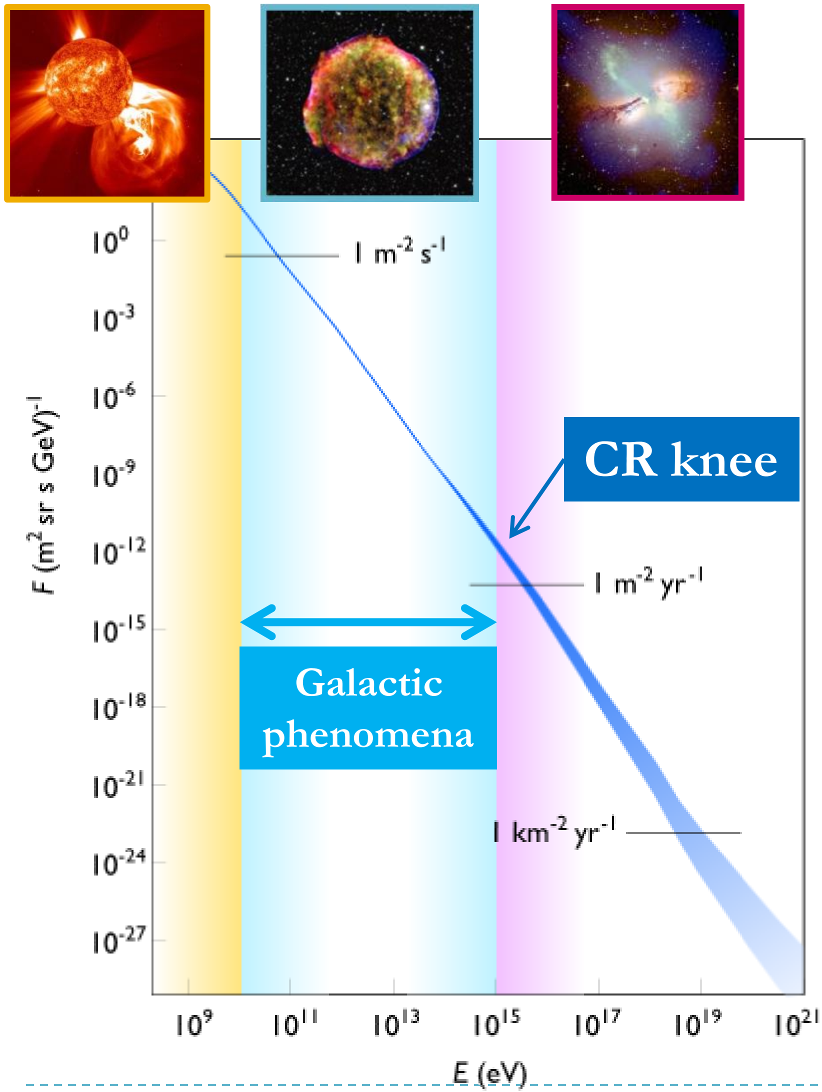
CaloCube: a new-concept calorimeter for the detection of high-energy cosmic rays in space

E.Vannuccini (INFN Florence)
On behalf of the collaboration

The CaloCube collaboration

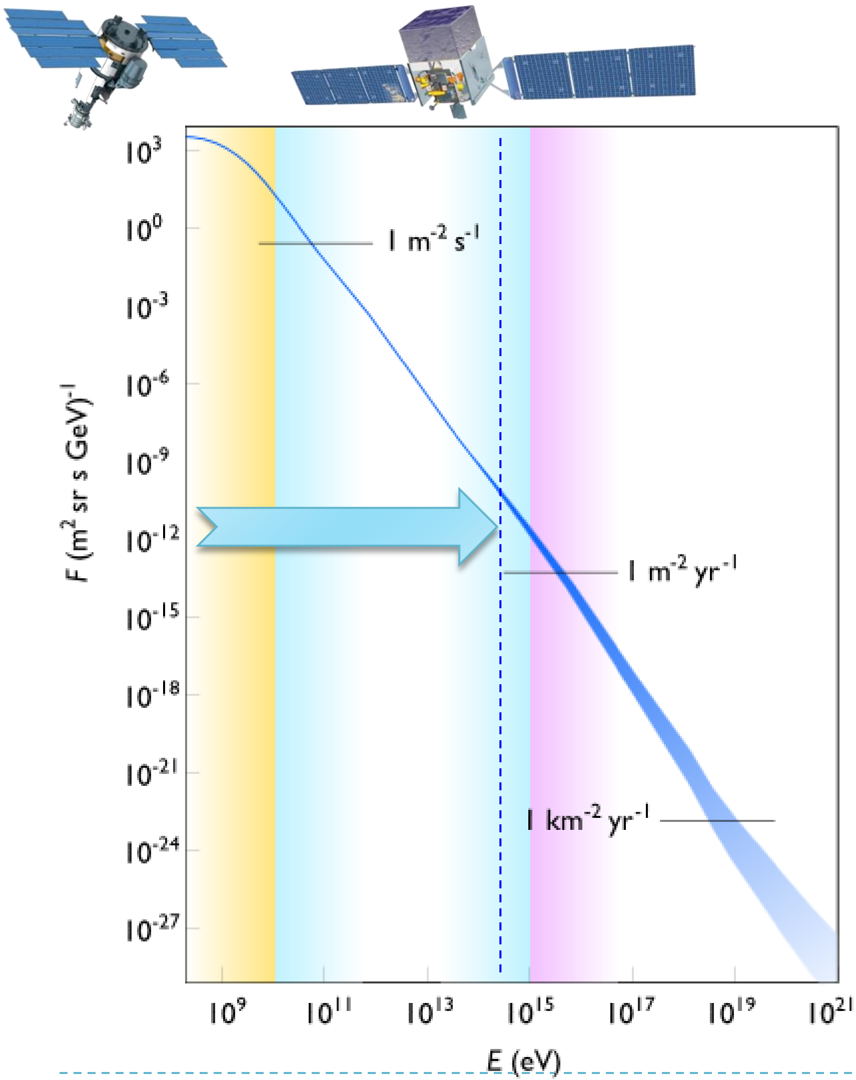
- R&D project financed by INFN for 3 years (end 2016)
  - Design and optimization of a calorimeter for measurements of high-energy cosmic rays in space
- Participants:
  - INFN: Catania/Messina, Florence,
    Milano (Bicocca), Pisa, Pavia, Trieste/Udine
  - CNR-IMM-MATIS Catania (dichroic filter deposition)
  - IMCB-CNR Napoli (Surface treatments and WLS deposition)
  - Contacts with CNR Firenze
- Wide range of expertises: calorimetry, cosmic-ray physics, VLSI analog design, scintillating crystals, polymeric coatings, interferometric filters,…
- In this talk, an overview of items mainly related to the activity of Florence group

Scientific background



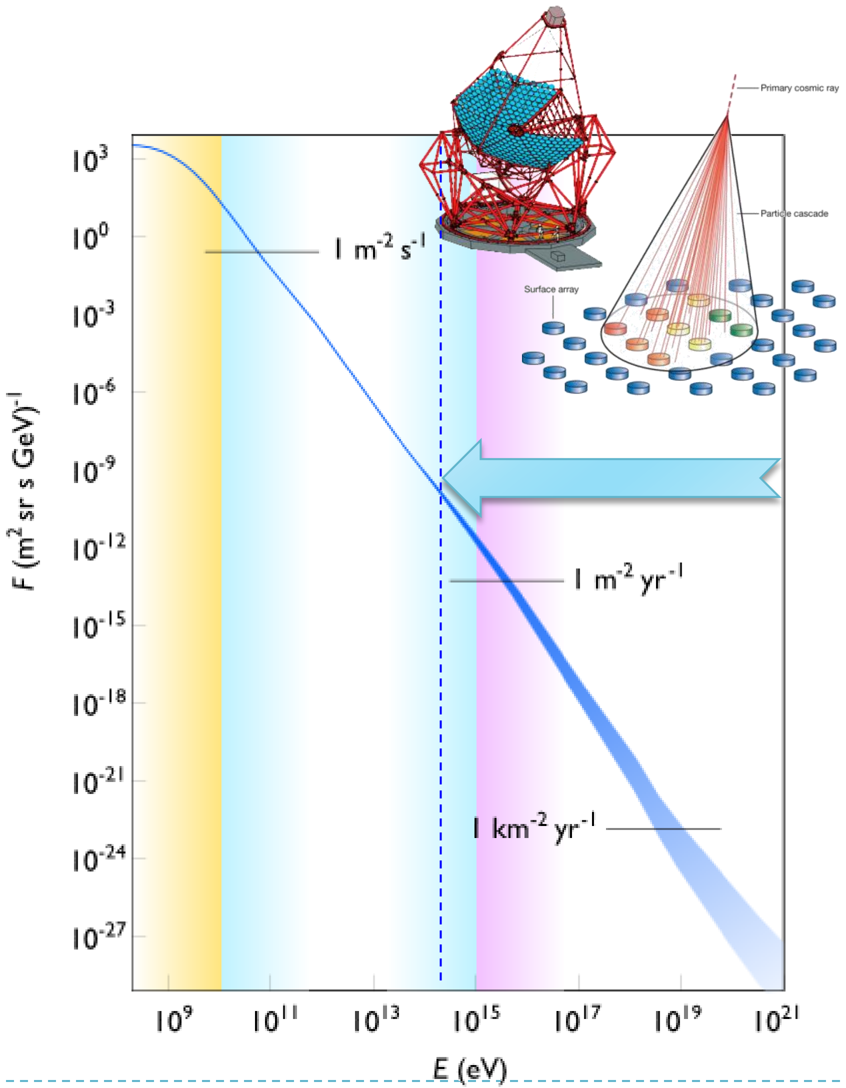
- Focus on **galactic cosmic** rays
- Key items:
  - Identification of acceleration-sites
  - Acceleration mechanisms
  - Diffusion and confinement within the Galaxy
  - Transition to extragalactic component
  - Additional component of dark matter?
- @ the «**knee**» → energy limit of galactic accelerators and/or confinement

Scientific background



- **Direct experiments**
  - Precise spectral measurements
  - Individual particle identification
  - Limited in energy due to statistics
- Nuclear component:
  - Measured up to 100TeV
  - Hardening @200GeV
  - Secondary nuclei (B) up to 1TeV/n
- Electron and positrons
  - Positron excess above 10 GeV
  - All-electron spectrum measured up to 1TeV
- Waiting for CALET,DAMPE and ISS-CREAM (?) data

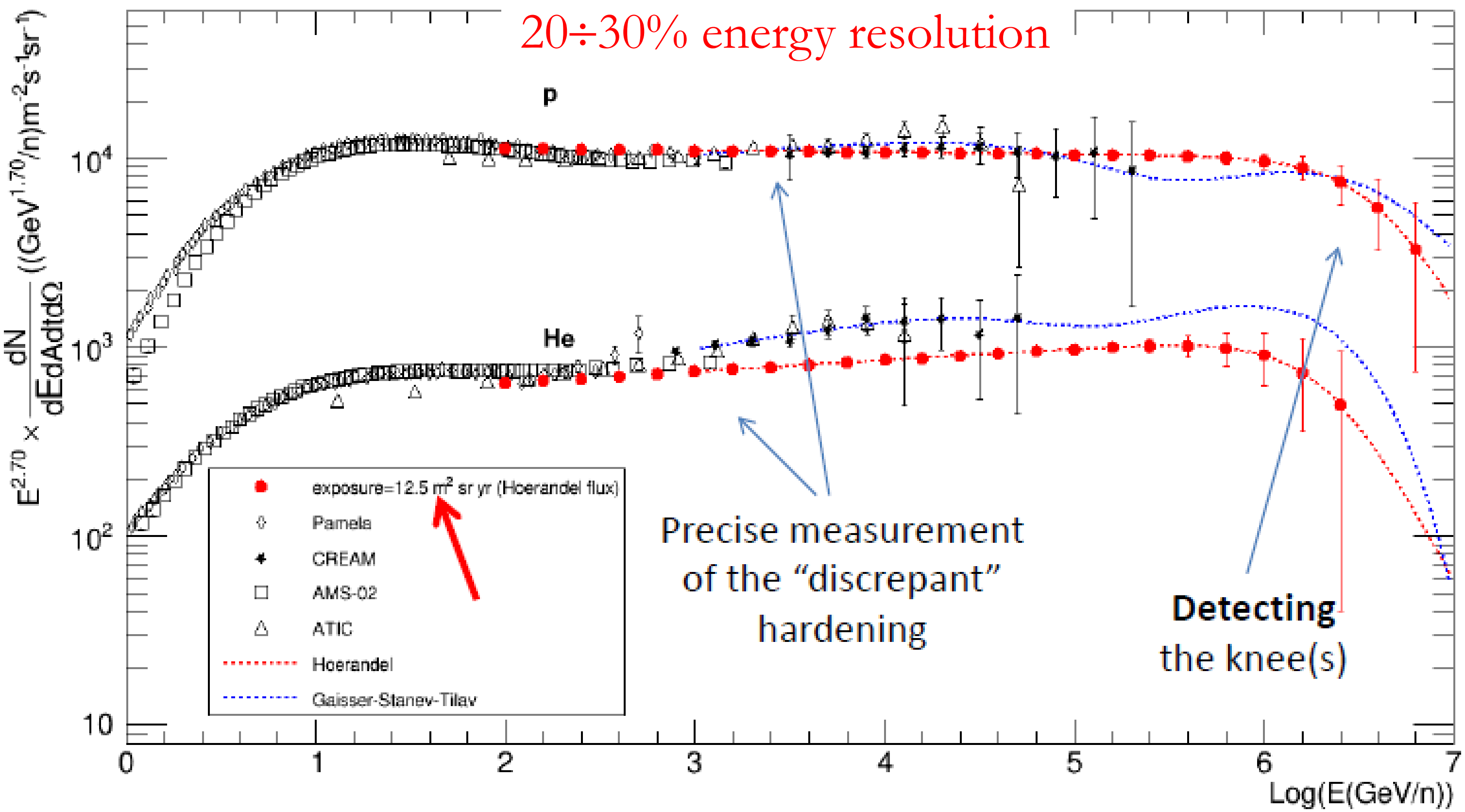
Scientific background



- **Indirect experiments**
  - Large statistics, down to 100TeV
  - Large systematics
  - Difficult composition measurements
- Nuclear component
  - Knee of inclusive «light» component (~p+He) ranging between 600TeV and 3PeV
  - Average composition progressively heavier across the knee
- Inclusive-electron component
  - Spectral cutoff observed at 1TeV

