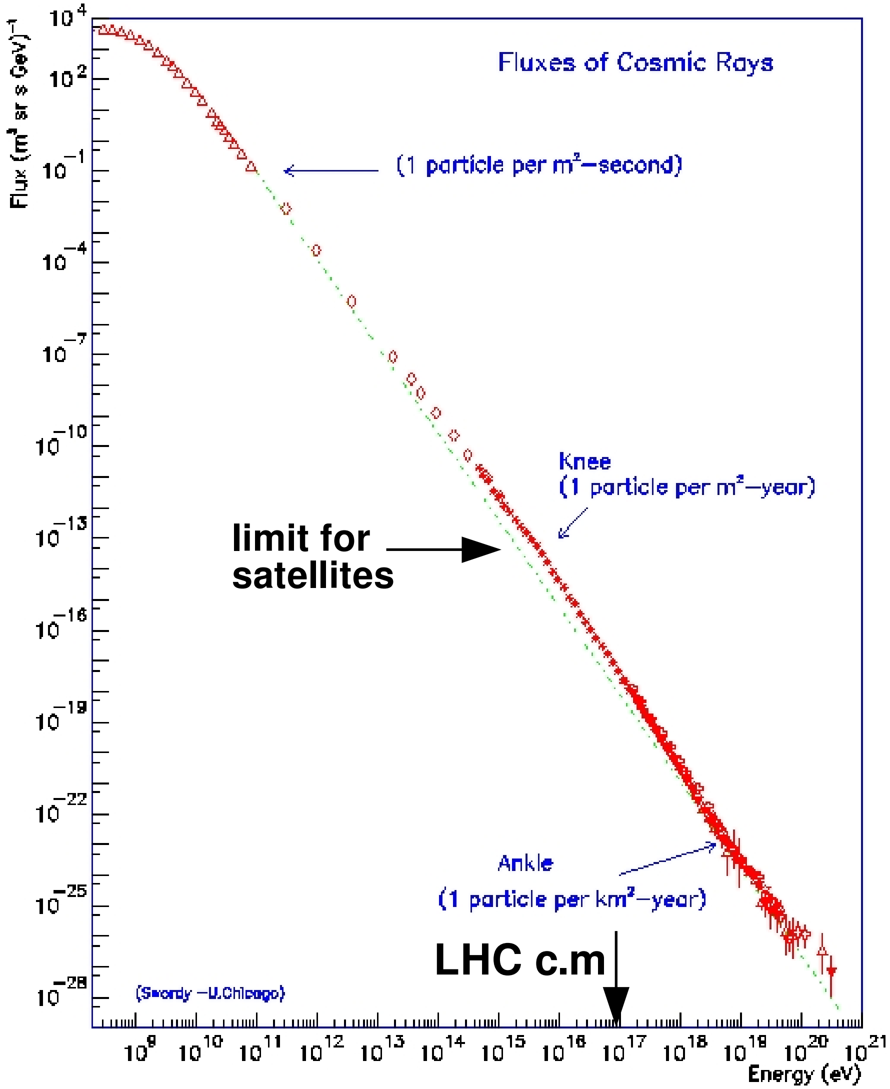
CaloCube: a high perfomances calorimeter for the detection of high- energy cosmic rays in space

Gabriele Bigongiari – INFN Sezione di Pisa
on behalf of CaloCube collaboration

The CaloCube Collaboration

- CaloCube is a three-years R&D project, approved and financed by INFN (Italy) in 2014, aiming to optimize the design of a space-born calorimeter for high energy cosmic rays measurements
- Participants:
  - INFN: Catania/Messina, Florence, Milano (Bicocca), Pisa, Pavia, Trieste
  - CNR-IMM-MATIS Catania
  - IMCB-CNR Napoli
  - Contacts with CNR Firenze
- In this presentations: scientific backgrounds (briefly), the CaloCube proposal, calorimeter performance (simulations and beam tests).

Cosmic Ray Spectrum



- From hundred GeV up to 100 TeV is well approximated by a single power law $\sim E^{-2.7}$
- Structure around PeV, the Knee: energy limit of galactic accelerators?
- Very steep flux
- Large acceptance for high energy cosmic rays measurements is required
- Indirect measurements on earth: very large acceptance $\rightarrow$ high statistics $\rightarrow$ high energy
- Issue: affected by large systematic errors

Future satellite experiments

- Direct measurement: limit in energy due to small acceptance:
  - Nuclei below 100 TeV/n
  - Electron+positron below 1 TeV

Typical payload limitations:
- **Mass (~10^3 Kg)**
- **Power (~10^3 W)**
- **Down link capability (~10^2 Gb/day)**
- **Volumes (few m^2)**

Direct measurements of cosmic ray proton and nuclei spectra up to 1 PeV/n and electron spectrum above 1 TeV require:

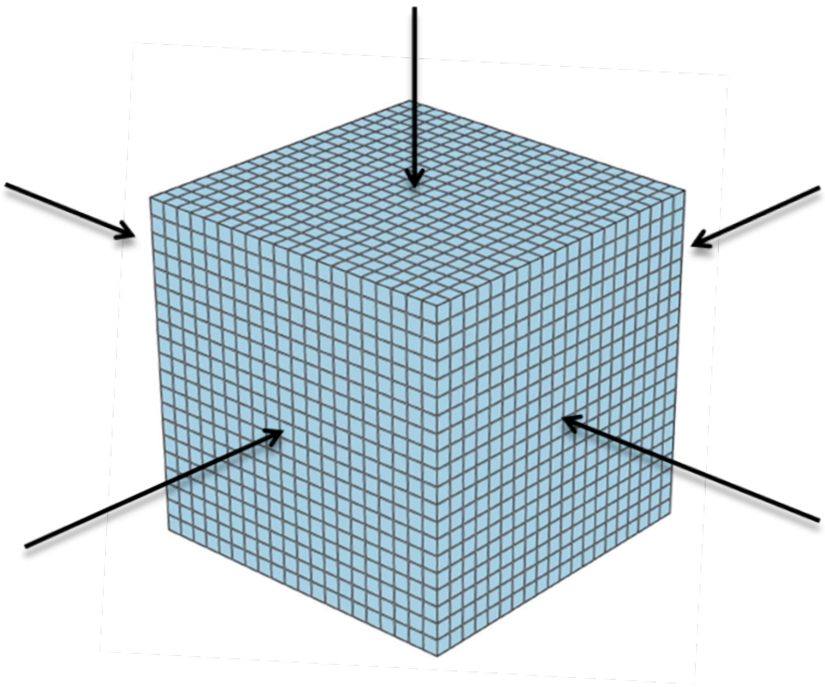
- Acceptance of few m^2sr
- Energy resolution better than 40 % for nuclei and 2% for electrons.
- Good charge identification and electron proton rejection power (at least 10^5)
- High dynamic range

The Challenge

- **Deep homogeneous isotropic calorimeter:** accepts particles from all the directions
- **Large acceptance due to 5 faces detection,** mechanical supports and earth on bottom side
- **3D segmentation:** good e/p rejection, identification of shower axis and shower starting point

Calocube baseline design

- **20x20x20 cubic crystals CsI(Tl)**
- **Side = Moliere radius (3.6 cm)**
- **Double photodiode readout**
- **Double gain front-end electronics**



MonteCarlo simulations

- Based on FLUKA package
- 20x20x20 CsI(Tl) crystals, side ~ Moliere radius
- Support structures are in carbon fiber
- Gap between crystals: 0.3 cm
- Energy deposit in scintillating crystals are converted into photo-electrons using:
  - CsI(Tl) light yield (54000 ph/MeV)
  - light collection (~ Active area of PD / Area of one face)
  - quantum efficiency of PD @ 550 nm (emission peak of CsI(Tl))
- Energy deposit in PD due to ionization is taken into account

