CaloCube

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

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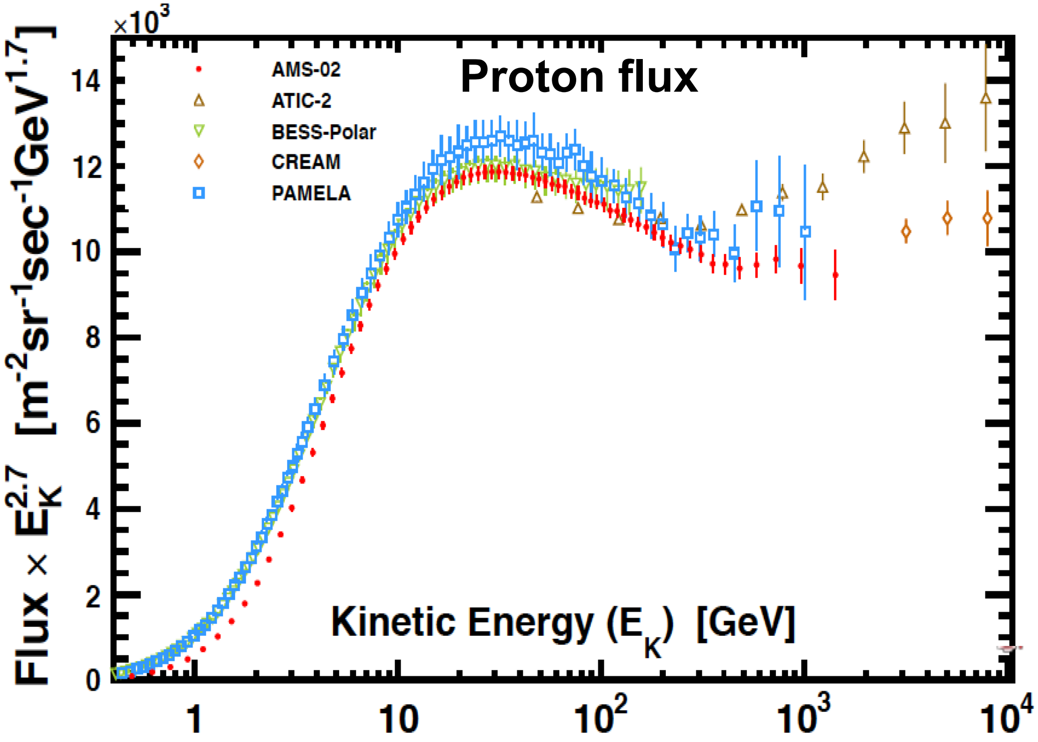
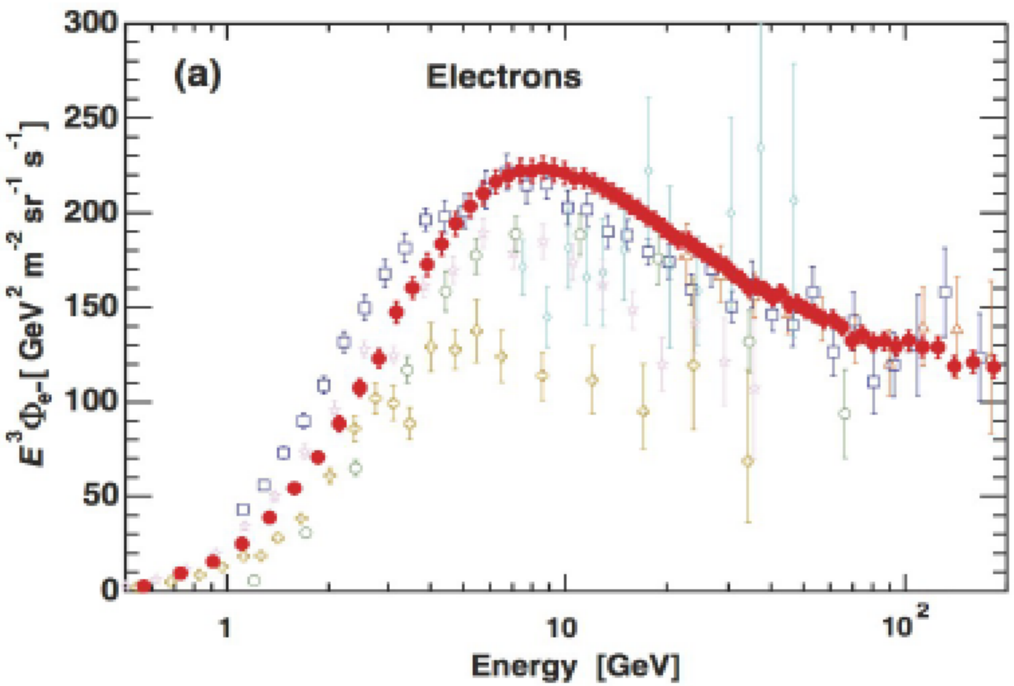
Physics motivation: direct measurement of CRs





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 knee may differ significantly 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), good charge measurement and good energy resolution for hadrons (much better than 40%)

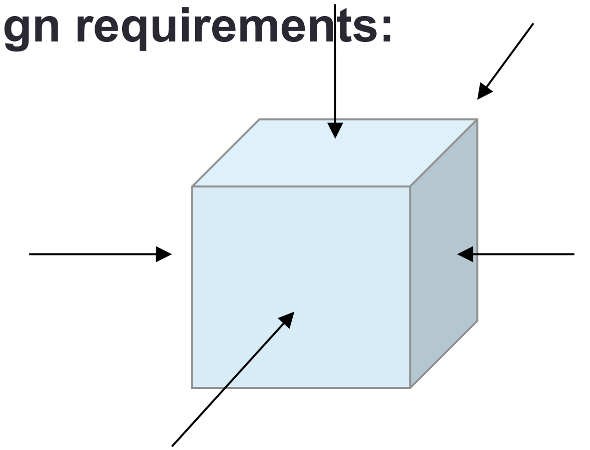
High energy Electrons+Positrons

- **Currently available measurements show some 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

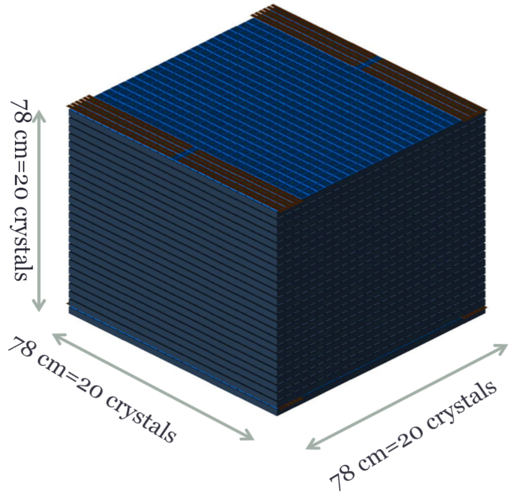
- **A deep, homogeneous and isotropic calorimeter can achieve design requirements:**
  - depth and homogeneity to achieve energy resolution
  (anyway a full containment HCAL is impossible in space!!)
  - isotropy to accept particles from all directions and increase GF



- **Proposal: a cubic calorimeter made of small cubic sensitive elements**
  - can accept events from 5 sides (mechanical support on bottom side) → GF×5
  - 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

Detector configuration: the starting point

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



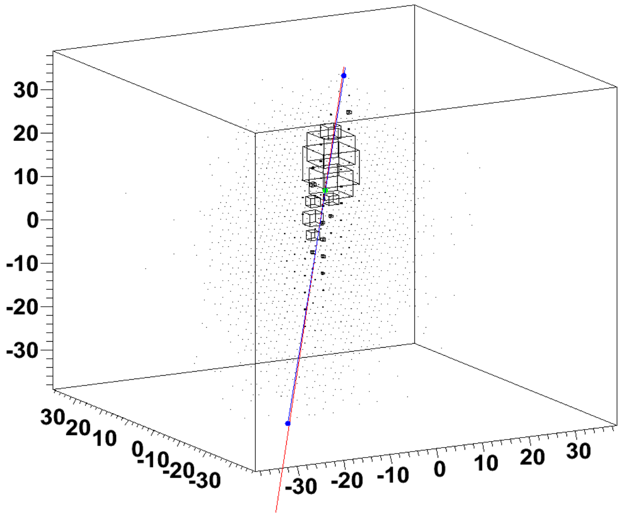
- **Scintillating cubes: tallium-doped cesium iodide (CsI(Tl)) crystals**
  - Density: 4.51 g/cm^3
  - X_0: 1.85 cm
  - Moliére radius: 3.5 cm
  - λ_I: 37 cm
  - Light yield: 54.000 photons/MeV
  - T_{decay}: 1.3 µs
  - λ_{max}: 560 nm

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^{2}sr)	**1.91**

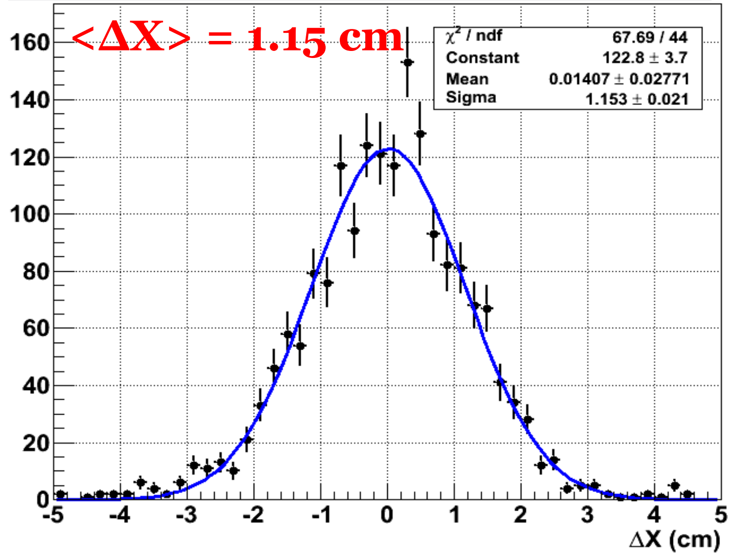
See for example:
N. Mori et al., *"Homogeneous and isotropic calorimetry for space experiments"*
NIM A732 (2013) 311-315

