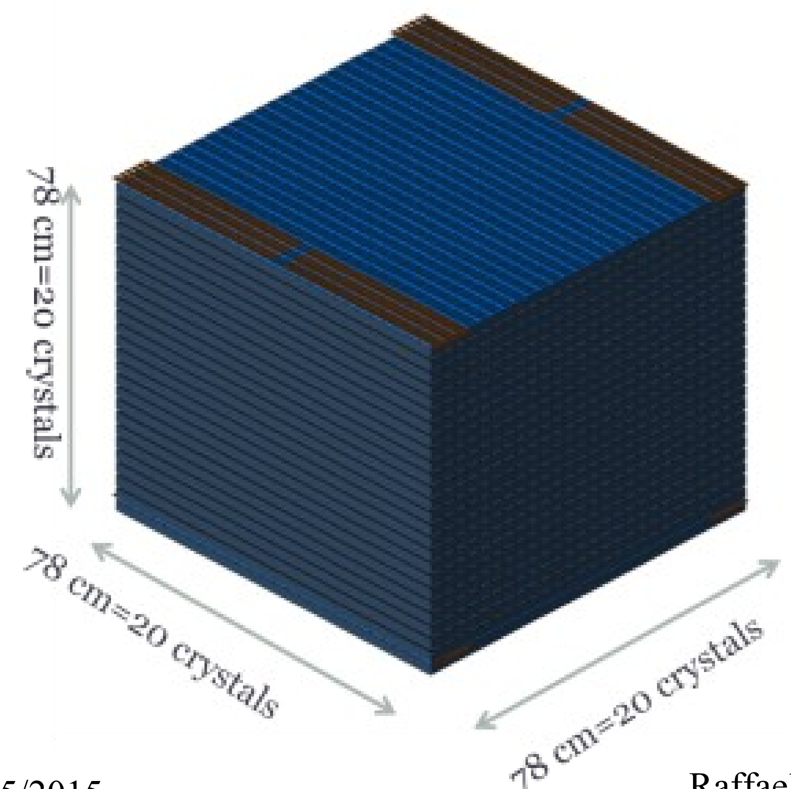
- Unfortunately fluxes at these high energies are extremely low and require very large acceptances if enough events are to be collected in a reasonable time.
- This contrasts with the lightness and compactness requirements for space based experiments.
- A novel idea in calorimetry is presented here which addresses these issues while limiting the mass and volume of the detector.

Proposition

- The proposed calorimeter has a high granularity coupled to a homogeneous segmentation both lateral and in depth.
- This unique design allows it to achieve excellent distinction between hadrons and electrons while maximizing the acceptance by increasing the number of entry windows to the detector.
- A small prototype has already being built and tested with ions. In this talk the results obtained will be presented in light of the simulations performed.

Baseline Calorimeter

- Assumption: detector weight ~ 1600 kg
- Baseline material CsI(TI): Density: 4.51 g/cm^3
  - x_0: 1.86 cm ; λ_I: 38 cm ; Moliere radius: 3.5 cm
  - Light yield: 54.000 ph/MeV ; τ_{decay}: 1.3 ms ; λ_{max}: 560 nm



N×N×N	**20×20×20**
crystal side (cm)	3.6
crystal volume (cm3)	46.7
gap (cm)	0.3
mass (kg)	1685
number of crystals	8000
size (m^3)	0.78×0.78×0.78
depth (R.L.) " (I.L.)	39×39×39 1.8×1.8×1.8
planar GF (m^{2}sr) *	1.91

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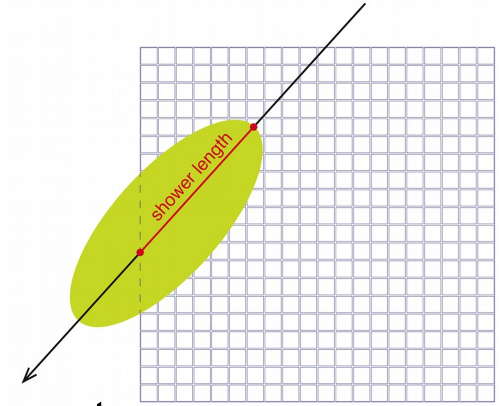
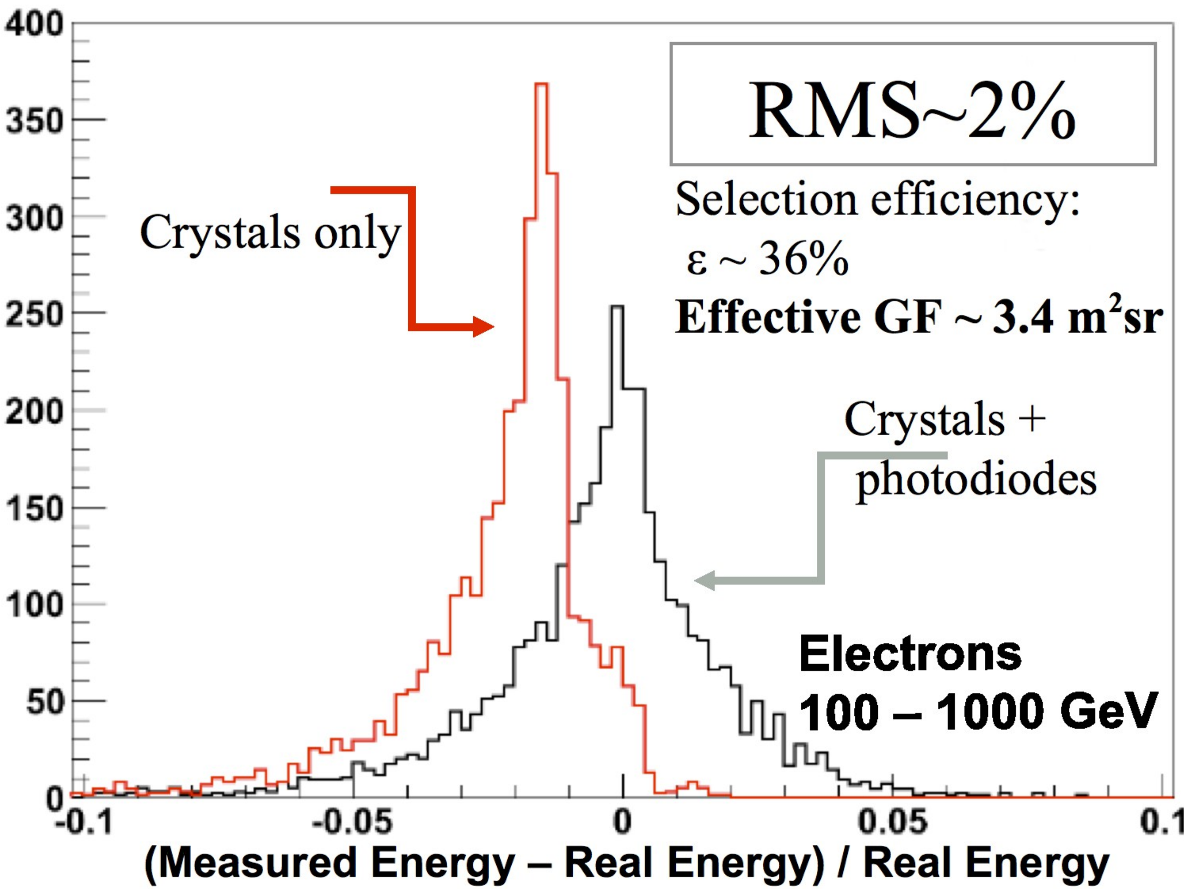
Simulations

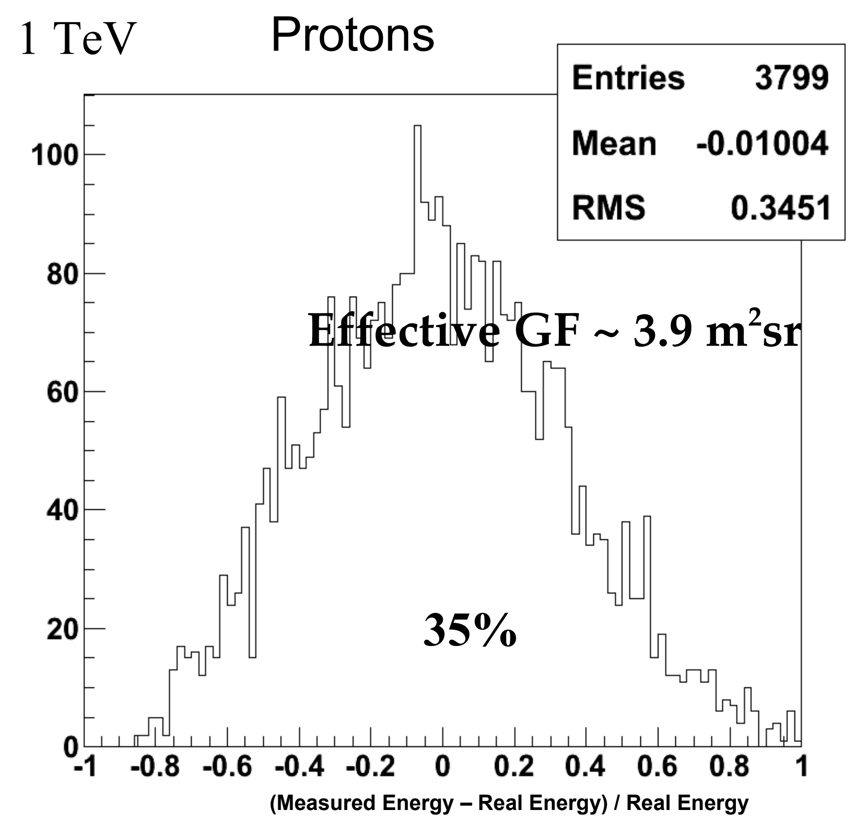


- FLUKA-based MC simulation
  - CsI(Tl) scintillating crystals
  - Silicon Photodiodes
  - energy deposit in the PD due to ionization is taken into account
  - geometry factor, light collection and quantum efficiency of PD, too
  - Carbon fiber support structure (filling the 3 mm gap)
  - Isotropic generation on the top surface but valid also for other sides
- Simulated particles (10^2 – 10^5 events per energy value) :
  - Electrons: 100 GeV → 1 TeV
  - Protons: 100 GeV → 100 TeV
- Simple requirements on shower containment
  - fiducial volume, length of reconstructed track, minimum energy deposit
  - vs
  - selection efficiency ε
- GF: (0.78*0.78*π) * 5 * ε $m^2 sr$ = 9.55*ε $m^2 sr$

Expected Performance



- Various geometries tried.
- Basic design similar for all.
- These plots for 36mm CsI



- Our first simulations indicate that we can achieve, with this high granularity design excellent performance both for electrons and nuclei.