$2.5\ m^2 sr \times 5$ yrs

20÷30% energy resolution



(From I.DeMitri, HERD workshop 2016)

Key items for the future

- Direct measurement of individual **proton** and **nuclei** spectra in space at high energy (up to **1 PeV**)
  - Needs
    - Extremely large acceptance (**few m^2sr**)
    - Good energy resolution (**better than 40%**)
    - Element identification capability

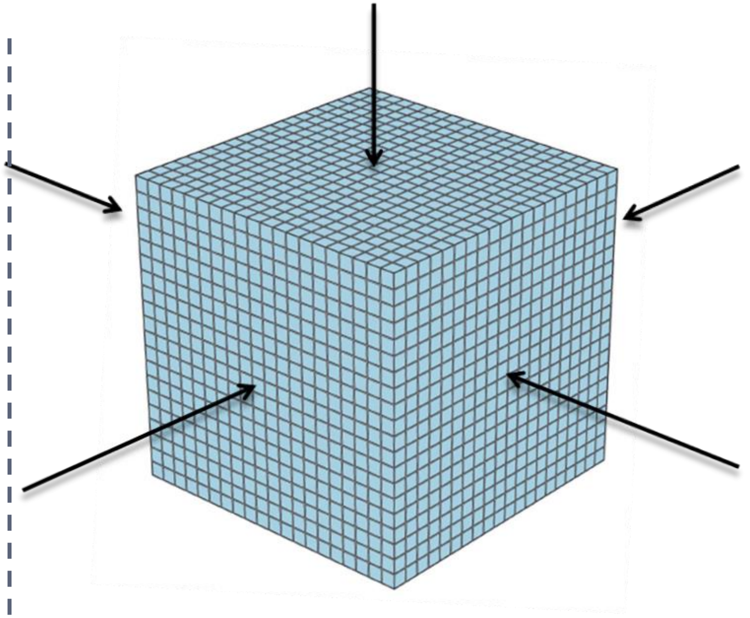
- Direct measurement of the **electron** component above 1TeV
  - Needs
    - Excellent energy resolution (**better than 2%**)
    - High h/e rejection power (**better than 10^5**)
    - Large acceptance above 1 TeV

- Most feasible choice:
  - **calorimeter** coupled to a **dE/dx-measuring device**

The challenge

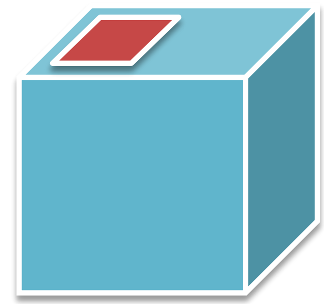
- Low flux of proton and nuclei
  - large acceptance required (at least few m^2sr)
- Space-borne instrument
  - Severe weight and size limitations → thin calorimeter (few i.l.s) !!!
  - Both geometrical factor and energy resolution are affected

- The proposed solution
  - Large acceptance
    - **Cubic geometry**, 5-facet detection
  - Good energy resolution
    - **Active absorber** (scintillating crystals)
  - Shower imaging
    - **3D segmentation** → isotropic response



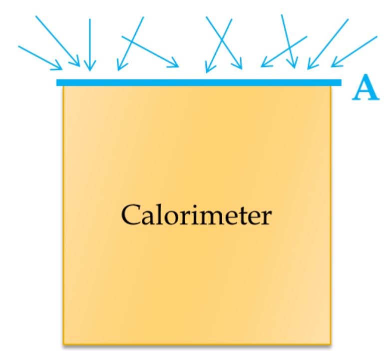
MC simulation

- Based on FLUKA package
- N×N×N cubic elements
- Active materials
  - Scintillating crystals
    - En.deposit-to-light conversion according to nominal L.Y.
  - Sensor
    - Si-Photodiods
    - Direct-ionization en.deposits taken into account
    - Signal induced by scintillation light according to nominal collection and quantum efficiencies



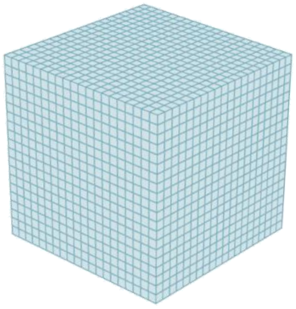
- Support structures
  - **Carbon fibers**, of reduced density, filling the gap among crystals
- Other features
  - Cherenkov and neutrons detection implemented
- Isotropic flux of particle on a generation surface A
- Effective geometrical factor

$$G_{eff} = A\pi \cdot \frac{N_{sel}}{N_{gen}}$$ → depends on selection



Geometry & materials

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

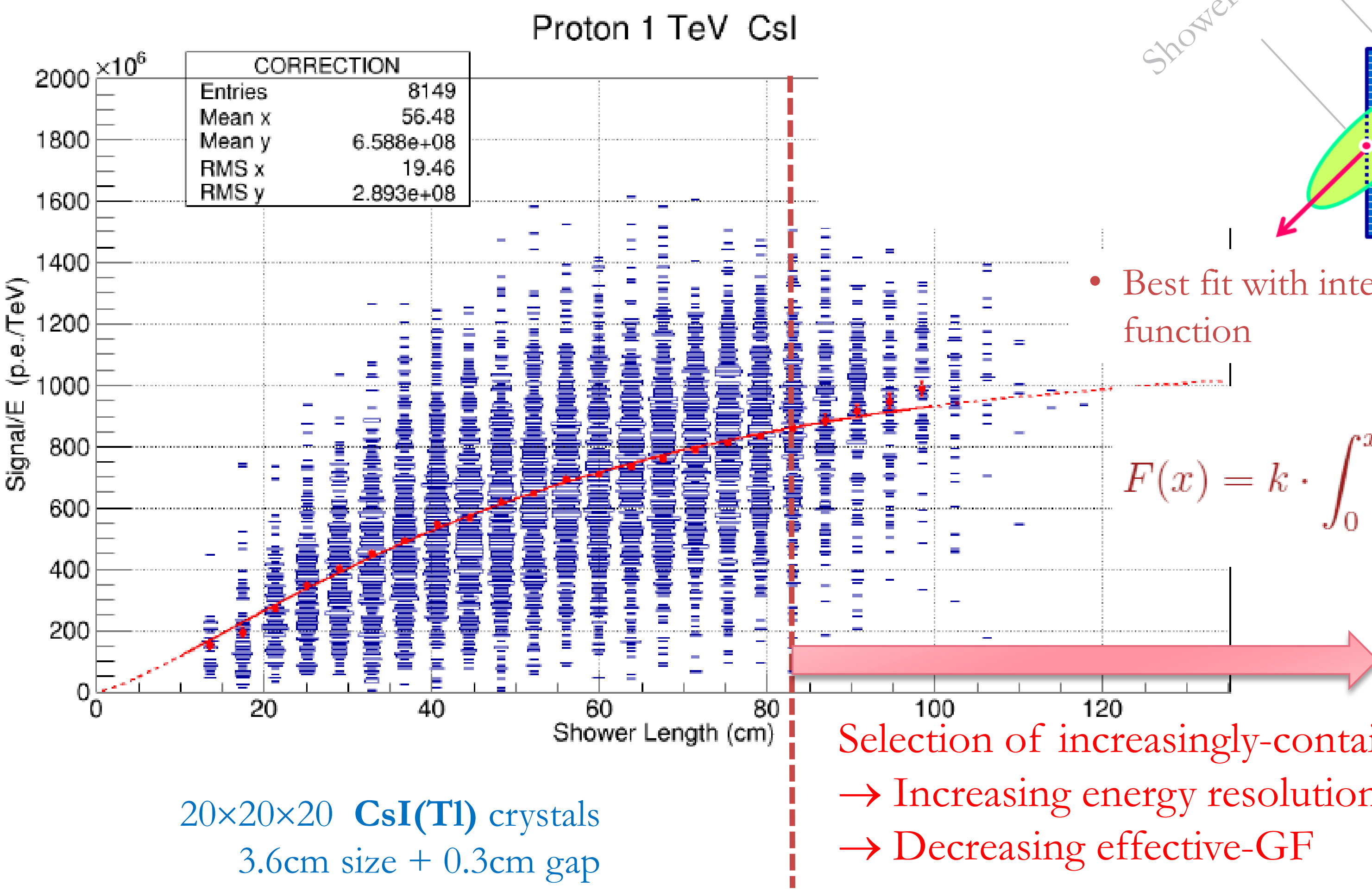


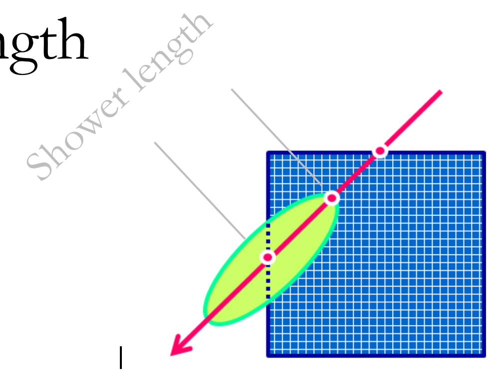
	CsI:Tl	**BaF_2**	**YAP:Yb**	**BGO**	**LYSO:Ce**
ℓ (cm)	3.60	3.20	2.40	2.30	2.10
gap (cm)	0.30	0.27	0.20	0.19	0.18
N° cristalli	$20 \times 20 \times 20$	$22 \times 22 \times 22$	$28 \times 28 \times 28$	$27 \times 27 \times 27$	$30 \times 30 \times 30$
L (cm)	78.00	76.34	72.80	67.23	68.40
λ_I totali (λ_I)	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 determine energy resolution