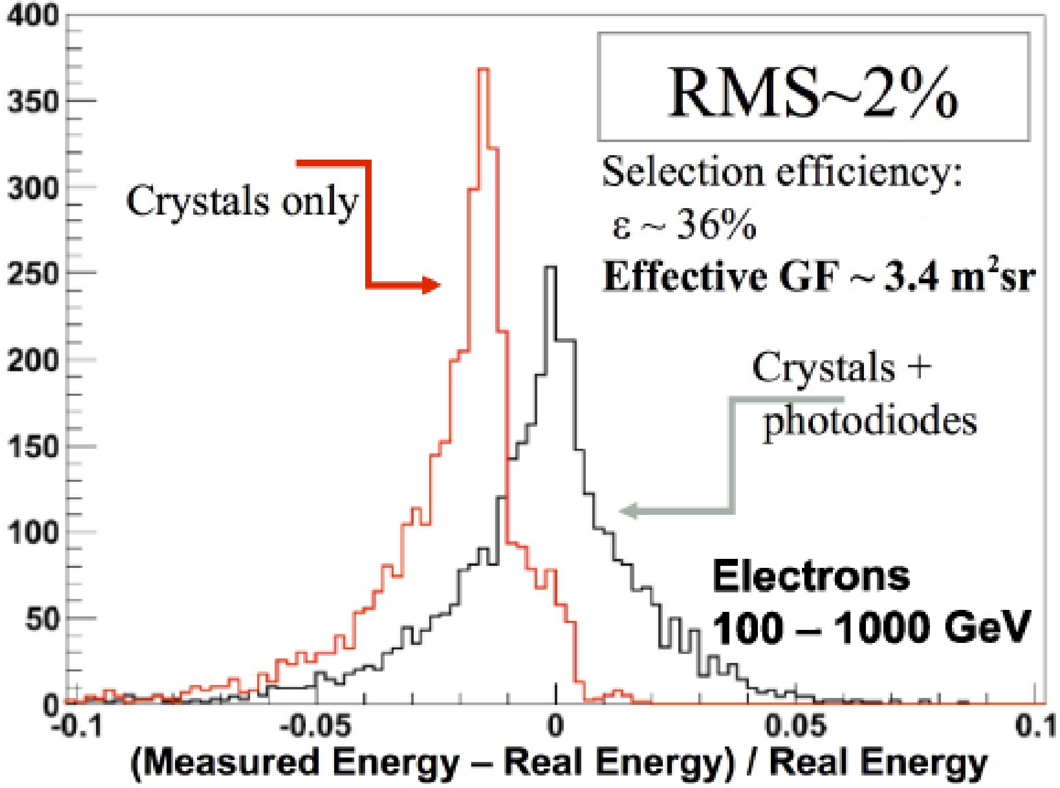
NxNxN	20x20x20
crystal side (cm)	3.6
crystal volume (cm^3)	46.7
gap (cm)	0.3
mass (kg)	1685
number of crystals	8000
size (m^3)	0.78x0.78x0.78
depth (R.L.) " (I.L.)	39x39x39 1.8x1.8x1.8
planar GF (m^2sr) *	1.91

*** GF only for one surface**

- Protons and electrons simulated with an isotropic generation on the top surface of the calorimeter
- **GF of 5 faces = 9.55 m^2sr**
- Effective geometric factor → $\mathbf{GF_{eff} = GF_{5faces} * \varepsilon_{selection}}$

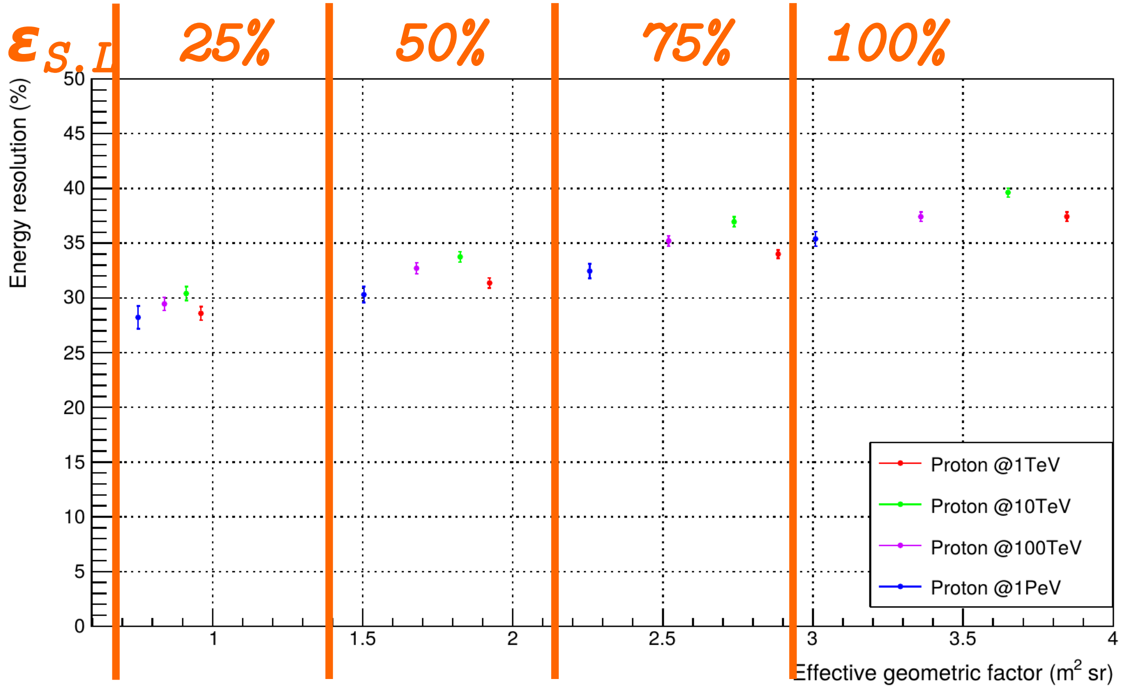
Electron energy resolution

- Isotropic flux of electrons form 100 GeV to 1 TeV
- Events selection: length of shower at least 22 X_0
  - Selection efficiency ~ 36%
  - Effective GF = 3.4 m^2sr
  - Energy resolution ~ 2 %
  - Direct ionization on PD ~ 1.7% of the mean signal
  - Low energy tails due to leakage and energy loss in passive materials (carbon fiber structures)



Proton energy resolution

- **Energy resolution for protons @ different energies and with different shower length selections**



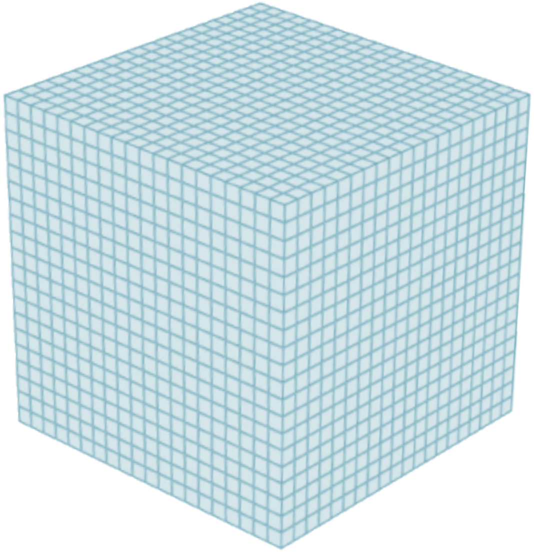
- **An increase in effective geometric factor (from ~ 0.8 m^{2}sr to ~ 3.5 m^{2}sr) translates in an increase of the energy resolution (from ~ 28% to ~37%)**
- **Energy resolution is almost constant with proton energy**

Geometry & Materials

- **Optimization of energy resolution and acceptance for protons**
- **Same simulations and analysis with different materials and distance among crystals (gap)**

- **Cube of cubes, 1 Moliere-radius size each**
- **Total weight ~2 tons**
- **Active-volume fraction 78%**