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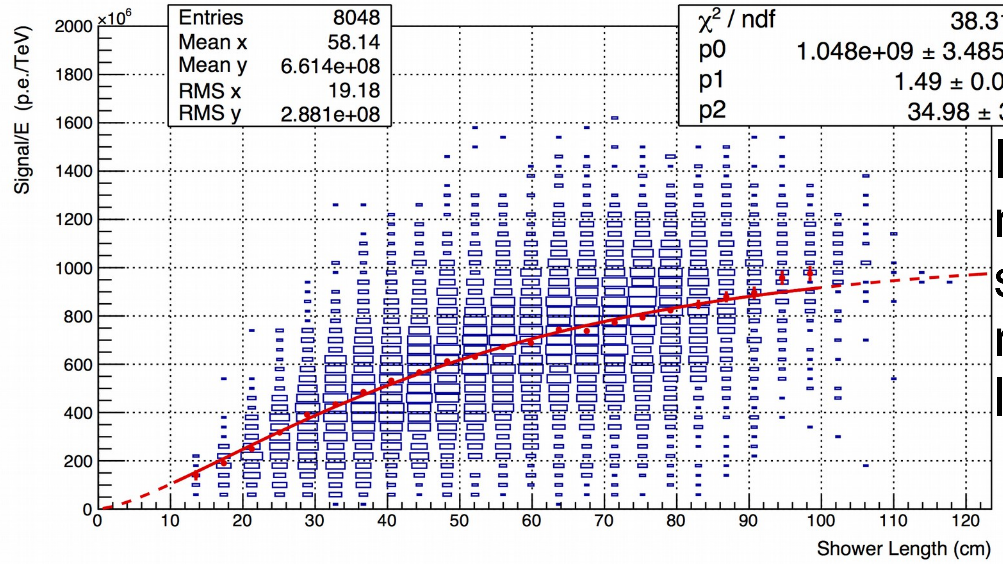
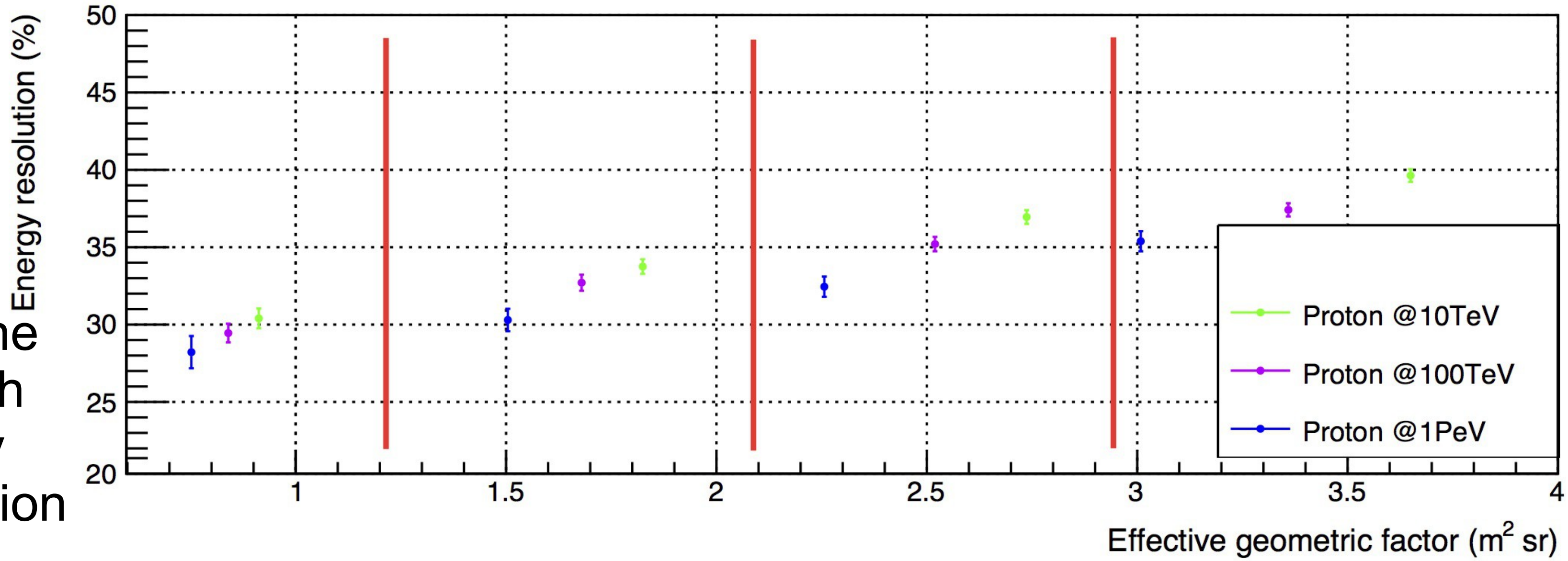
Proton/Nuclei Energy Measurement



In general since the hadron shower is not contained in the calorimeter, the showering particle true energy is reconstructed using both shower length and energy deposit information.



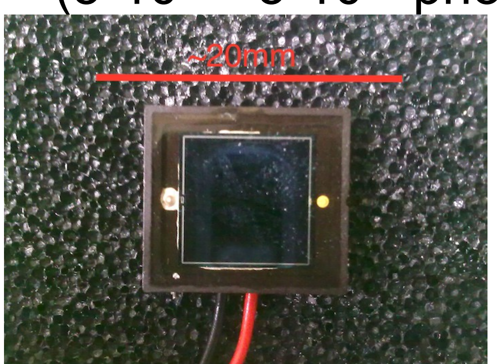
Shower length is the parameter on which selection efficiency and energy resolution depend.

Light Signal Estimation

- Optical Signal:
  - Single crystal deposit up to 10% of a particle's energy (100 TeV!)
- CsI(Tl) :
  - 1MIP/cm = 1.25MeV/(g/cm^2)· 4.5g/cm^3 = 5.62 MeV/cm
  - For 3.6 cm size 1 MIP≈ 20MeV
  - Signal from 0.5 MIP to 5·10^6 MIP
  - CsI(Tl) light yield is 54 photons/keV
  - 1 MIP ≈10^6 photons
- Dynamic range required

(5·10^5 − 5·10^{12} photons) ≈10^7

- Dual photodiode:
  - **Large PD** ; Size 9.2 x 9.2 mm2 ; GF= 0.065
  - Q_{pd} = 0.6 , $\varepsilon_{collection}$ = 0.9
  - 1MIP ≈ 10^6 ph· Q· GF ≈ 35 · 10^3 e- = 5.6 fC
  - Range : 0.5-5·10^6 MIP ~ 3fC - 30 nC
  - **Small PD** ; GF ~ 400 times lower
  - Max. signal (5·10^6 MIP) – 75 pC
  - **Dynamic range with 2 PD**
  - 75pC/3fC ≈ 2-3 10^4