Monte Carlo simulation

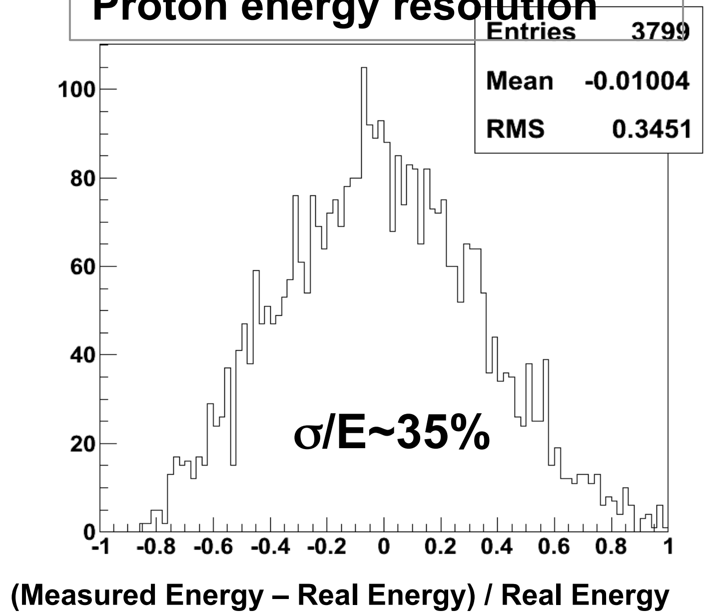
Electron image



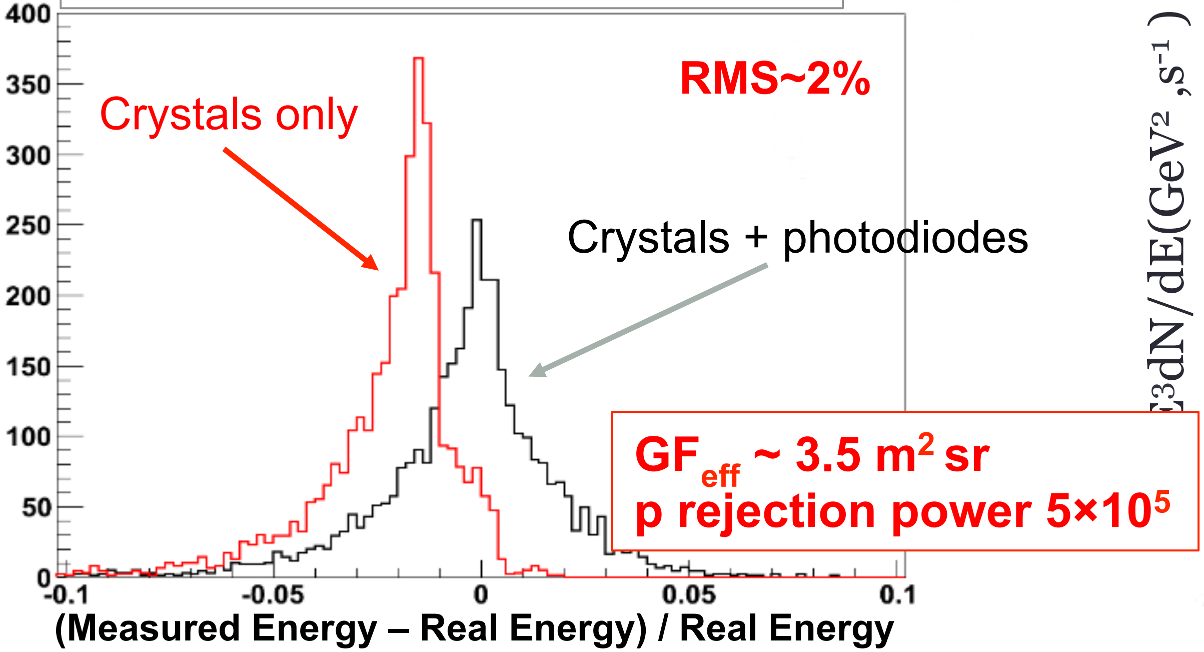
Shower starting point resolution



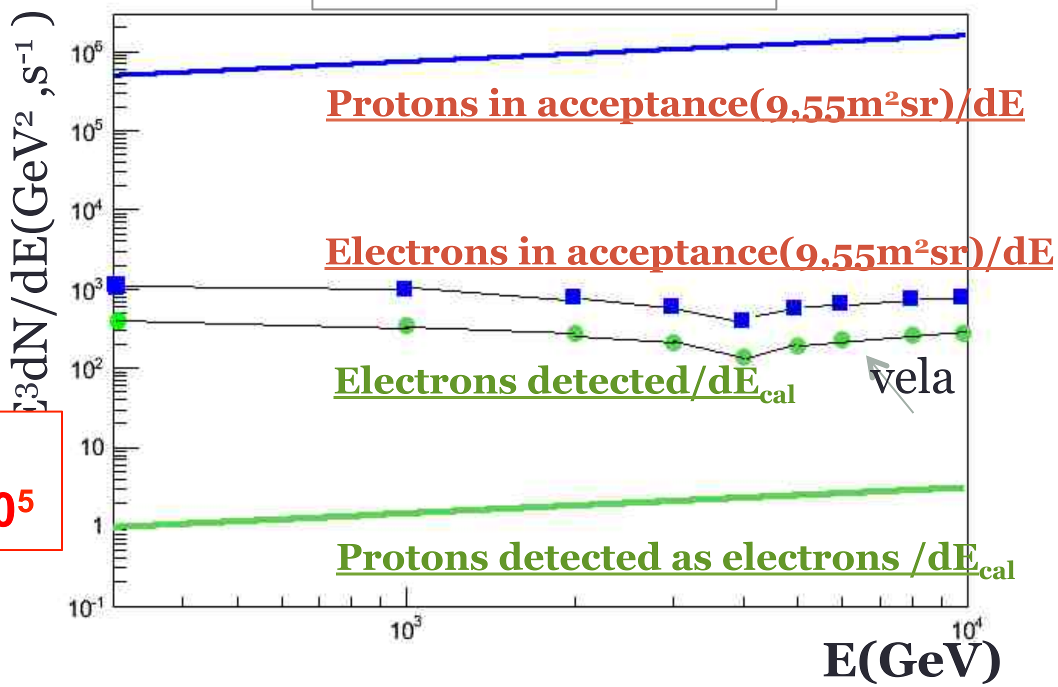
Proton energy resolution



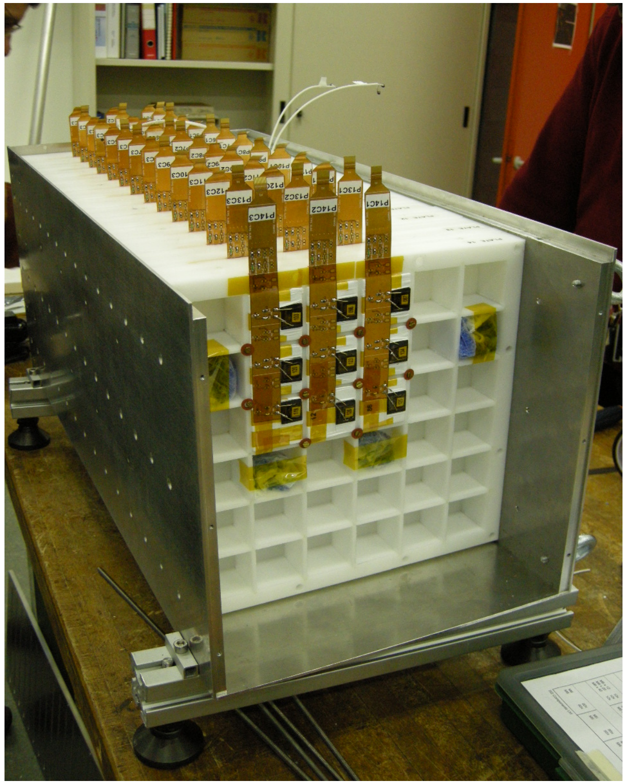
Electrons 100 – 1000 GeV resolution

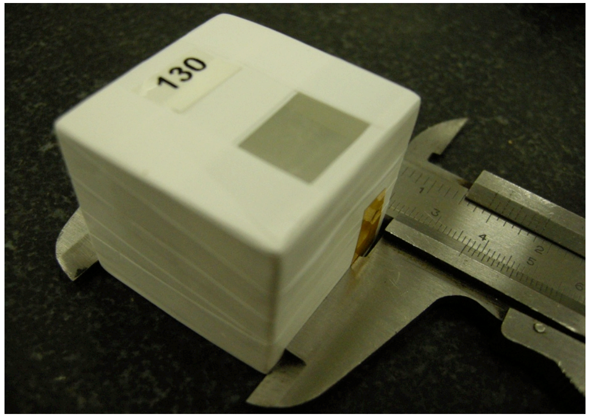


e/p discrimination

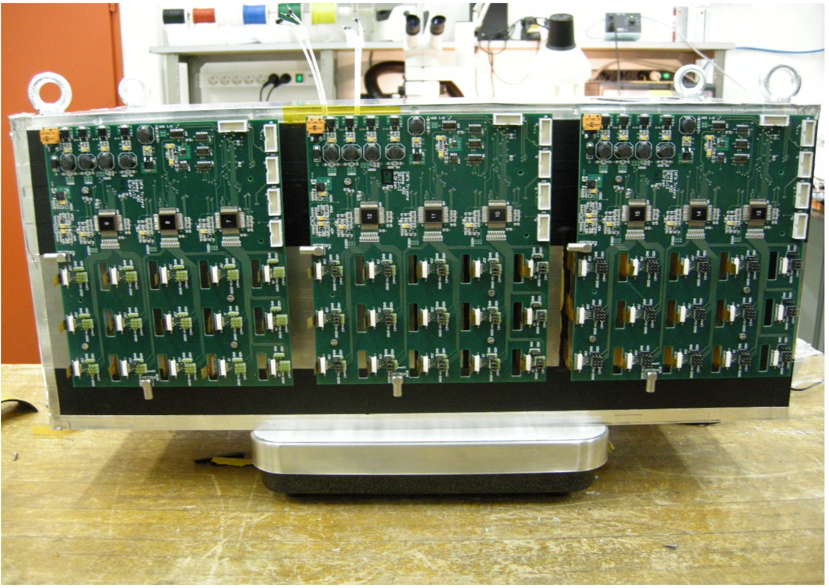


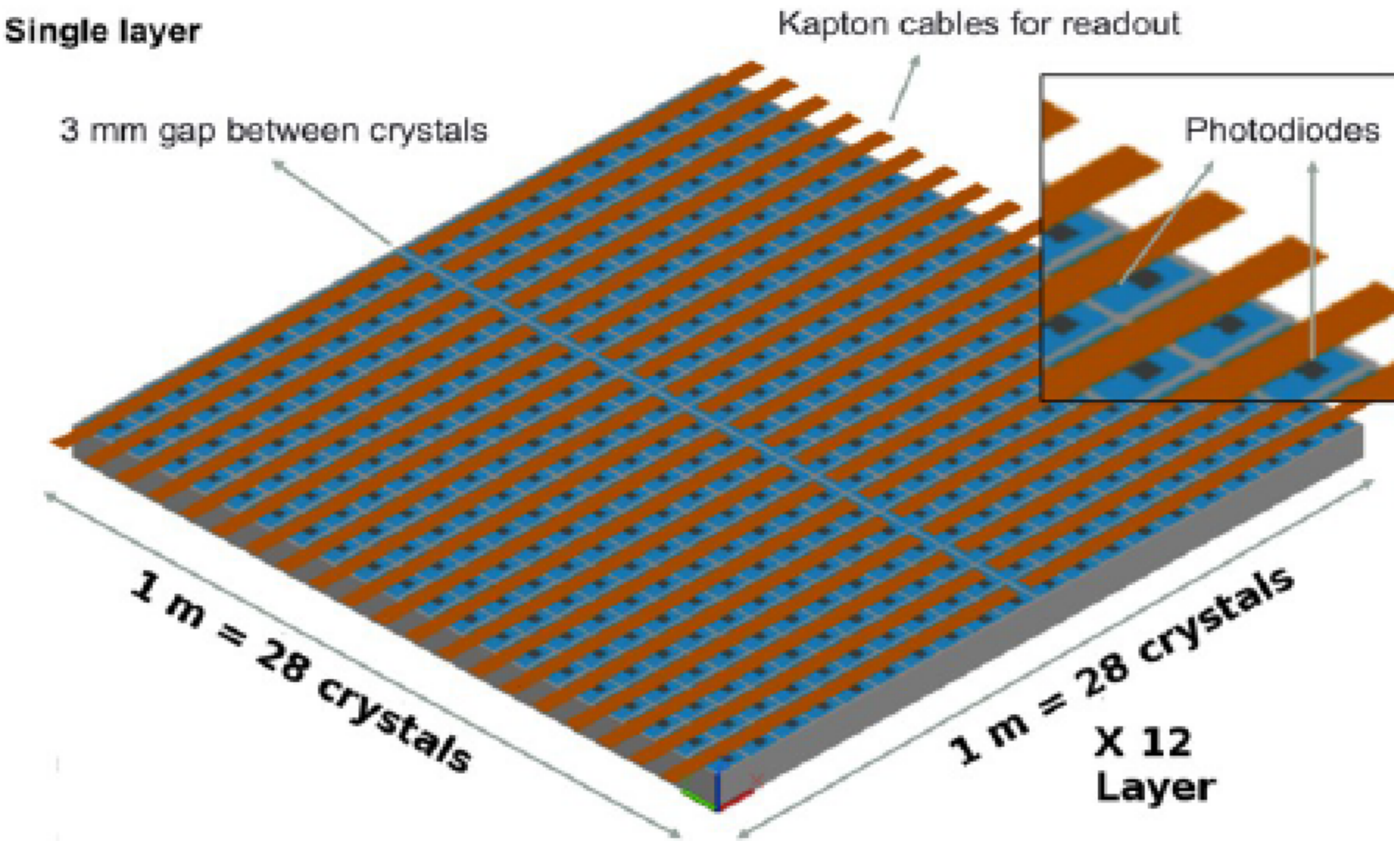
Prototype (1)





14 Layers, 9 crystals per layer
126 crystals in total
50.4 cm of CsI(Tl), 27 X0 ; 1.44 λ_I
126 photo diodes readout by 9 CASIS1.2A

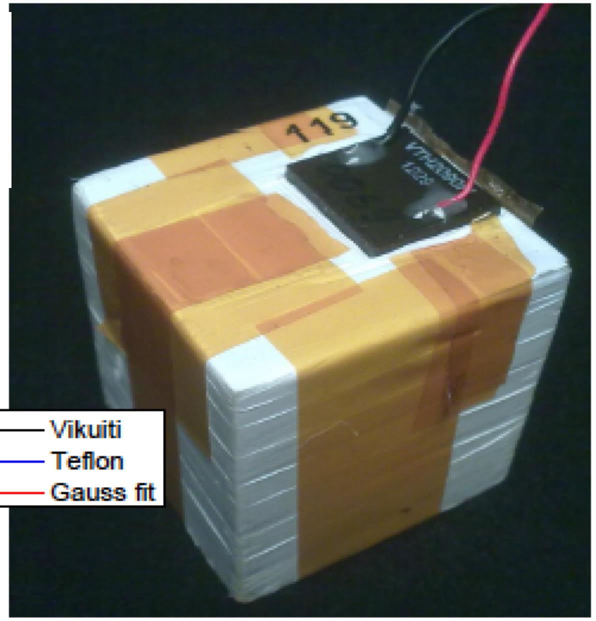


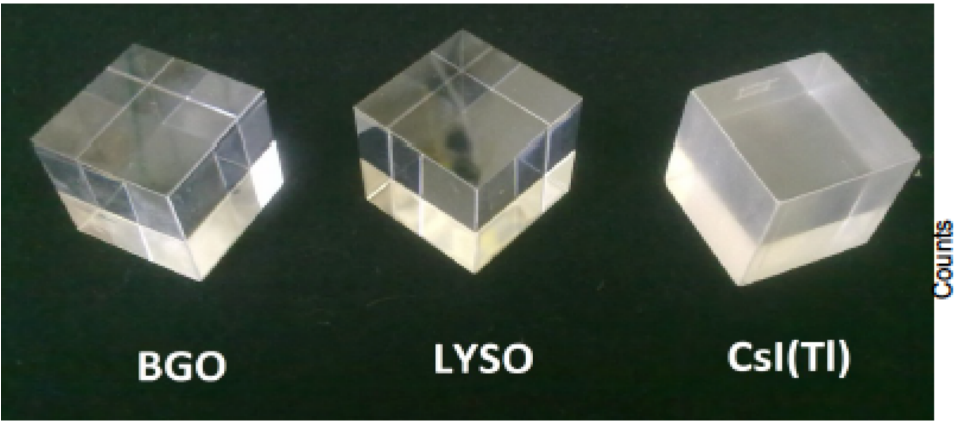


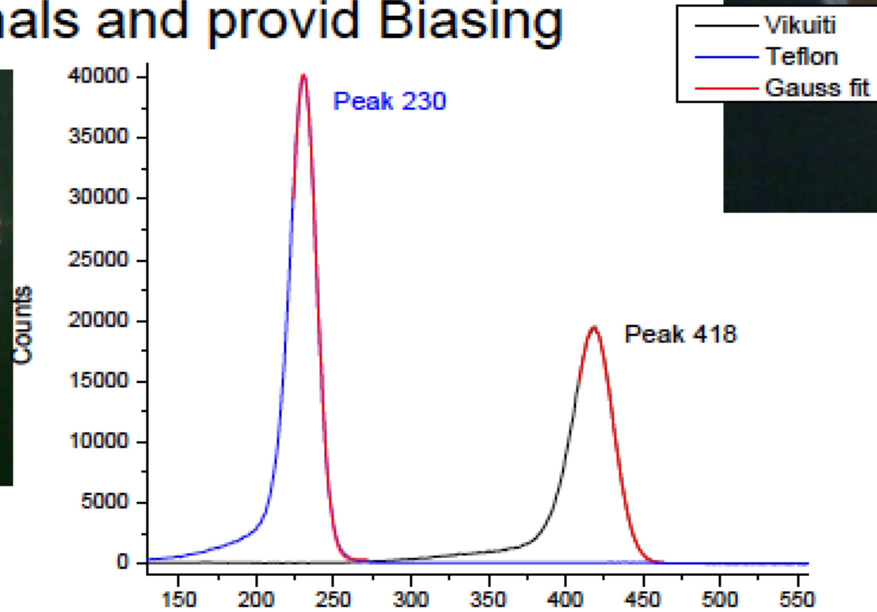
Crystals, PD, DAQ: INFN Firenze **FE electronics: INFN Trieste** **Mechanics: INFN-Pisa**

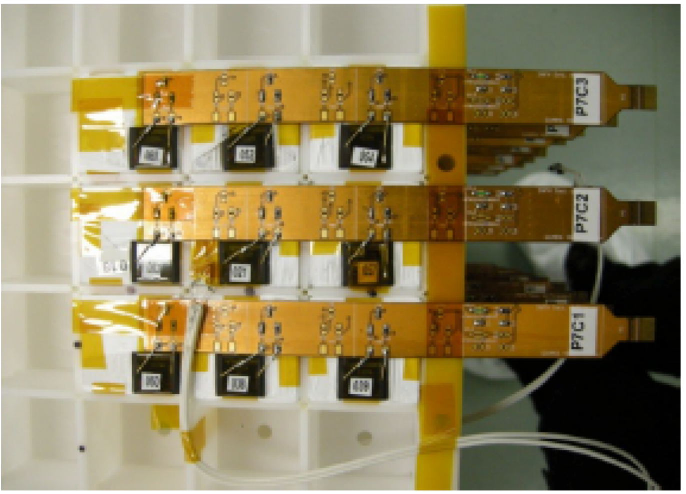
Prototype (2)

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



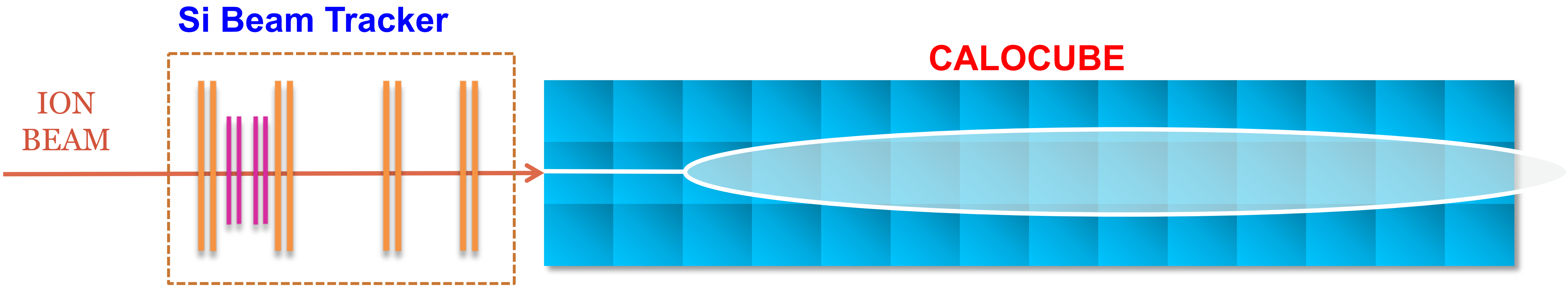






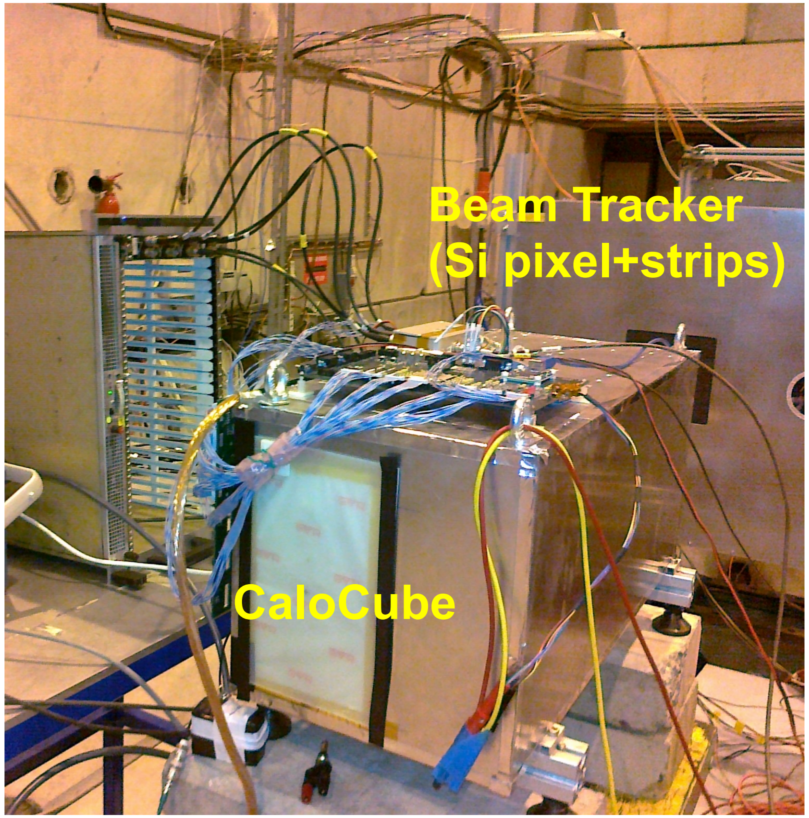
- Test of 9 crystals CsI:Na, CsITl, YAG:Ce, BaF2, YAP:Ce, LuAG:Ce, BSO, BGO, LYSO:Ce
- Various wrapping tried (Vikuiti, Teflon, Tedlar)
- Also comparison made on surface treatment