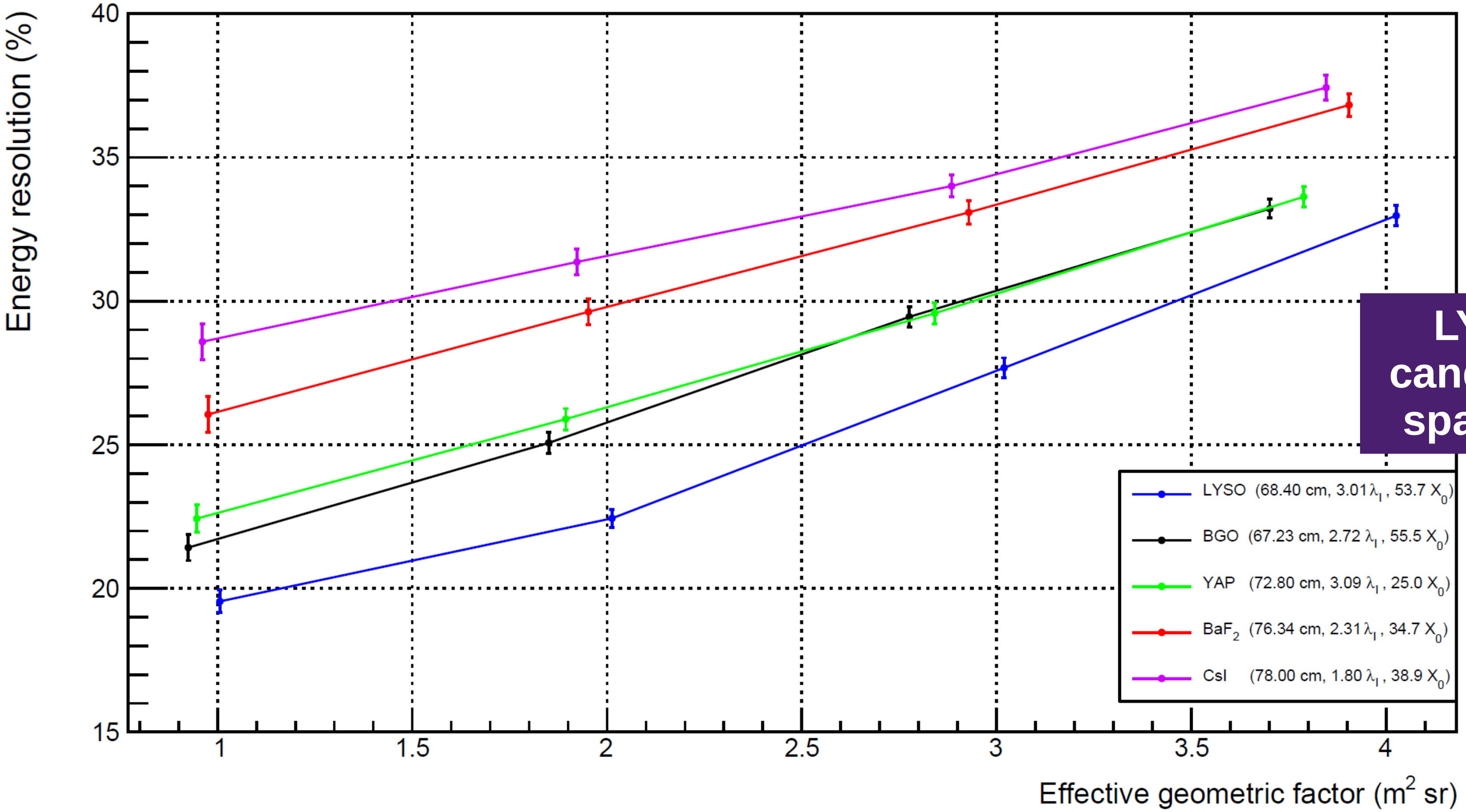
	CsI:Tl	**BaF_2**	**YAP:Yb**	**BGO**	**LYSO:Ce**
ℓ (cm)	3.60	3.20	2.40	2.30	2.10
gap (cm)	0.30	0.27	0.20	0.19	0.18
N° cristalli	$20 \times 20 \times 20$	$22 \times 22 \times 22$	$28 \times 28 \times 28$	$27 \times 27 \times 27$	$30 \times 30 \times 30$
L (cm)	78.00	76.34	72.80	67.23	68.40
λ_I totali (λ_I)	1.80	2.31	3.09	2.72	3.01
X_0 totali (X_0)	38.88	34.73	24.96	55.54	53.75
G $(m^2 sr)$	9.56	9.15	8.32	7.10	7.35



Best choice dictated by balance between **size** (density of the absorber) and **shower-containment** (interaction length), which determines energy resolution

Materials: energy resolution vs acceptance

- **Proton @ 1TeV**
- **Effective geometric factor = $GF_{single\_face} * 5 * \varepsilon_{Selection}$**



LYSO is a good candidate for future space calorimeters

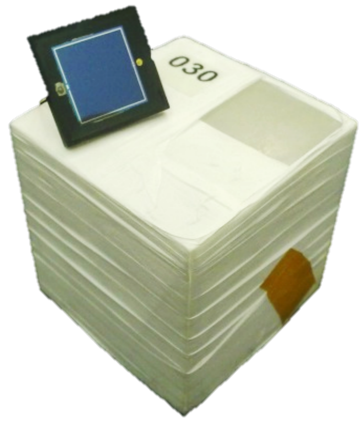
Sensors

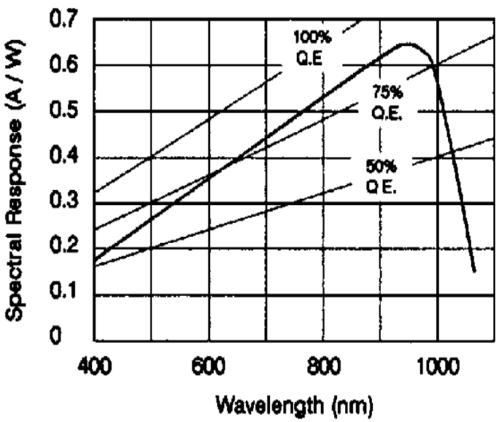
Large area photodiode VTH2090:

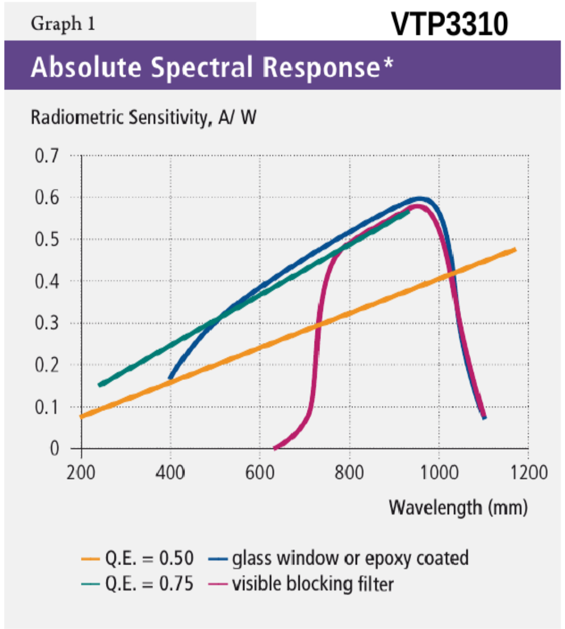
- Active area 84.64 mm^2
- 1 MIP in CsI(Tl) ~ 7fC
- Max signal 30 nC (>> CASIS range)

Small area photodiode VTH9412:

- Active area 1.6 mm^2
- Max signal 300 pC (> CASIS range)