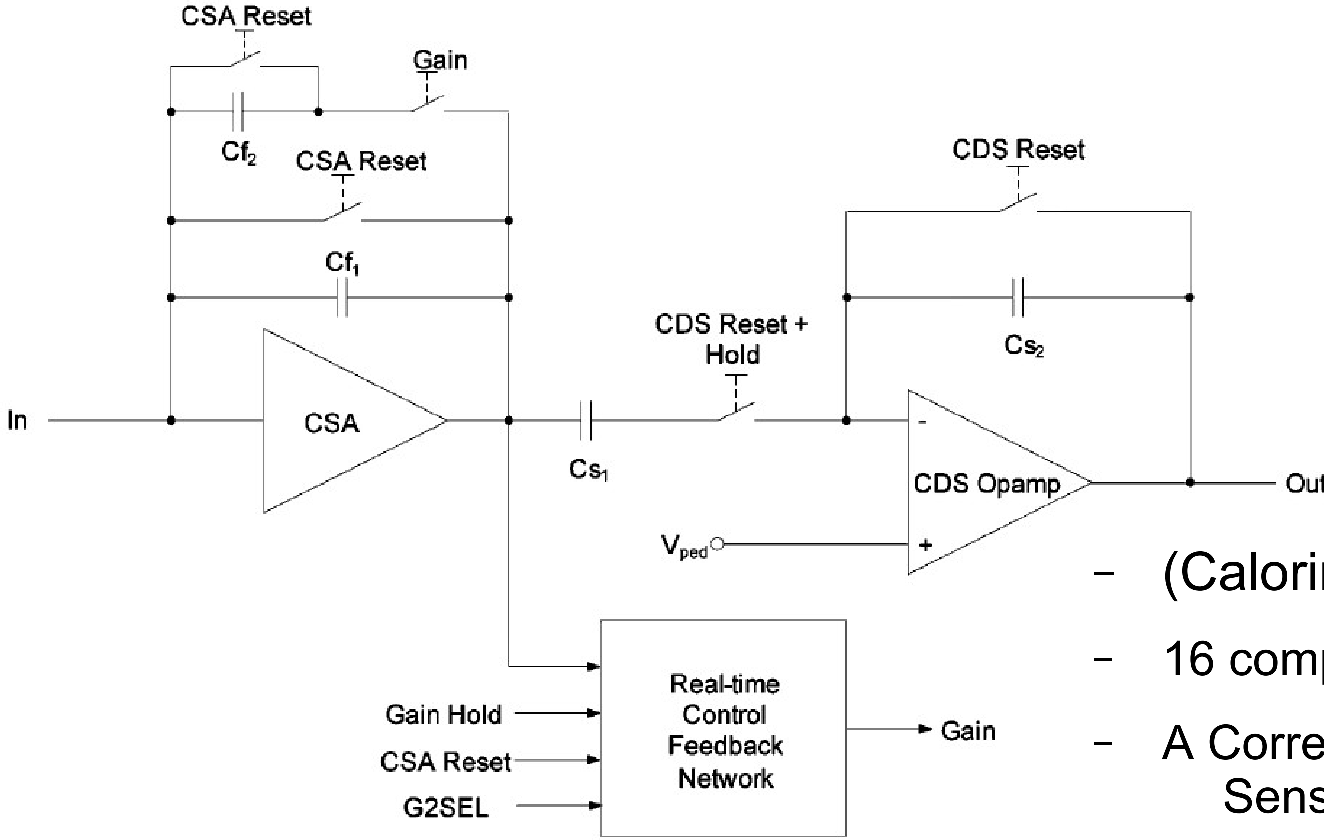


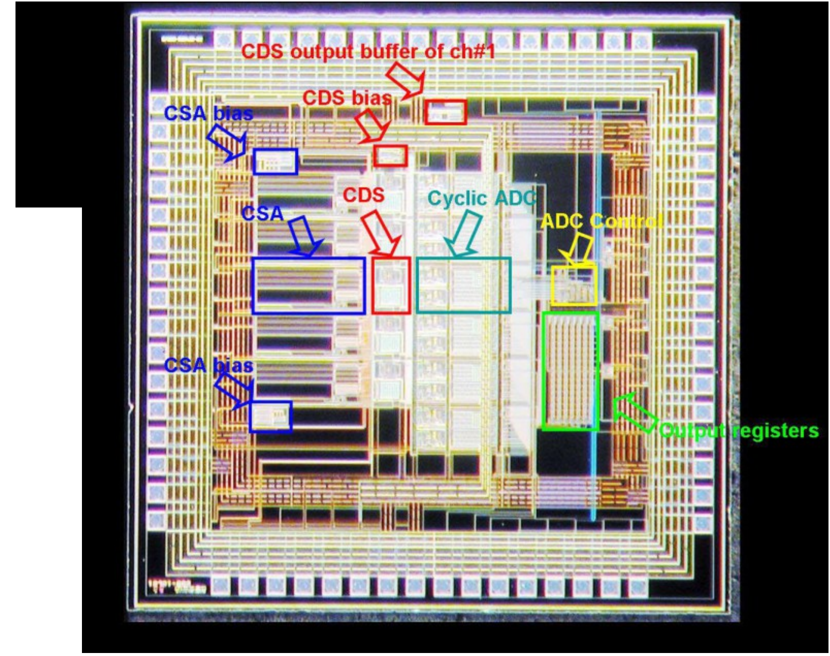
At least 2 Photo Diodes are necessary each crystal to cover the whole huge dynamic range from 1 MIP to 10^{7}MIP

large-area PD 9.2 x 9.2 mm^2 for small signals (Excelitas VTH2090)

small-area PD 0.5 x 0.5 mm^2 for large signals

Front End CASIS

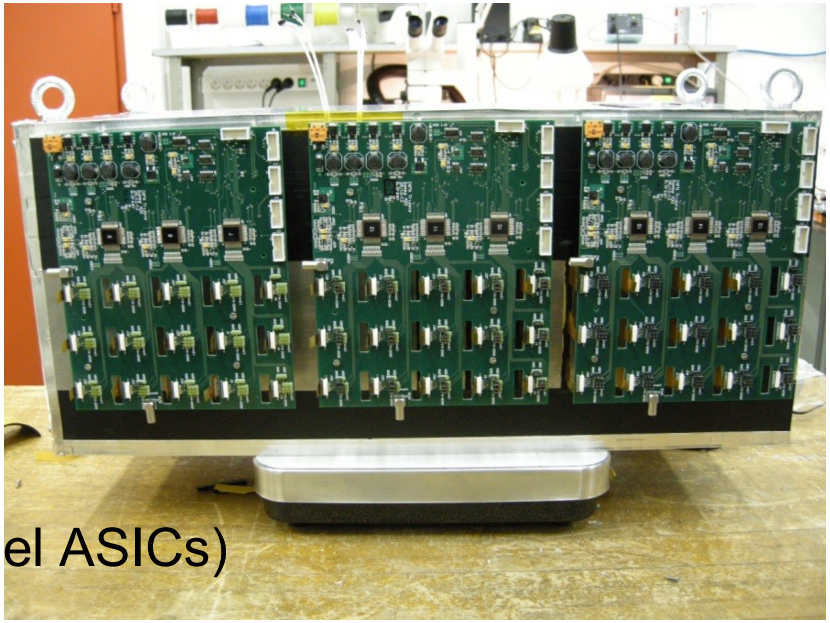


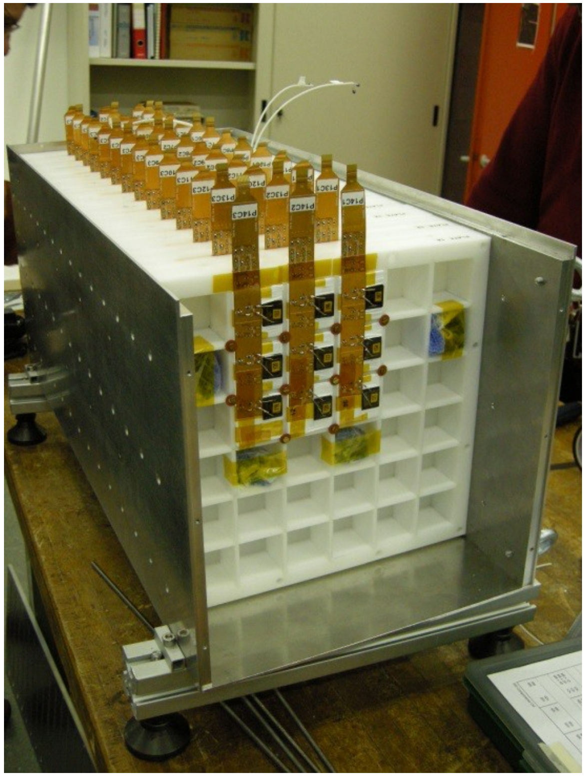


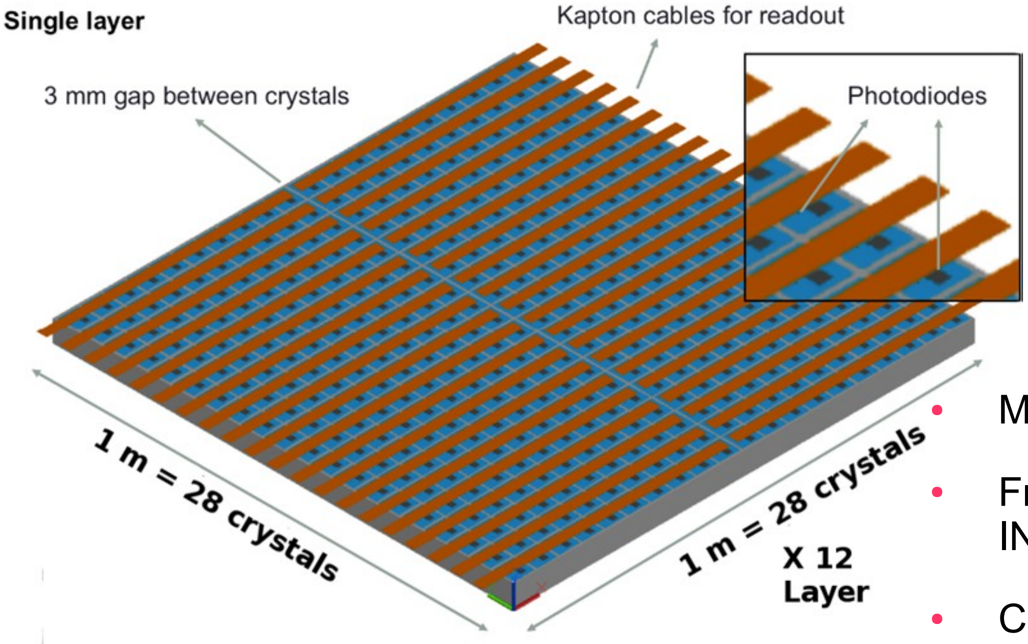
- (Calorimetry in Silicon for the Space)
- 16 complete front-end/ADC channels
- A Correlated Double Sampling Charge Sensitive Amplifier
- Double Gain with a real-time automatic gain selection
- Fast (10 MHz clock) Cyclic ADC (future)
- Dynamic range 10^5 ; max. signal ~50pC