Beam tests @ SPS H8 line

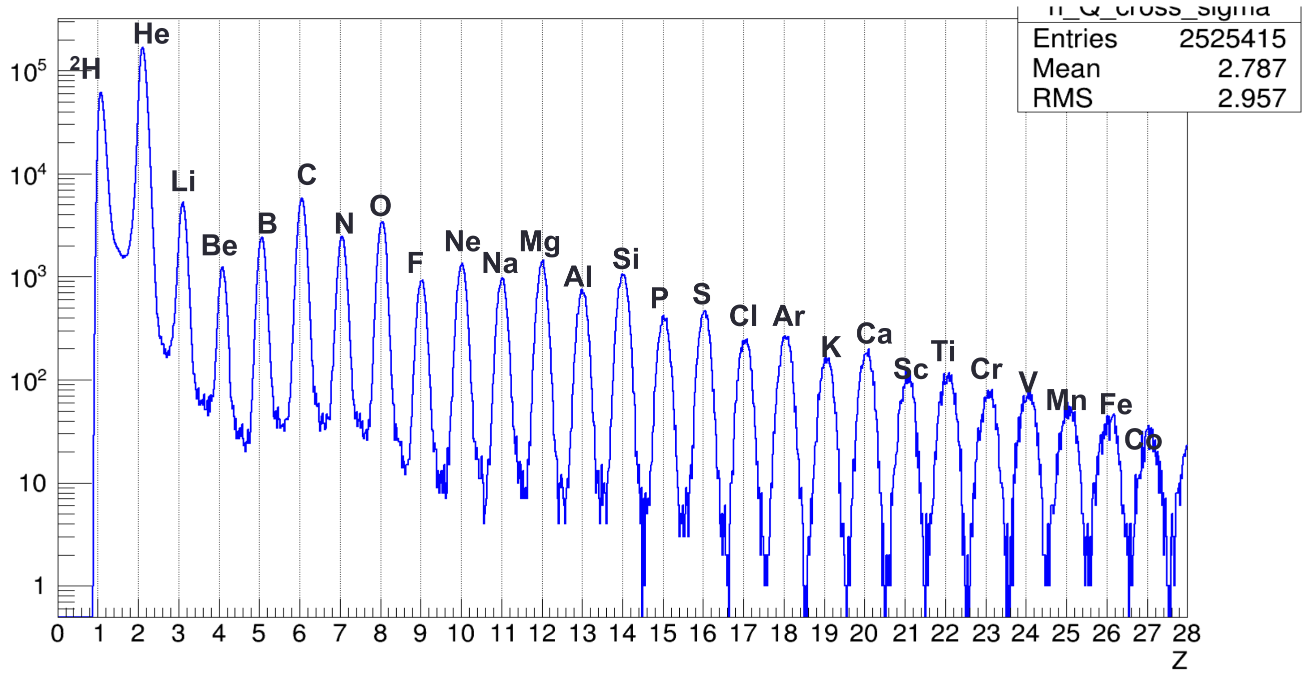


Feb. 2013 Pb beam on Be target @ 13, 30 GeV/n   Fragmented ions A/Z=2

Mar. 2015 Ar beam on Polyethilene target @ 19, 30 GeV/n   Fragmented ions A/Z=2

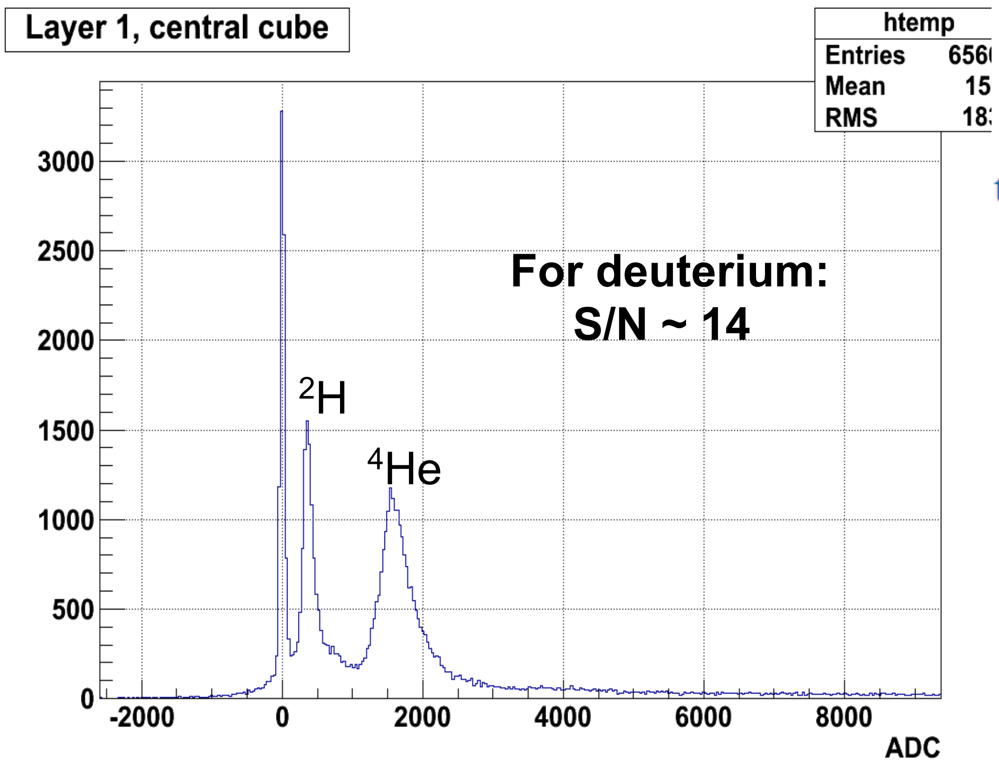


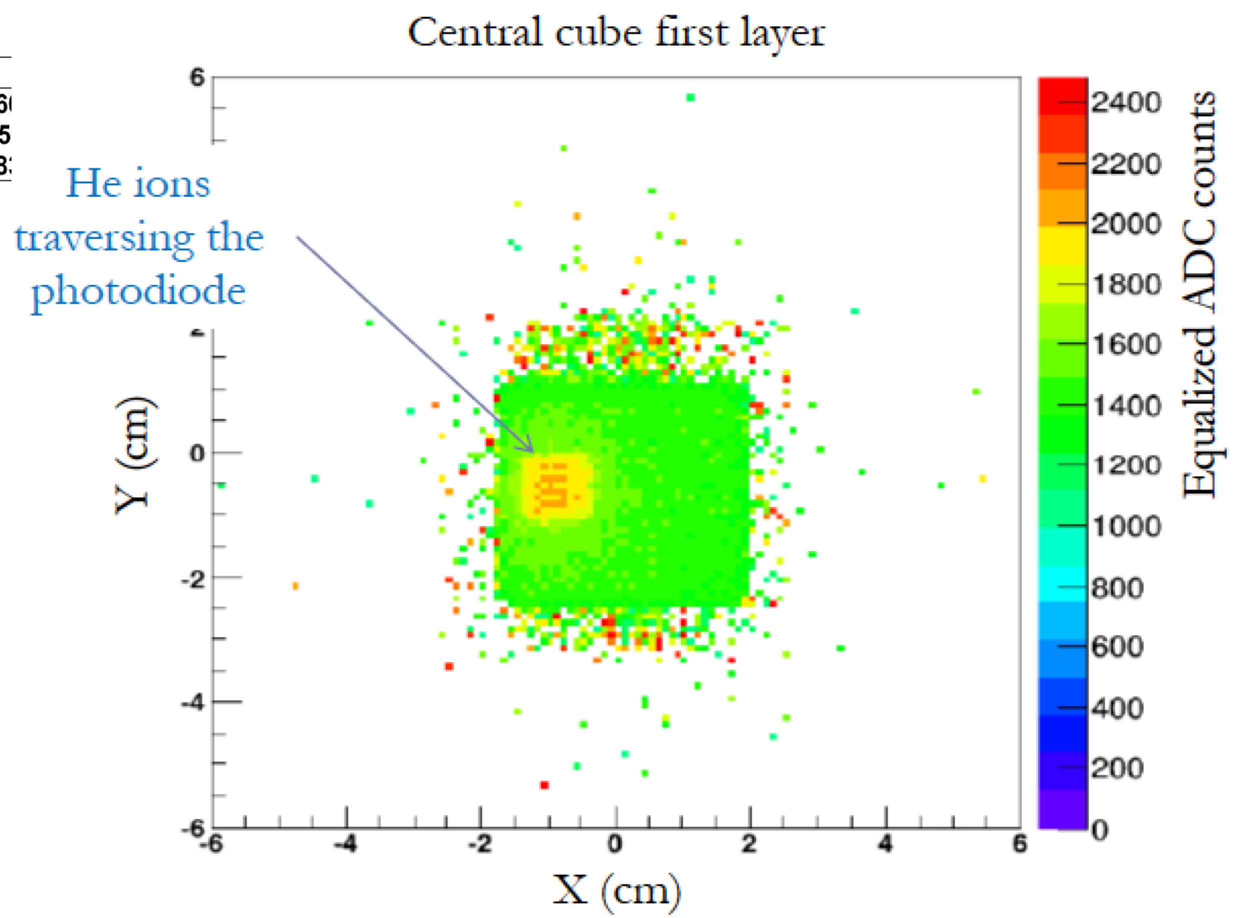
Charge tagging with 12 dE/dx samples (4 Si pixel + 8 Si-strip layers)



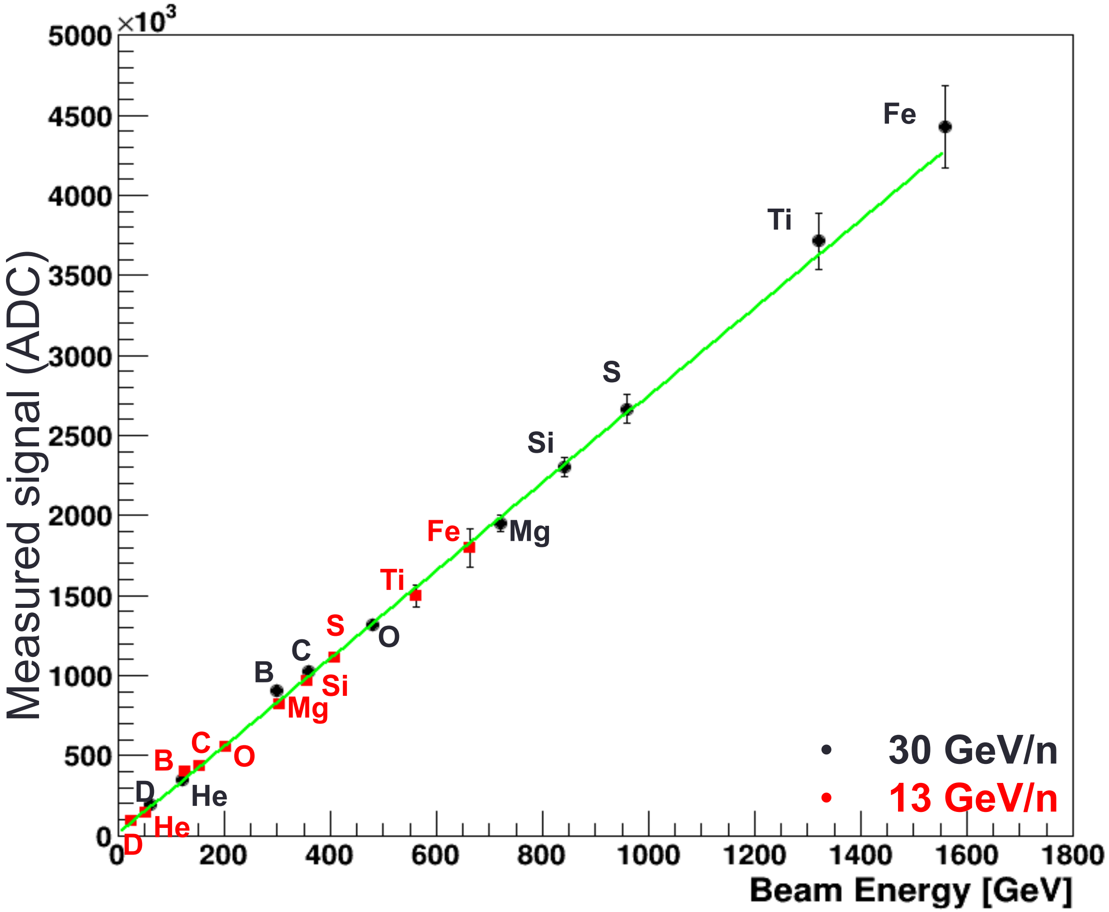
Excellent charge resolution: ~ 0.1 e   B/C

