CALOR2016,
15-20 May 2016
EXCO in Daegu (Republic of Korea)

CaloCube: an innovative homogeneous calorimeter for the next-generation space experiments

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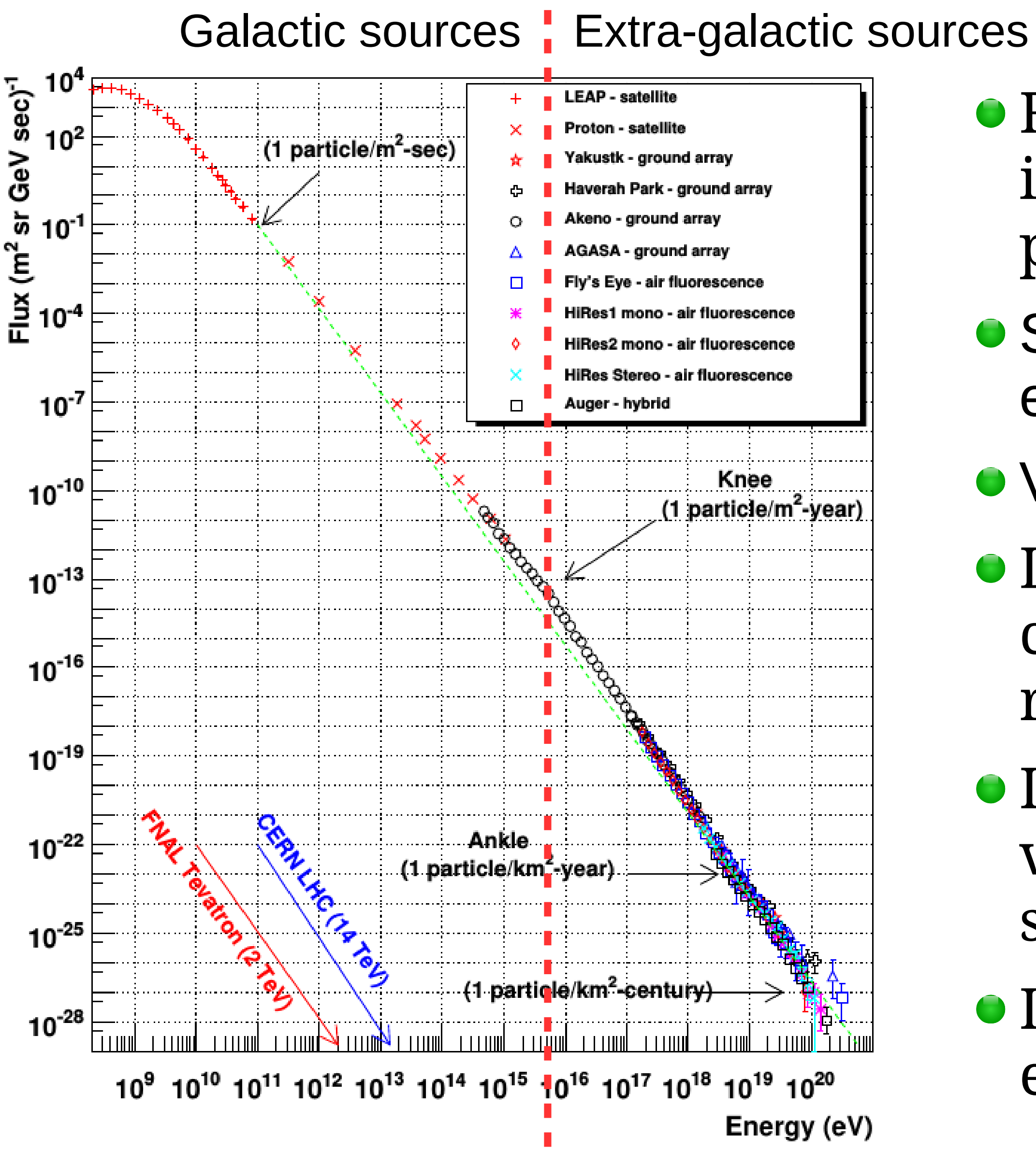
On behalf of the CaloCube collaboration

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,Firenze,Milano (Bicocca),Pisa, Trieste/Udine
  - CNR-IMM-MATIS Catania
  - CNR-IFAC Firenze
  - IMCB-CNR Napoli
- In this presentations: scientific backgrounds (briefly), the CaloCube proposal, calorimeter performance (simulations and beam tests).

Galactic cosmic rays 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 → high statistics → 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

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^2str
- 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

Typical payload limitations:

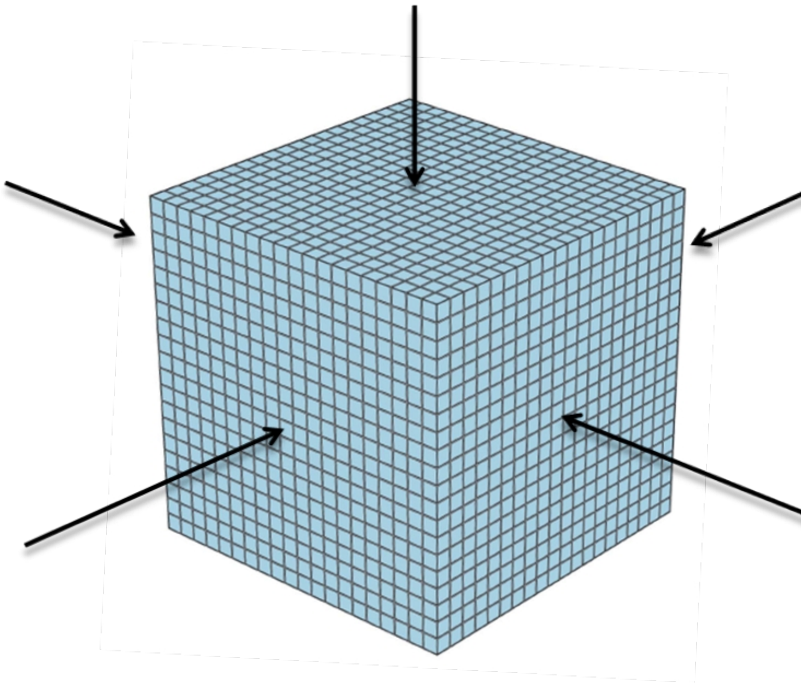
- Mass (~10^3 Kg)
- Power (~10^3 W)
- Down link capability (~10^2 Gb/day)
- Volumes (few m^2)