Prototype (1)

- 14 Layers ; 9 crystals in each layer
- 126 Crystals in total - 126 Large Photodiodes
- 50.4 cm of CsI(Tl) ; 27 X_0, 1.32 λ_I
- Photodiodes read-out by 9 CASIS1.2A (16-channel ASICs)



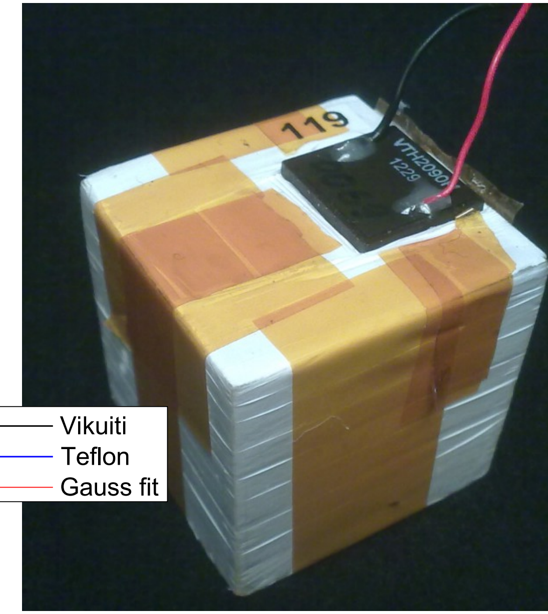


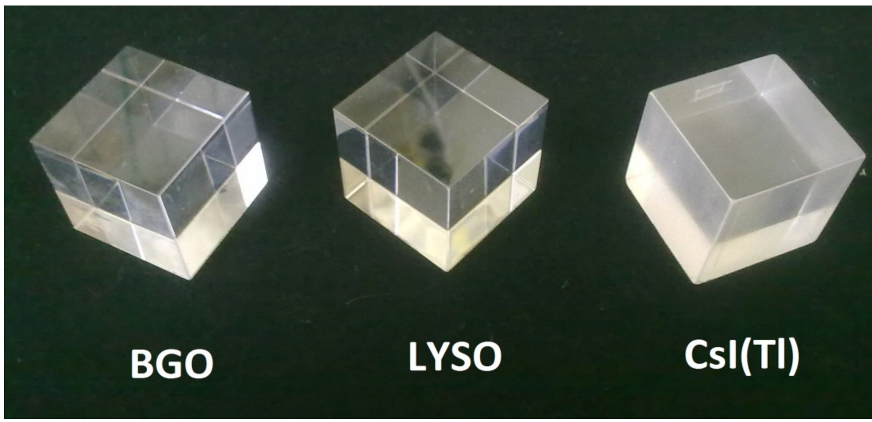


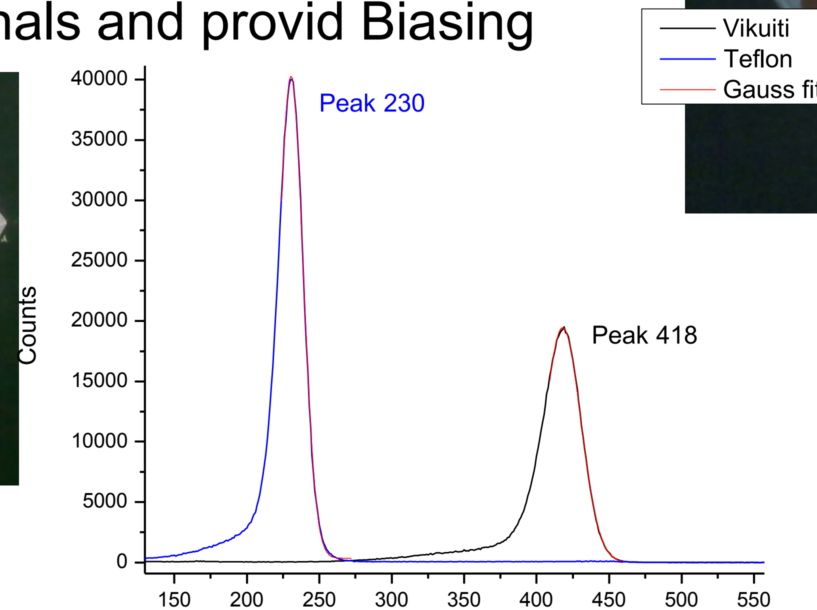
- Mechanics: INFN Pisa
- Front-end electronics: INFN Trieste
- Crystals, photodiodes, DAQ, assembly:INFN Firenze

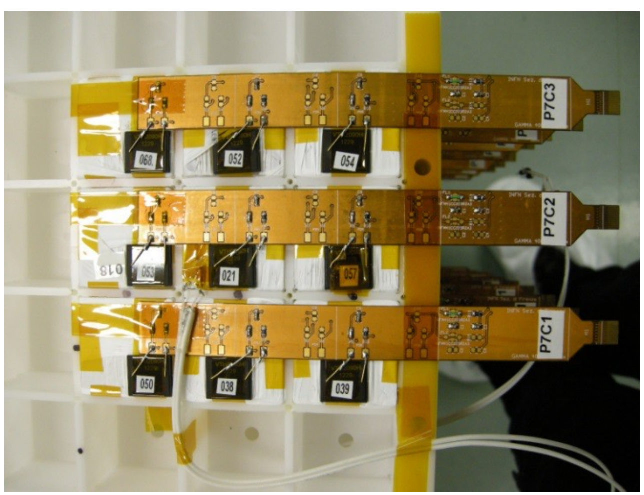
Prototype (2)

- CsI(Tl) cubes , 36 mm side, wrapping 150 micron of teflon
- VTH2090 PD (large).
- Kapton cables to collect the signals and provid Biasing





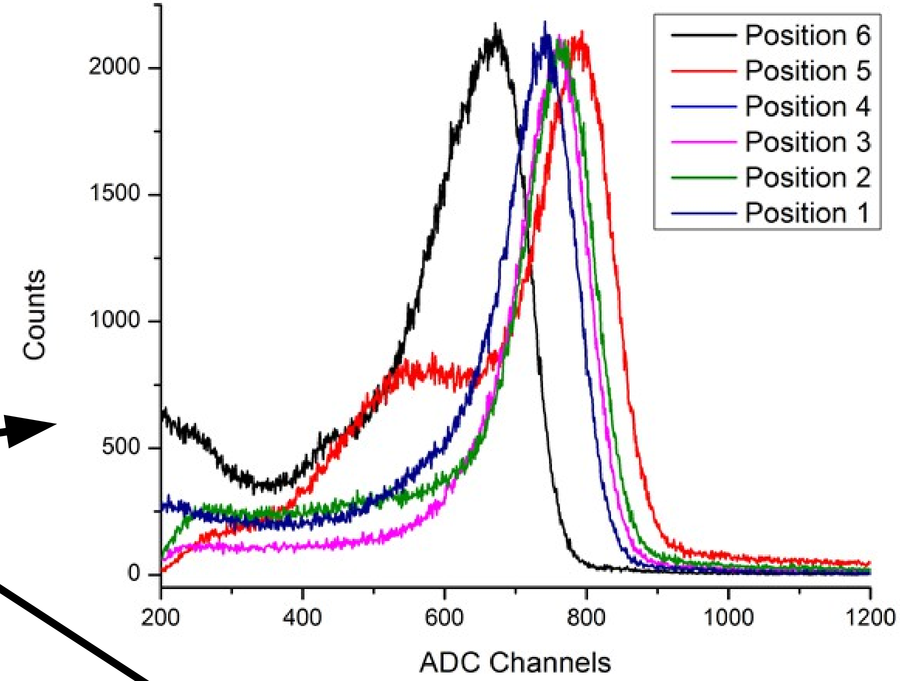


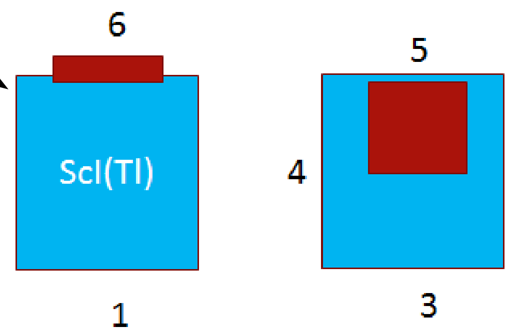


- Other materials also tested but as single crystals
- Also comparisons made on surface treatment (Simulation/Amptek system)
- Various wrappings tried (i.e. Vikuiti , 1.8 gain)