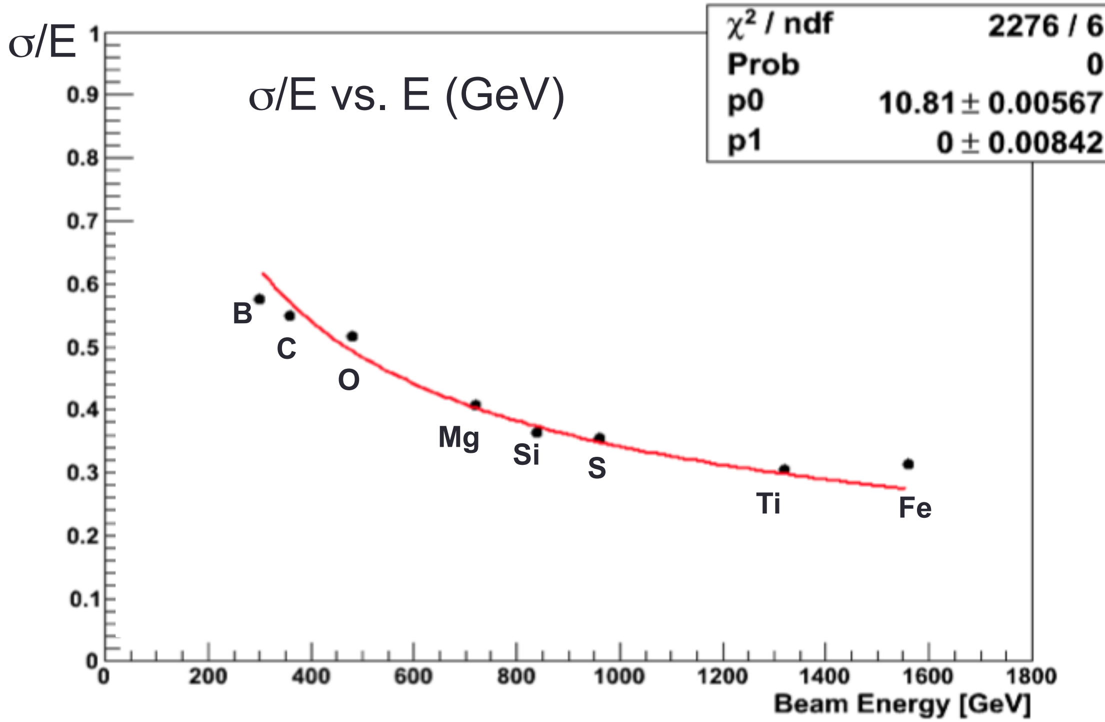
Pulse height spectrum in a crystal

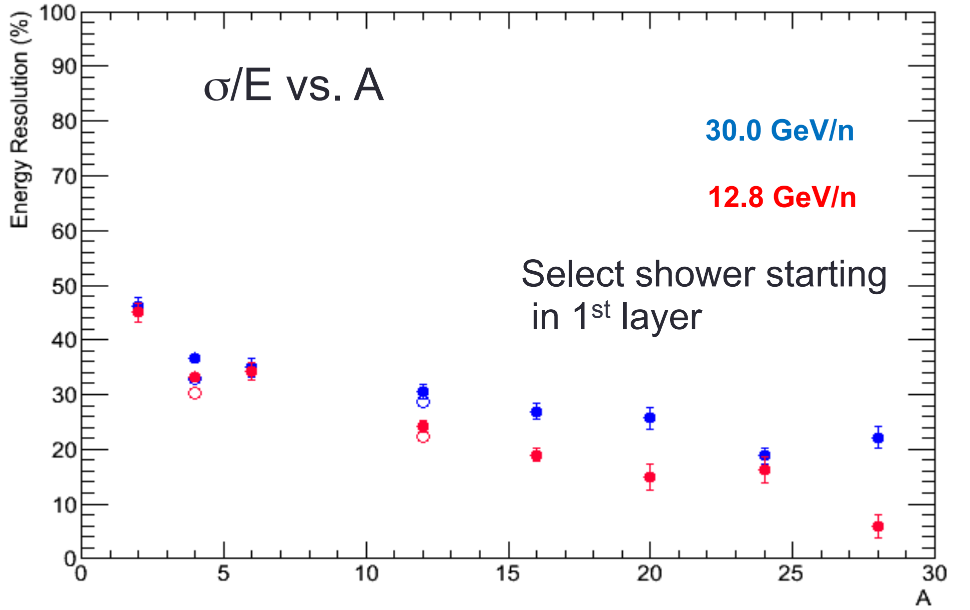




Energy linearity and resolution

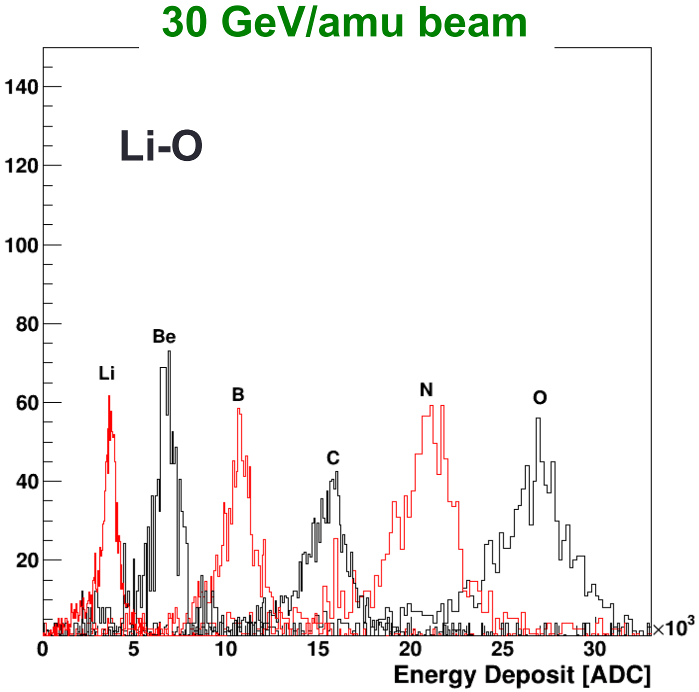


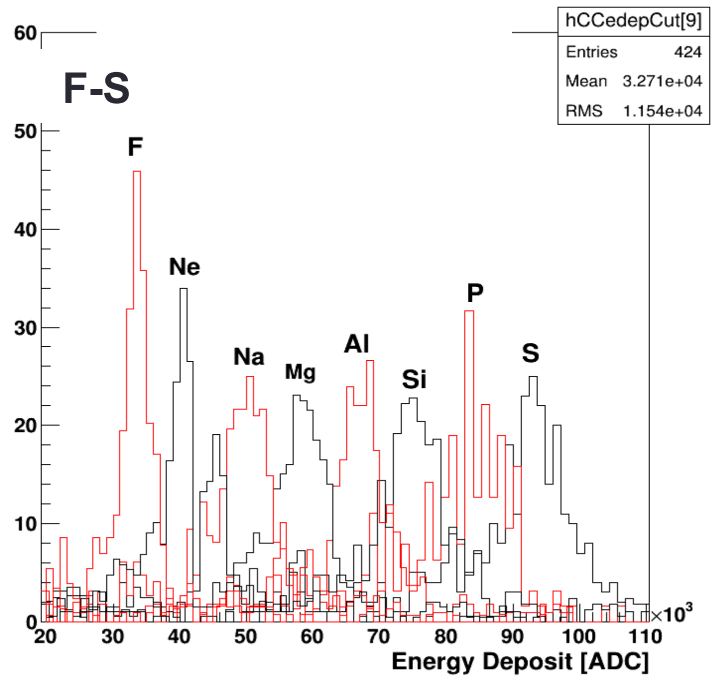


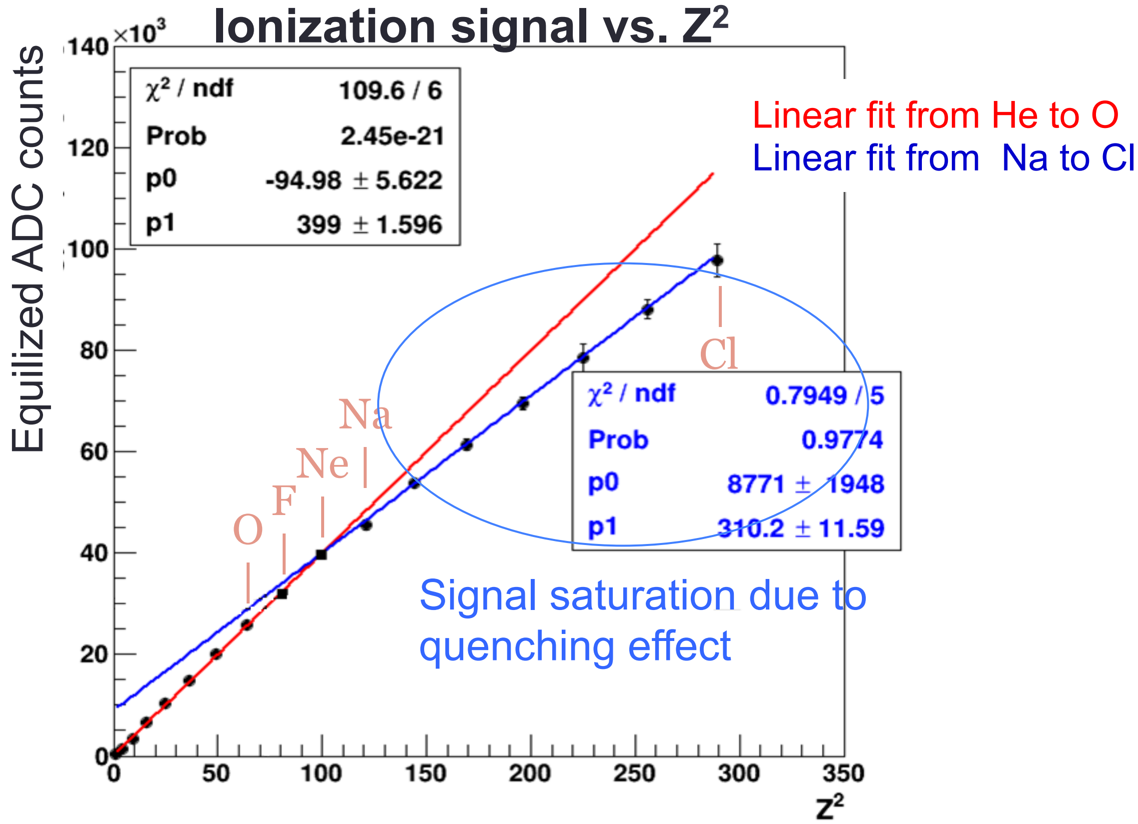


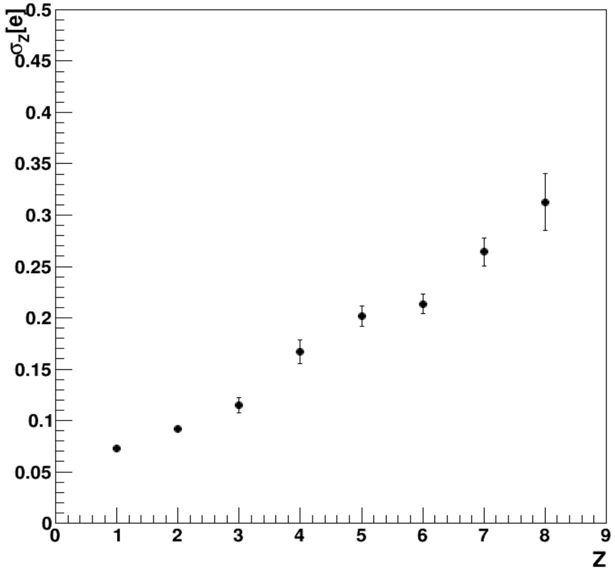
Good energy resolution even with significant lateral and longitudinal leakage.

Charge ID: Non-interacting nuclei 1st layer crystals









Quite poor charge separation (~0.3 e at O) but the prototype was not optimized for this purpose

The CaloCube project

- Improve the existing Cubic Calorimeter concept to:
  1. Optimize the overall calorimeter performances, in particular the hadronic energy resolution
  2. Optimize the charge measurement
  3. Build up a prototype fully space qualified

  by developing highly innovative techniques that are one of the core interest of the INFN CSN5

- Calocube funded by CSN5 (Progetto Call 2013) for 3 years (2014-2016)

- The project has a real and strong interest for the **GAMMA400** experiment

- Groups involved:
  1. INFN: Firenze, Catania/Messina, Pavia, Pisa/Siena, Trieste/Udine
  2. External institutions
     - IMCB-CNR Napoli → Surface treatments and WLS depositions
     - CNR-IMM-MATIS Catania → Dichroic filters depositions
  3. External companies: FBK, ST Microelectronics

Optimize the charge identifier system

Study how to improve PID capability with a different configuration of sensitive elements on the faces of the calorimeter.

Basic idea: replace the cubes on the calorimeter surface with a stack of thinner scintillating squared tiles in order to perform multiple measurement of dE/dx of the incident nuclei.

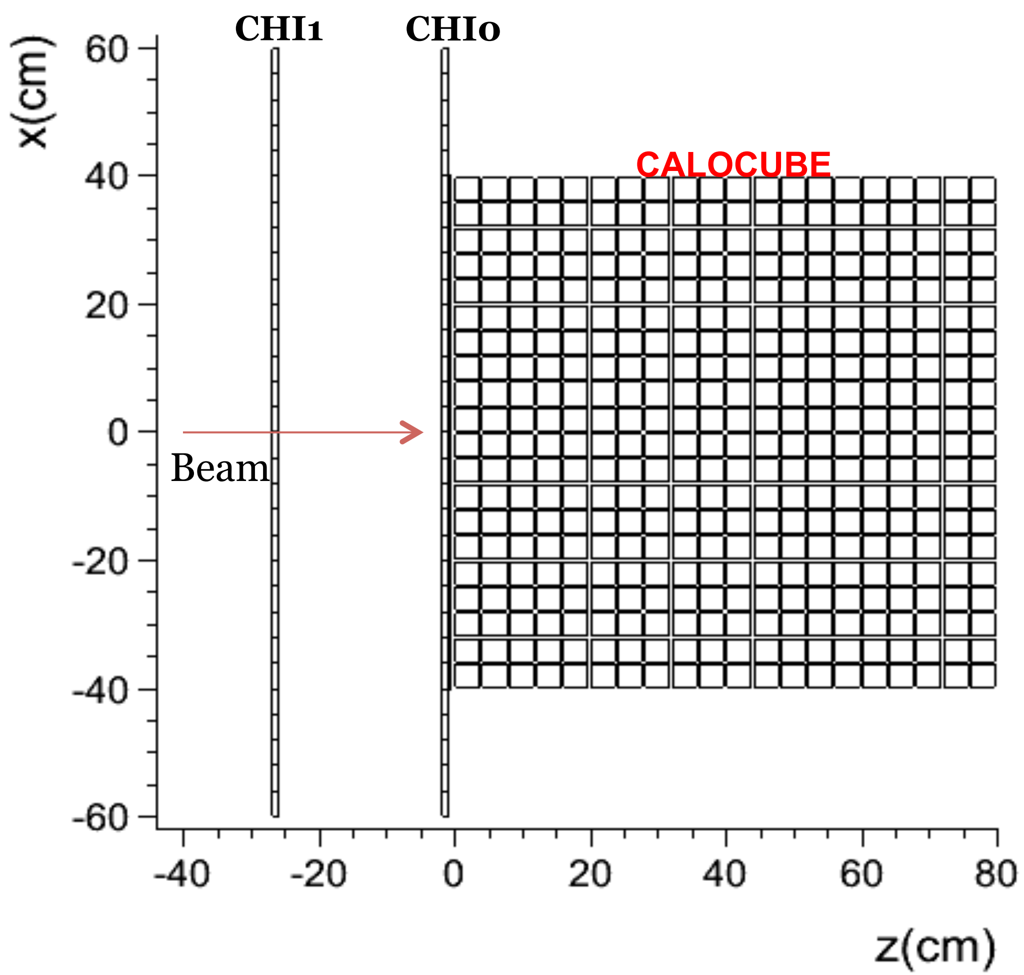
Advantages:

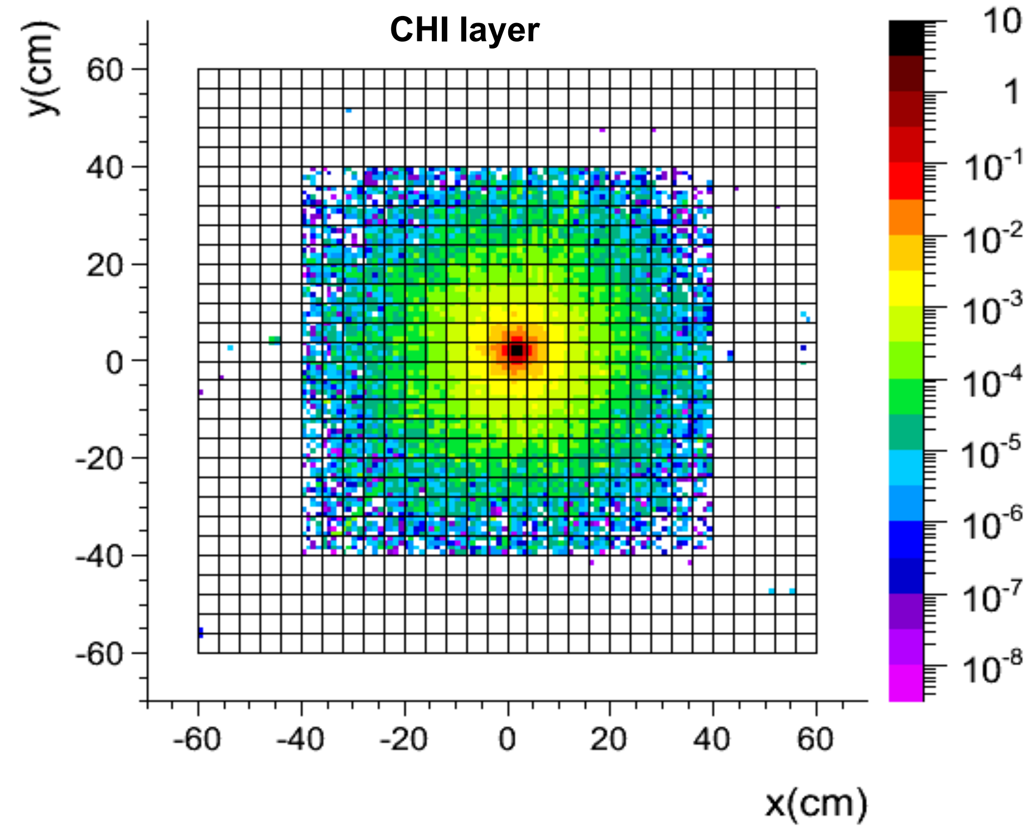
- Multiple dE/dx samples would allow to tag and remove early interacting nuclei which represent a a dangerous background in secondary/primary abundance measurement
- Pixel geometry of the tiles would allow to isolate the ionization signal generated by the incoming particle, reducing the effect of back-scattered shower particles, thereby minimizing the probability of misidentification.
- Possible additional materials to shield the backscattering
- Easier and cheaper technology than silicon arrays.
- Charge identifier system integrated in the calorimeter (same R&D for sensors and electronic)

Monte Carlo simulation: geometry

- FLUKA version 2011.2b.5 (feb. 2014)
- CaloCube: 20×20×20 cubes with 3.6 cm side spaced by 0.4 cm
- CHarge Identifier: 2 layers of 30×30 squared tiles (4×4×0.9 cm^3) with no gaps between tiles.

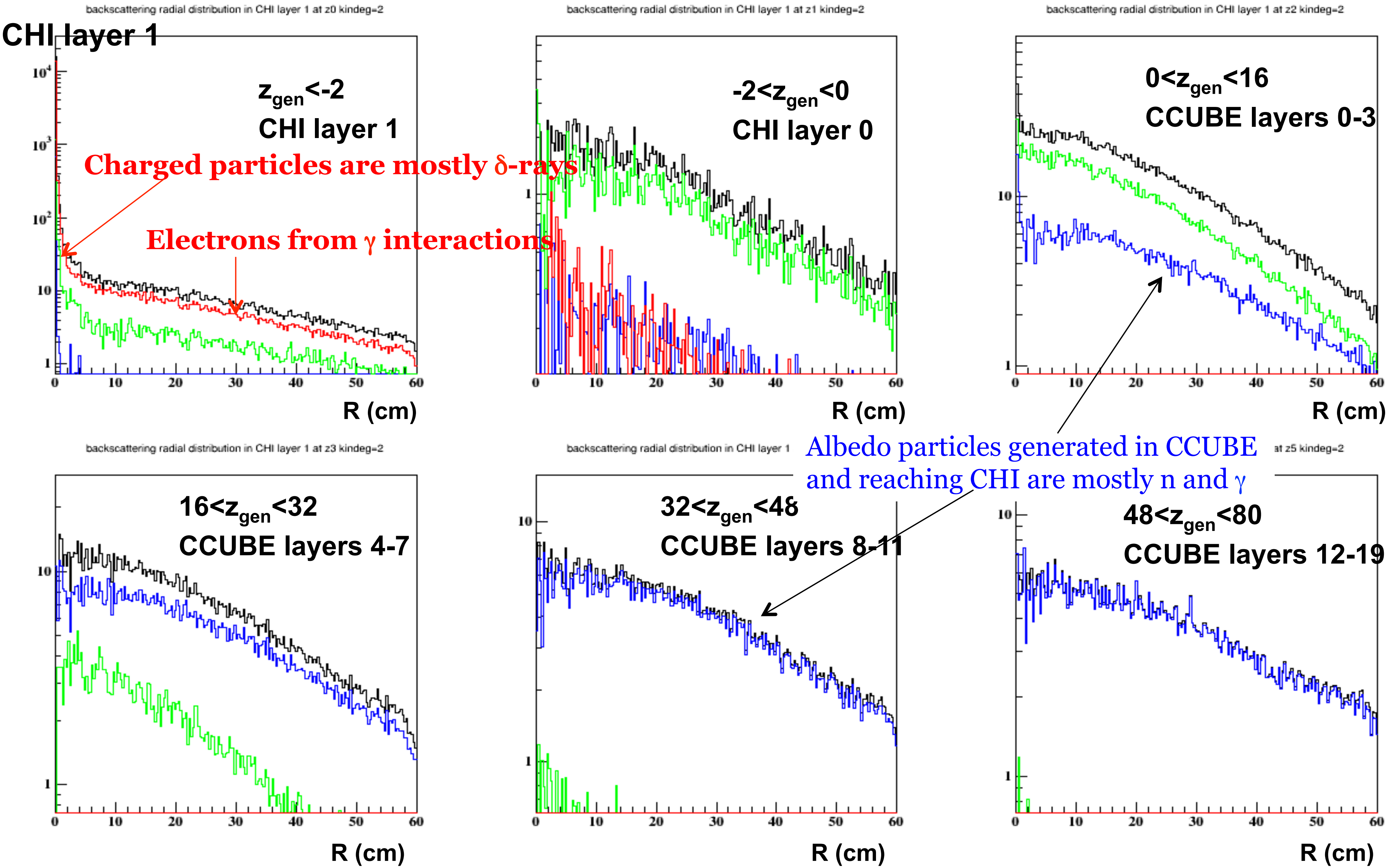
Layer#0 placed on the CaloCube surface. Layer#1 placed upstream CaloCube at a distance of 25 cm.