The CaloCube proposal

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

BASELINE DESIGN

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



MontCarlo simulation

- 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 (54 ph/keV)
  - 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 too

N×N×N	**20×20×20**
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)	0.78×0.78×0.78
depth (R.L.) " (I.L.)	39×39×39 1.8×1.8×1.8
planar GF (m^2sr) *	1.91

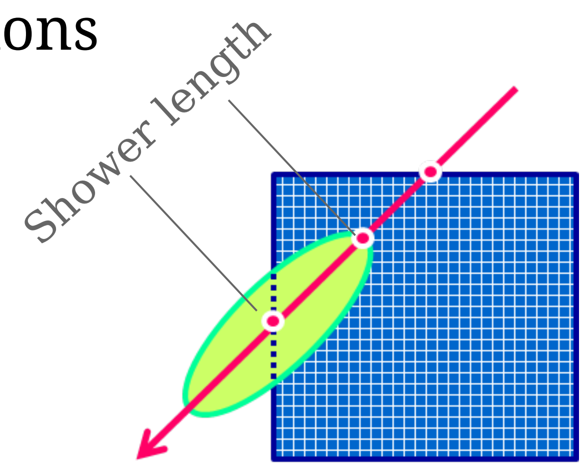
* GF only for one surface

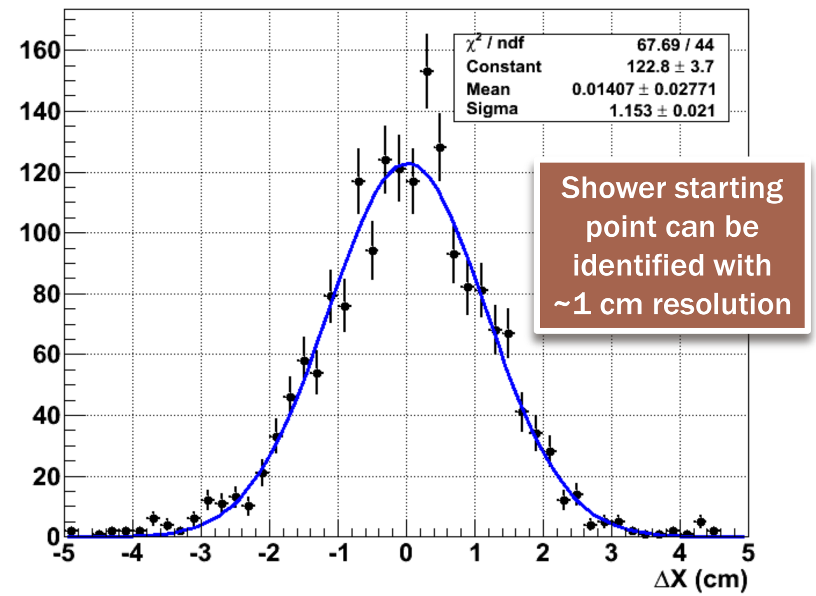
MontCarlo simulation (2)

- Protons and electrons simulated with an isotropic generation on the top surface of the calorimeter
- **GF of 5 faces = 9.55 m²str**
- Effective geometric factor → $\mathbf{GF_{eff} = GF_{5facet} * \varepsilon_{selection}}$

High granularity:

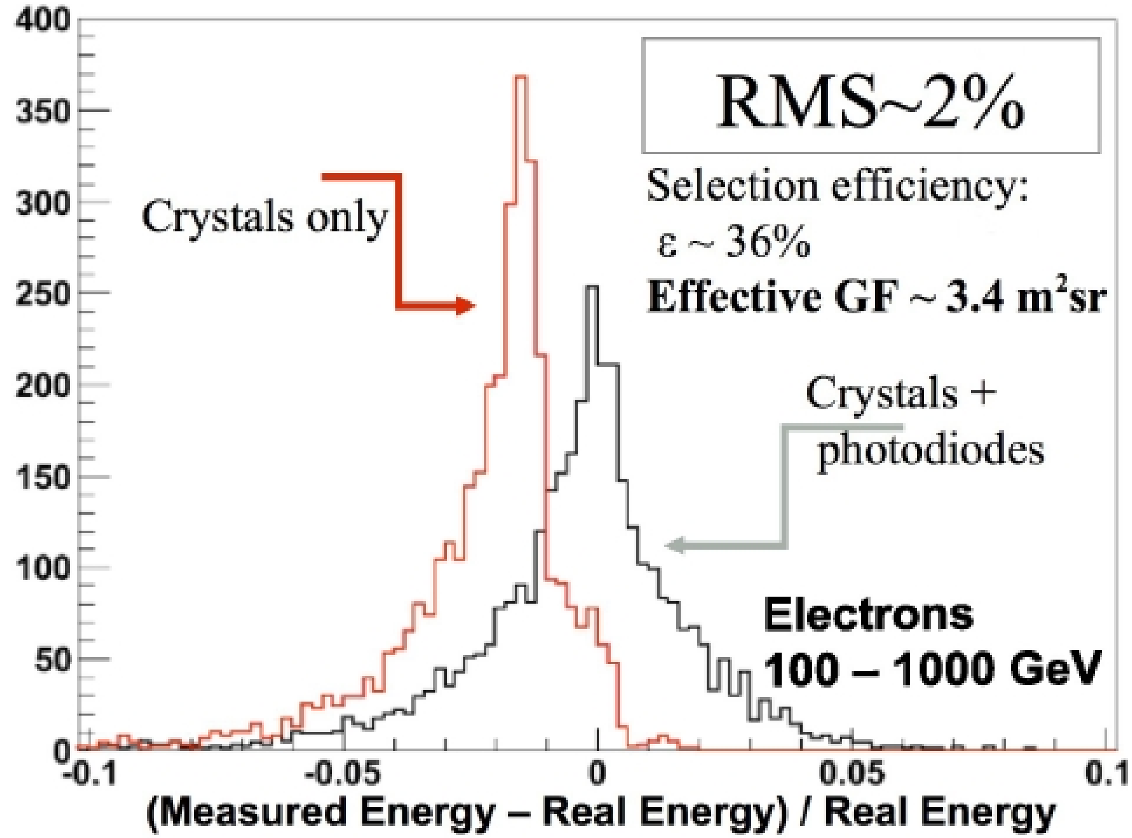
- Good identification of shower starting point
- Good shower axis and shower length reconstructions