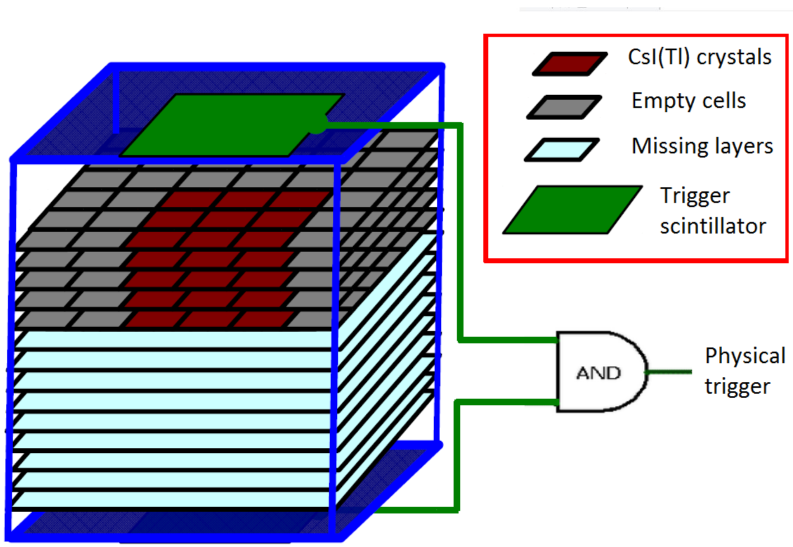
Laboratory tests

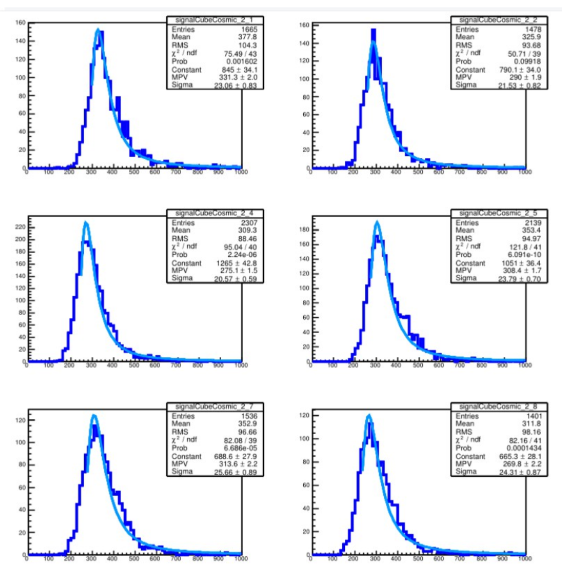
- Performed a large variety of tests both single channel mode (crystal) and with CASIS on the calorimeter
- Light collection vs PD position
- Cosmic Rays (CASIS) :
  - MPV 270 - 330 ; S/N 11 – 14.6





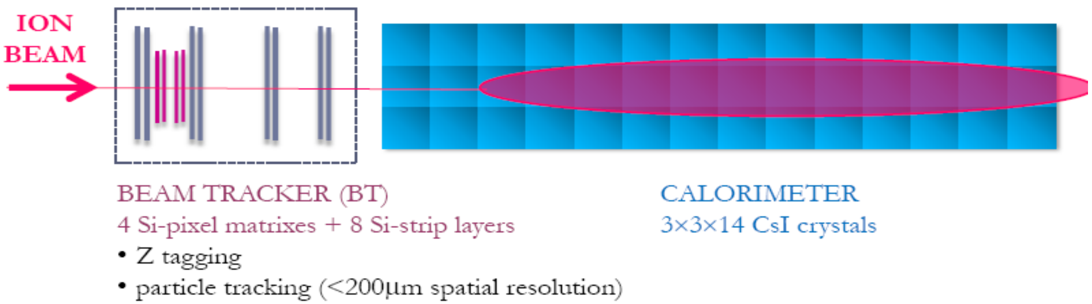
Face 6: ~650 ADC channels
Others: ~780 ADC channels

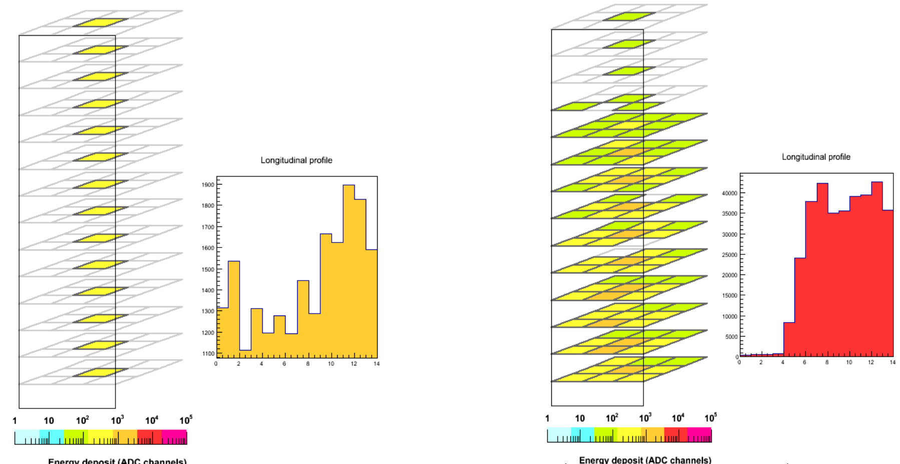




Test Beam

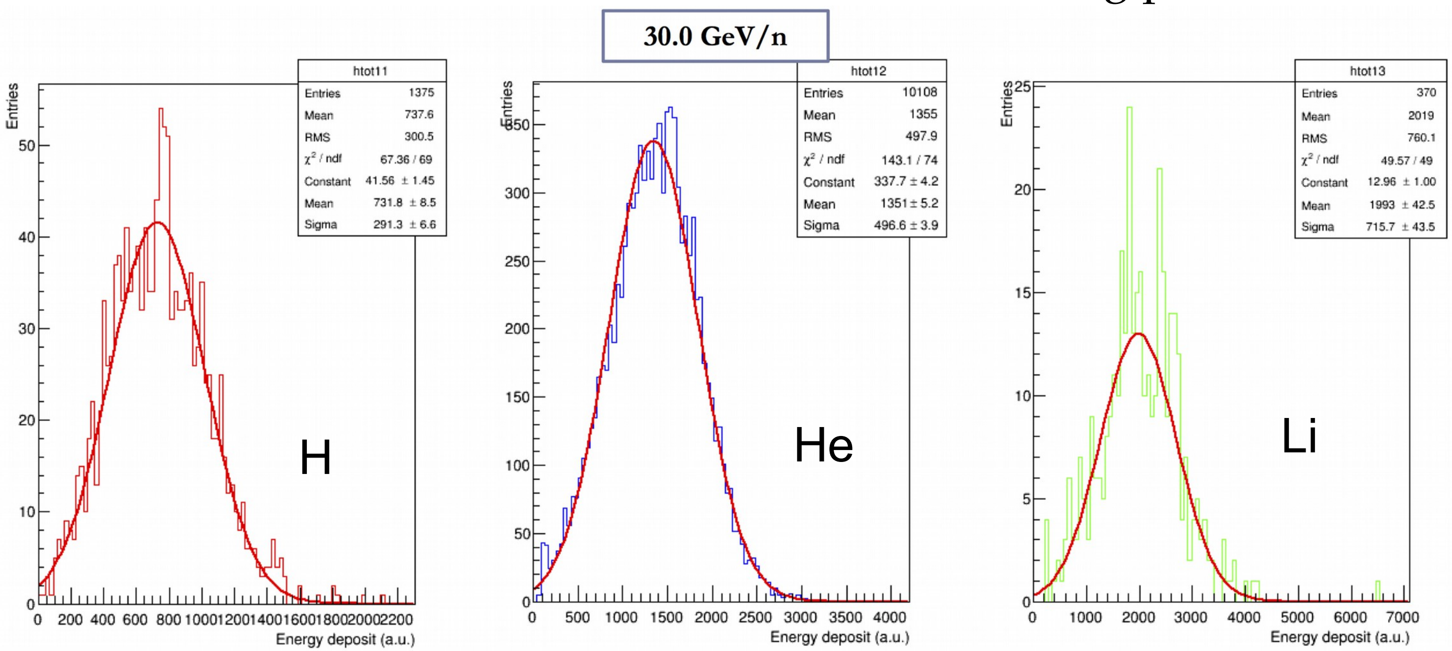
- CERN SPS H8 Ion Beam: Z/A = 1/2, 12.8 GV/c and 30 GV/c
- Silicon tracker before the prototype





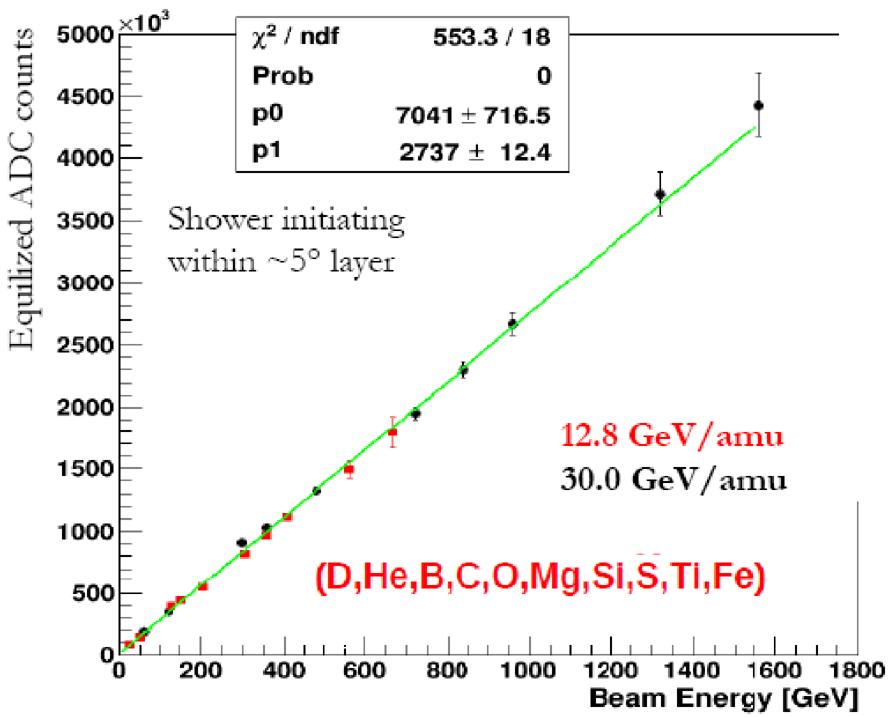
Non-interacting particle

hadronic shower



Interacting Nuclei

- Charge selected by Beam Tracker in front of the calorimeter
- Good linearity even with just the large-area photodiode