Energy determination

- Deposited energy depends on the shower length





- Best fit with integral of a gamma function

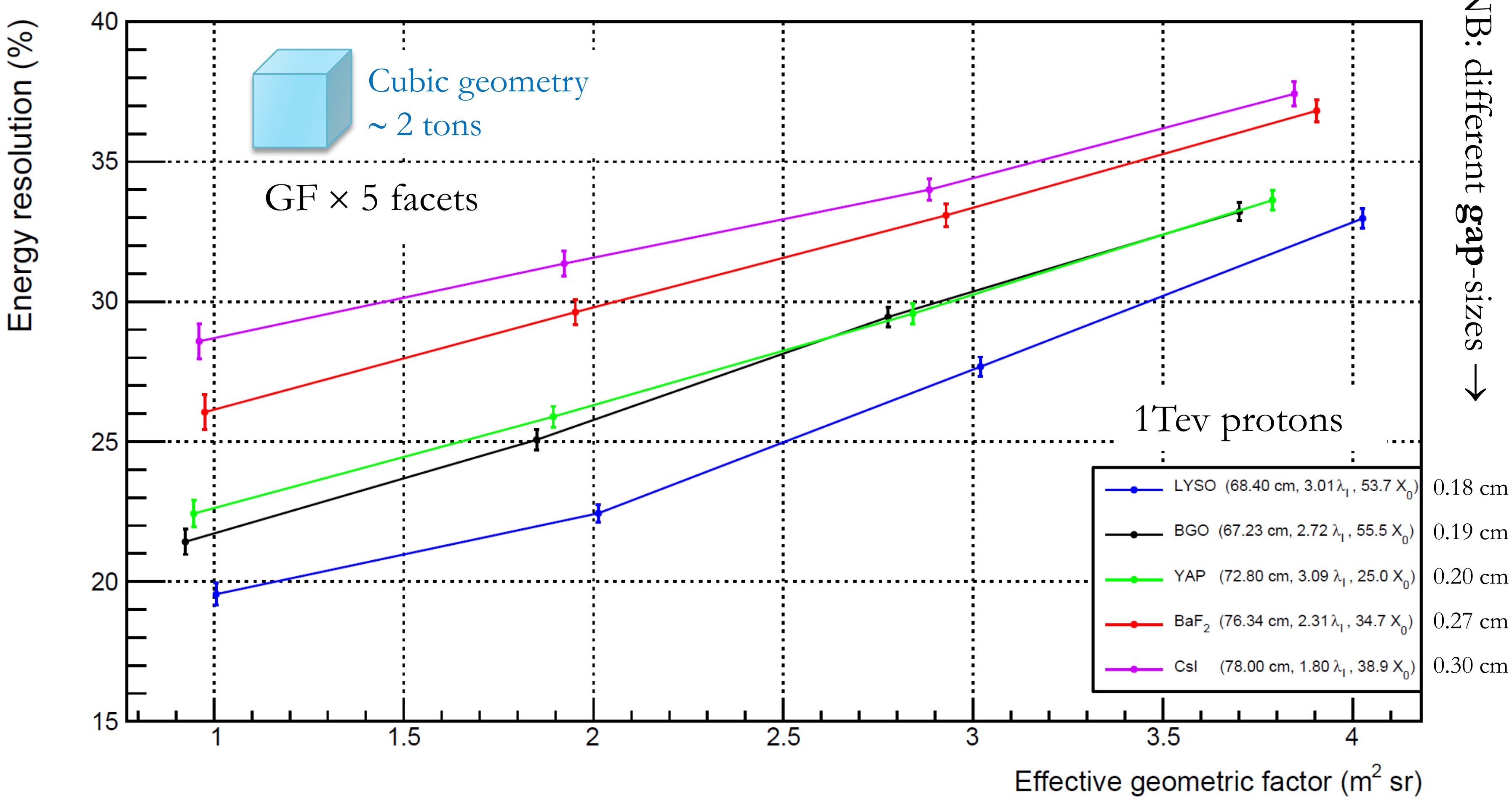
$$F(x) = k \cdot \int_0^x b \, \frac{(bt)^{a-1} \, e^{-bt}}{\Gamma(a)} \, dt$$

Selection of increasingly-contained events
→ Increasing energy resolution
→ Decreasing effective-GF

20×20×20 **CsI(Tl)** crystals
3.6cm size + 0.3cm gap

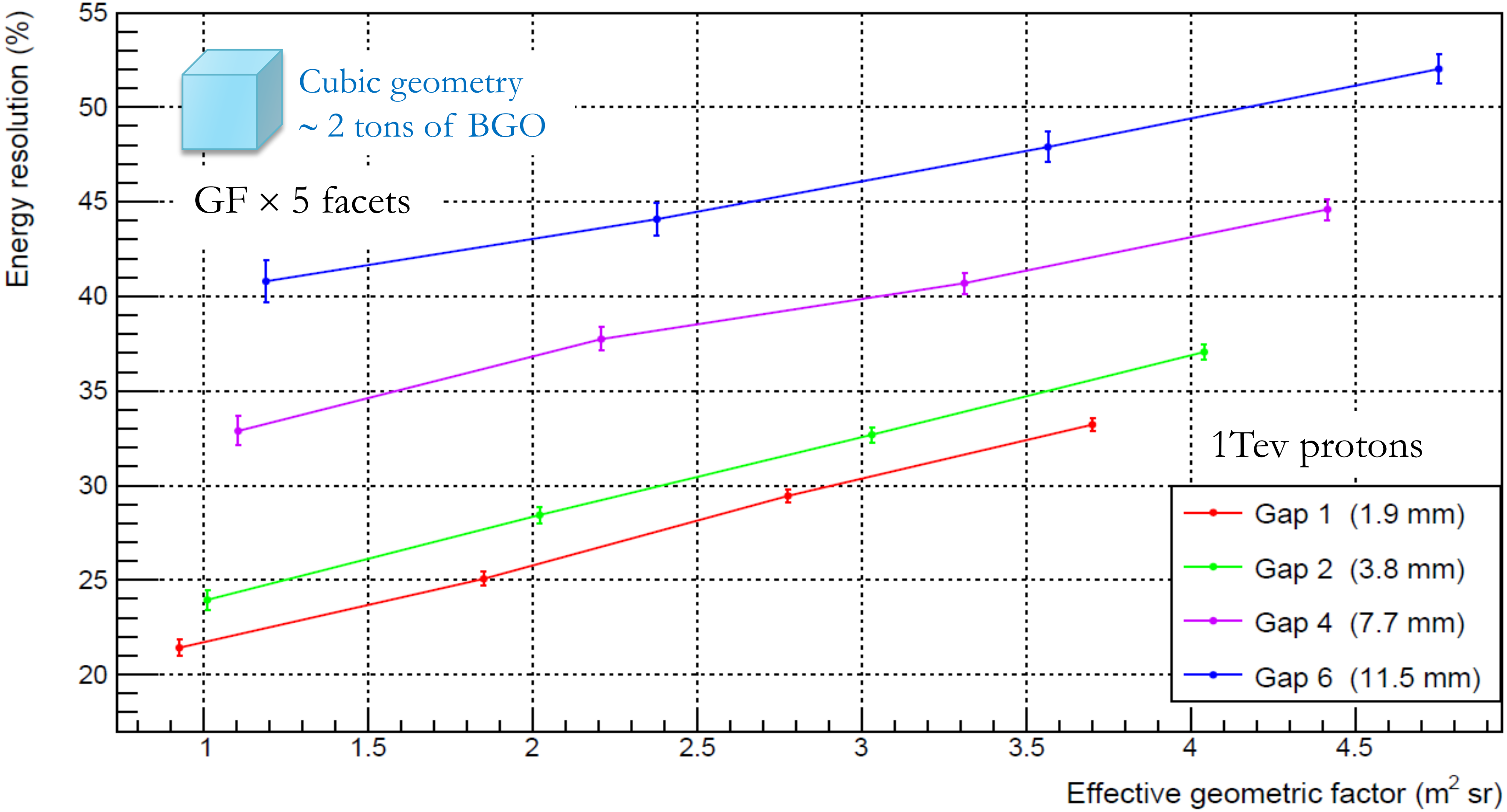
Energy resolution ↔ Effective GF

Dependence on various scintillating material



Energy resolution ↔ Effective GF

Dependence on distance among crystals



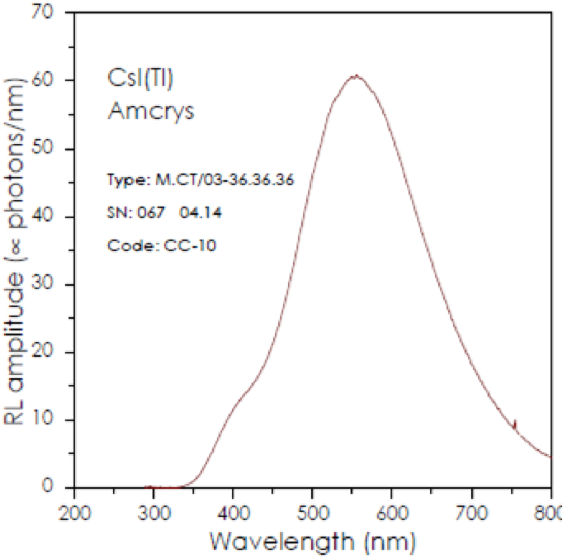
Scintillating material

- **CsI(Tl)** crystals

Density	**4.51 g/cm^3**
Wavelength @max	**550 nm**
Light output	**54 ph/keV** (45 % of NaI(Tl))
Primary decay time	**1 ms**

- Produced by **Amcrys**
- **3.6 cm** side (~ 1 Molière radius)

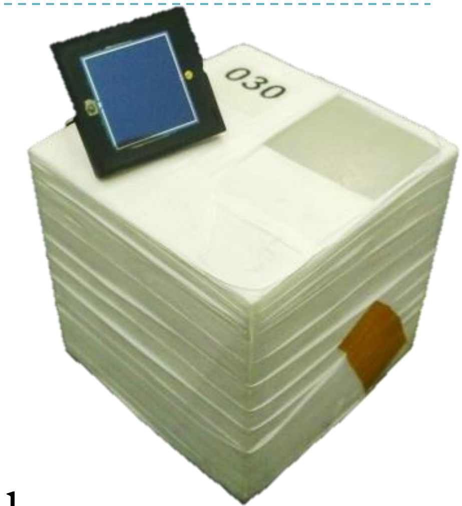
- Expected optical signal
  - 1MIP → ~ 20 MeV ~ 10^6 ph/facet
  - (assuming 80% collection efficiency on one facet from ray-tracing simulation with diffusive surface)



Sensors

- Detector requirements:
  - Sensible to MIPs
  - Shower reconstruction capabilities up to 1PeV
    - From MC, up to 10% of incident energy deposited on a single crystal

→ Dynamic range ($0.5 \div 5 \cdot 10^6$ MIP)



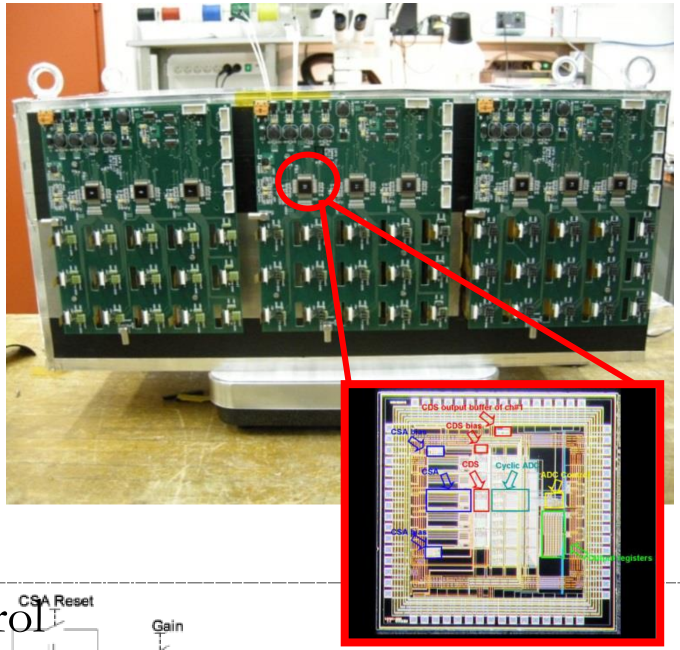
- At least 2 Photo Diodes necessary for each crystal
  - Large-area PD for small signals
    - VTH2090 (Excelitas)
    - Expected electrical signal
      - 1MIP ~ $4 \cdot 10^4$ e^- ~ 7 fC
      - Max signal ~ $2 \cdot 10^{11}$ e^- ~ 30nC
  - Small-area PD for large signals
    - T.b.d. (VTP9412H, VTP3310H,…)
    - With GF ~ 600 times lower → Max.signal ~ 50pC

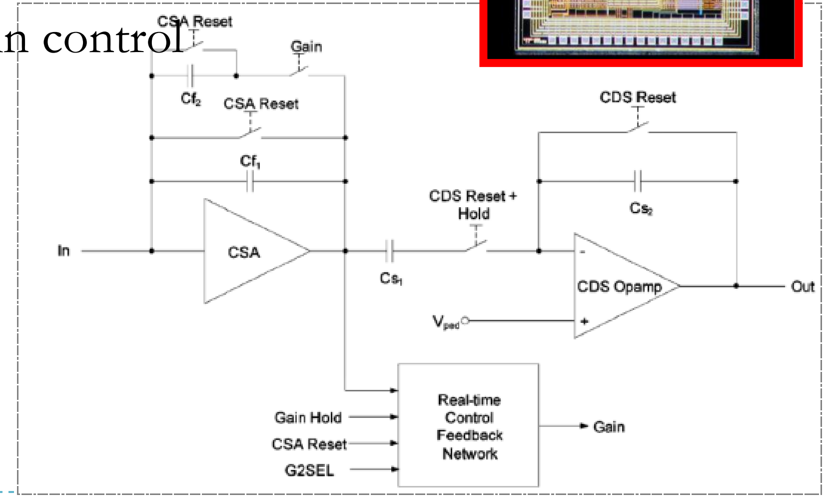
	VTH2090
Active area	84.6 mm^2
Q.E. @CsI(Tl) peak	75%
C_J	70pF @30V