Generated protons @ 1,10, 100, 1000 TeV
with normal incidence in x=2 y=2 z=-80

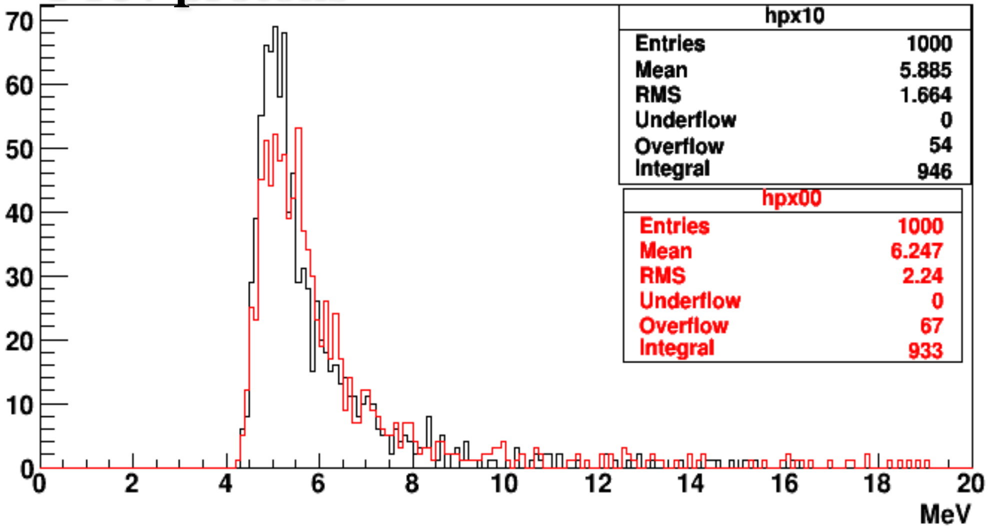
Radial distribution in CHI of albedo particles for different depth of generation in Calocube



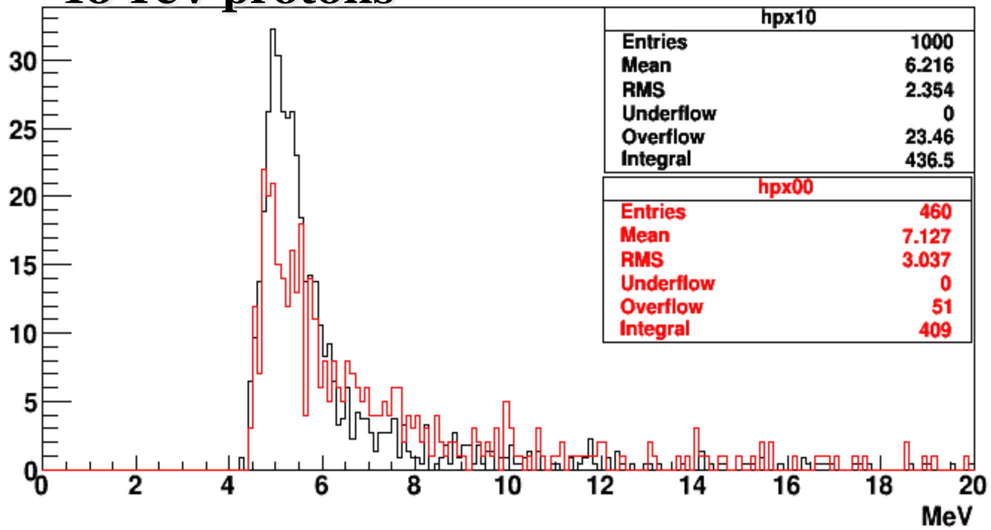
All particles   Charged particle   Neutron   Photons

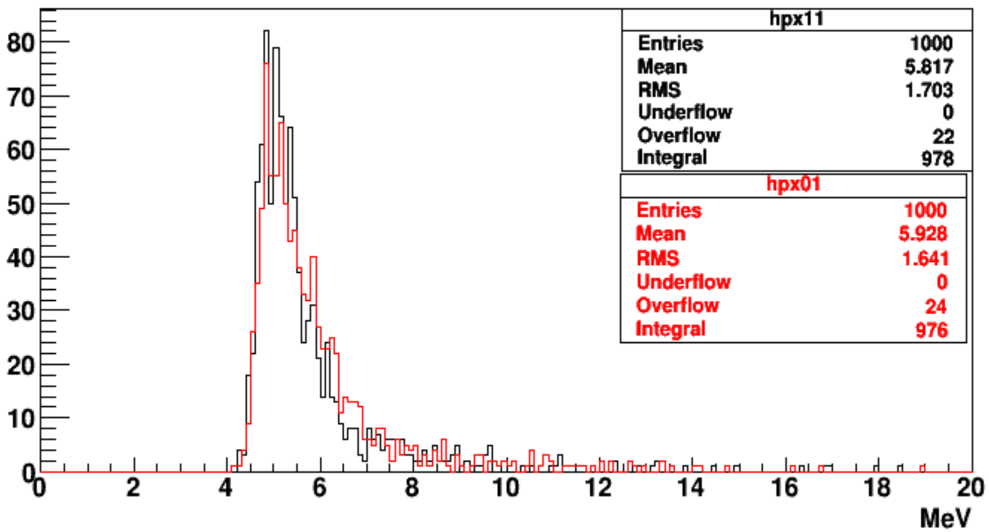
Energy deposited in the CHI tiles crossed by the beam particle

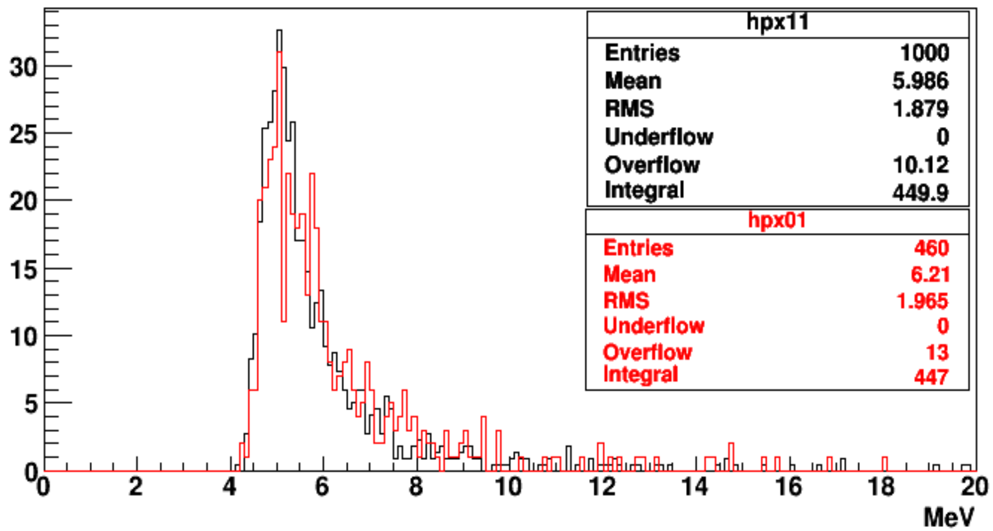
1 TeV protons



10 TeV protons





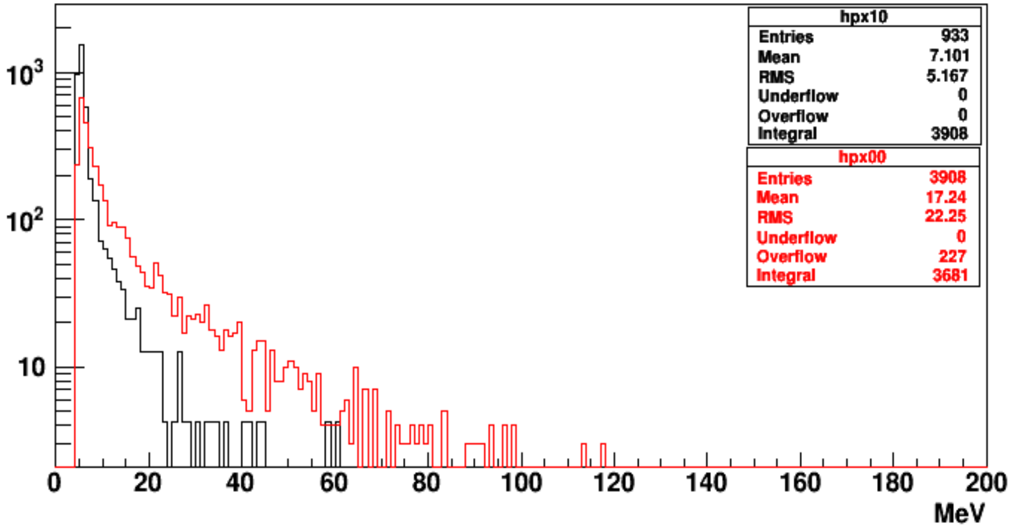


Red : CaloCube placed downstream CHI layers

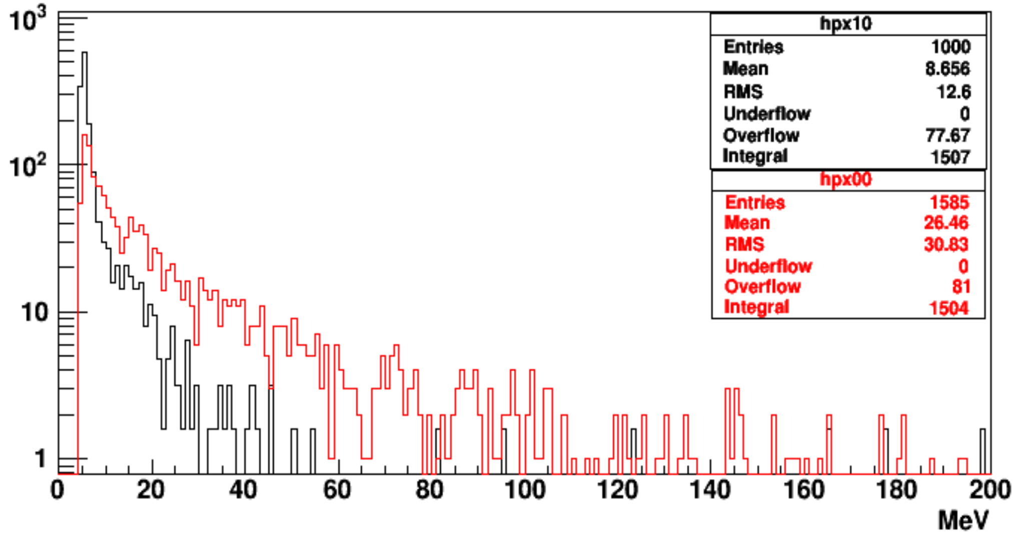
Black: CHI layers alone, CaloCube removed

Energy deposited in the CHI tiles crossed by the beam particle (2)