Electrons 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^2str**
- **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)

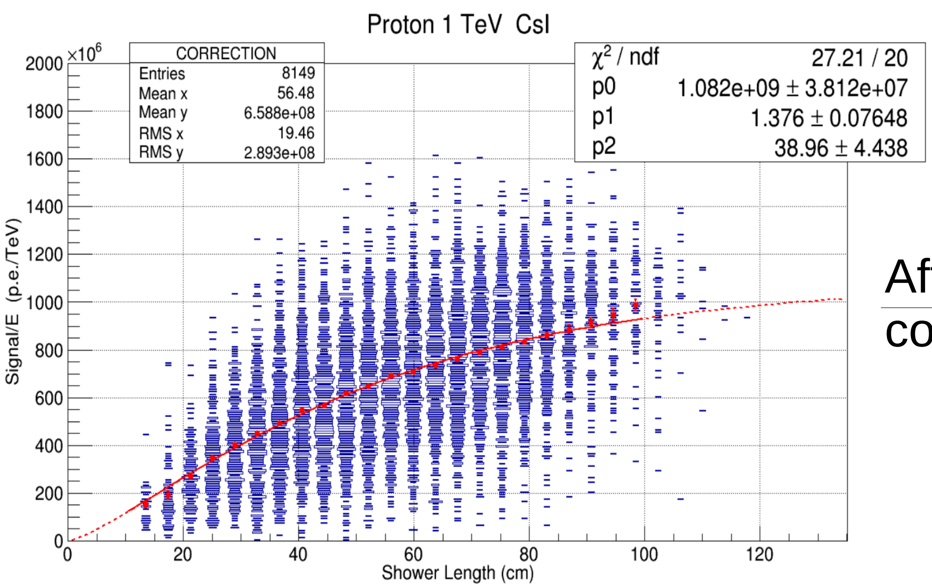


Proton: E. dep. vs shower lenght

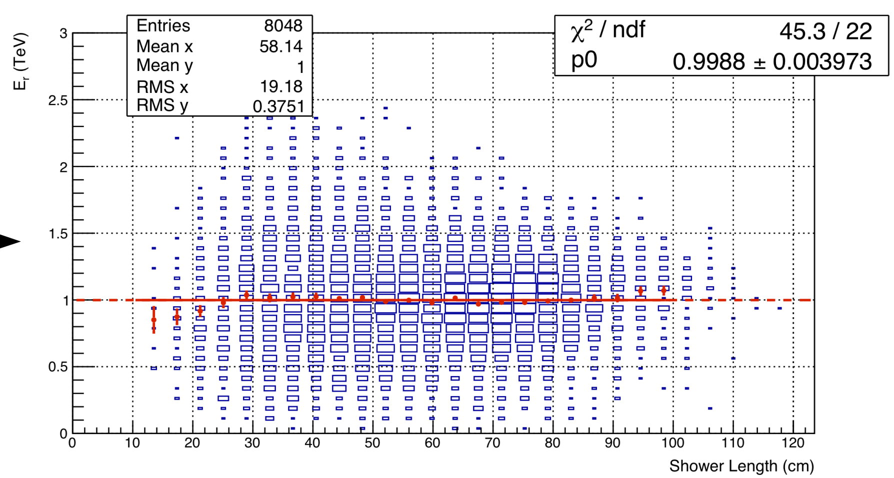
- In order to get a good energy resolution for protons, offline compensation method is needed: the energy deposit in calorimeter strongly depend on the shower length
- E.dep vs shower length: fitted with the integral of a gamma function