Front-end electronics

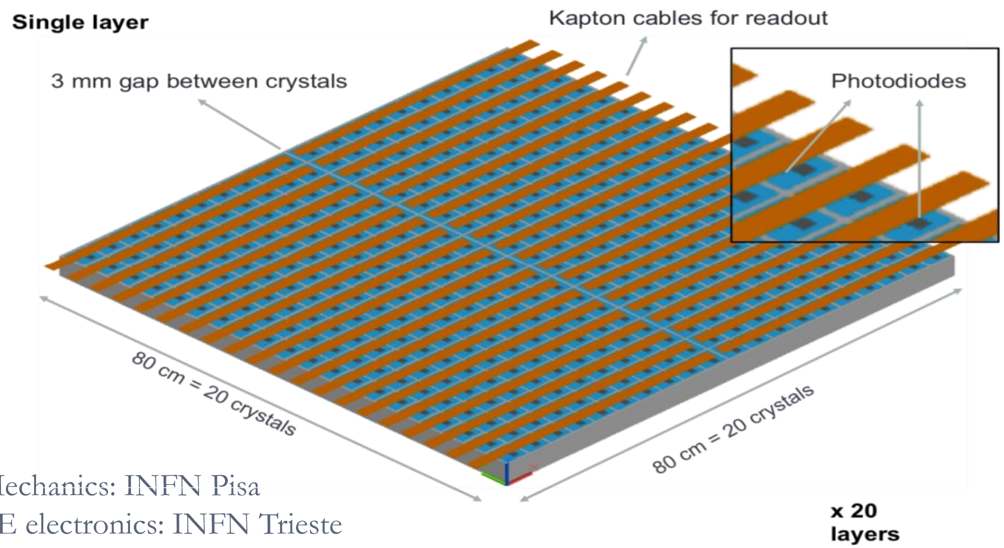
- CASIS chip (V1.1)
  - R&D project by INFN
  - Developed by INFN-Ts
  - Designed for Si-calorimetry in space

  - 16 independent analog channels
    - CSA
    - Correlated double sampling system
    - Double gain (1:20) with automatic gain control
  - Characteristics:
    - Dynamic range ~ 52.2 pC
    - ENC ~ 2280e^- + 7.6e^-/pF
    - 2.8 mW/ch

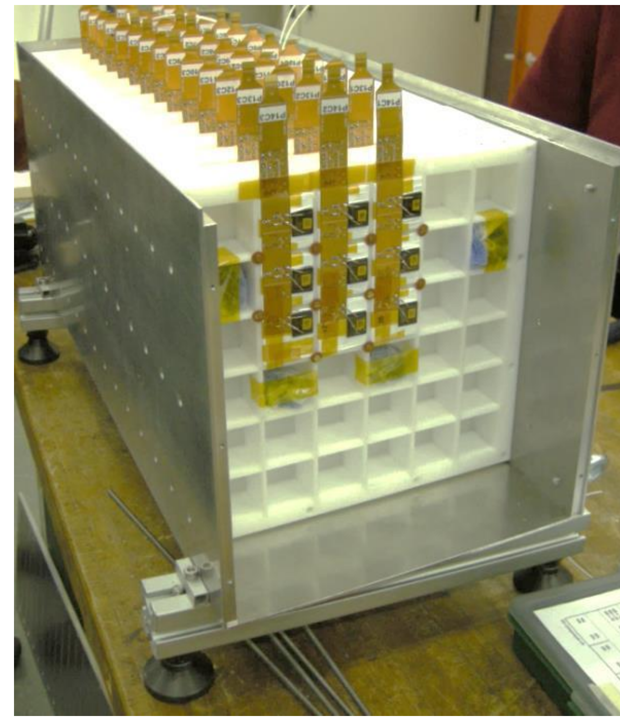




The prototype calorimeter assembly



- Mechanics: INFN Pisa
- FE electronics: INFN Trieste
- Crystals, PDs, DAQ, assembly: INFN Firenze

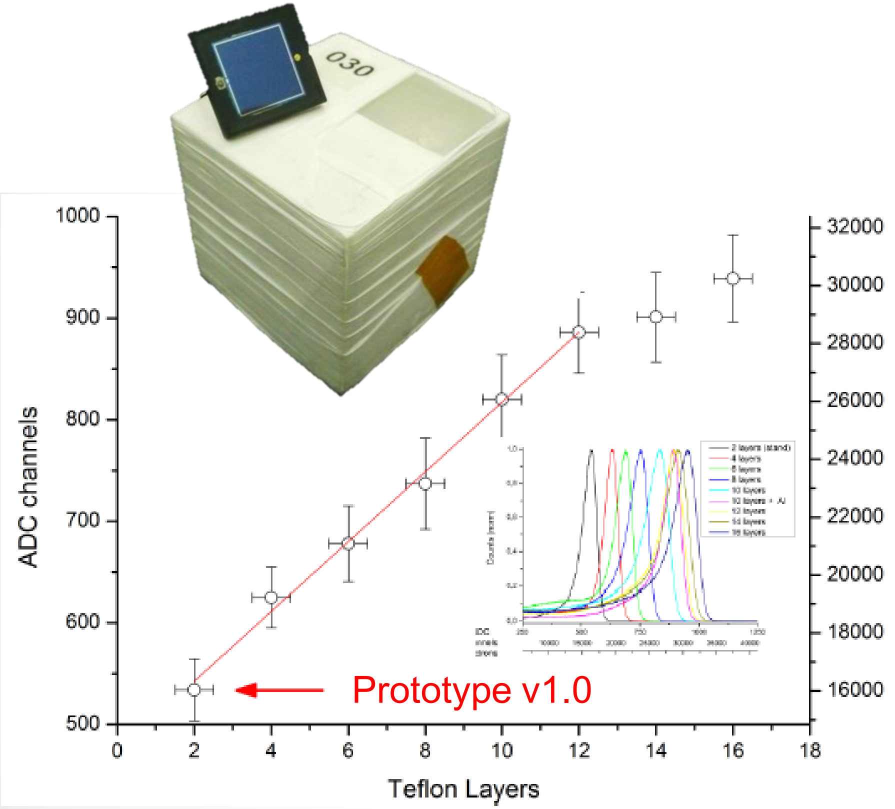


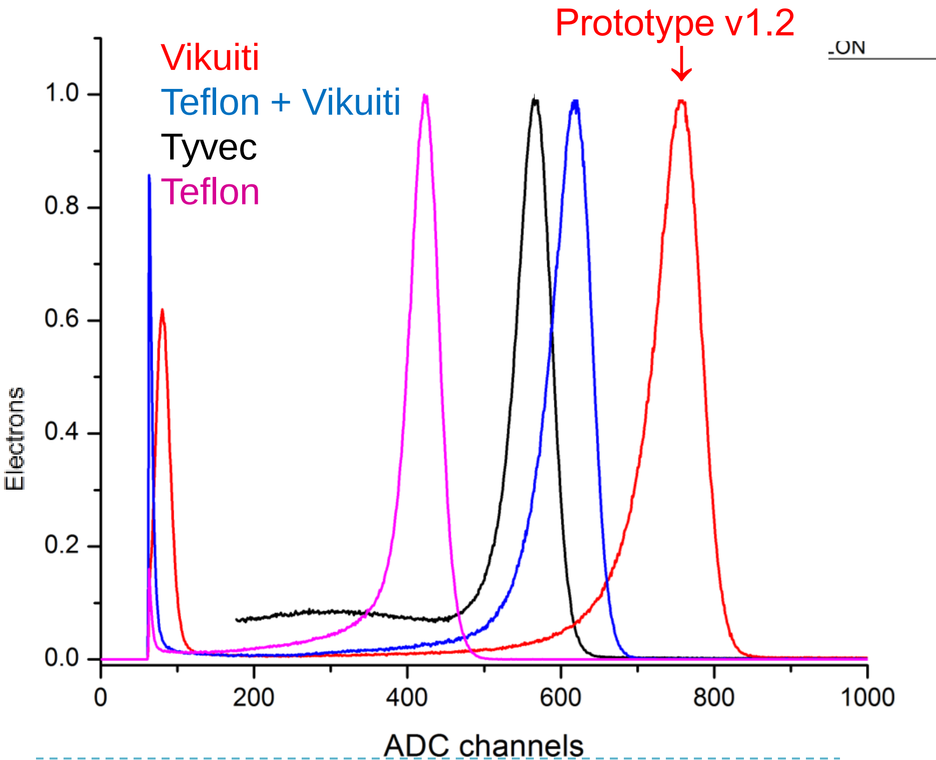
- **4mm** gap between active elements
- 3×3 elements for each plane
  - ~ **1.5 R_M** shower containment
- Up to 15 layers
  - active depth **28.4 X_0 → 1.35 λ_I**
- Three upgrades (v1.0-1-2), tested with particle beams

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

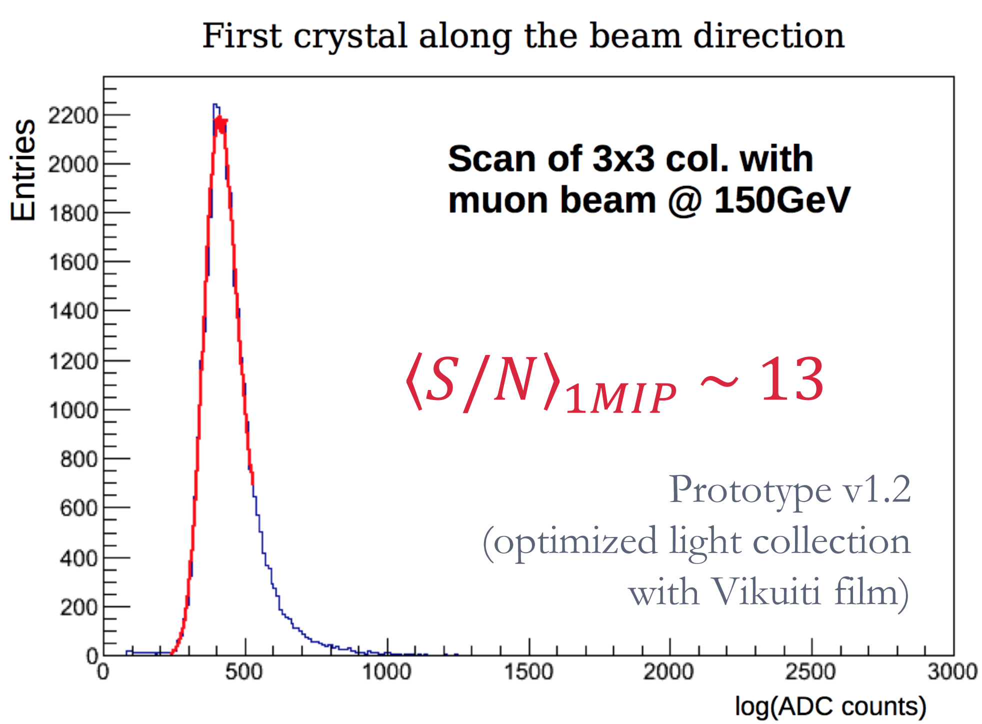
Light-collection optimization

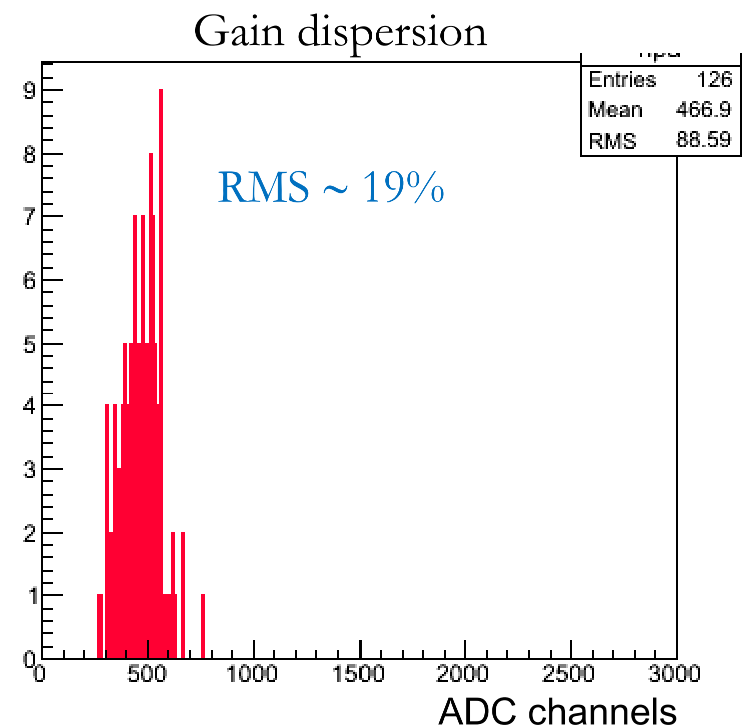
- Studied with signal induced by 5,5 MeV α from Am source
- Setup:
  - single cube (matte) coupled to VTH2090 PD
  - Readout by commercial CSA and DPA modules (Amptek)