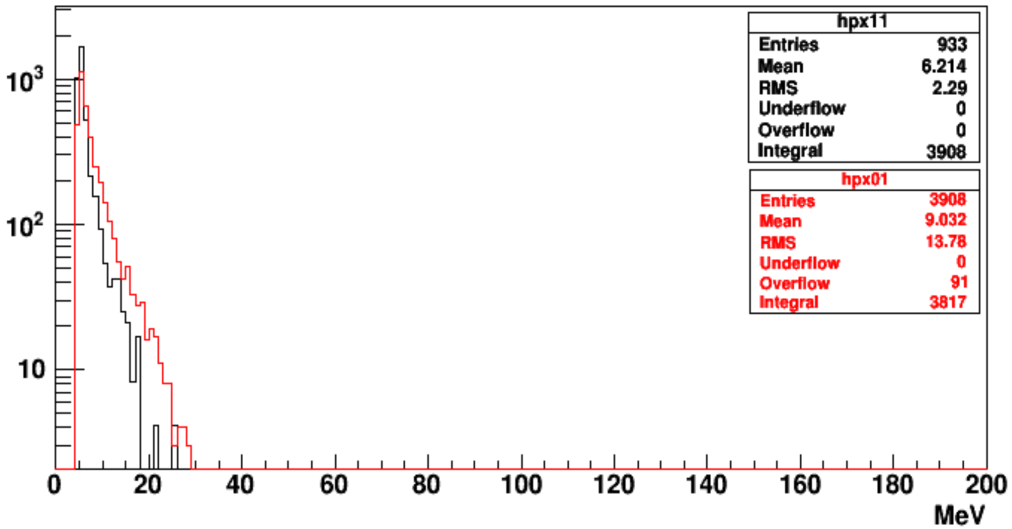
100 TeV protons CHI layer0



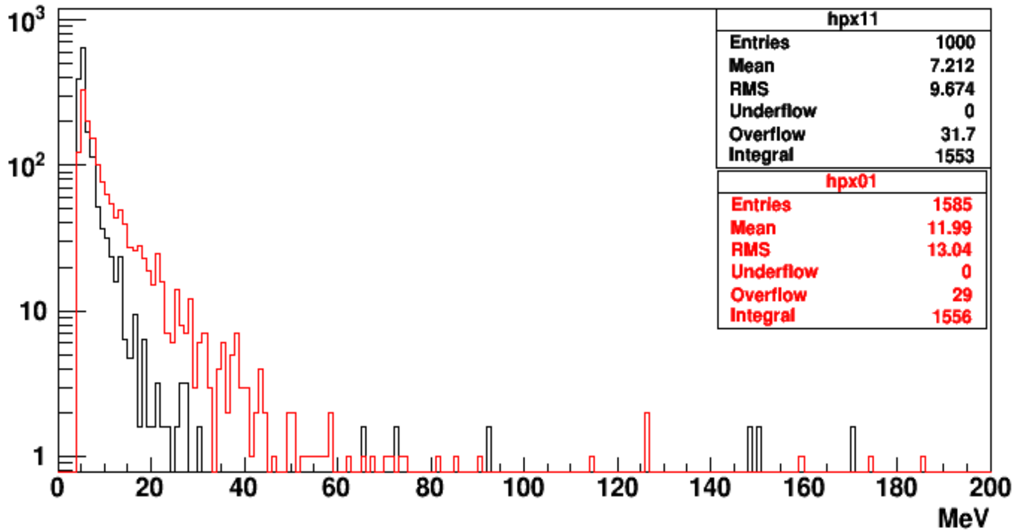
1000 TeV protons CHI layer0



CHI layer1

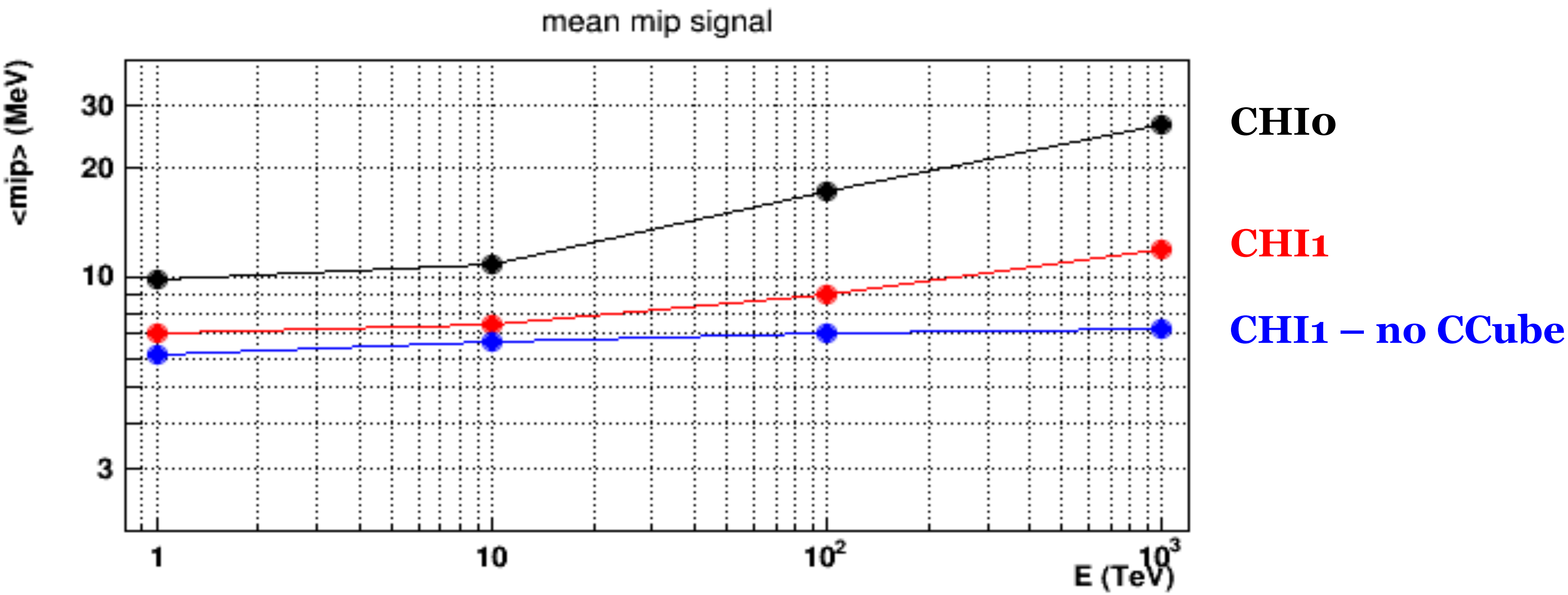


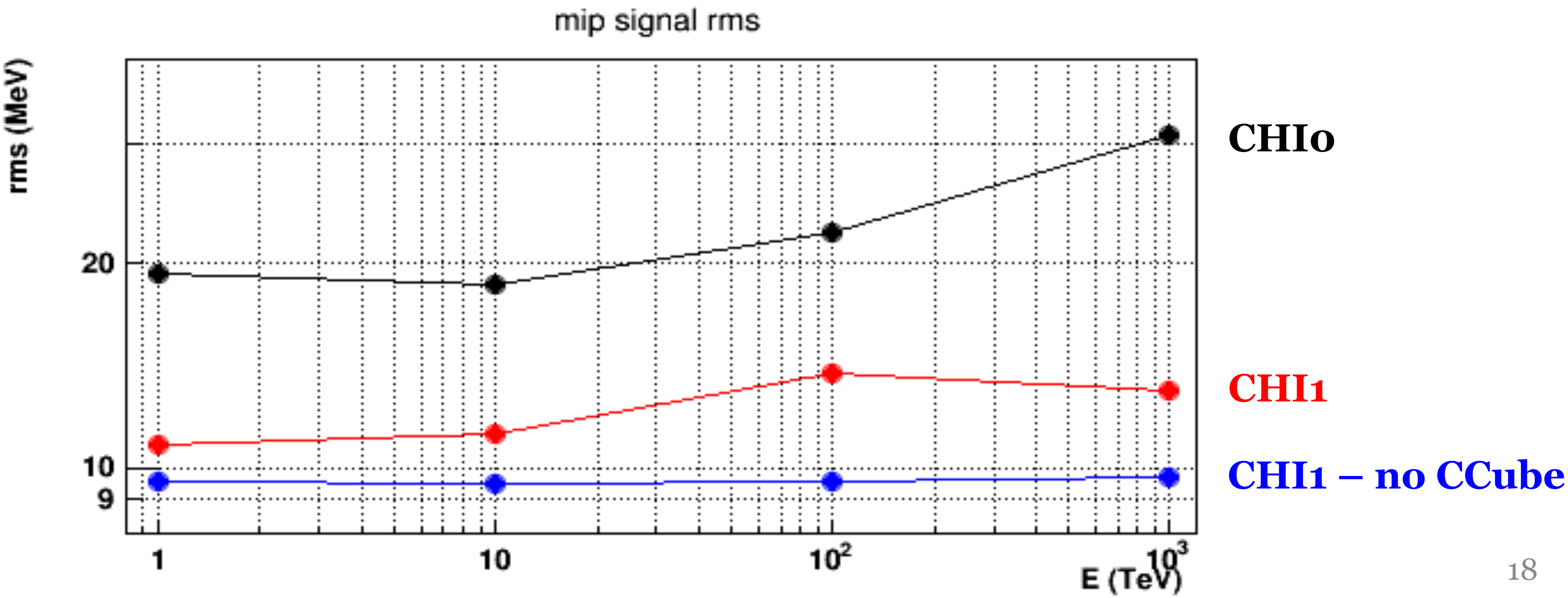
CHI layer1



Red : CaloCube placed downstream CHI layers

Black: CHI layers alone, CaloCube removed


mean mip signal
<mip> (MeV)
30
20
10
3
1
10
10^2
10^3
E (TeV)
CHI0
CHI1
CHI1 – no CCube


mip signal rms
rms (MeV)
20
10
9
1
10
10^2
10^3
E (TeV)
CHI0
CHI1
CHI1 – no CCube

Charge ID - Summary and future work

- Distance the CHI from the CCUBE surface allows to reduce the effect of worsening of backscattered particles on the charge measurement.
- However with current configuration, charge assessment is critical for proton above hundreds of TeV.

- Possible improvements

➢ With current configuration:
  - Reduce tile surface to 2x2 cm^2 or less to collect less albedo signals in a single tile.
  - Thinner tiles to reduce the probability of interaction of nuclei in the CHI.
  - Use a pair of nearby layers to correlate signals.
  - Is it feasible practically ? In which size and shapes can CsI crystals be machined?

➢ Study in details the energy spectra of albedo particles. Investigate if it is possible to shield albedo photons ?

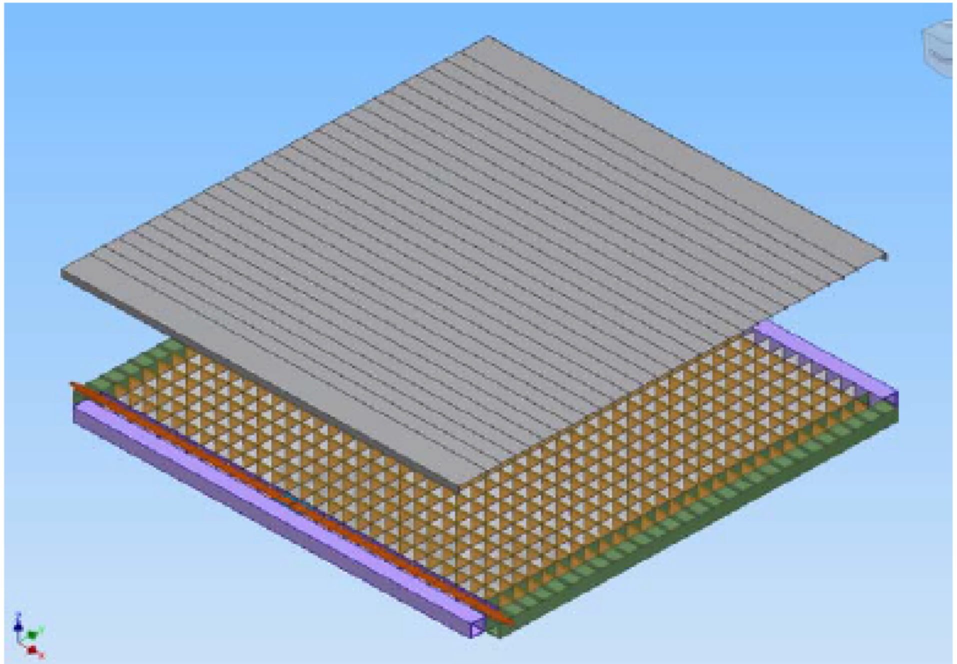
➢ Cerenkov could be exploited to measure the heavy nuclei charge. Study the Cerenkov signals produced by albedo particles.

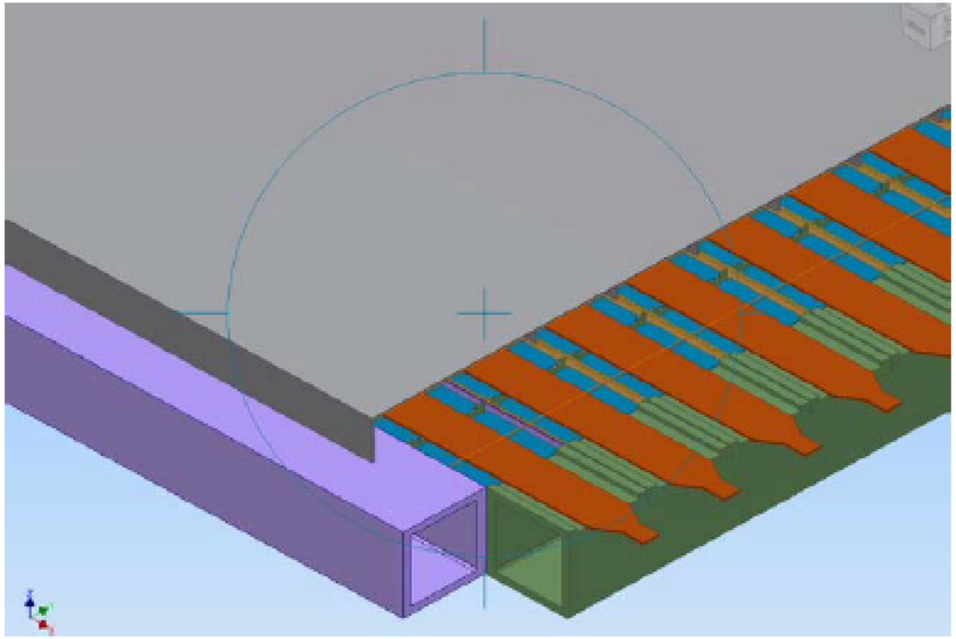
Mechanical design

• Alla fine dello scorso anno abbiamo definito il disegno di un vassoio prototipo in fibra di carbonio per l'esperimento CaloCube e abbiamo affidato ad un ditta (LOSON) la sua realizzazione.

• Questo prototipo prevede l'alloggiamento dei cristalli di un layer del calorimetro di Calocube : 28 x 28 cristalli.

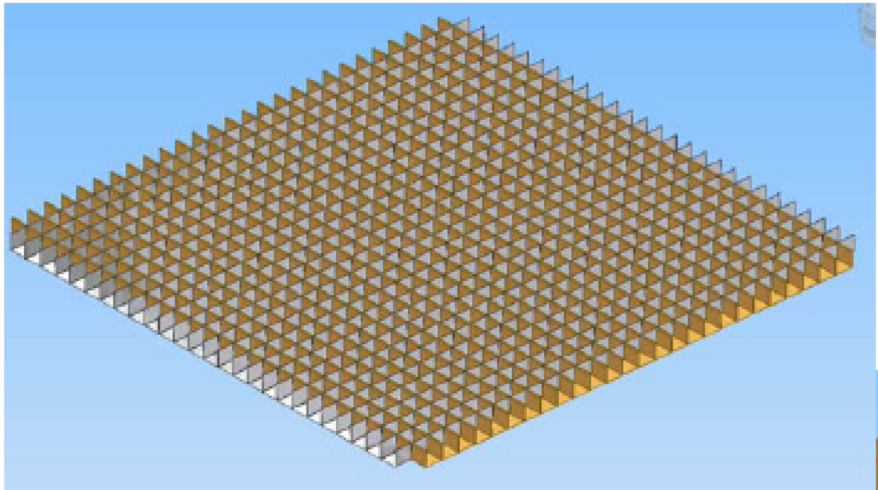
• Il vassoio è composto da un pattern regolare di spazi, per alloggiare i cristalli, una una cornice esterna leggera integrata + un tappo di chiusura.

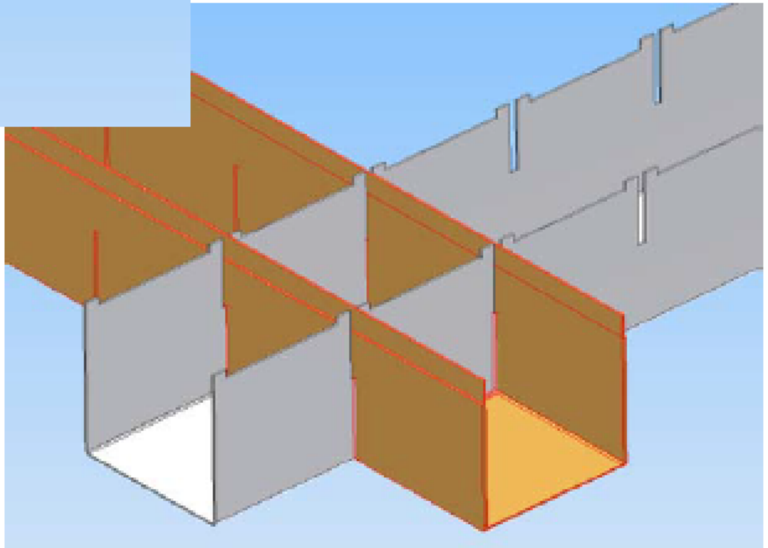




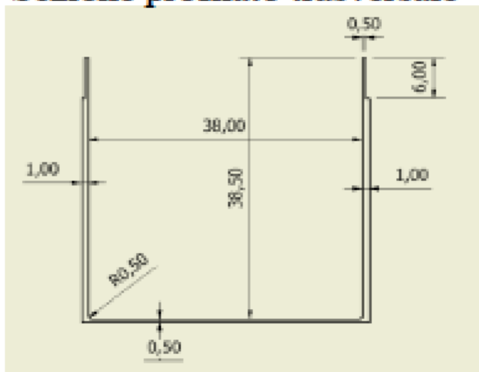
Mechanical design (2)

- L'alloggiamento dei cristalli è ricavato dall'incollaggio di semplici profilati a U in fibra di carbonio (opportunamente tagliati..).
- Abbiamo due tipi di profilati: quello trasversale, lungo l'asse X, e quello longitudinale, lungo l'asse Y.
- Dall'incollaggio di questi profilati ricaviamo anche la parete di base del vassoio.