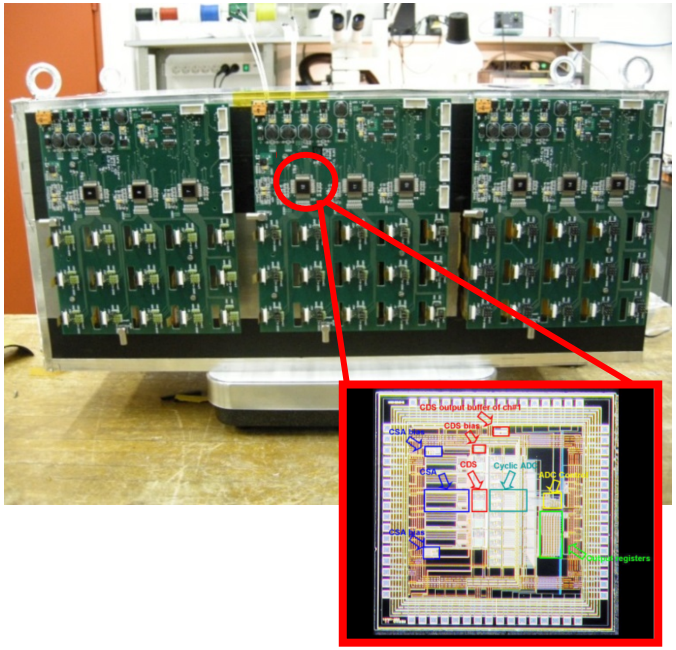




BigPD/SmallPD = 100

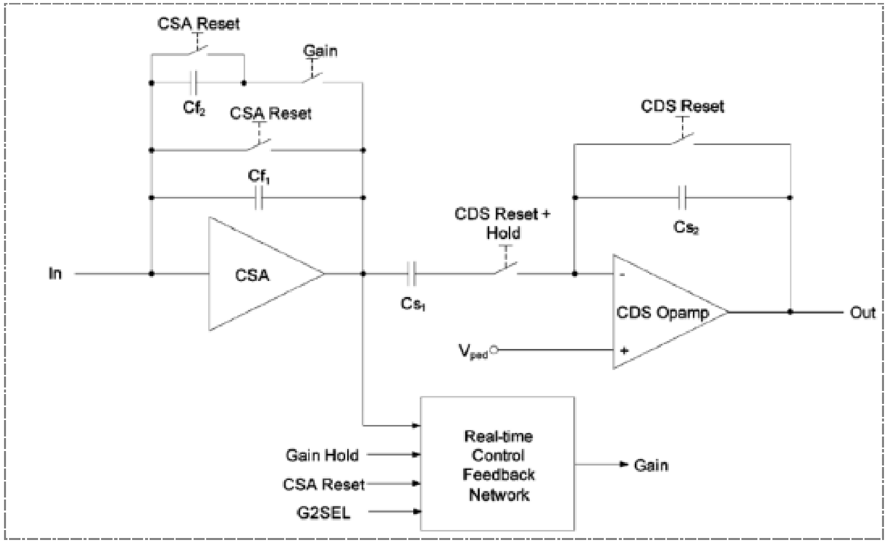
Front-end electronics

- **ASIC chip developed by INFN Trieste**
- 16 channels
- Charge Sensitive Amplifier
- Double-gain 1:20 with an automatic gain-selection circuitry
- Correlated Double Sampling (CDS) filter.

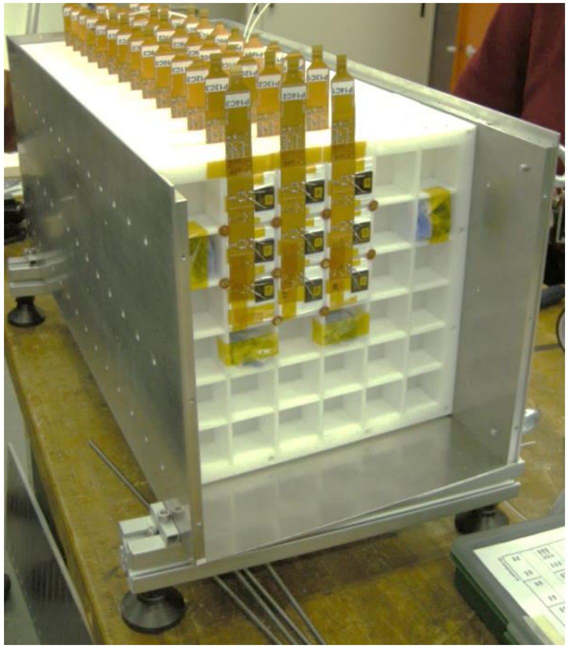


PERFORMANCE

- High dynamic: from fC to 52.6 pC
- Low noise (ENC ~ $2280e^{-} + 7.6e^{-}/pF$)
- Low power consumption: 2.8 mW/channel



Prototype

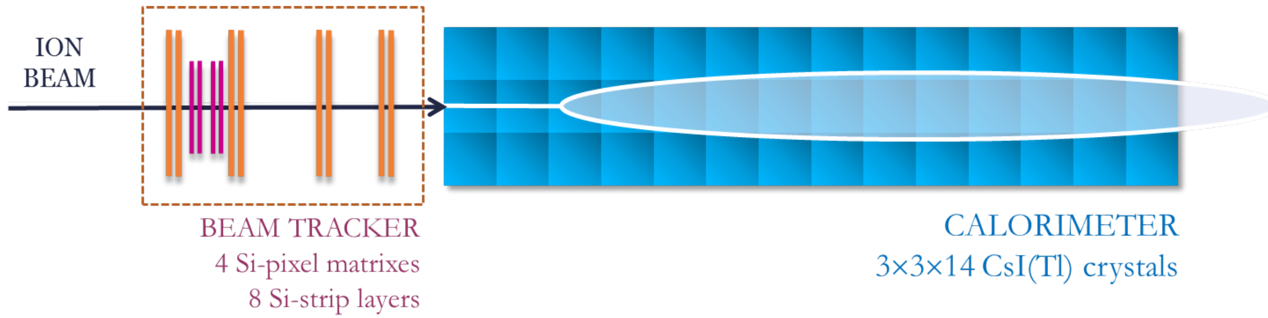


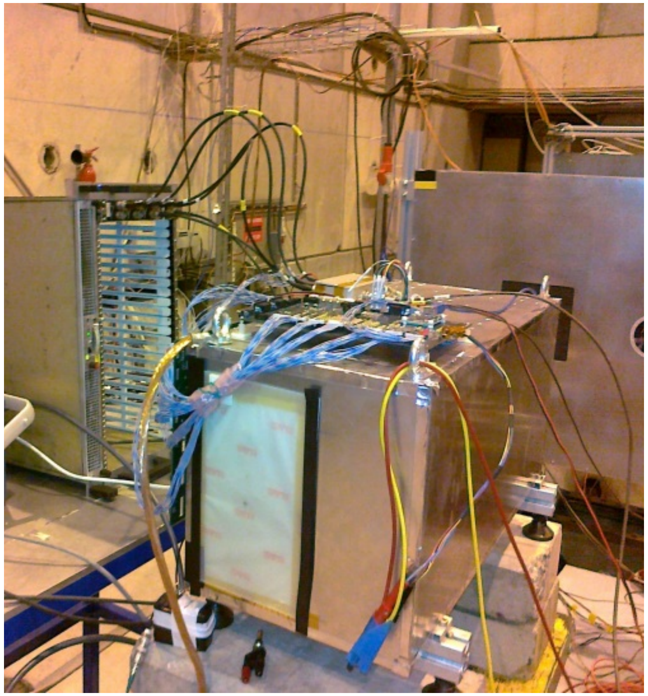
- **15 Layers**
- **3 x 3 CsI(Tl) crystals in each layer**
- Crystal side ~ Moliere radius (3.6 cm)
  - ~ **1.5 R_M** shower containment
- Gap 0.4 cm
- A big PD (VTH2090) for each crystals
- A small PD for 3 crystals
- **Depth for vertical track:**
  - active depth **28.4 X_0 → 1.35 λ_I**
- Wrapping materials:
  - Version 1.0: Teflon
  - Version 1.2: Vikuiti
- 3 front-end electronics board:
  - 9 CASIS chip, 3 ADC