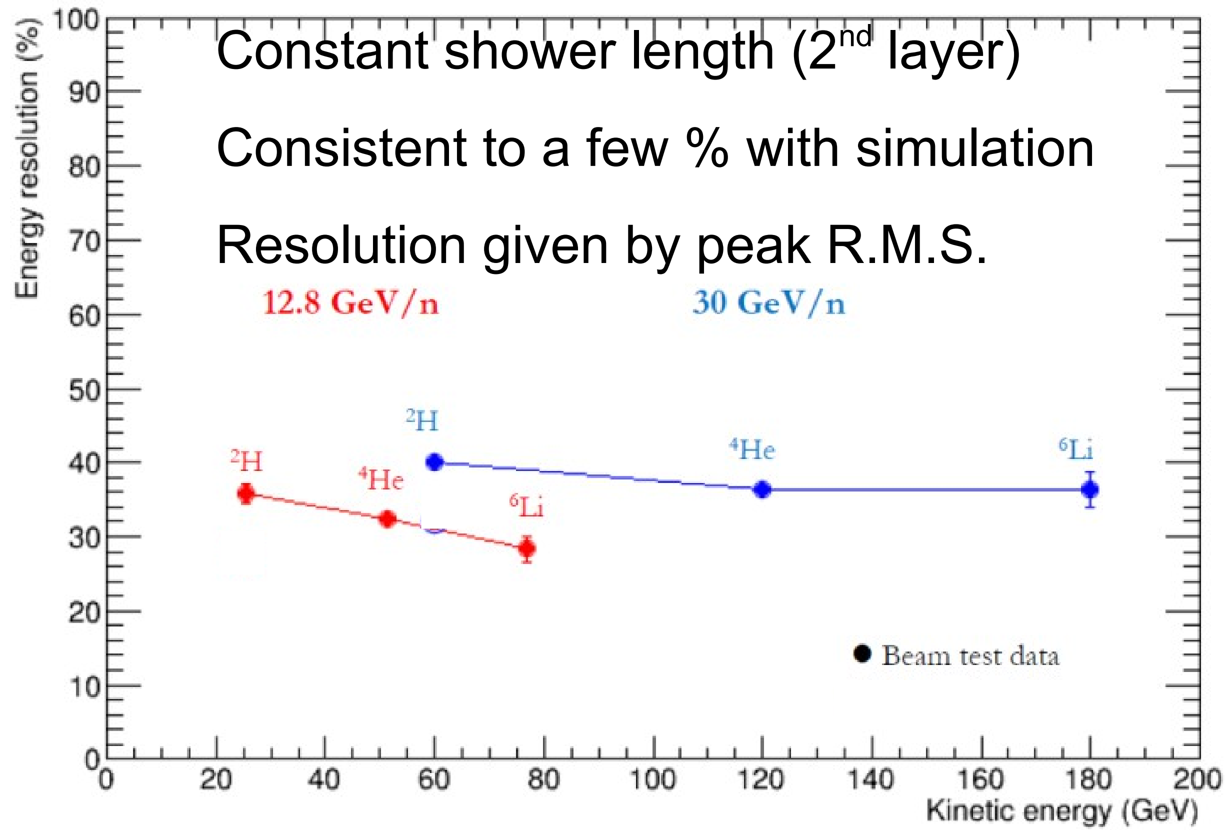


Courtesy of G. Bigongiari (

Constant shower length (2nd layer)

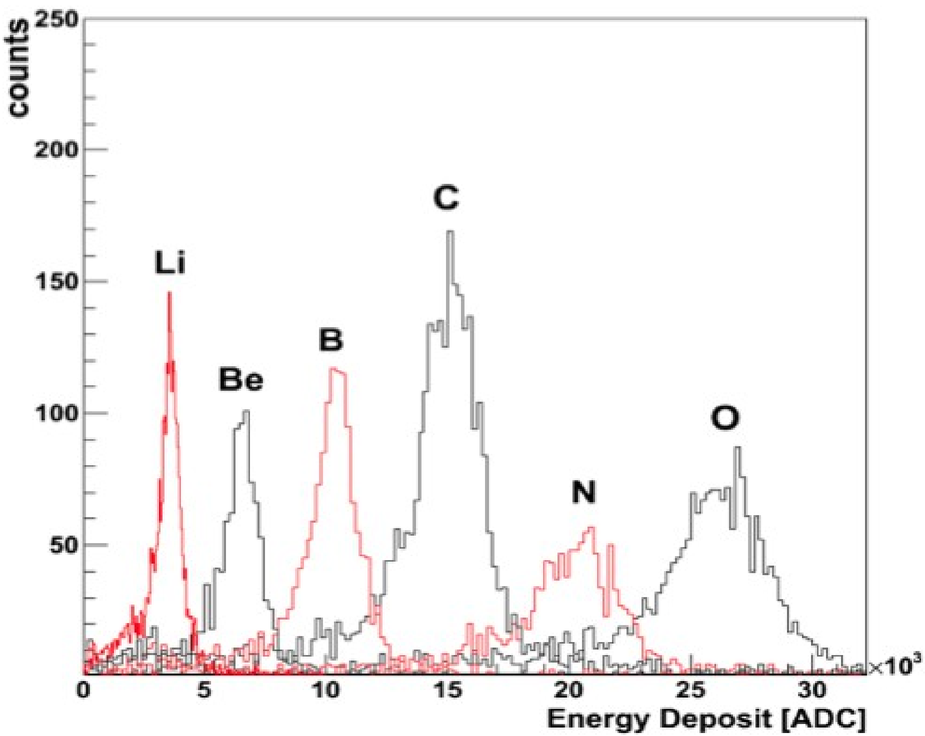
Consistent to a few % with simulation

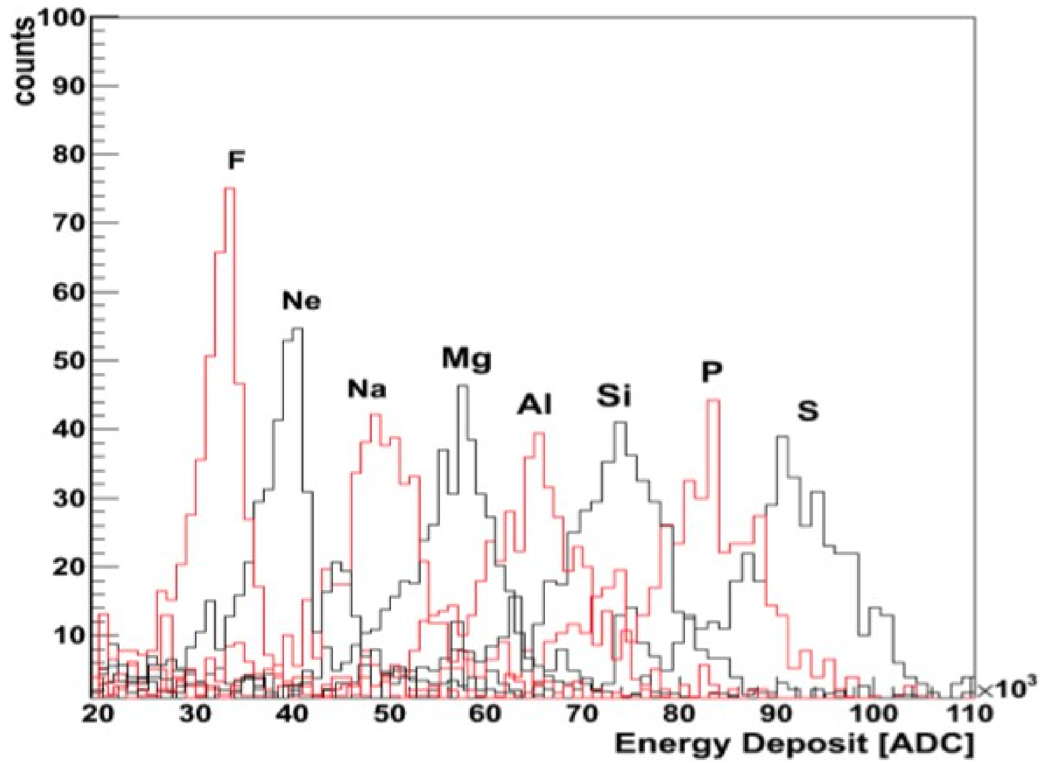
Resolution given by peak R.M.S.