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

- Event by event correction of the energy deposit

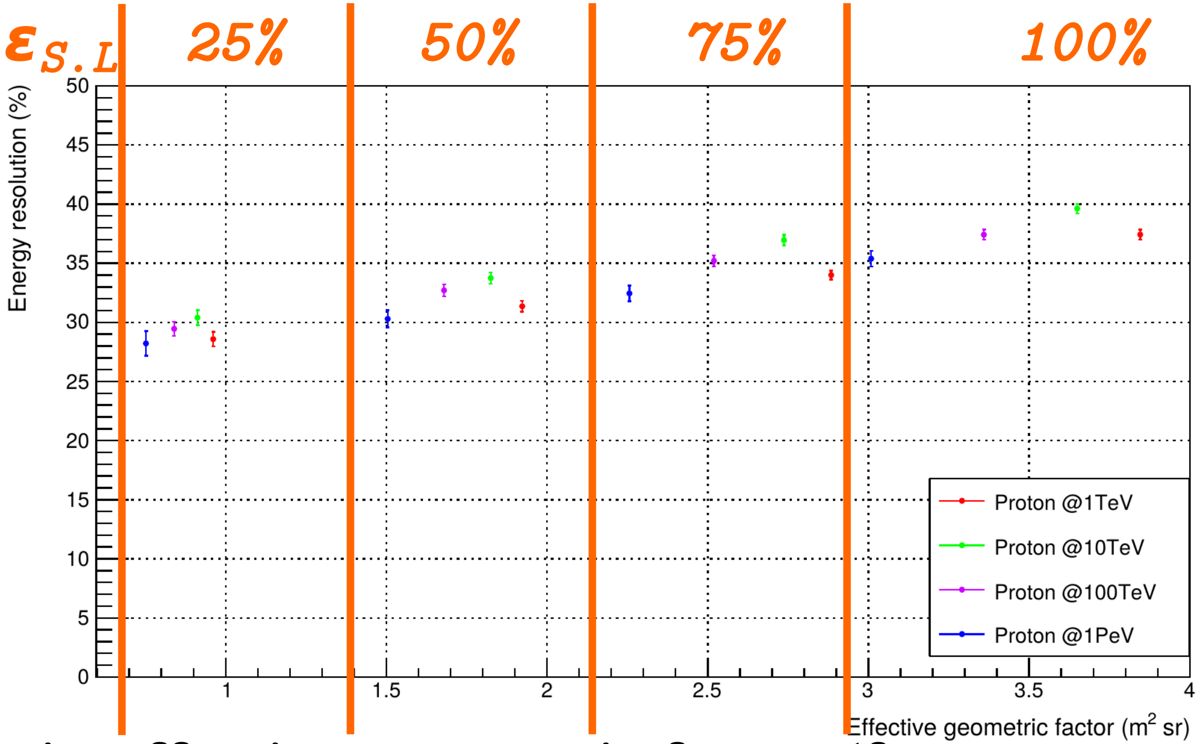


After corrections



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^2str to ~ 3.5 m^2str) translates in an increase of the energy resolution (from ~ 28% to ~37%)
- Energy resolution is almost constant with proton energy

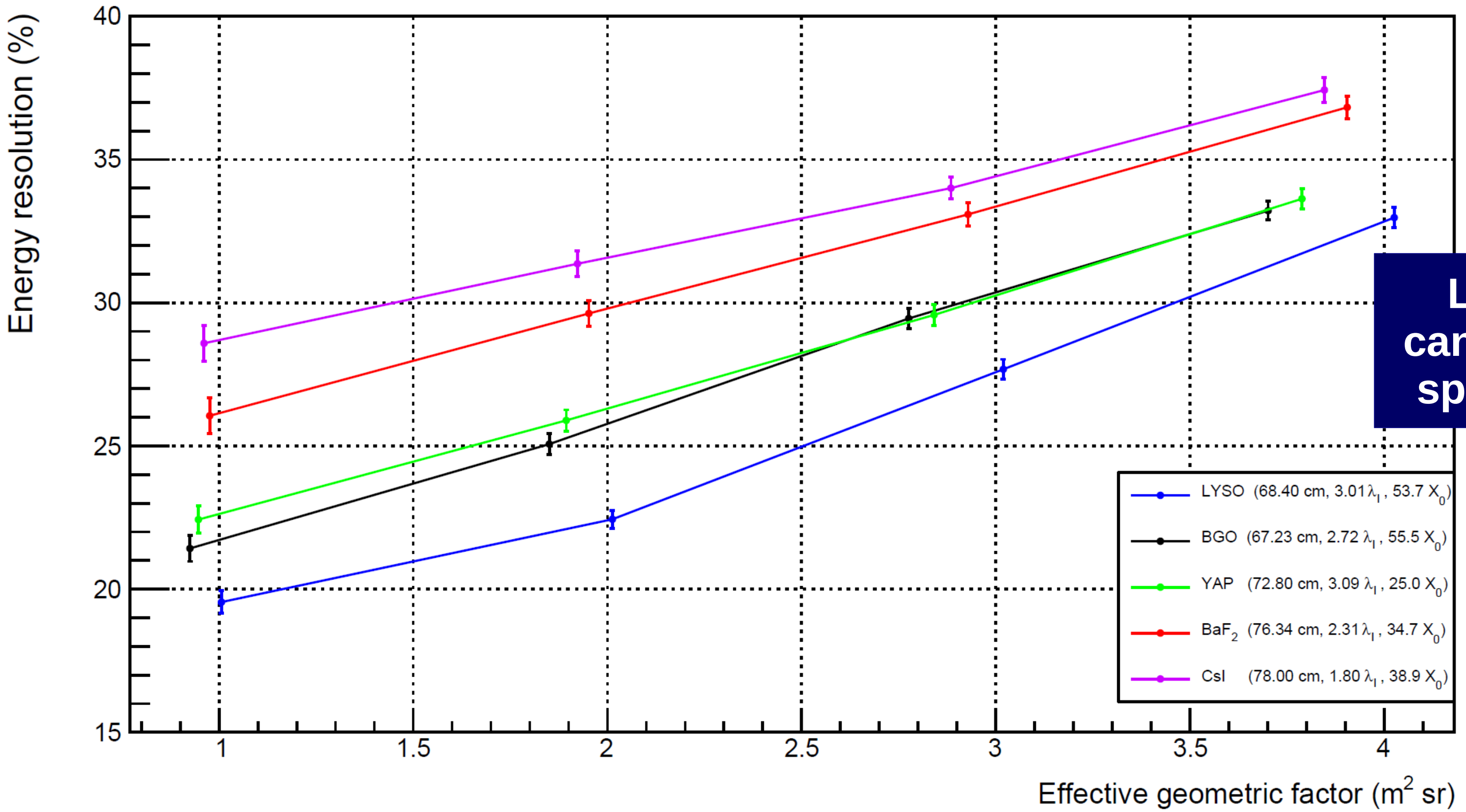
Geometry & materials

- Optimization of energy resolution and acceptance for protons
- Same simulations and analysis with different materials and distance among crystals (gap)
- Total weight (~2000 kg) and fraction of active materials (~ 80%) unchanged
- Crystal side = Moliere radius