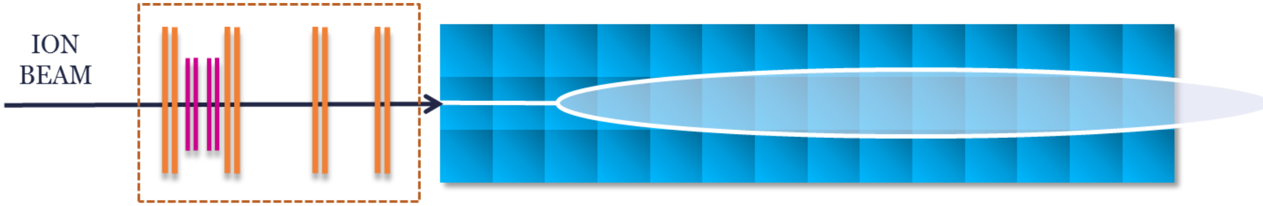
Single-crystal calibration



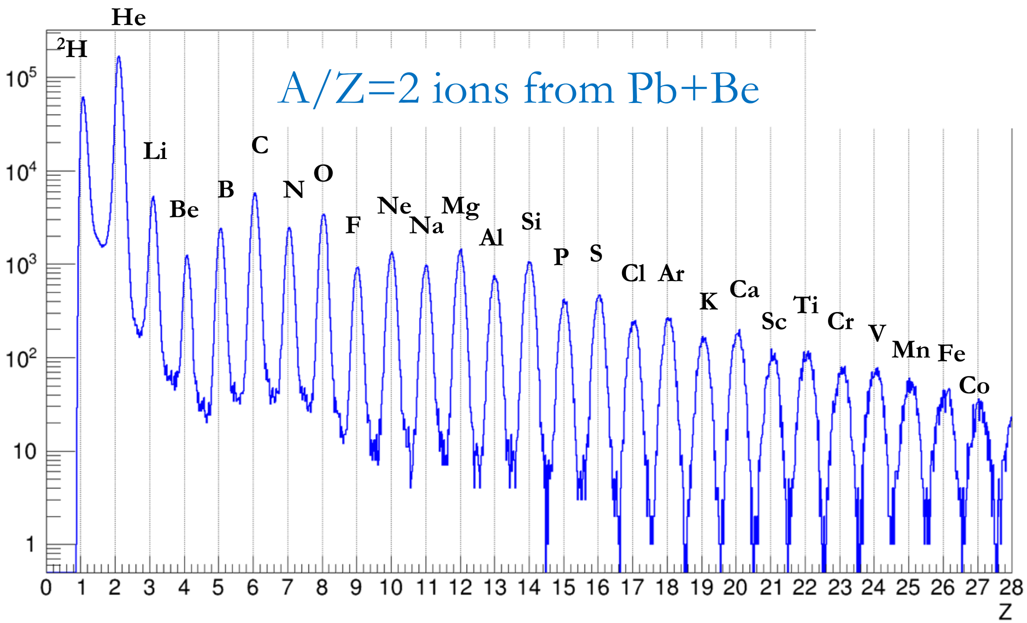


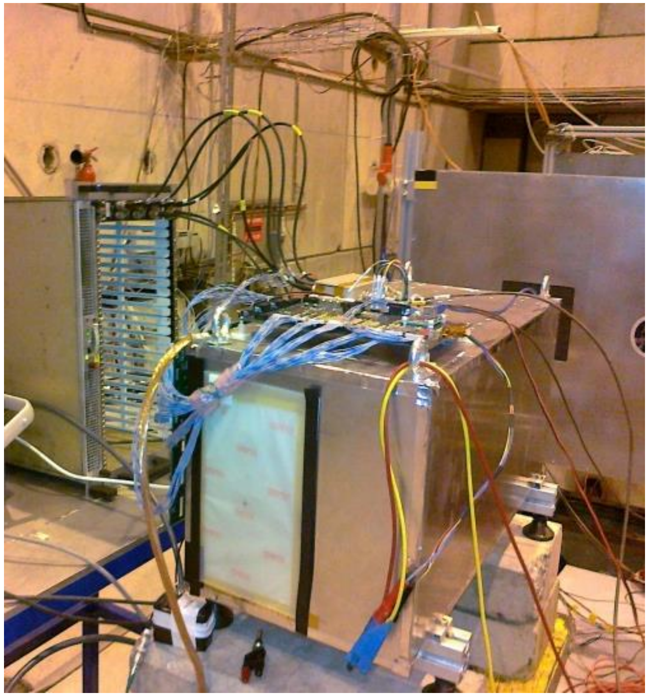
- Signal induced by MIPs used to equalize crystal responses

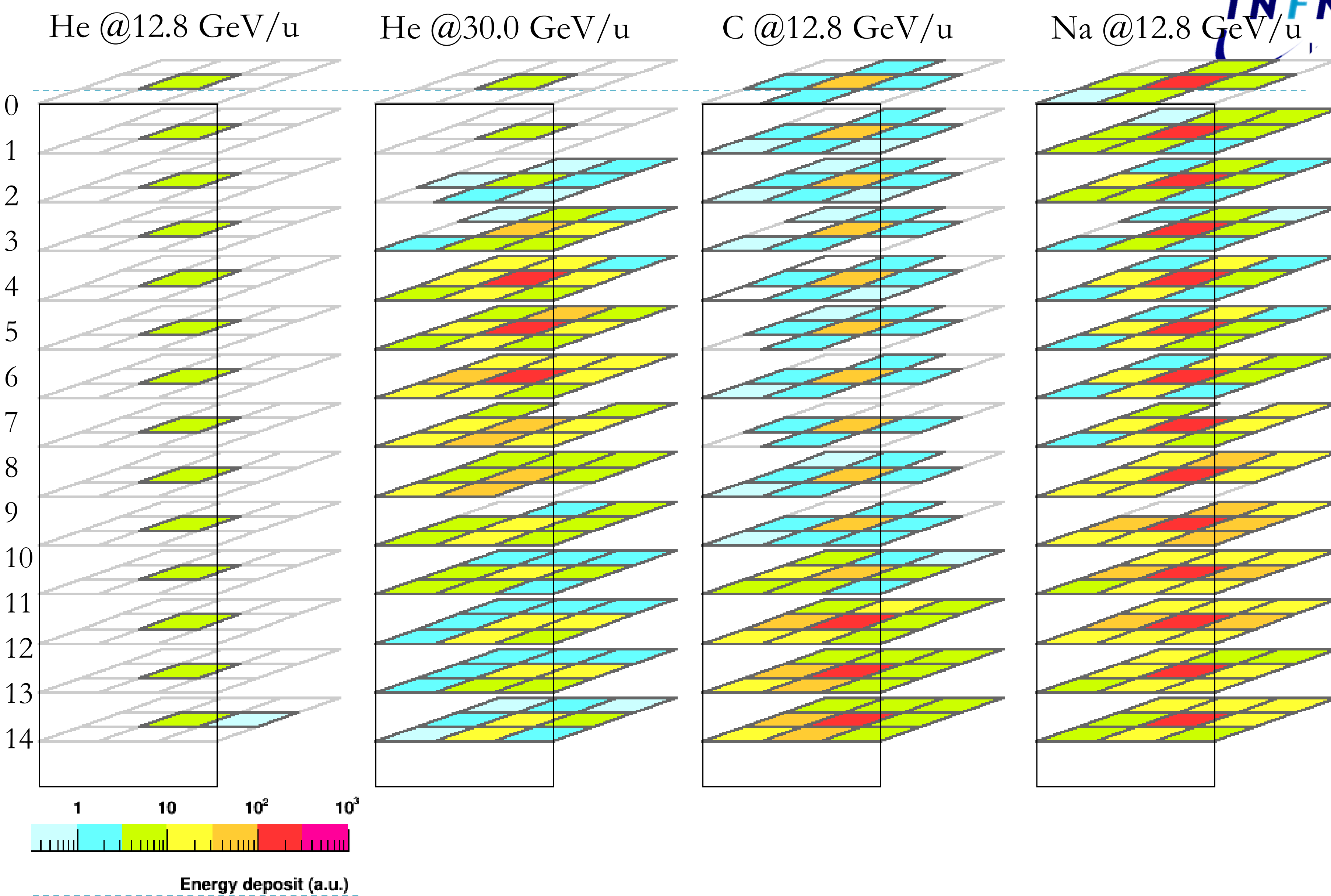
Test with ion-beam



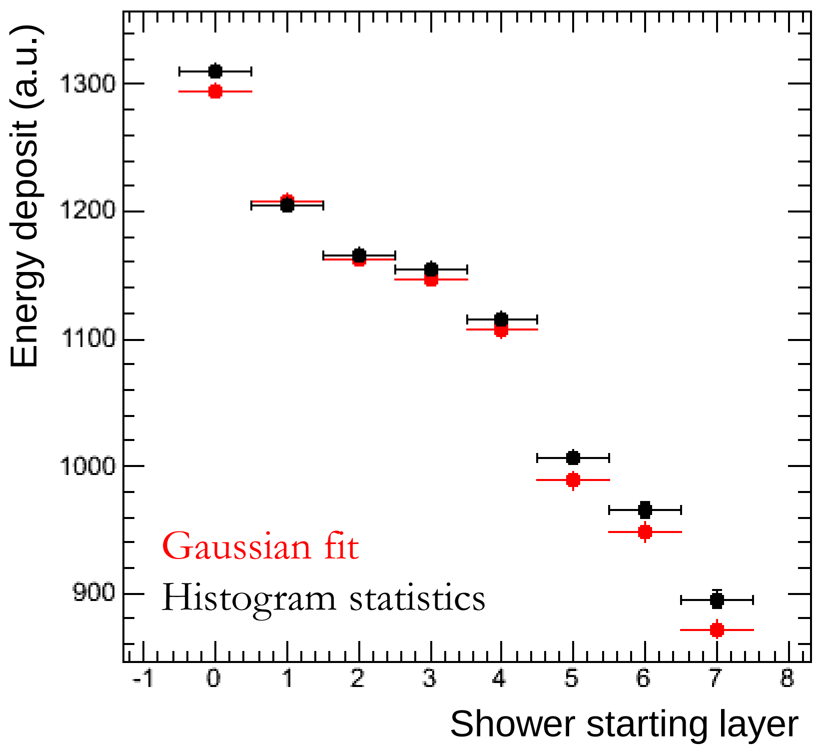
Precise beam position & Z-tagging from BT (INFN Pisa/Siena)