Nuclei ID

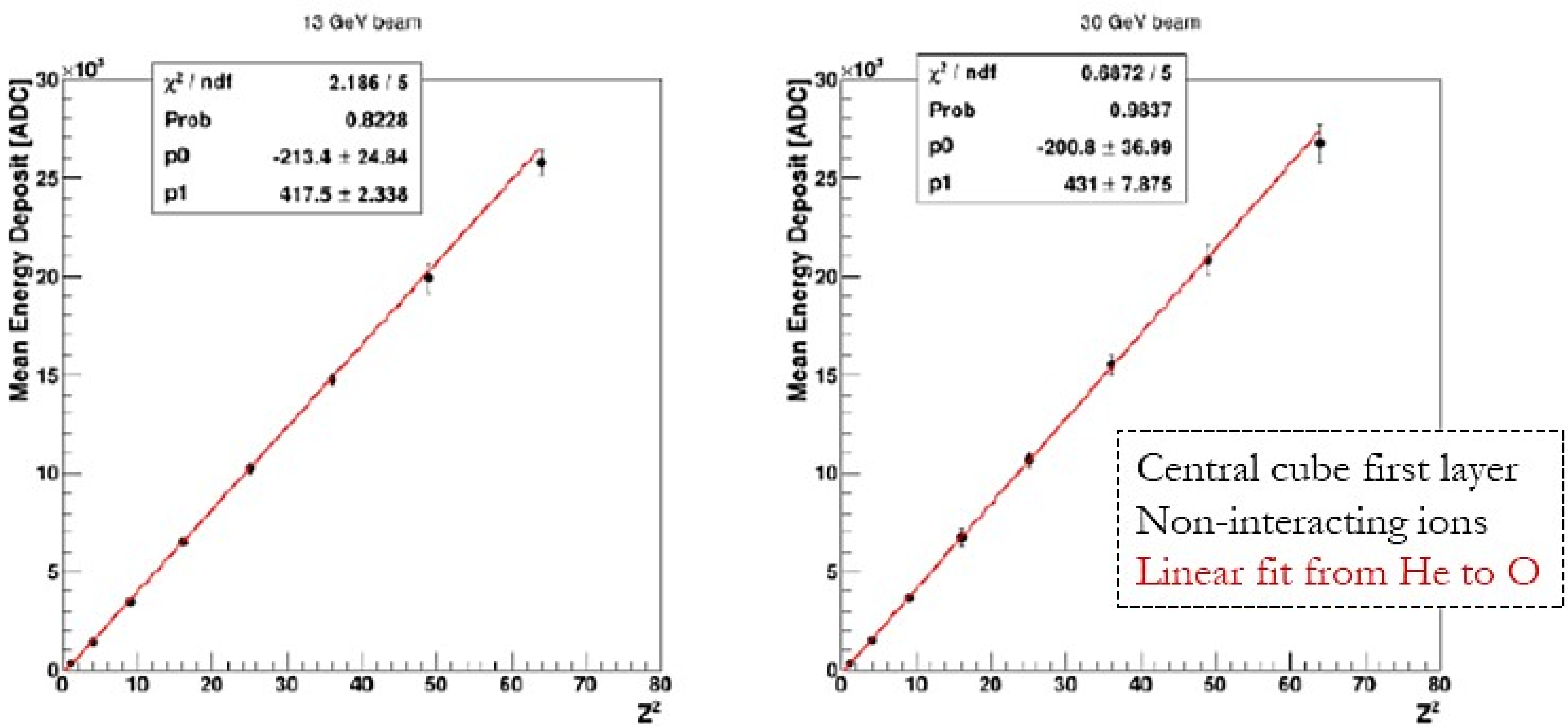
- Charge selected by separate Silicon Tracker
- Non-interacting particles, first crystal layer





Non-interacting nuclei

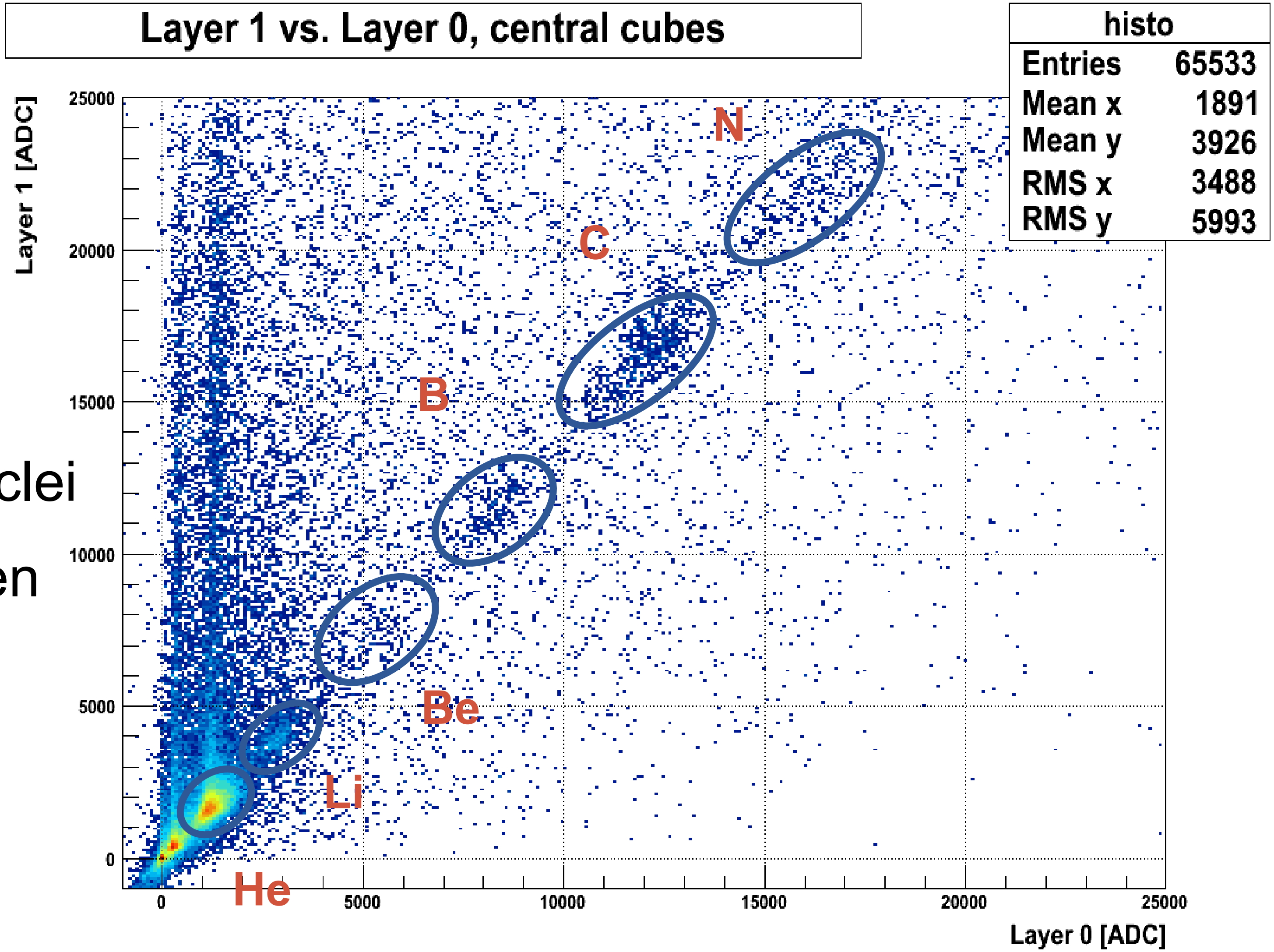
- Charge linearity (first plane) with Z^2 .



Courtesy of G. Bigongiari (UniSi)

Nuclei ID

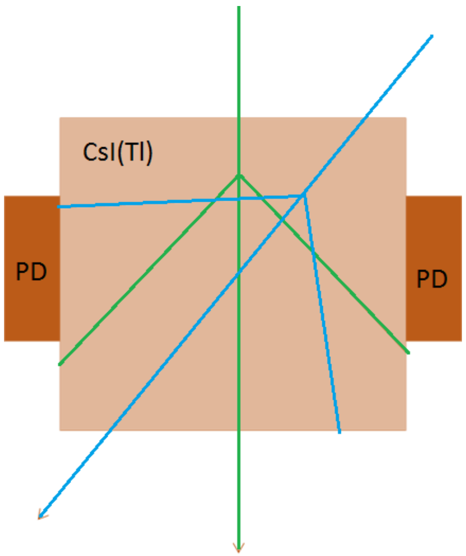
On layer 0:
D: Z=1 <ADC>=330
He: Z=2 <ADC>=1300
Li: Z=3 <ADC>=3000
Be: Z=4 <ADC>=5300
B: Z=5 <ADC>=8250
C: Z=6 <ADC>=12000
N: Z=7 <ADC>=16000

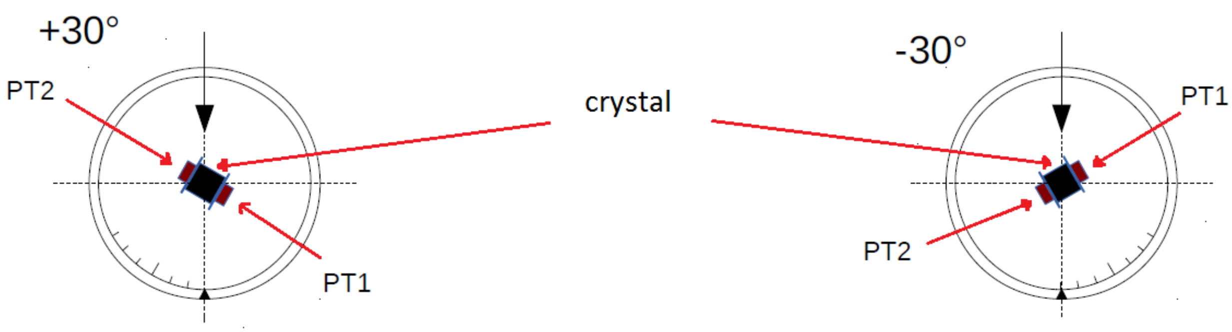


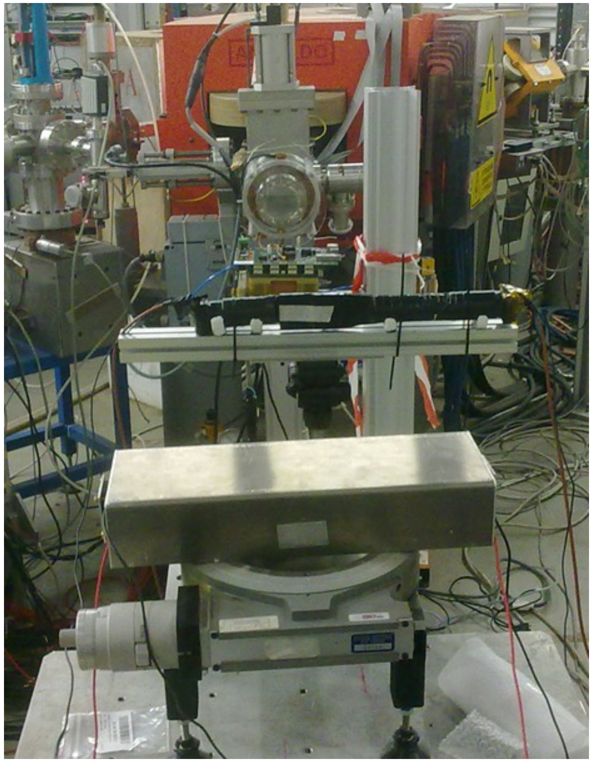
- Non interacting nuclei
- Correlation between central crystals in layers 0 and 1