Three upgrades (v1.0-1-2), tested with particle beams

Feb 2013	v1.0	Ions Pb+Be 13-30 GeV/u
Mar 2015	v1.1	Ions Ar+Poly 19-30 GeV/u
Aug/Sep 2015	v1.2	μ, π,e 50-75-150-180 GeV

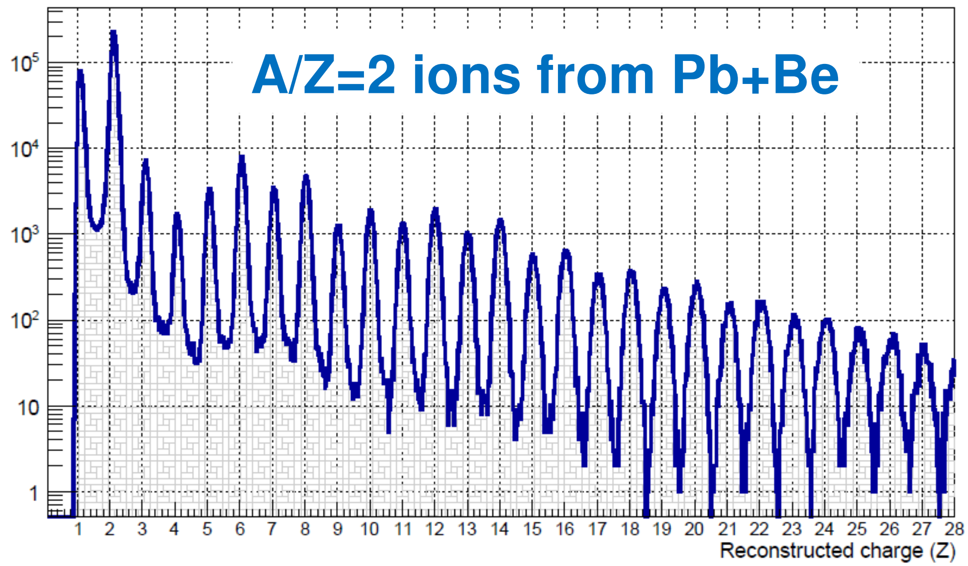
Test with ion-beam

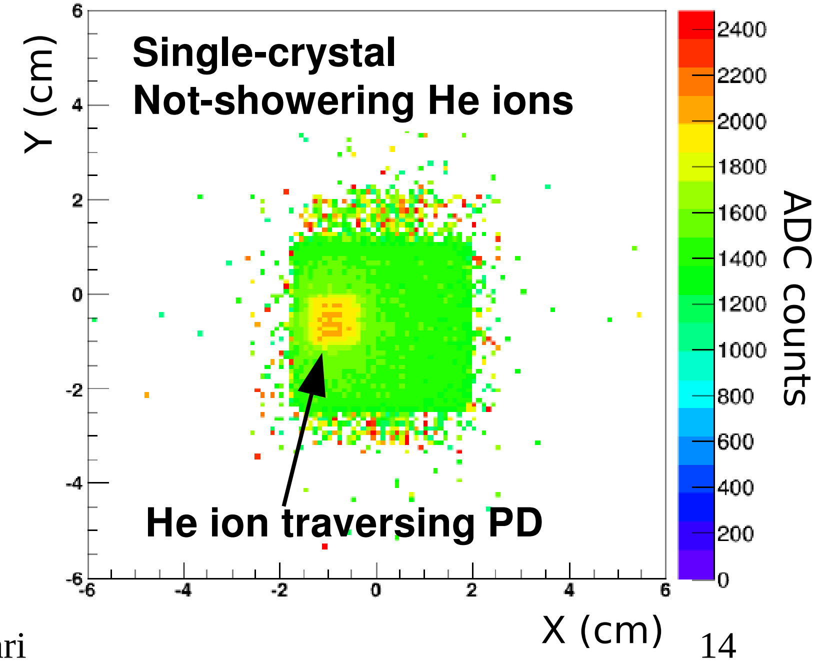




Prototype v1.0 exposed to ion beams of 13 and 30 GeV/n (Feb-2013 @CERN-SPS)

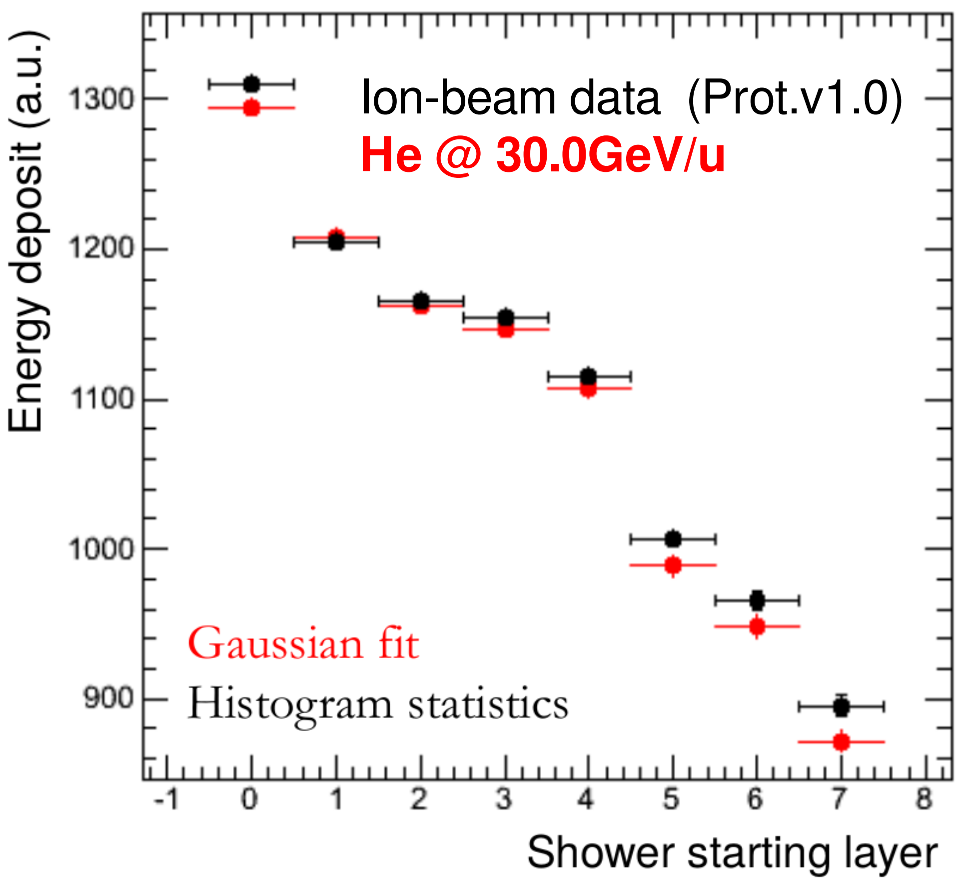
Precise Z-tagging & beam position from BT (INFN Pisa/Siena)