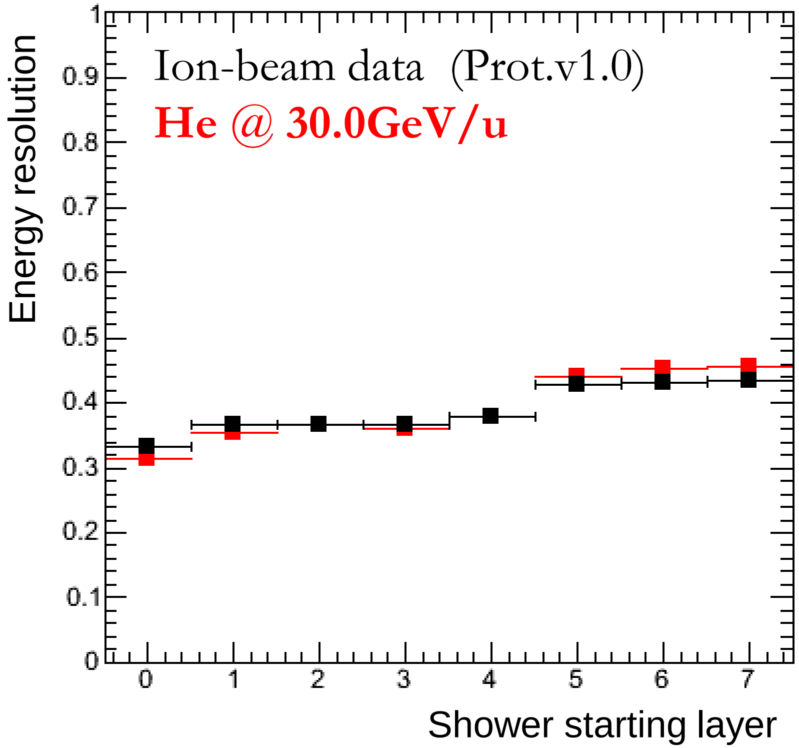




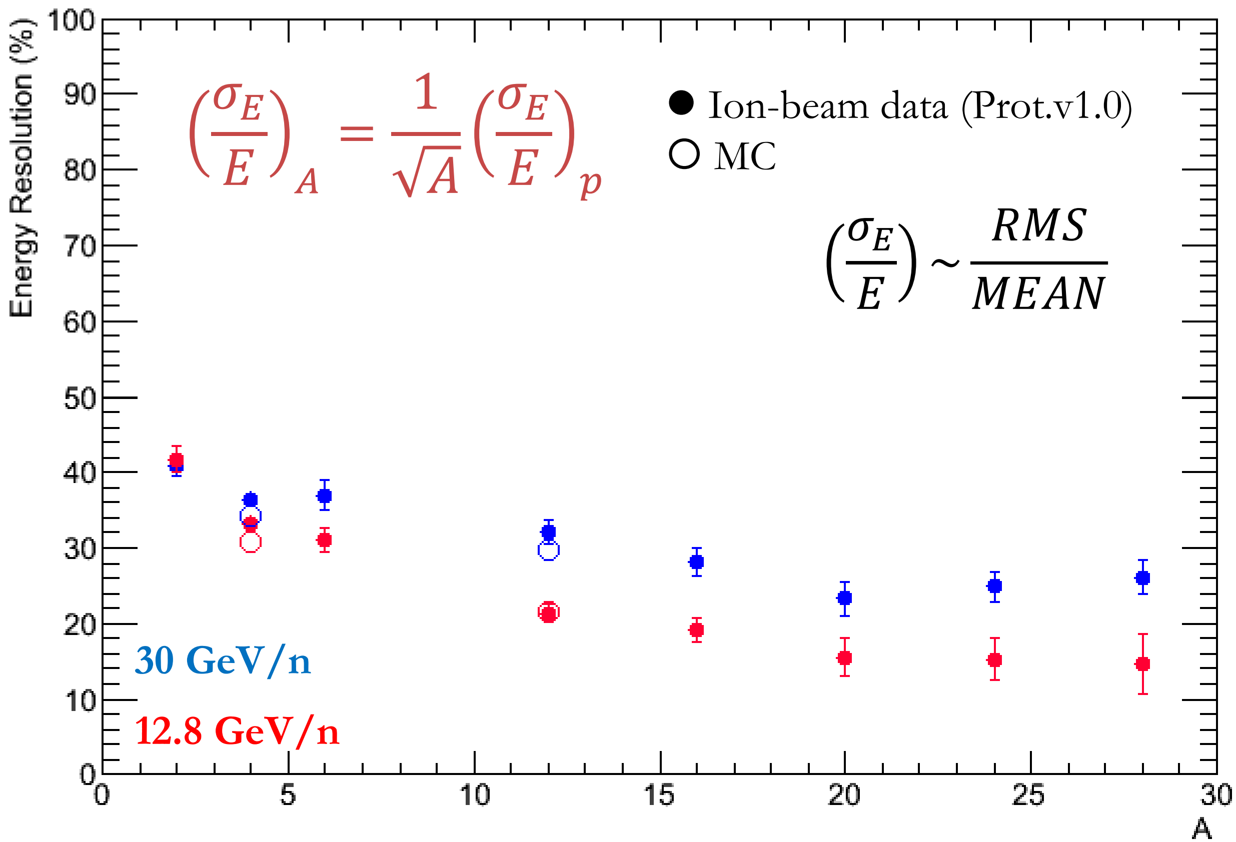

He @12.8 GeV/u
He @30.0 GeV/u
C @12.8 GeV/u
Na @12.8 GeV/u
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
1
10
10^2
10^3
Energy deposit (a.u.)

Energy resolution –vs– shower containment





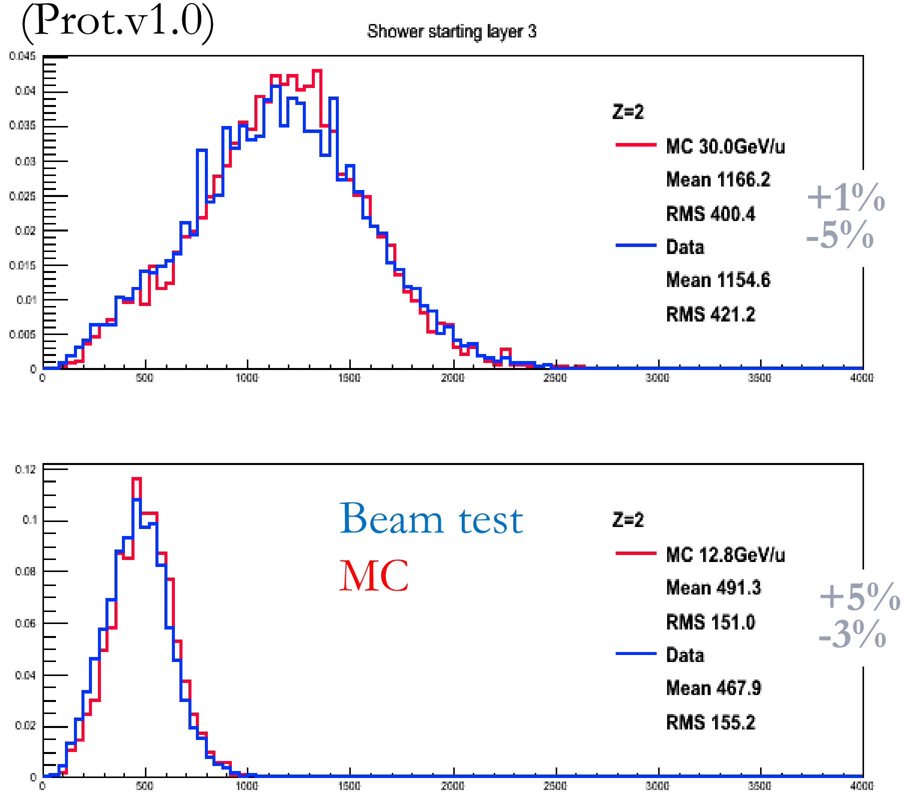
Energy resolution –vs– A

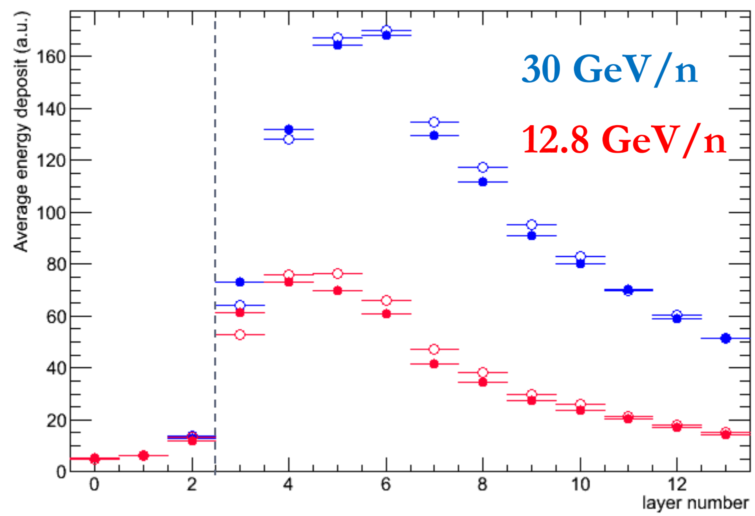


Showers starting on layer 3

Beam-test –vs– MC data

(Prot.v1.0)



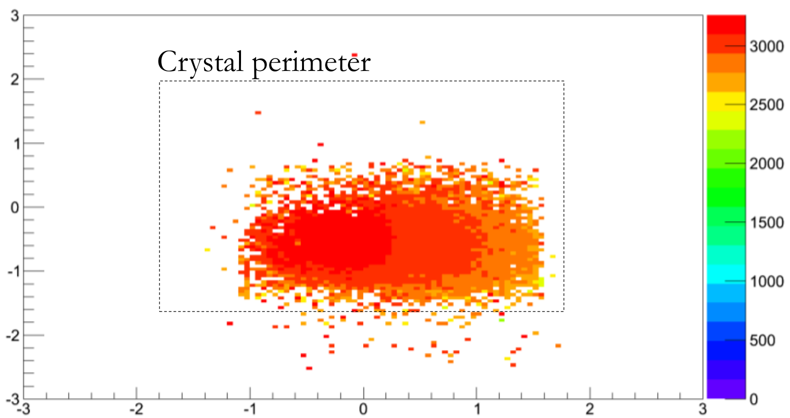


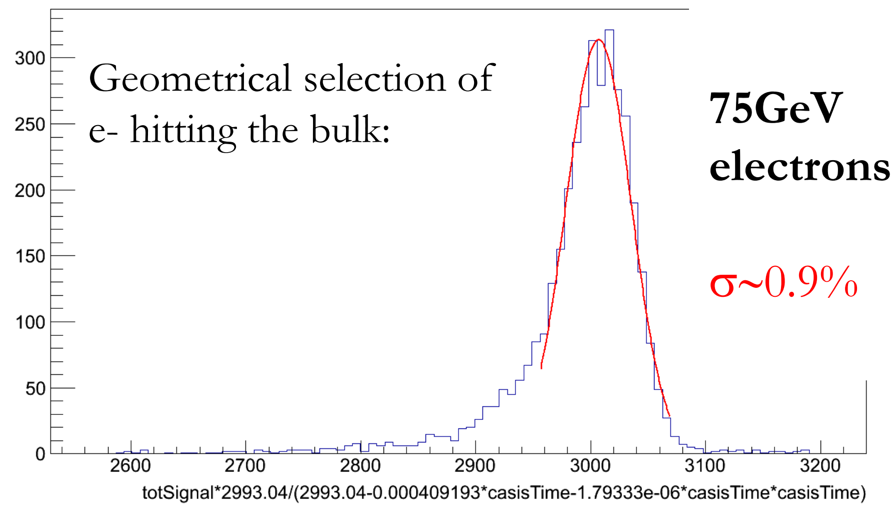
- Prot. v1.0 affected by instrumental effects → MC fine tuning:
  - 14% optical cross talk
  - 4.5% additional gaussian spread to single-crystal signal

- Agreement with MC prediction at few % level
- Measured energy resolution systematically worse than expected
- Improved performances expected for v1.1 (analysis underway)

Electron-beam test

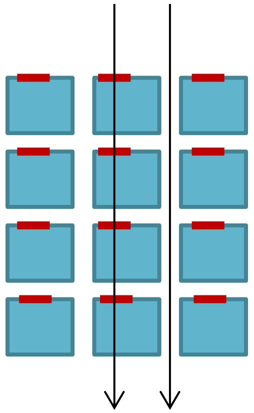
Prototype v1.2 (preliminary)