	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

Materials: en. res. vs acceptance

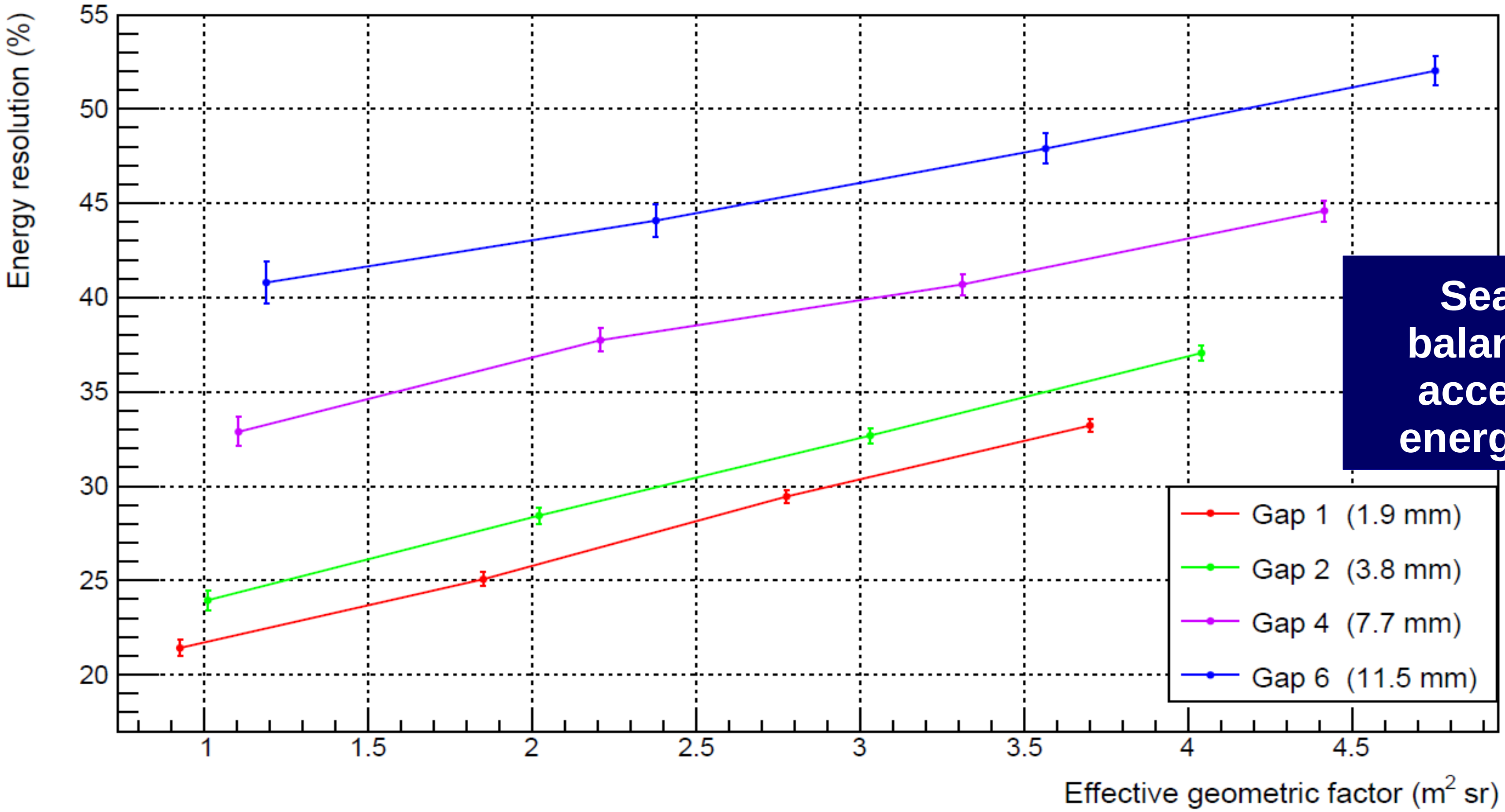
- Proton @ 1TeV
- Effective geometric factor = $GF_{single\_face} * 5 * \varepsilon_{Selection}$



LYSO is a good candidate for future space calorimeters

Gaps: en. res. vs acceptance

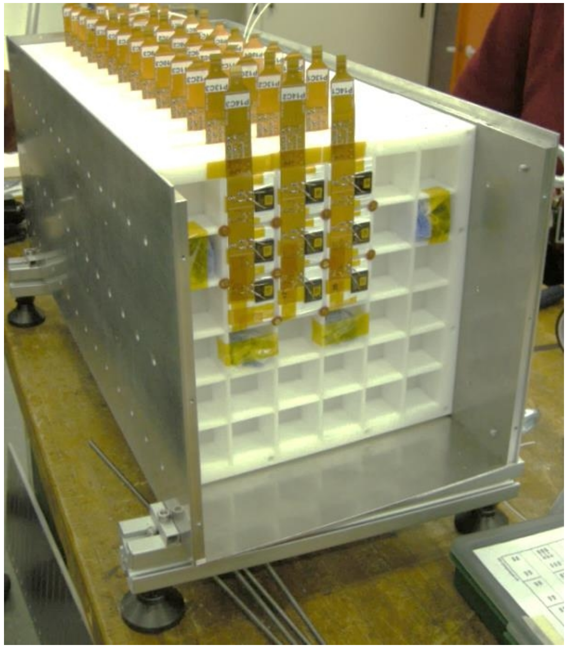
- Proton @ 1TeV, CsI(Tl)
- Effective geometric factor = $GF_{single\_face} * 5 * \varepsilon_{Selection}$