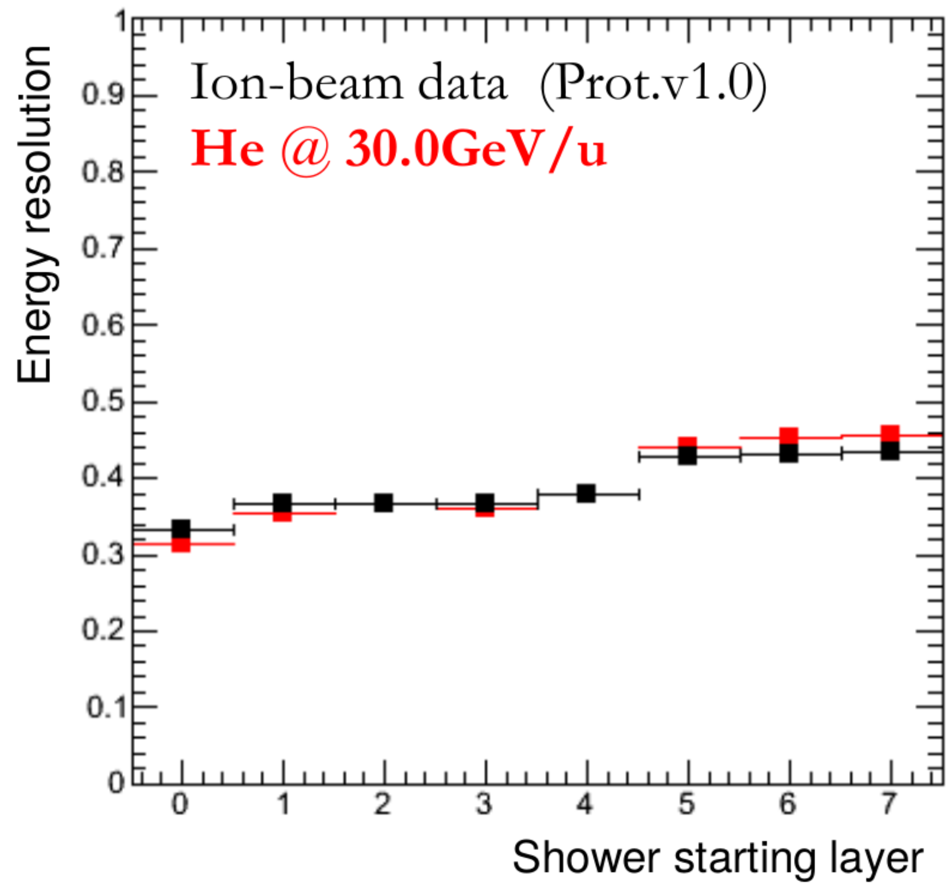




Energy deposit vs shower containement

- Double thresholds algorithm is used in order to found the shower starting point

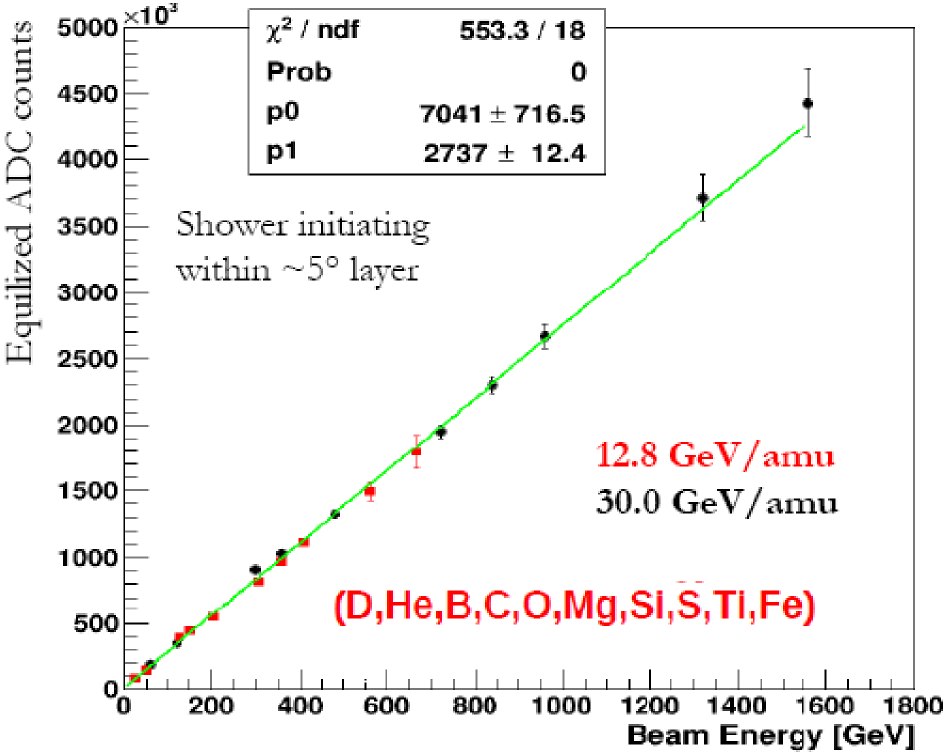


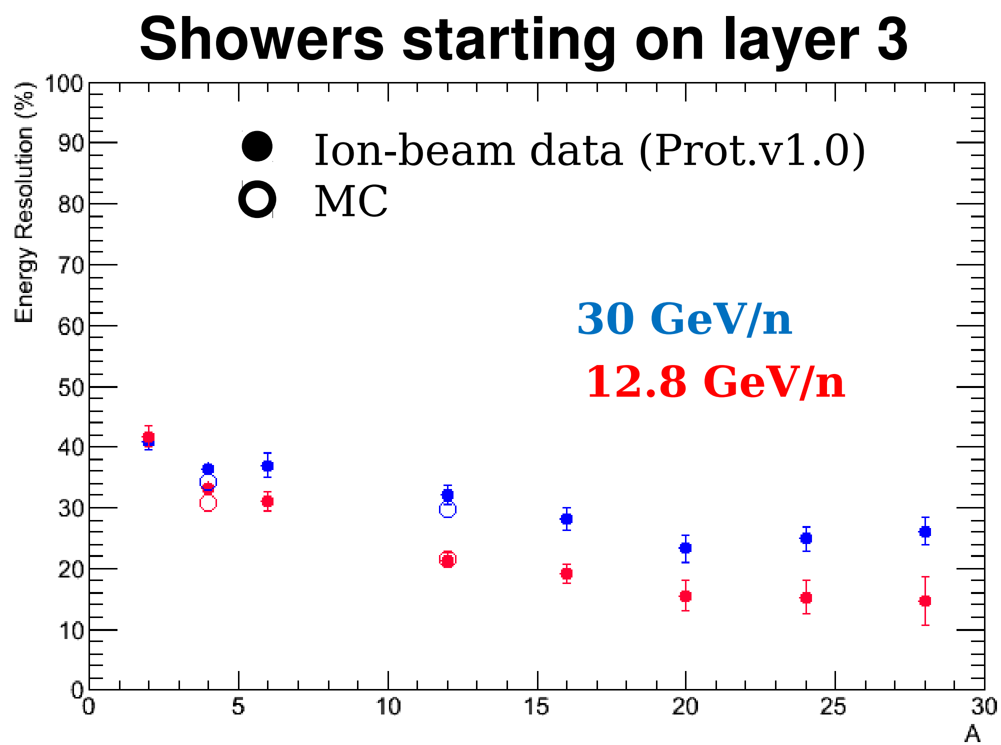


Linearity vs beam energy

Good linearity up to 1.6 TeV of ion energy with just the large area photodiode

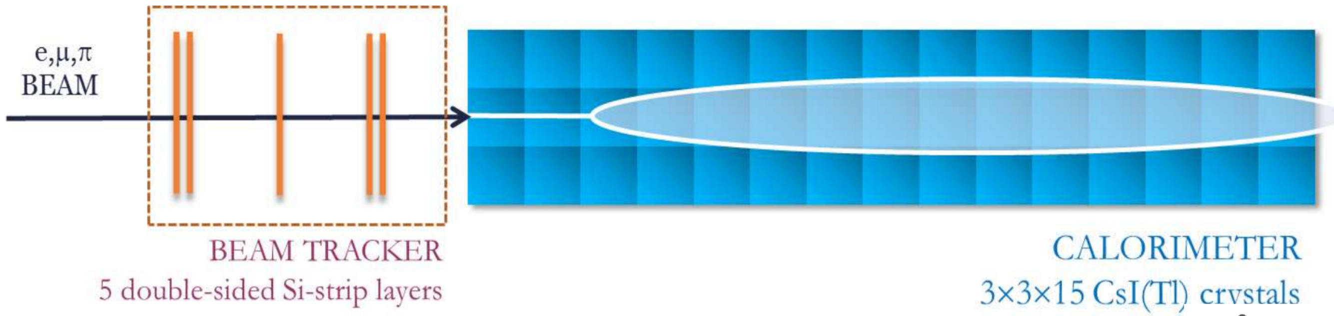
Energy resolution improves with A. Good agreement between data and MC