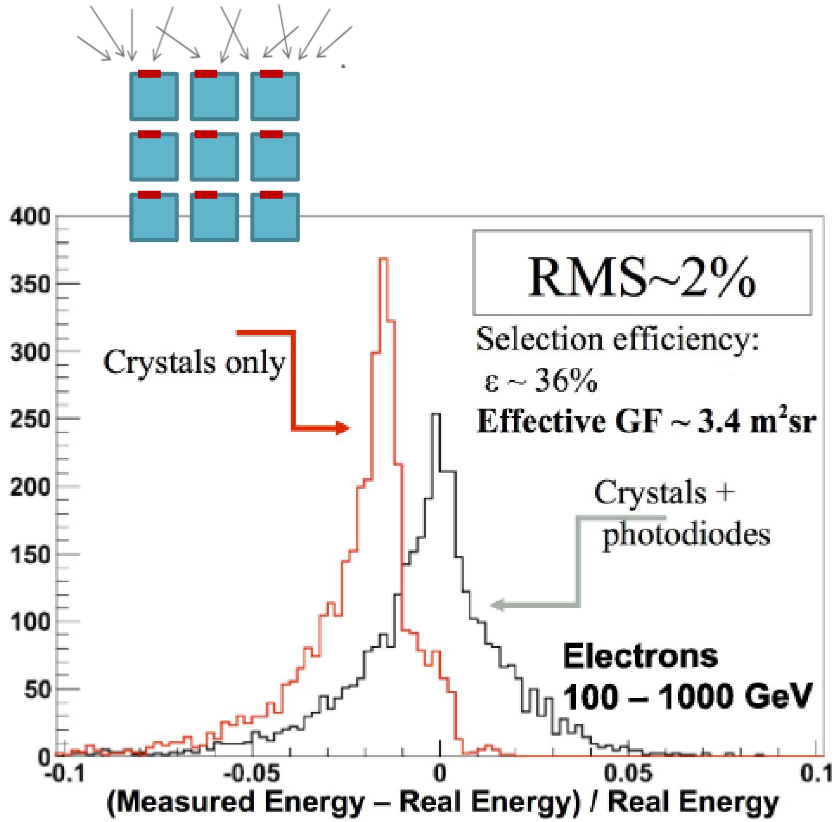


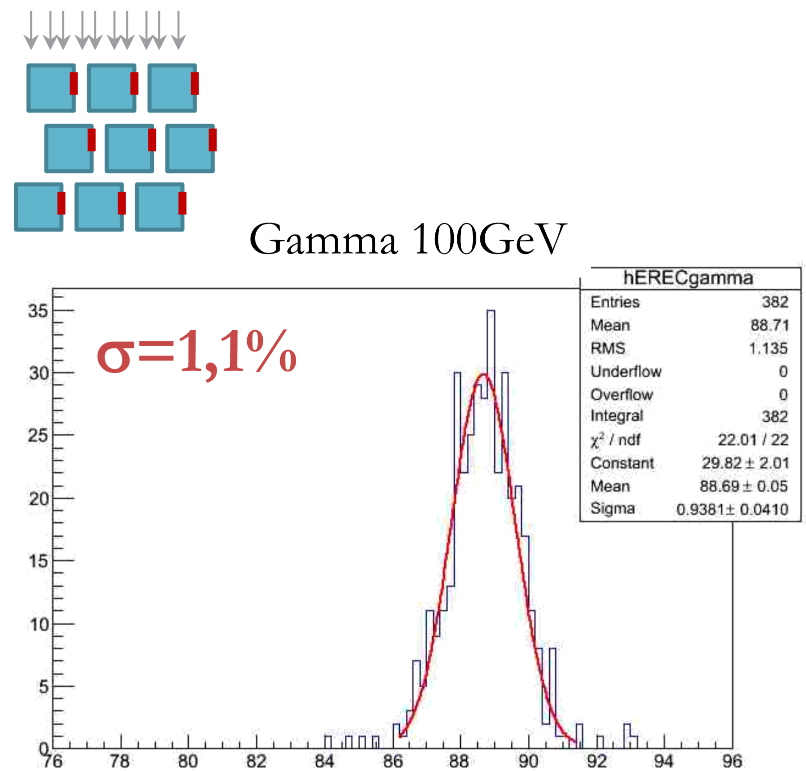
- Large variations (~10%) on the collected energy depending on inpact position: crystal bulk, sensor, borders (known geometrical effect, not a surprise)

- Good resolution, but still instrumental effect to be undertood



Expected CaloCube performances for e.m.-showers





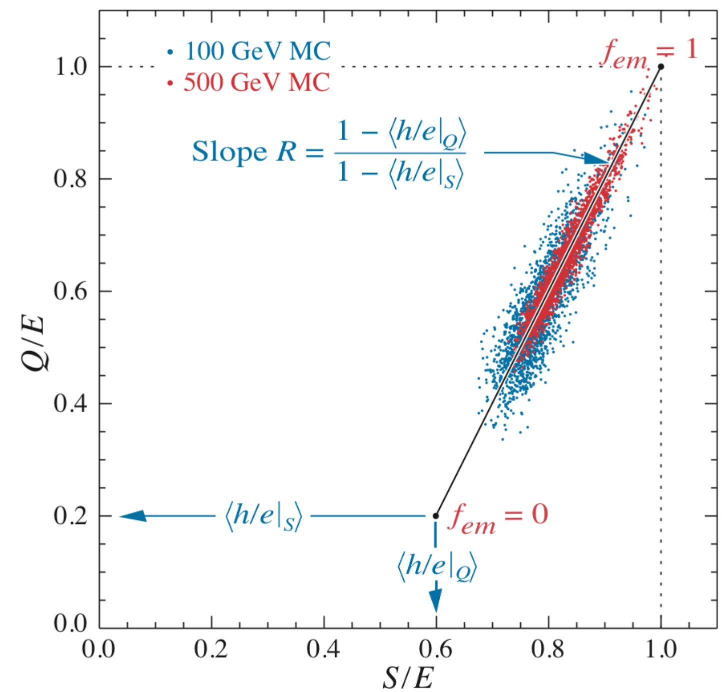
- CaloCube baseline design (CsI 20×20×20)
- Isotropic flux of electrons 100GeV÷1TeV (CR-like)

- CaloCube design optimized for gamma detection

Dual readout

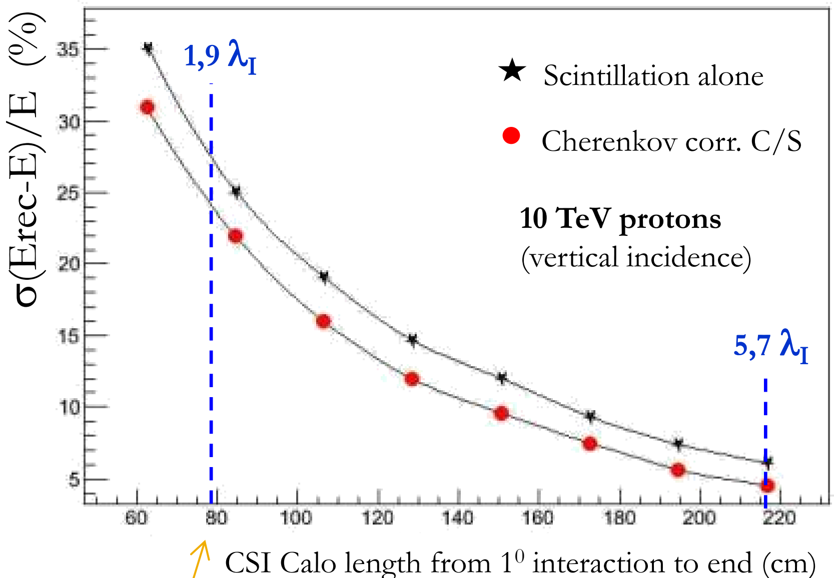
- Simultaneous detection of Cherenkov and scintillation light useful to increase performances
  - Event-by-event correction for fluctuations in shower e.m.-fraction
  - Significant improovements in total absorption calotrimeters

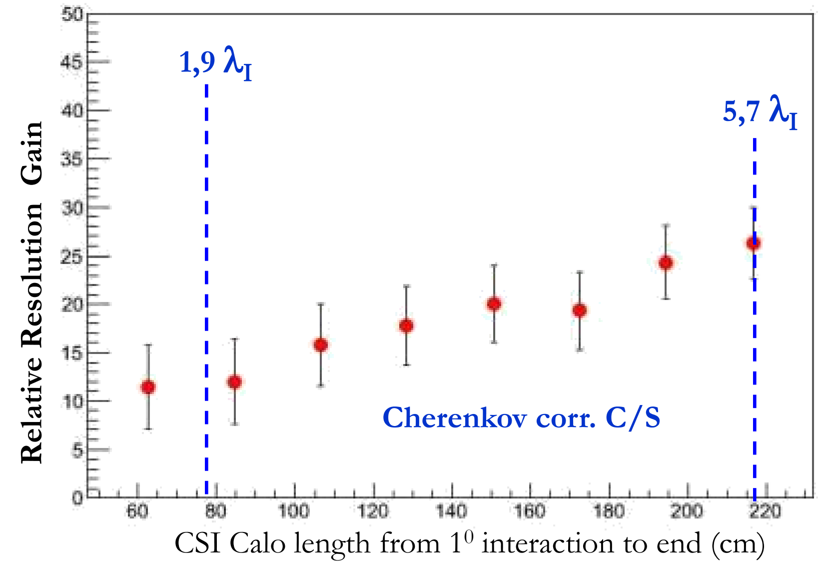
(Groom, JP, 2012)

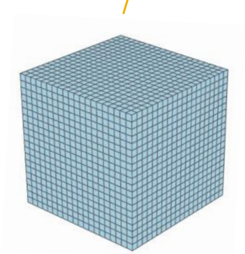


- What for CaloCube?
  - Thin calorimeter → resolution dominated by leakage
  - Cherenkov signal extraction from CsI(Tl) crystals

Dual readout applied to CaloCube geometry





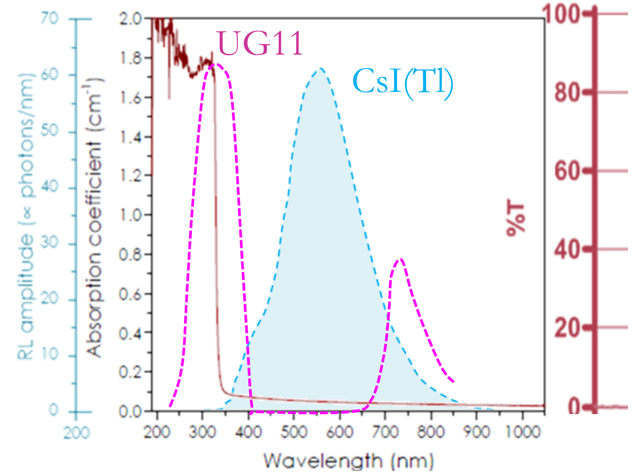


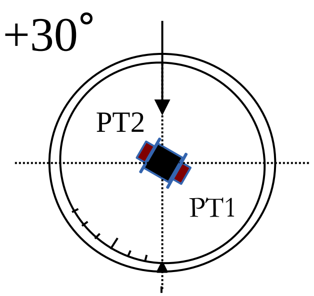
Baseline design
CsI(Tl)
20×20×20

- Dual readout applied to 60×60×60 CsI crystals 0.3mm gap
  - Selection of progressively contained shower
- Moderate resolution improvement, increasing for increasing depth
- From the space point of view
  - Equivalent to add (or save) 4 layers (~ 0.3t weight)
  - Could provide cross-calibration and cross-linearity check ??
  - …as far as it is technologically feasible

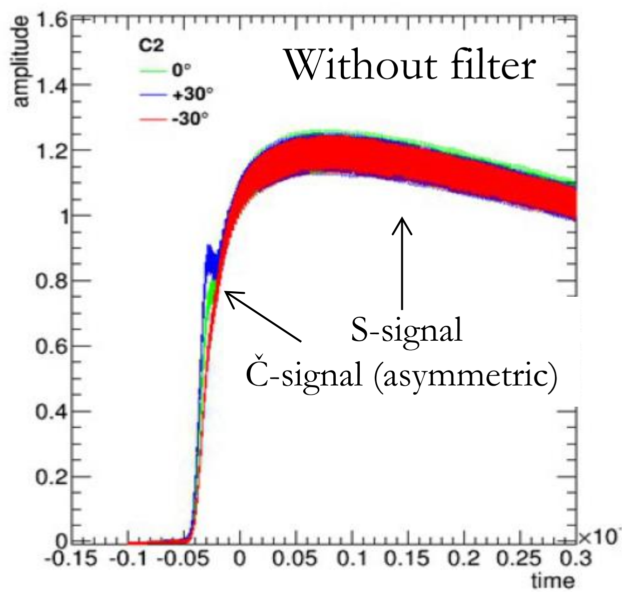
Cherenkov signal in CsI(Tl)

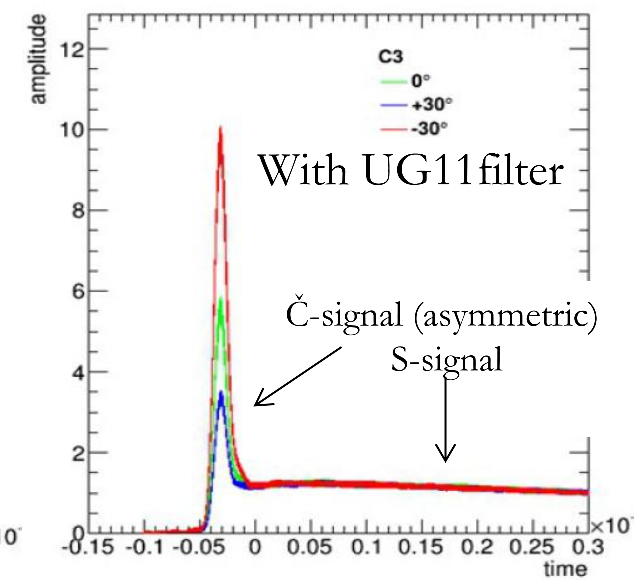
- CsI(Tl) transparent down to 340 nm
- Separation based on <u>timing</u> (promt-vs-delayed) and <u>wavelength</u> (uv-vs-green)
- Test @BTF with 460MeV e^-
  - Absorber wrapping (to keep Č directionality)
  - Two PMTs on opposite side, readout by oscilloscope





(See P.Lenzi talk)





Summary

- The CaloCube R&D project, aiming to develop a novel design calorimeter, optimized for high-energy cosmic-ray measurements in space, was presented.