Cherenkov light detection

- Could be useful to increase performance (DREAM like).
- Very difficult to separate from scintillation (CsI(Tl))
- Timing and wavelength
- Test performed at BTF-Frascati (460MeV e^-)
- 2 phototubes on opposite faces of a crystal







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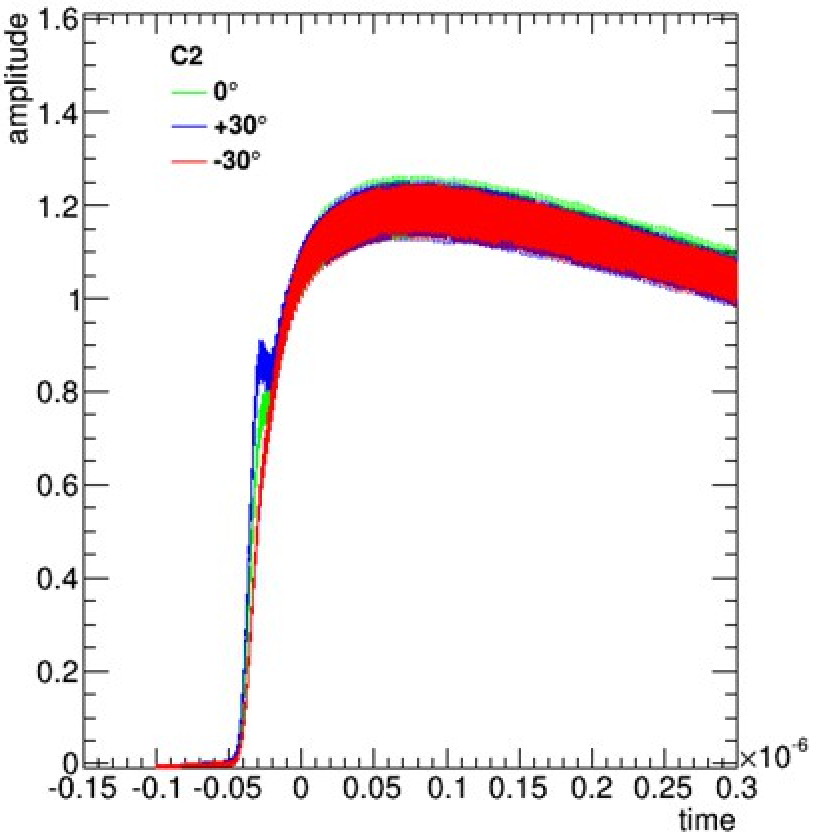
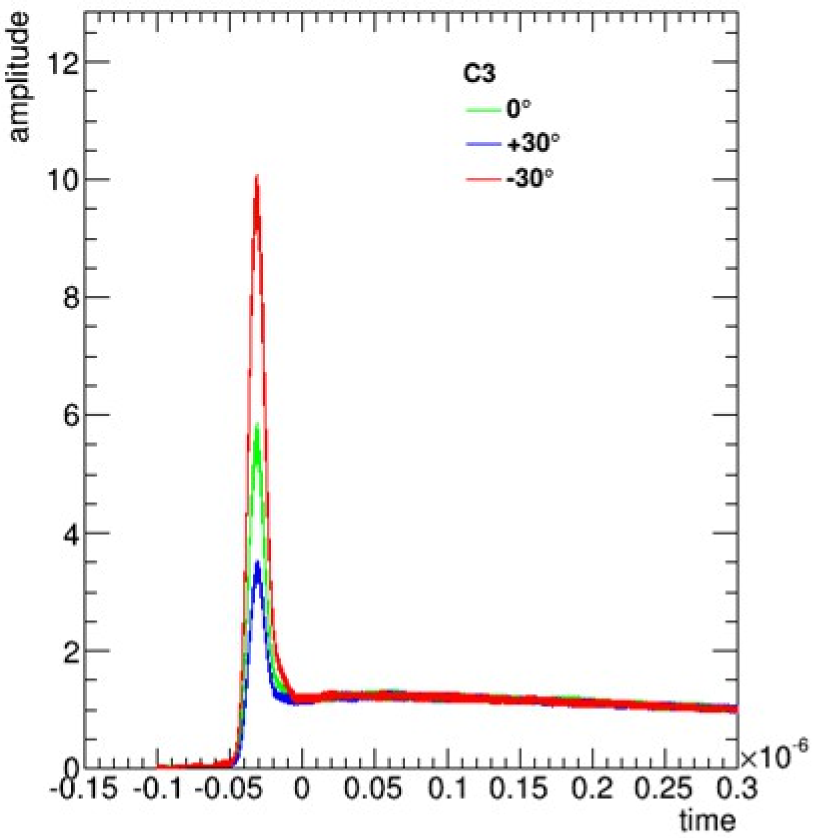
BTF results

- Cherenkov visible even in CsI(Tl)
- CsI(Tl) signals with black wrapping (no reflections)
- Without and with UV filter (visible blocking)





Conclusions

- Thank You to the organisers for this opportunity
- Calocube has been financed by CSNV grant of 900000 Euros for three years (end 2016)
- Researchers involved have expertise not only in calorimetry and cosmic ray physics but also in “non- conventional” areas ranging from polymeric coatings to interferometric filters to VLSI analog design
- UV detection with advanced photodetectors (SiC) for PET financed by CSN V; CLASSIC (P.Lenzi -INFN Firenze and Catania)

Calocube Collaboration

- INFN-CT- ME
- INFN-FI
- INFN-MIB
- INFN-PI
- INFN-PV
- INFN-TS
- INFN-UD
- CNR-IMM-MATIS Catania : Dichroic filters depositions
- IMCB-CNR Napoli : Surface treatments and WLS depositions
- Also close contacts with CNR Firenze

BACKUPS:

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Direct Measurements at the knee

- **Some figures:**
  - 10 years exposure
  - no nearby e^- sources
  - "Polygonato" model for hadrons (J. Hörandel, APP 19 (2003), 193-220)

Electrons							
GF ($m^2 sr$)	dE/E	Depth (X_0)	e/p rej. factor	E>0.5 TeV	E>1 TeV	E>2 TeV	E>4 TeV
1	2%	39	$>10^5$	$\sim 6*10^4$	$\sim 1.2*10^4$	$\sim 1.8*10^3$	$\sim 2*10^2$

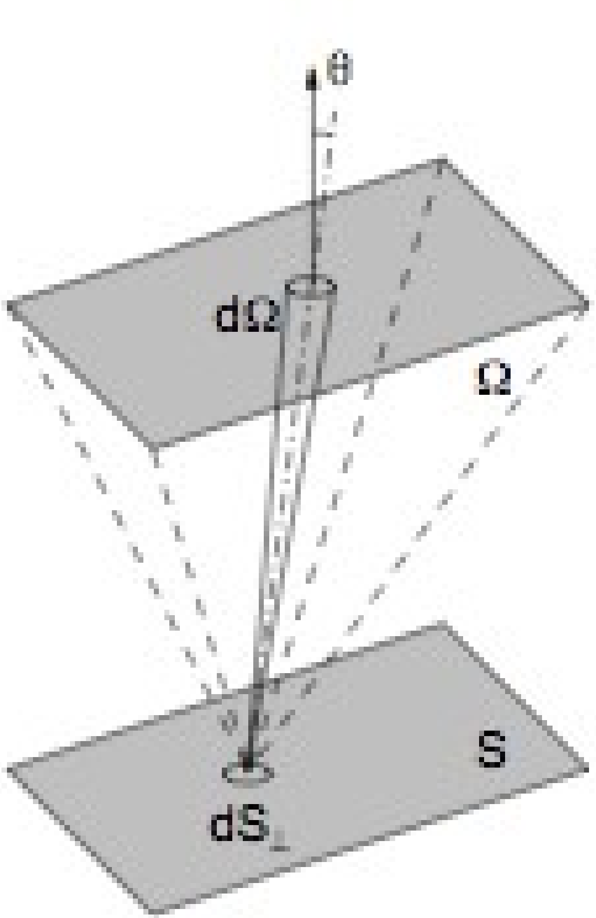
~ knee ↓ (E>2000 TeV)

Protons and Helium												
GF ($m^2 sr$)	dE/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
1	40%	1.8	$7*10^3$	$6.8*10^3$	$4.2*10^2$	$4.3*10^2$	$1.1*10^2$	$1.4*10^2$	$2.5*10^1$	$4.0*10^1$	$4.2*10^0$	$9*10^0$

A geometric factor of some m^2 sr is necessary
to collect a reasonable amount of statistics

Geometric Factor

- Entry points on the whole surface
- Angle of entry isotropic



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