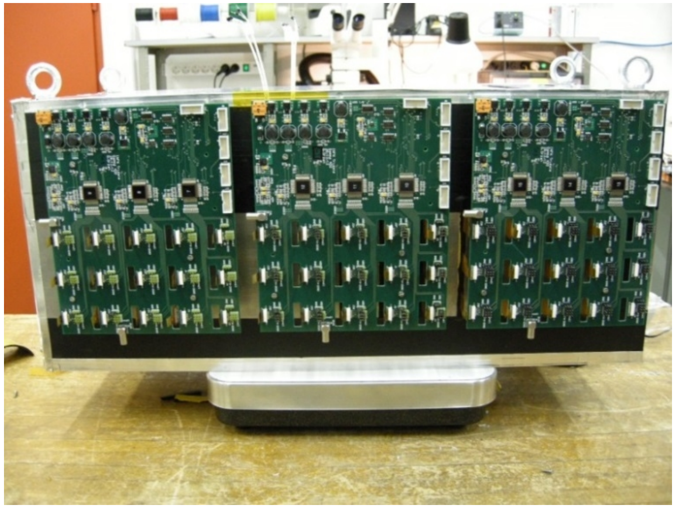


Searching for balance between acceptance and energy resolution

Prototype

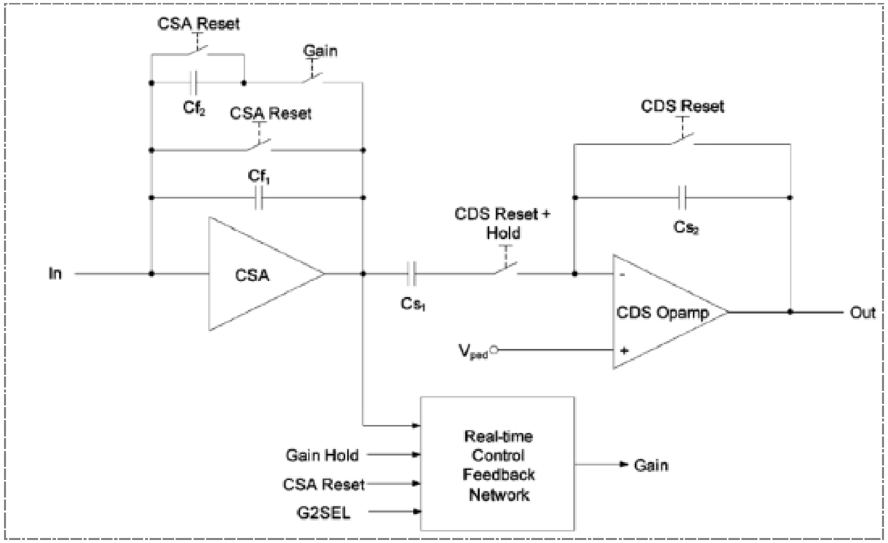
- **15 Layers**
- **3 x 3 CsI(Tl) crystals in each layer**
- Crystal side ~ Moliere radius (3.6 cm)
- Gap 0.4 cm
- A big PD (VTH2090) for each crystals
- A small PD for 3 crystals
- **Depth for vertical track: 29 X_0 <--> 1.46 λ_I**
- Wrapping materials:
  - Version 1.0: Teflon
  - Version 1.2: Vikuiti
- 3 front-end electronics board: 9 CASIS chip, 3 ADC





CASIS chip

- **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

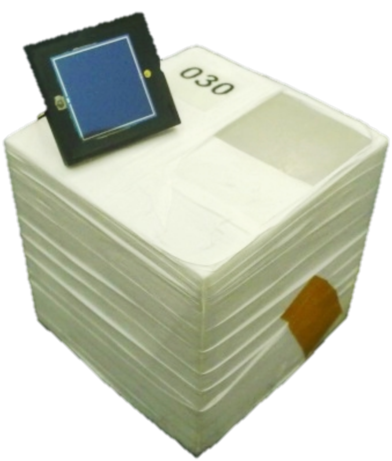
Photodiodes

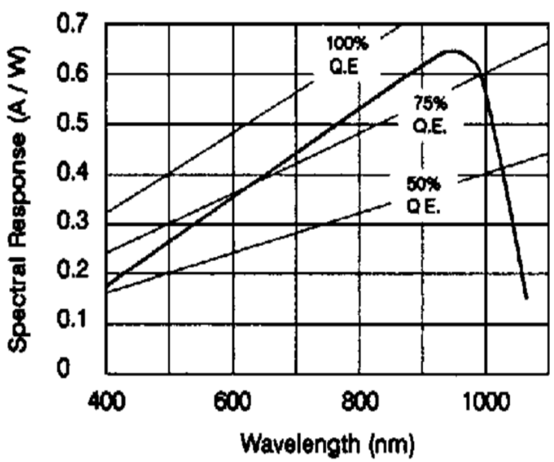
Large area photodiode VTH2090:

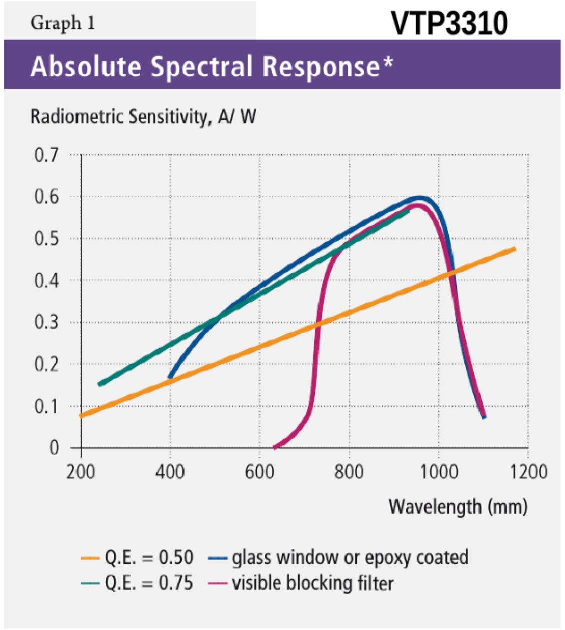
- Active area 84.64 mm^2
- 1 MIP in CsI(Tl) ~ 7fC
- Max signal 30 nC (>> CASIS range)

Small area photodiode VTH9412:

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







Energy range assuming BigPD/SamllPD = 100

Single crystal max energy
With big PD: ~ 30 GeV
With small PD: ~3 TeV

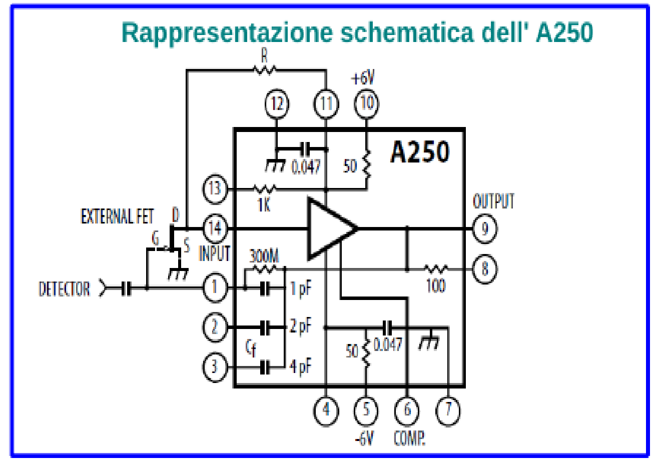
→

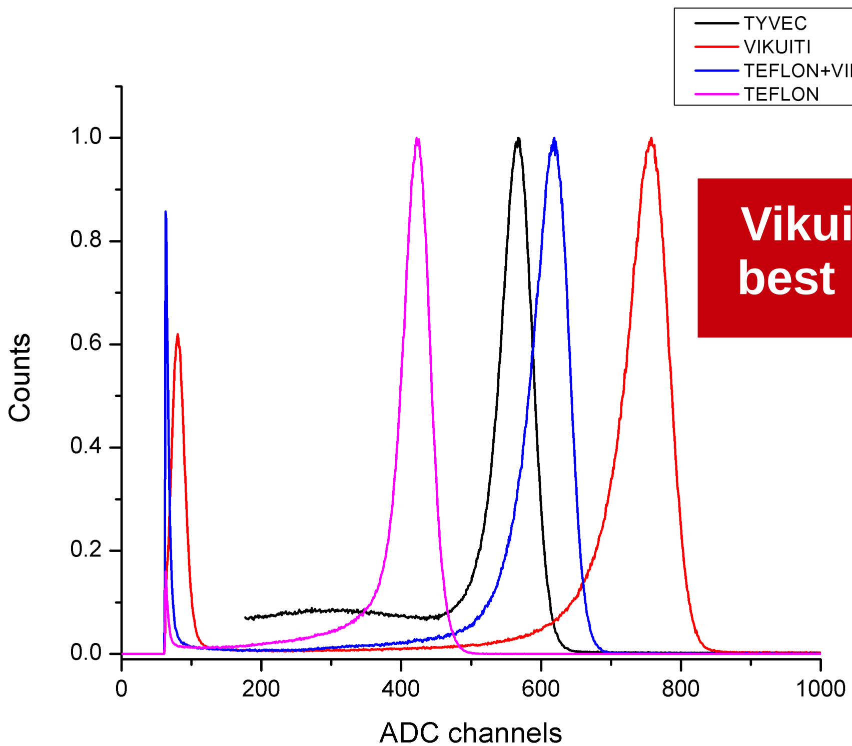
Beam test: saturation of front-end electronics with big PD for electron @ 150 GeV

Wrapping materials

Measurements setup:

- Single crystal with large area photodiode
- 5.5 MeV alpha source
- Low noise charge amplifier Amptek A250





Vikuiti achieves the best light collection

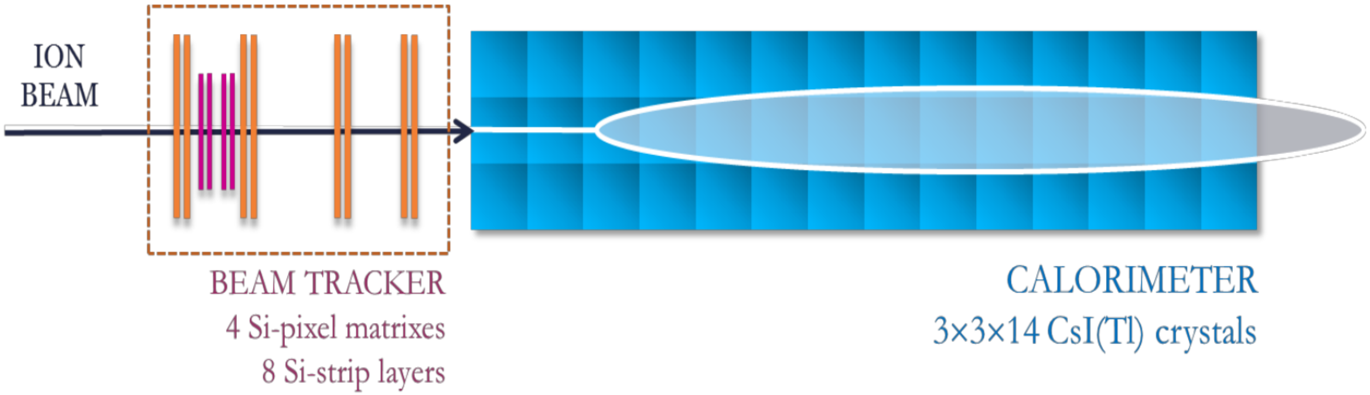
A crystal of prototype V1.2: Vikuiti is the wrapping material