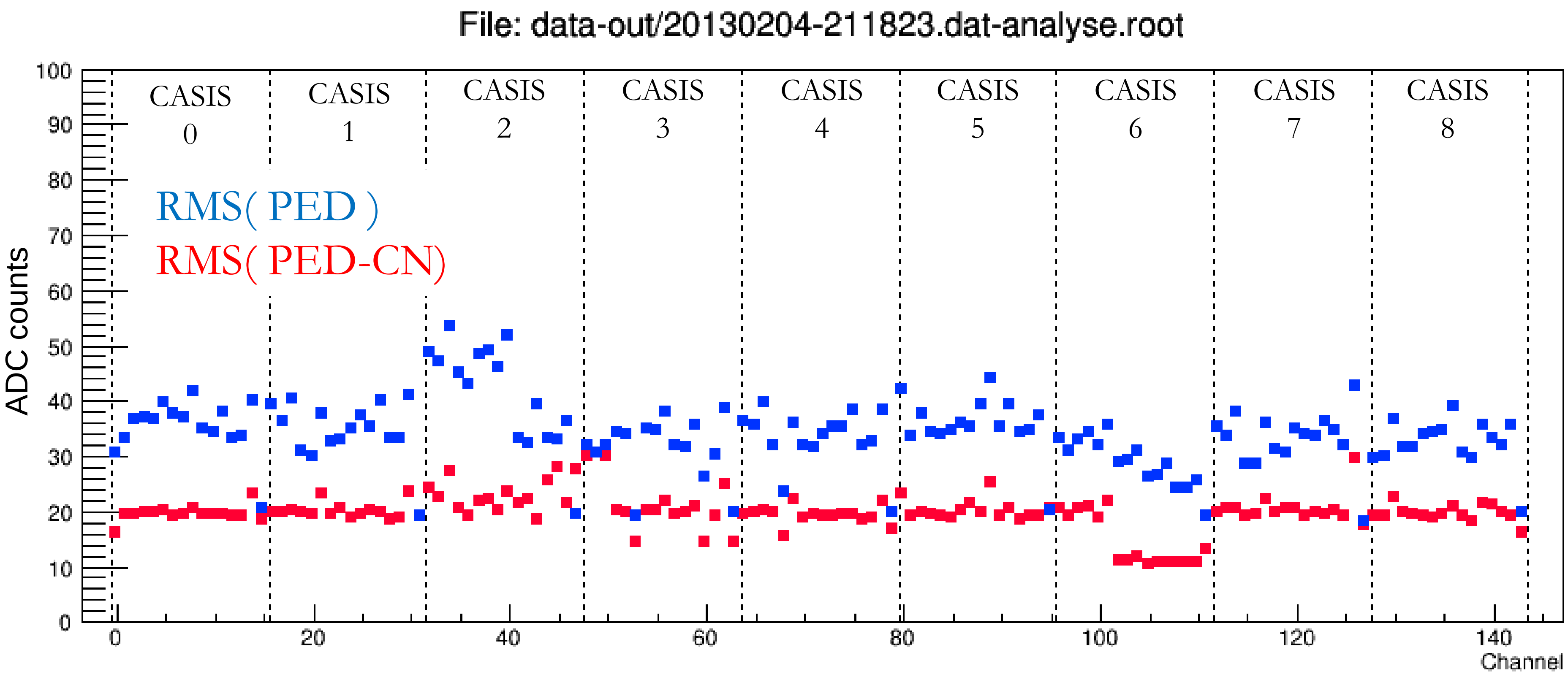
- As a proof-test of the CaloCube concept, a prototype made of CsI(Tl) has been constructed and tested, in several versions, with particle beams, obtaining performances close to the expectations
  - The final version, made of 5×5×20 crystals and readout by two PDs, covering the full required dynamic range, is under construction and will be tested during summer 2016 @SPS

- Dual readout compensation technique has been investigated and the possibility to extract Cherenkov signal from CsI(Tl) crystals was verified

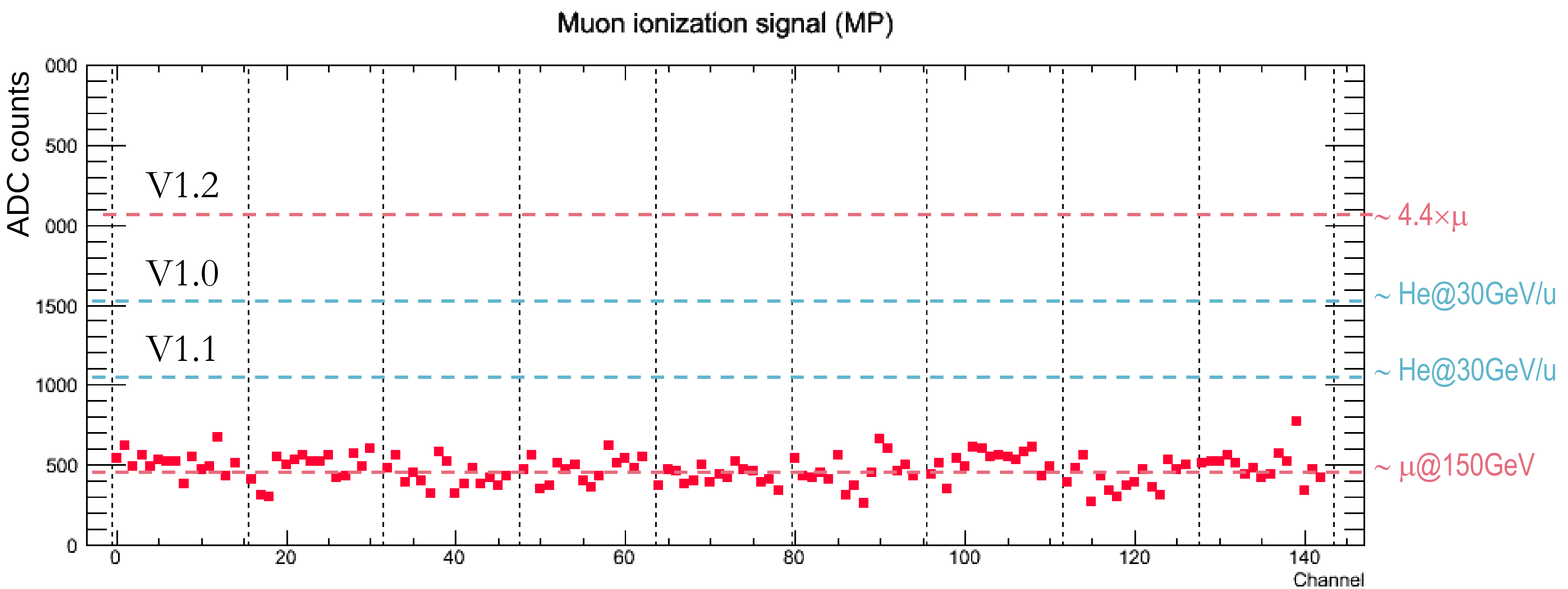
- Thanks to the organizers for this opportunity

Spares

Channel Noise

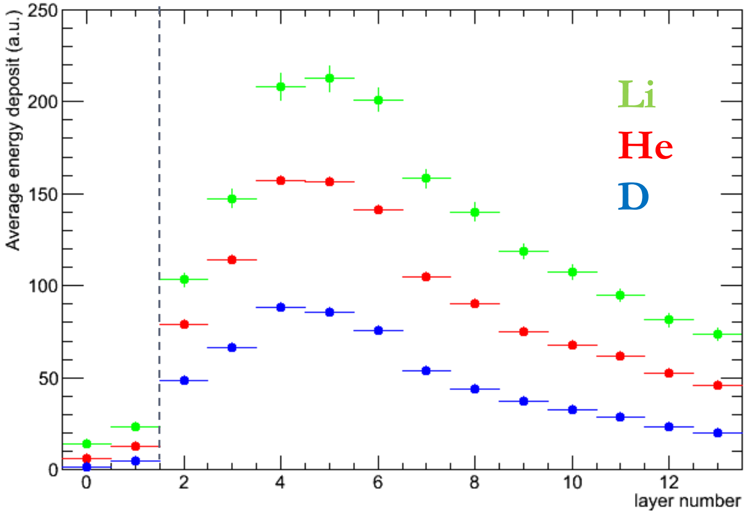


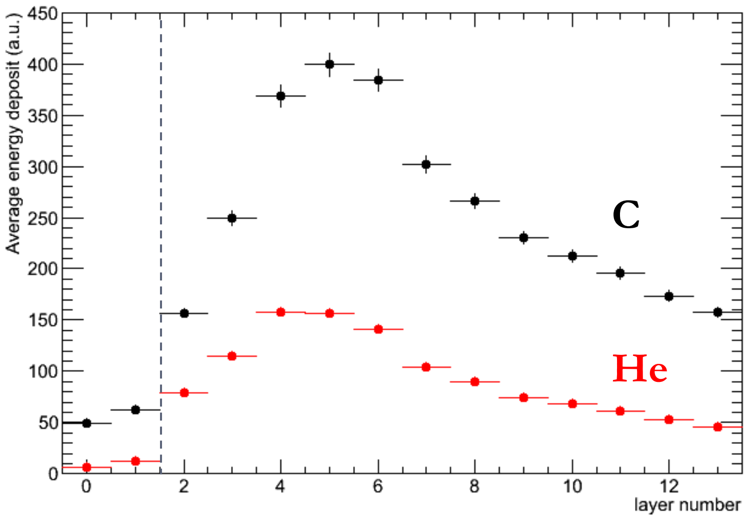
- Channel pedestals (PED) evaluated by acquiring off-spill events
- Random noise (RN) ⊕ common noise (CN) ~ **30÷40 ADC counts**

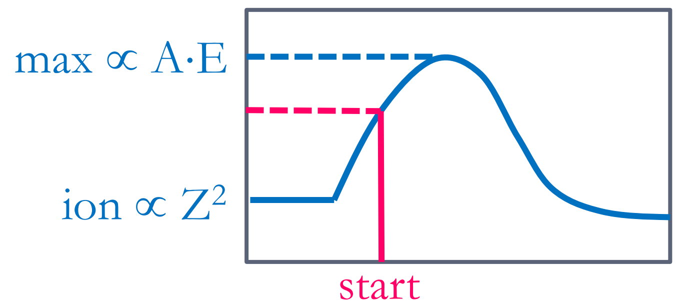


Muon ionization signal (MP)
ADC counts
000
500
000
1500
1000
500
0
V1.2
V1.0
V1.1
0
20
40
60
80
100
120
140
Channel
~ 4.4×μ
~ He@30GeV/u
~ He@30GeV/u
~ μ@150GeV

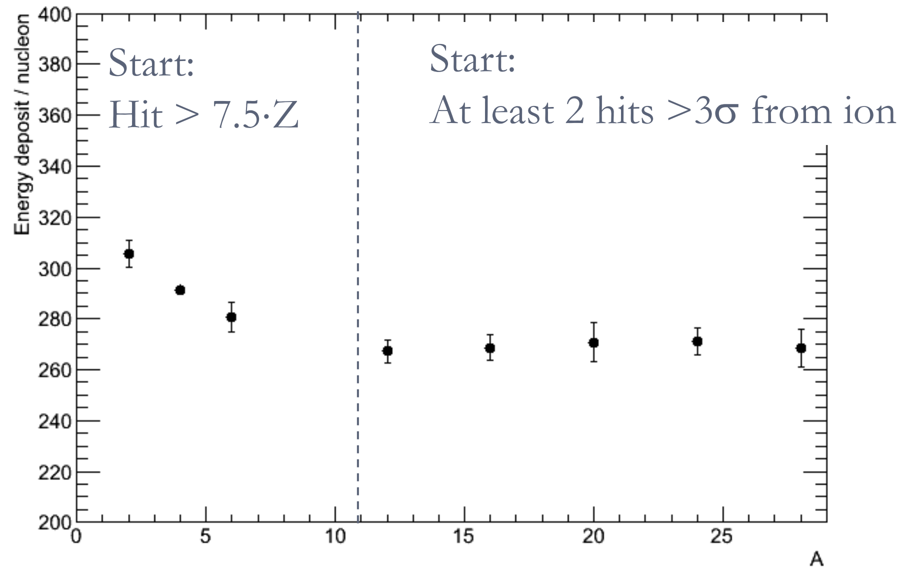
Shower profile







Shower start on layer 2



Ions @ 30.0GeV/u
Prototype v1.0