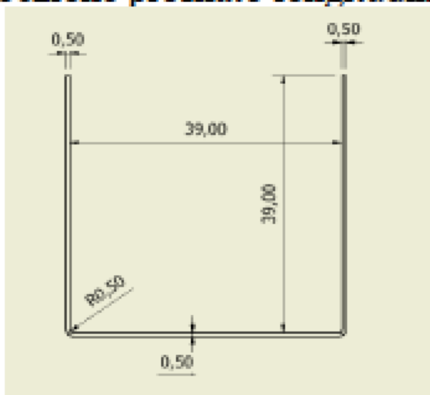


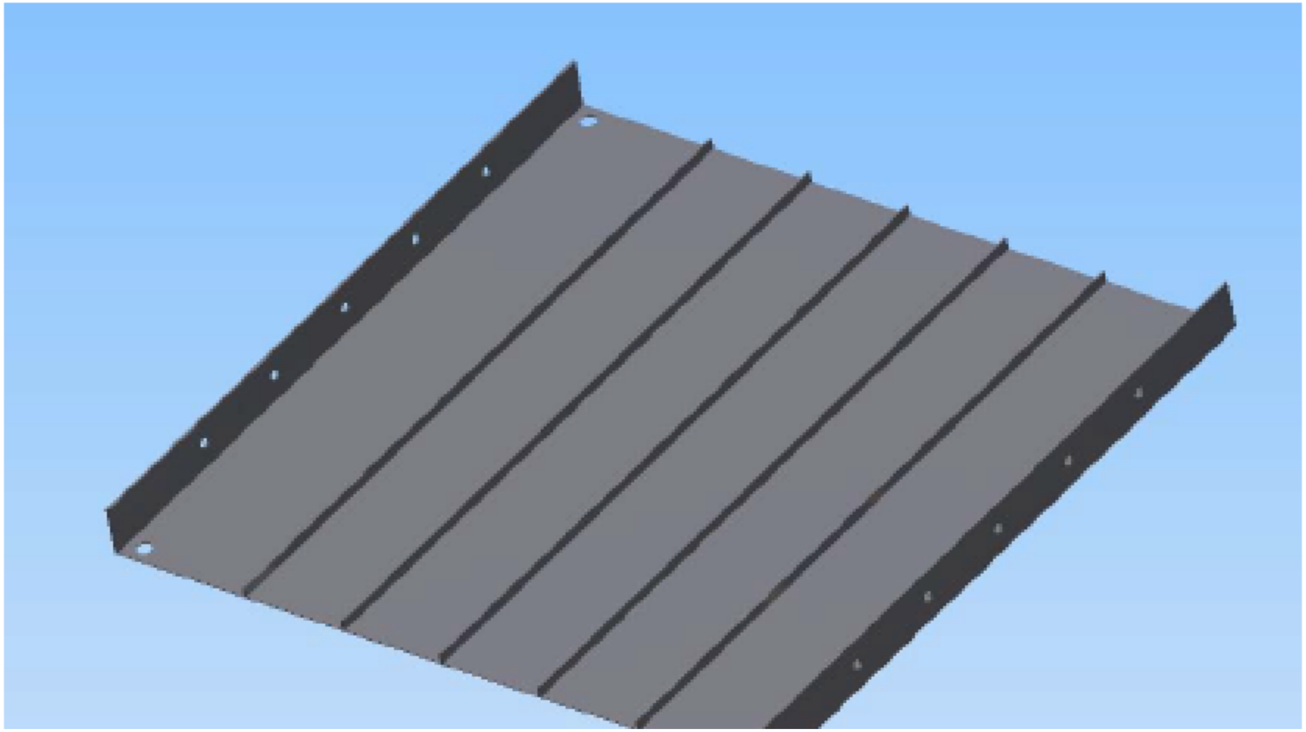


Sezione profilato trasversale

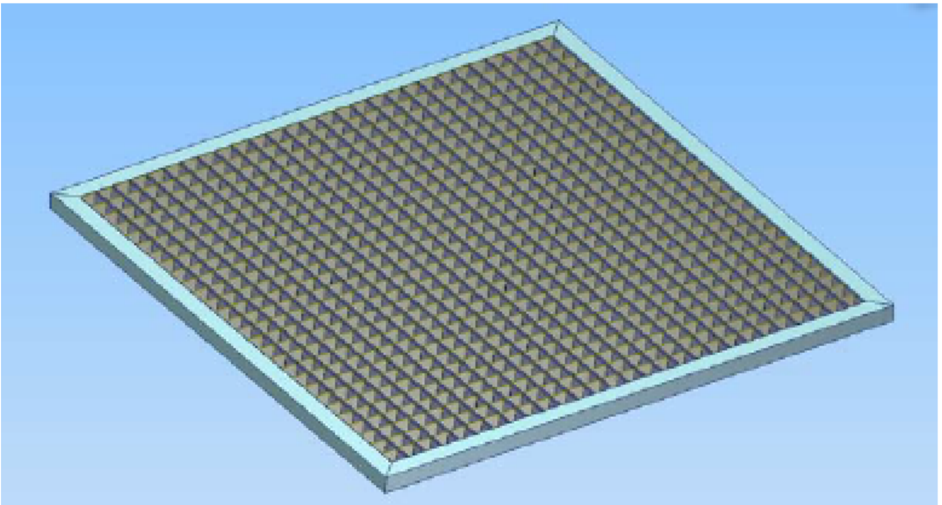


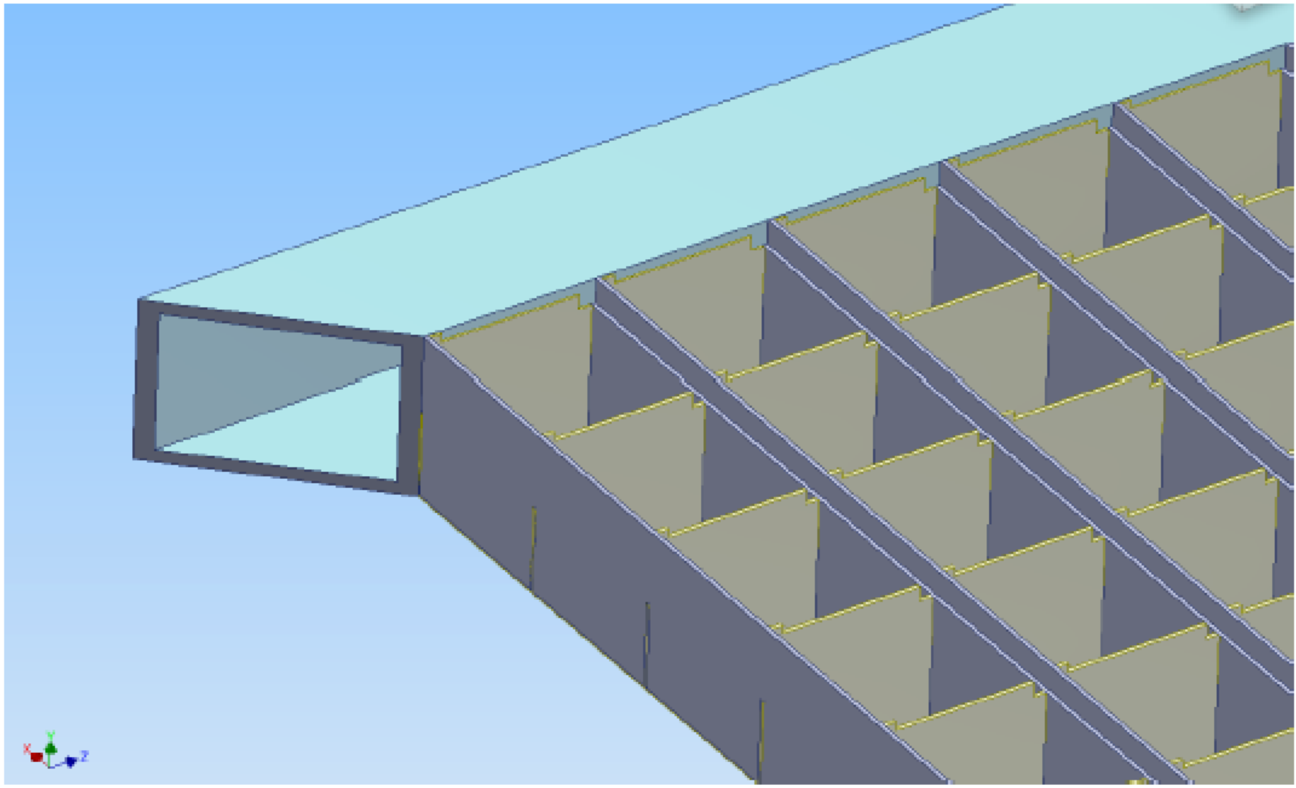
Sezione profilato longitudinale





Tappo superiore con alette trasversali che si incastrano nel vassoio.





Cornice esterna con profilo cavo e sezione quadrata.

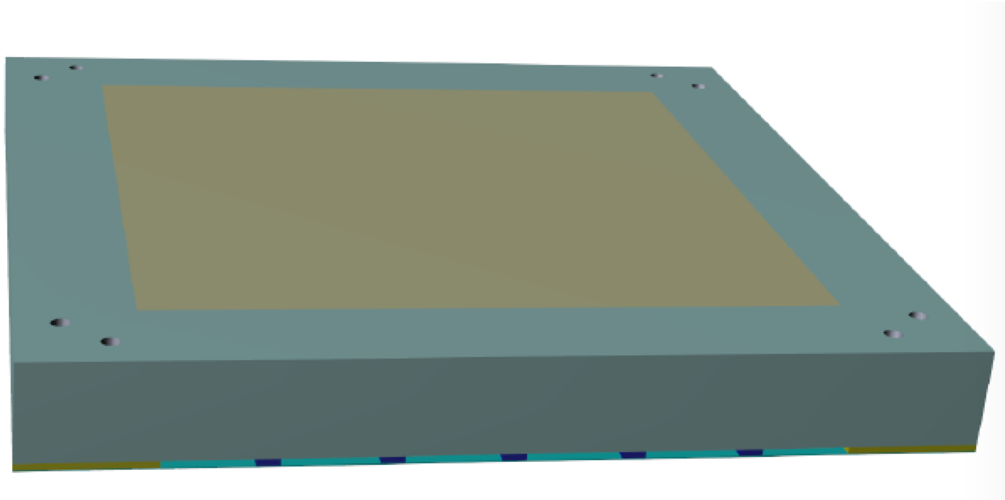
Prototipo del vassoio

- Simulazione agli elementi finiti (FEM) dello spettro di autofrequenze della struttura meccanica del calorimetro sottoposto ad accelerazioni tipiche delle fasi di lancio.

- In parallelo, abbiamo ordinato il calcolo FEM dell'oggetto e la realizzazione di un prototipo 6x6 con la stessa configurazione (dimensione delle celle e realizzazione della fibra).

- Realizzazione (in officina a Siena) degli stampi e attrezzature per la laminazione e incollaggi dei profilati a U che compongono il vassoio prototipo per l'alloggiamento dei cristalli.

- Prototipo 6x6 in via di realizzazione (entro agosto).



Attività del gruppo di Pisa/Siena nel 2016

- Proseguimento dello studio di fattibilità del Charge Identifier con configurazioni del detector e del readout modificate (maggiore distanza dalla superficie del calorimetro, differenti segmentazioni) rispetto alle due analizzate finora. La realizzazione di strutture di test prototipali è subordinata all'ottenimento di soddisfacenti risultati dalle simulazioni.

- Meccanica
  - Realizzazione degli stampi e attrezzature per la laminazione e incollaggi dei profilati a U che compongono il vassoio 28x28 per l'alloggiamento dei cristalli.
  - Finalizzazione del FEM della struttura e eventuali modifiche al disegno.
  - Realizzazione del prototipo finale del vassoio (28x28).
  - Test di qualifica dei prototipi insieme al gruppo di Firenze.

- Analisi dei dati raccolti nei vari test beam e simulazioni.

CALOCUBE - Richieste di servizi in sezione per il 2016

- Progettazione meccanica (4 weeks uomo)
- Officina Meccanica (2 weeks uomo): realizzazione di test articles/prototipi

Nome	Qualifica	% CALOCUBE
P. Maestro	RU Unisi + INFN Gruppo Collegato	50
P.S. Marrocchesi	PO Unisi + INFN Gruppo Collegato	30
Arta Sulaj	Assegnista ricerca Unisi	100
TOTALE FTE		**1.8**

Preventivi CALOCUBE - Pisa per il 2016

Consumo	Metabolismo di laboratorio	2
	Schede elettroniche per DAQ	3
	Cristalli sottili per test	6
	stampi e attrezzature per laminazione incollaggio vassoi per 28x28 cristalli	5
	Sensori per monitoraggio risposta cristalli con temperatura	3
Apparati	Strutture in fibra di carbonio per meccanica	60
Inventariabile	2 USB extender + fibra per DAQ	1
Missioni	Test beam al SPS-CERN (SJ a disponibilità fascio)	3
	meeting di collaborazione, test di qualifica della meccanica	5
TOTALE		88

BACKUP SLIDES

Sensors and FE electronics

- **Two different photodiodes are necessary on each crystal to cover the whole huge dynamic range from 1/3 MIP to 10^7 MIPs.**

- **Excelitas VTH2090 photodiodes have been used**

  9.2x9.2 mm^2 area

  Only one PD per crystal used with the prototype

- **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

1- Optimization of the overall calorimetric performance

- Optimize the hadronic energy resolution by means of the dual - or multiple - readout techniques and/or using cubes made by different materials
  - 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

3- Build up a prototype fully space qualified

- Space qualification

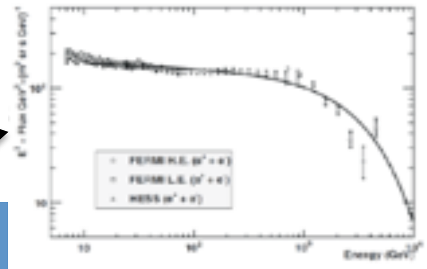
Basic idea: demonstrate that such a complex device can be built with space qualified technologies

  - 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

- Test Beam activities:
  - LNF
  - SPS
  - Messina LINAC

Expected number of events

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



Knee

Electrons					
Effective GF (m^2 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

Protons and Helium – Polygonato Model

Effective GF (m^2 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 (m^2 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

Readout sensors and dynamic range estimation

Two different PDs are necessary on each crystal to cover the whole huge dynamic range from 1/3 MIP to 10^7 MIPs.

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 = 54000 ph/MeV

Light yield for cube = 54000*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 = $3x10^4$ 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^-

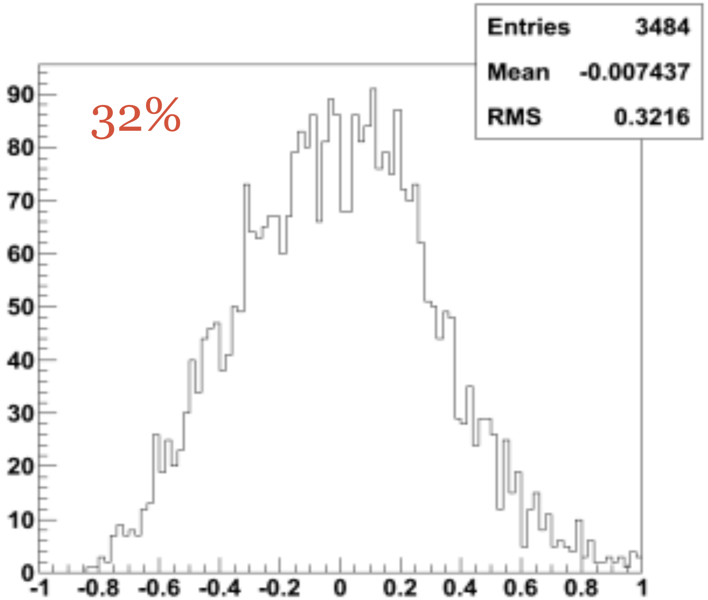
Requirements on the preamplifier input signal:

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

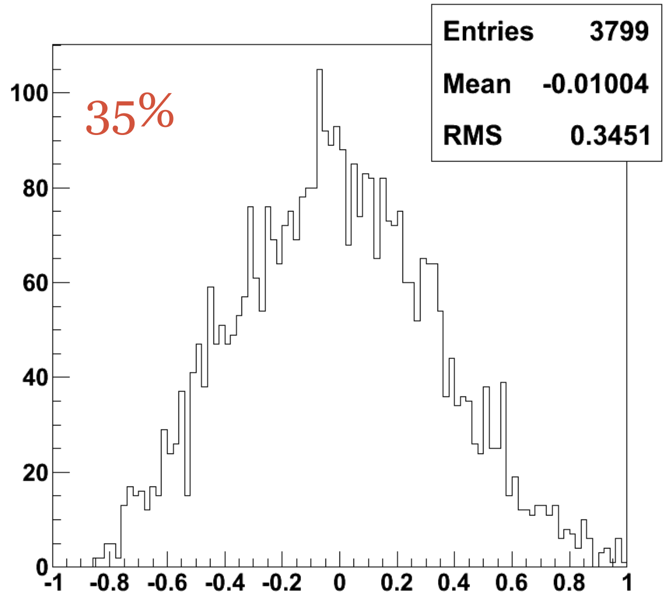
Maximum: 0.1xE_{part}= 100 TeV=**5.10^6 MIP**=4.10^8 e^- = 64 pC (Small area PD)