Beam test with electrons

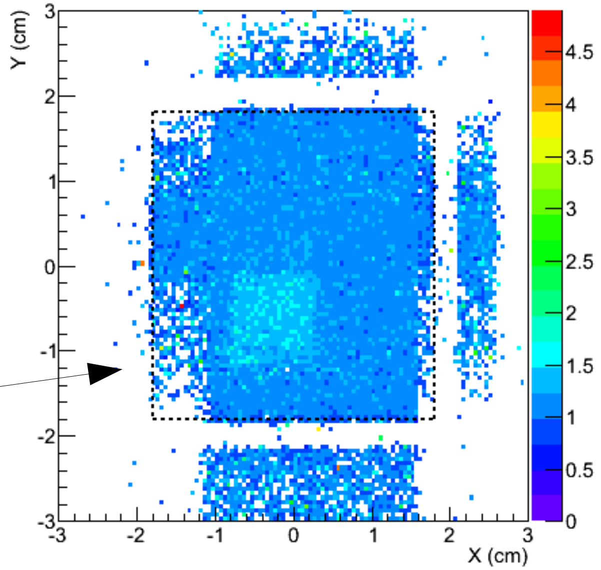
- CERN, SPS, H8 area, Electron from 50 GeV to 200 GeV
- Tracking is performed with ADAMO, 5 layer of silicon micro-strip detector, double sided (X,Y)



Energy deposit by muons @ 150 GeV in the central cube of the first layer

Good identification of crystals positions

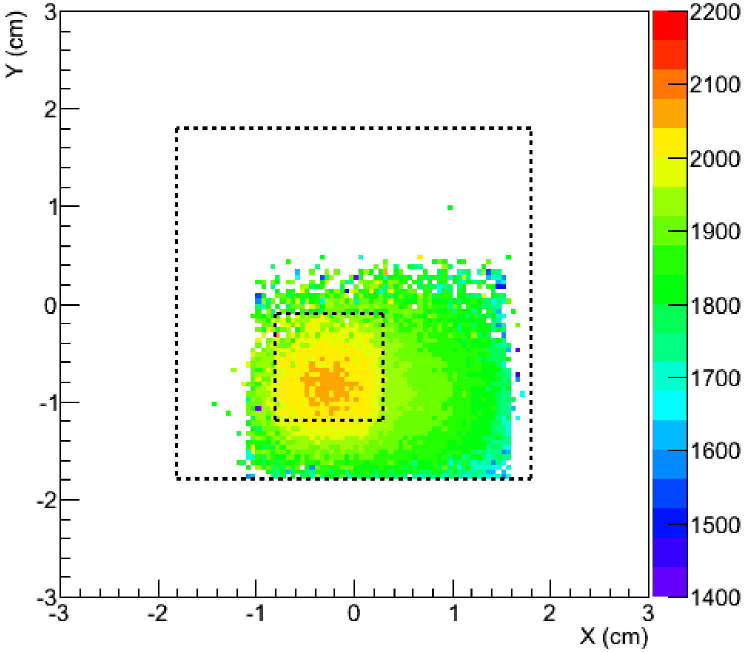
Reconstruction of PD position is also possible because of direct ionization



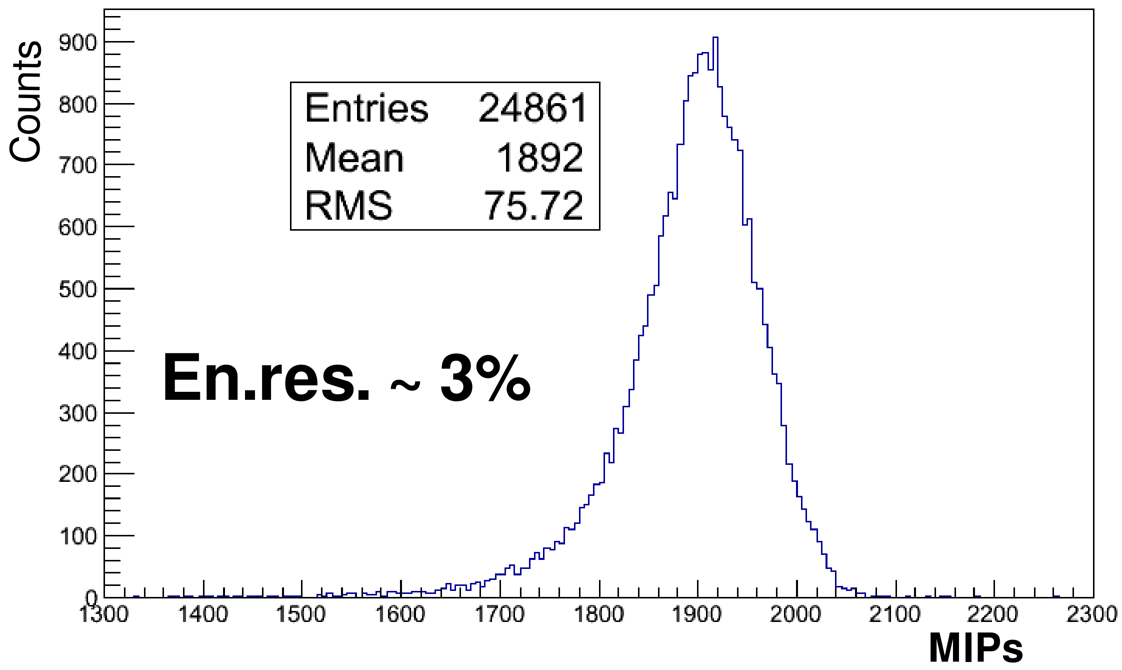
Energy deposit by electrons

- **Electrons @ 50 GeV: the PD direct ionization has big impact on the energy deposit (and energy resolution) because all tracks are vertical**

Electron @ 50 GeV



Electron @ 50 GeV

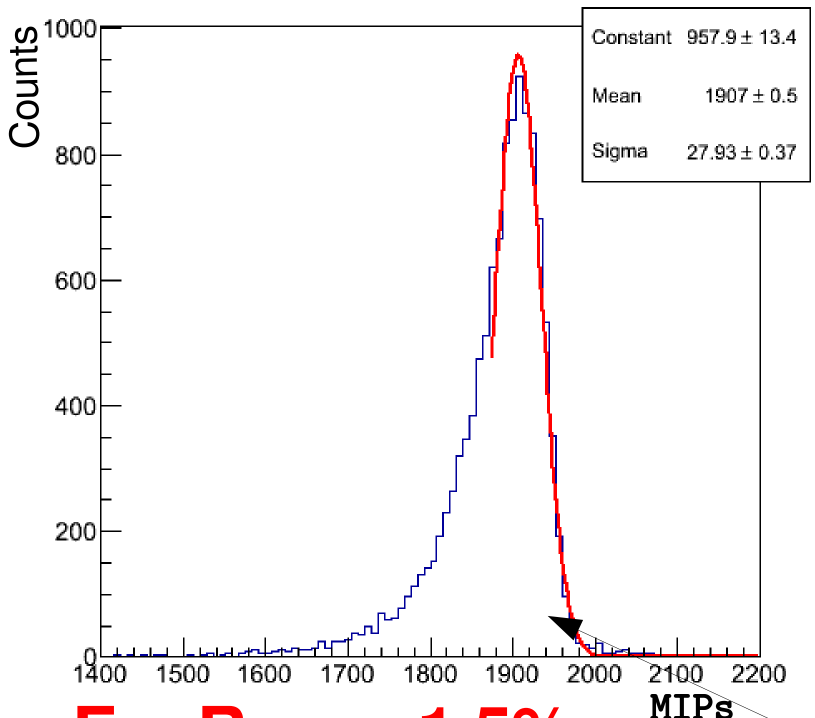


- In order to study the prototype performance a FLUKA based simulation with detailed prototype geometry was developed