Proton energy resolution

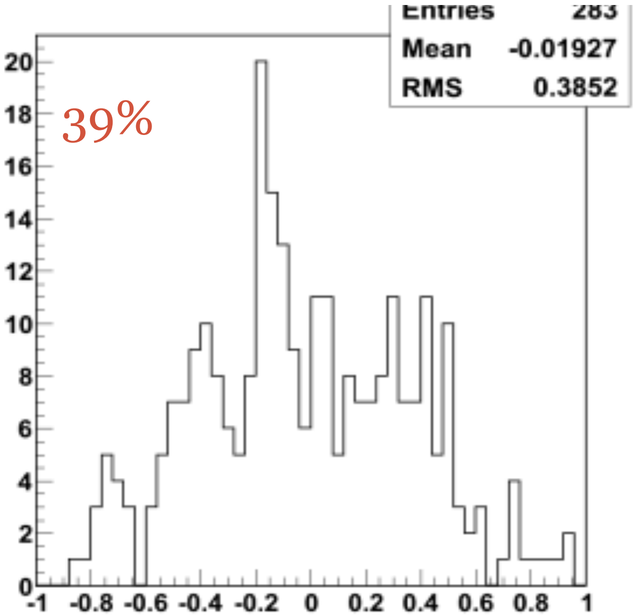
100 – 1000 GeV



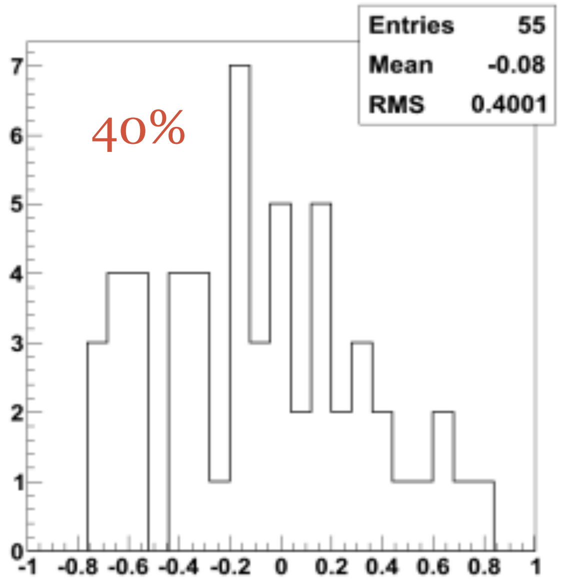
1 TeV



10 TeV

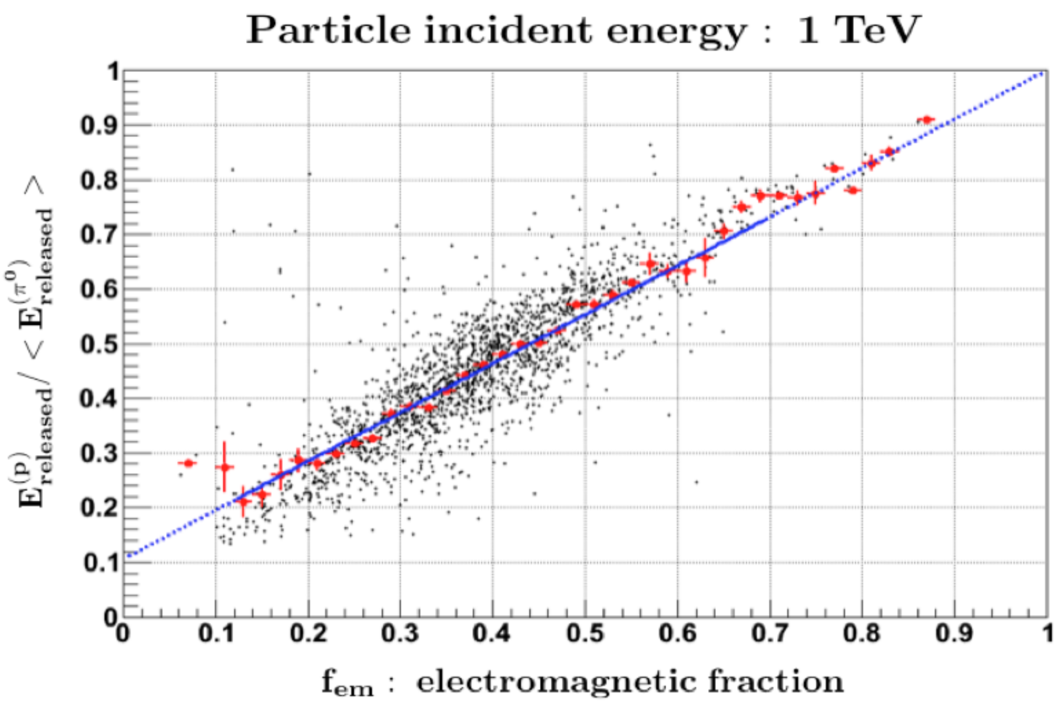


100 TeV

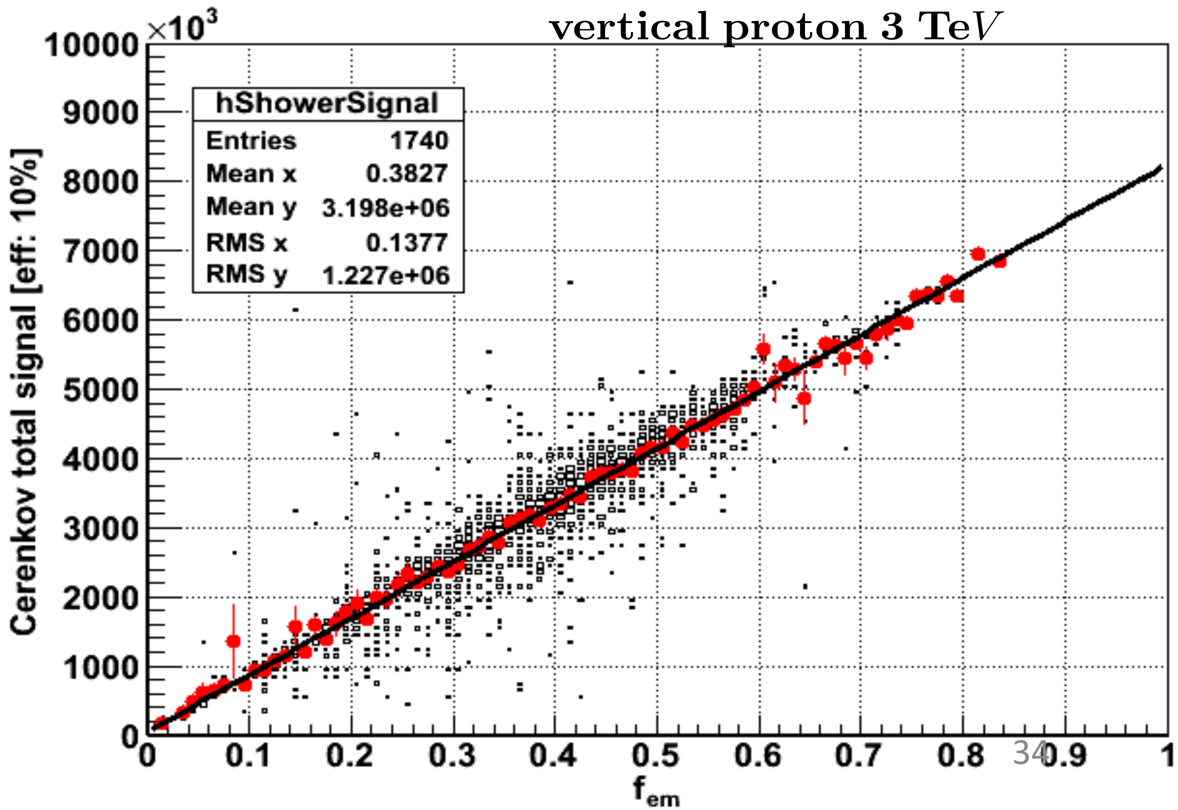


(Measured Energy – Real Energy) / Real Energy

The Principle of compensation: f_{em}



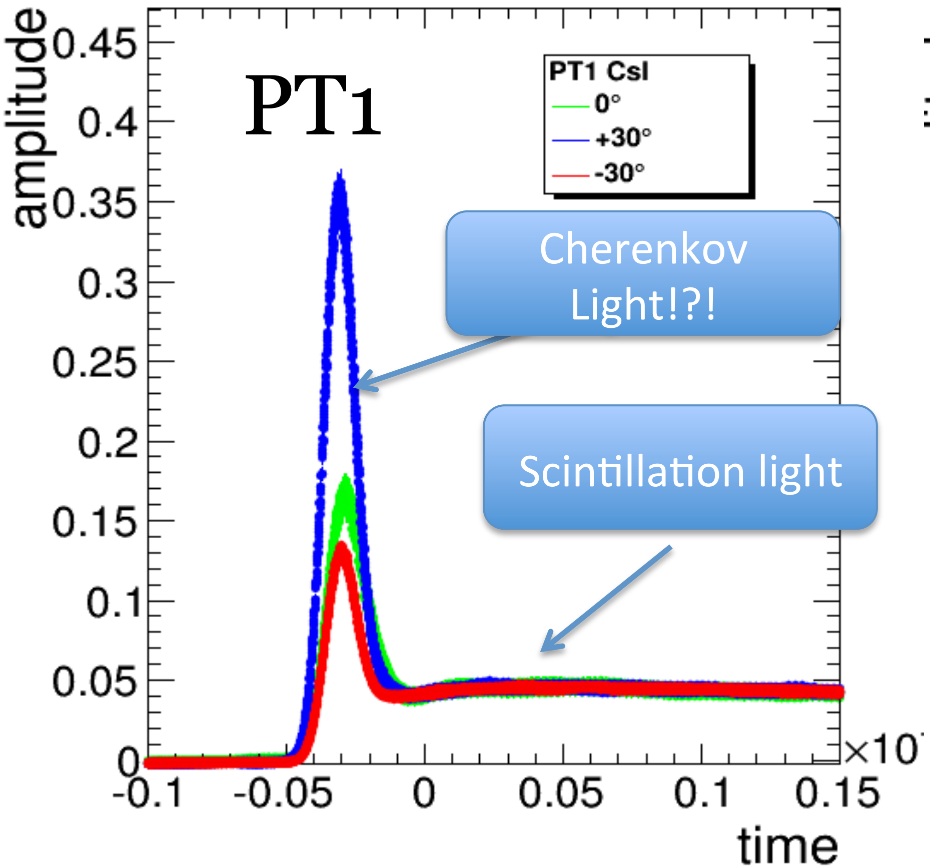
Cherenkov light detection is a tool to estimate f_{em} in a CsI(Tl) CaloCube!

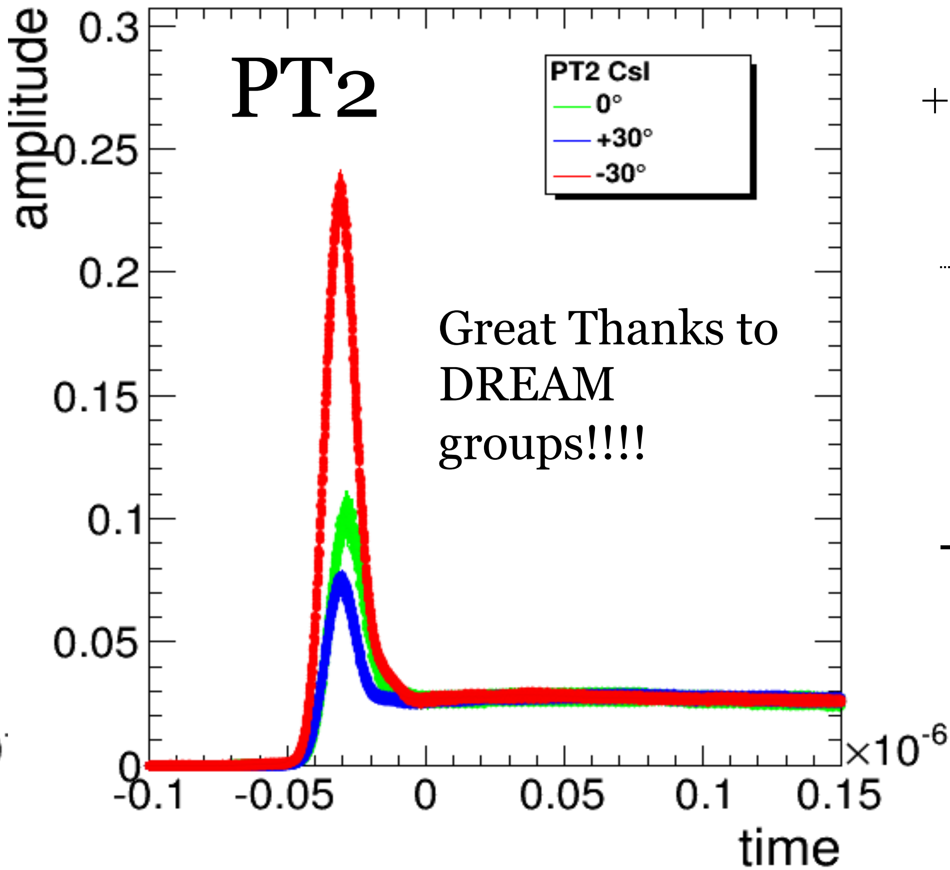


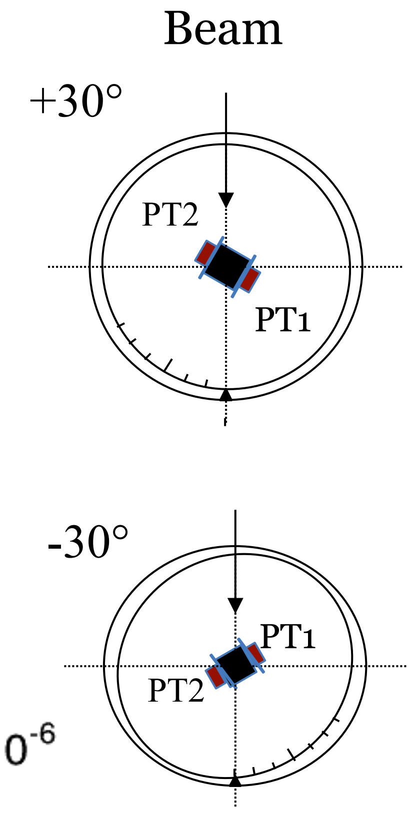
BTF Test beam of the prototype with 500 MeV electrons at the end of September

CsI cube wrapped in black, 2 phototubes, both with UV filters (DREAM-like)

Signal time profile averaged over many events



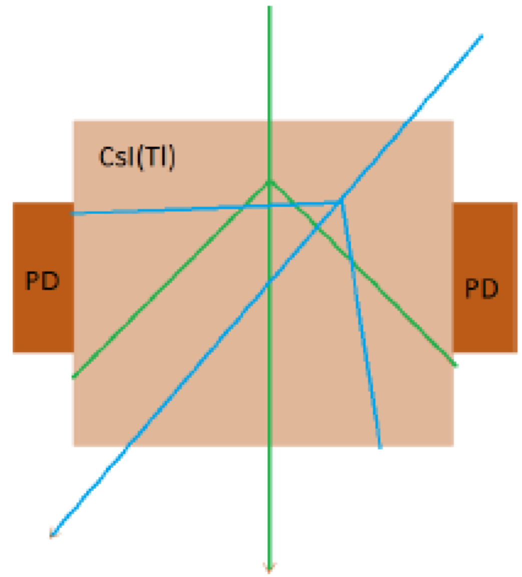


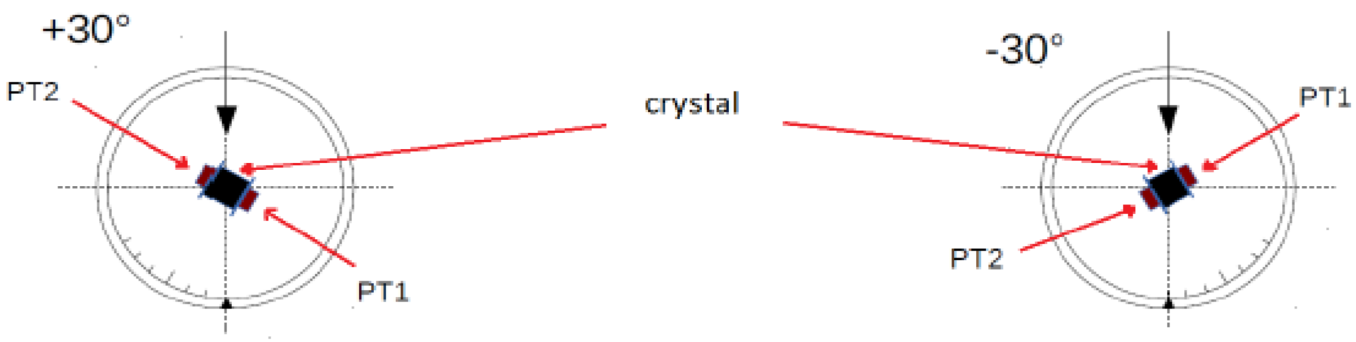


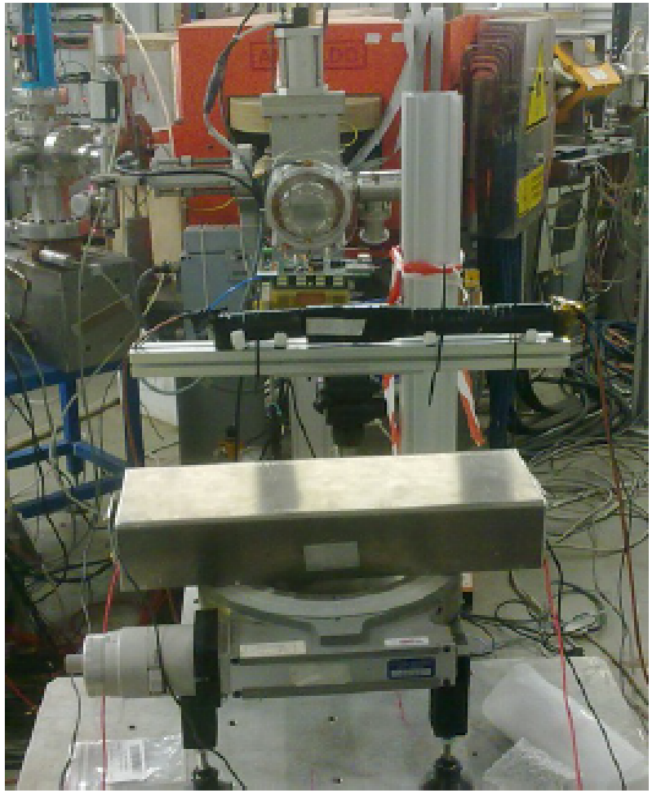
It seems that we could disentangle Ch from scintillator in CsI(Tl)!

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







Raffaello D'Alessandro
Università di Firenze e INFN

The WP organizations

			Task	Unit(s)	1st sem.	2nd sem.	3rd sem.	4th sem.	5th sem.	6th sem.
WP1	Adriani	**System design, software and simulation, prototype construction**	Definition of the baseline geometry	FI	x					
			Study of the optimal crystals	FI	x					
			Study of Čh and n detection	FI	x					
			Optimized design	FI, PI	x					
			MC and analysis tools	FI, PV	x	x	x			
			CCUBE prototype design	FI, PI, PV			x	x		
			CCUBE prototype assembly	FI			x	x	x	
			Project coordination and management	FI	x	x	x	x	x	x
WP2	Maestro	**Charge identifier system**	MC studies (geometry, backscatt.)	PI	x					
			Readout studies	PI	x	x				
			Characterization and lab. tests	PI		x	x			
			Assembly of 1st prototype	PI			x			
			Preliminary beam test	PI				x		
			Prototype design and assembly in CCUBE	PI				x	x	
			Beam test and data analysis	PI						x
WP3	Ricciarini	**Crystals/radiators and optical treatments**	Development of light collection systems	FI	x	x				
			Dichroic filter prototype and tests	CT/FI	x	x	x			
			WLS prototype and tests	NA/FI	x	x	x			
			Batch production of filters and WLS for CCUBE	CT/NA				x	x	
WP4	Bonvicini	**Photodetectors and electronics**	Optimization of photodetectors for the different signals	TS	x	x				
			New version of the CASIS chip	TS	x	x	x	x		
			Unified electronic chains for beam tests.	TS/FI/CT	x	x	x	x		
			Read-out electronics for the slow neutron components	TS		x	x	x		
			Fast digitizer for Čh pulse shape discrimination	PV		x	x	x		
WP5	Albergo	**Beam tests**	Crystals beam tests	CT,FI,PI,PV,TS	x	x	x			
			System beam tests	CT,FI,PI,PV,TS				x	x	x
WP6	Castellini	**Space qualification**	Study of general requirements and test procedures	FI	x	x				
			Thermal analysis and cooling	FI			x	x		
			Mechanical structure design	PI		x	x			
			CCUBE mechanical structure production	PI				x	x	

FTE in the various INFN RU

	Name	Role	%	
Catania/Messina	Albergo Sebastiano	Prof. Ordinario	10	
	Falci Giuseppe	Prof. Associato	10	
	Lamberto Antonio	Professore a contratto	20	
	Mezzasalma Angela	Professore Associato	30	
	Rappazzo Gaetana	Professore a contratto	30	
	Trifiro' Antonio	Ricercatore	10	
			1.1	**Total FTE**
Firenze	Adriani Oscar	Prof. Ordinario	50	
	Bongi Massimo	Ricercatore	70	
	Bottai Sergio	Ricercatore	30	
	Castellini Guido	Ass.Senior	0	
	Chiari Massimo	Ricercatore	10	
	Lenzi Piergiulio	Assegnista	30	
	Ricciarini Sergio Bruno	Ricercatore	70	
	Starodubtsev Oleksandr	Assegnista	70	
	Detti Sebastiano	Collaboratore Tecnico E.R.	50	
			3.8	**Total FTE**
Pavia	Cattaneo Paolo Walter	Primo Ricercatore	20	
	Nardo' Roberto	Tecnologo E.P.	10	
	Rappoldi Andrea	Primo Tecnologo	10	
			0.4	**Total FTE**
Pisa/Siena	Maestro Paolo	Ricercatore	40	
	Marrocchesi Pier Simone	Prof. Ordinario	30	
	Sulaj Arta	Assegnista	100	
			1.7	**Total FTE**
Trieste/Udine	Bonvicini Valter	Primo Ricercatore	10	
	Cauz Diego	Ricercatore	20	
	Gregorio Anna	Ricercatore	20	
	Pauletta Giovanni	Prof. Ordinario	20	
			0.7	**Total FTE**
			7.7	**Grand total FTE**