Mc data vs beam data

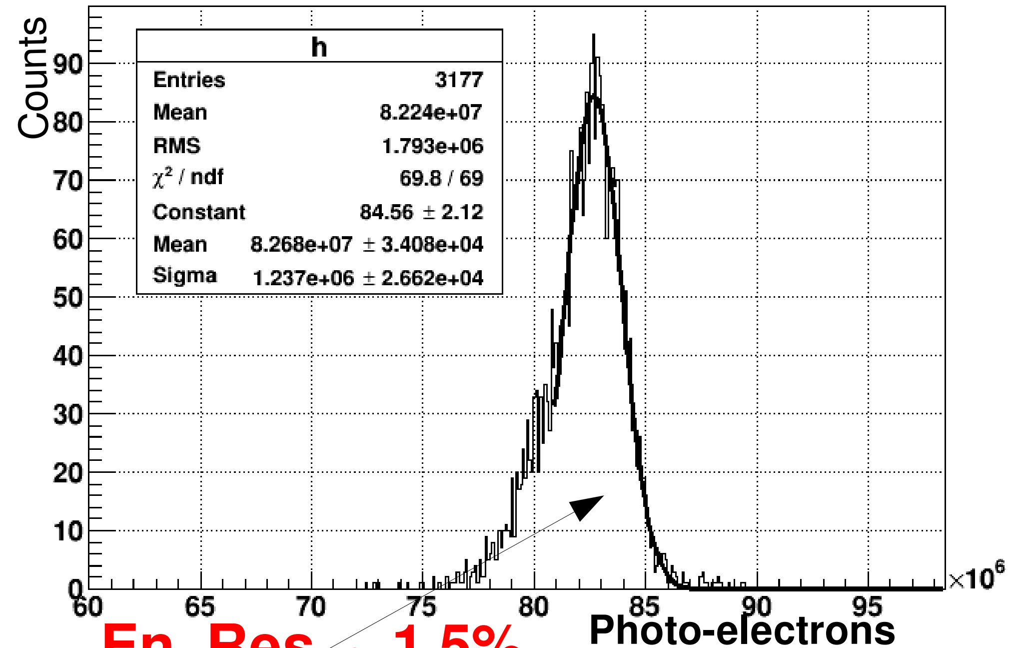
- Electrons @ 50 GeV energy deposit after <u>geometrical selection of events with direction that does not intercept the PD</u> (both in simulation and beam data)

Beam data: Electron @ 50 GeV



En. Res. ~ 1.5%

MC data: Electron @ 50 GeV

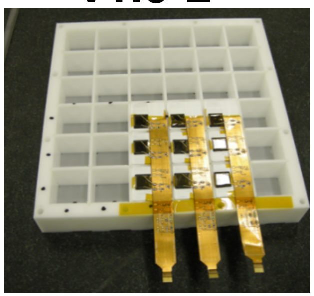


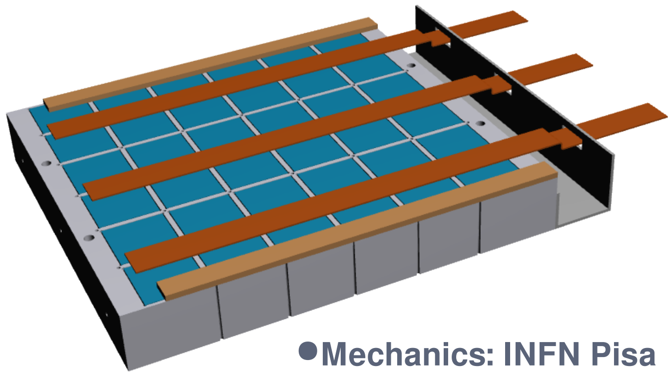
En. Res. ~ 1.5%

- **Very good agreement between simulation and beam data**

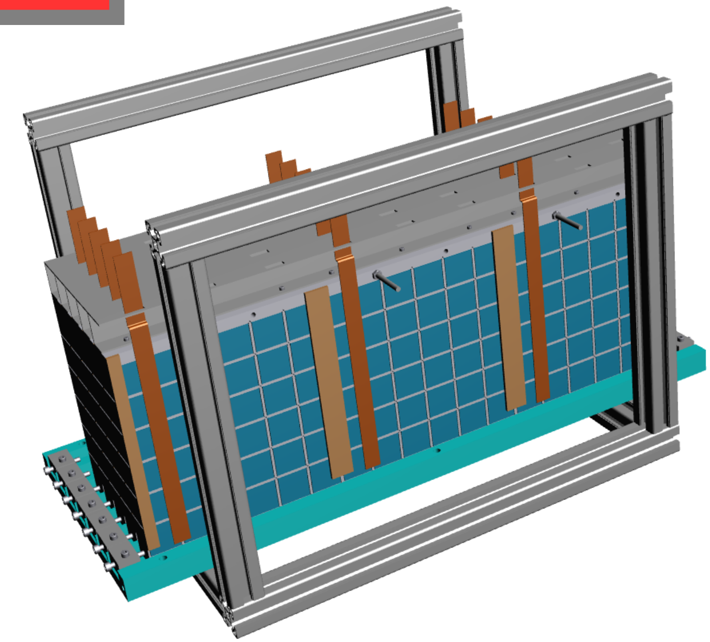
Prototype upgrade (v2.0)

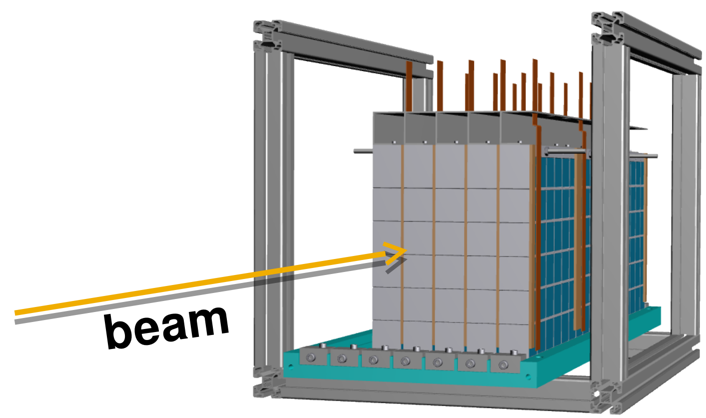
v1.0-2





● Mechanics: INFN Pisa





- **Prototype mechanics completely redesigned**
  - **18 trays x 25 crystals each**
  - **trays mounted sideways!**

- 18 layers along the beam line
  - active depth **35.0 X_0 $\rightarrow$ 1.6 λ_I**
- 5x5 elements for each layer
- PDs placed laterally

Summary

- The CaloCube R&D project, aiming to develop a novel design calorimeter, optimized for high-energy CR measurements in space, was presented.
- As a proof-test of the CaloCube concept, a prototype made of CsI(Tl) has been constructed and tested, in several versions, with particle beams, obtaining performances close to the expectations
- A comparative study of CsT(Tl) vs other materials is under progress
- Other items, not covered by this presentation:
  - Study of alternative dual-readout approach (e.g. BaF2 slow/fast component...)
  - Beam-test activity @BTF for Cherenkov readout
  - Study of full mechanical structure, qualified for space
  - Study of crystal-calibration system based on LED-light