Small PD

Big PD

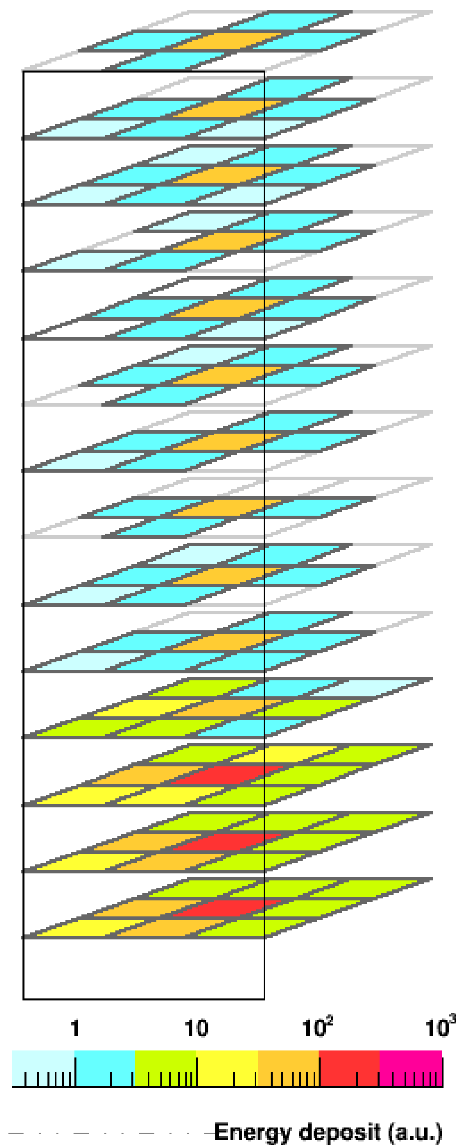
Beam test with ion

- CERN, SPS, H8 area, Ion beam, Z/A =1/2, 12.8 GeV/n and 30 GeV/n
- Ion from Deuterium to Iron
- Charge identification and tracking is performed with silicon strips and pixels by INFN of Pisa/Siena



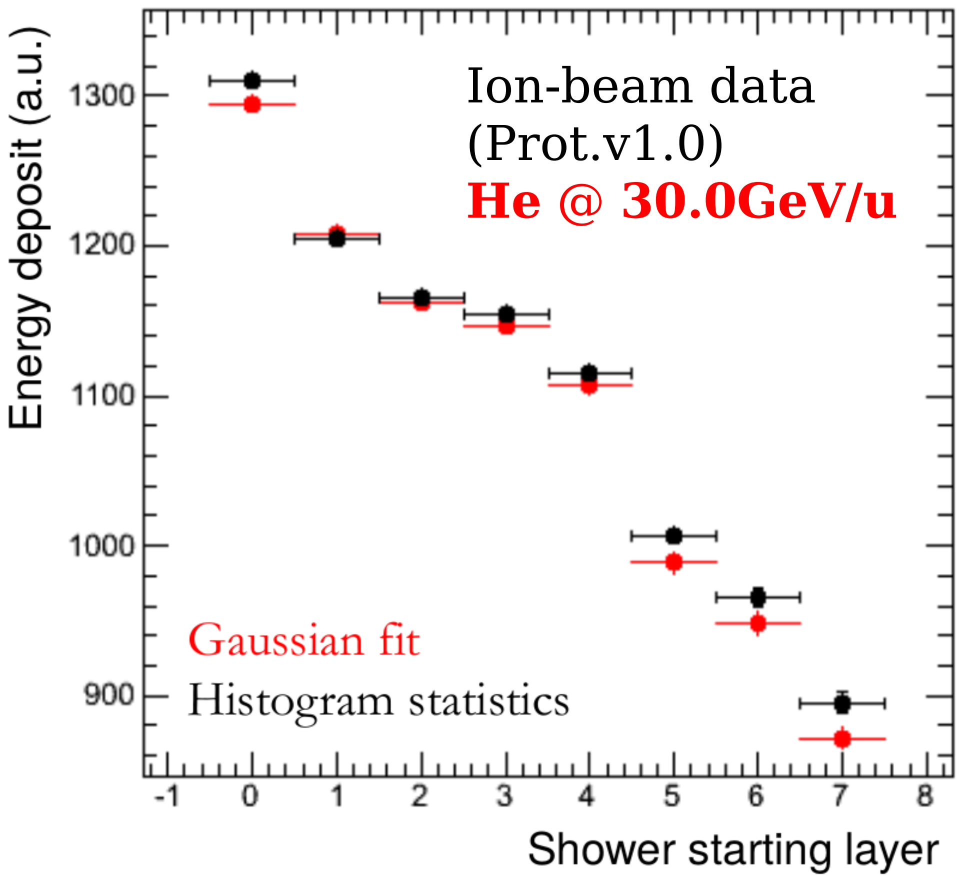
Protons and Ion: the energy deposit and energy resolution strongly depend on the shower starting point

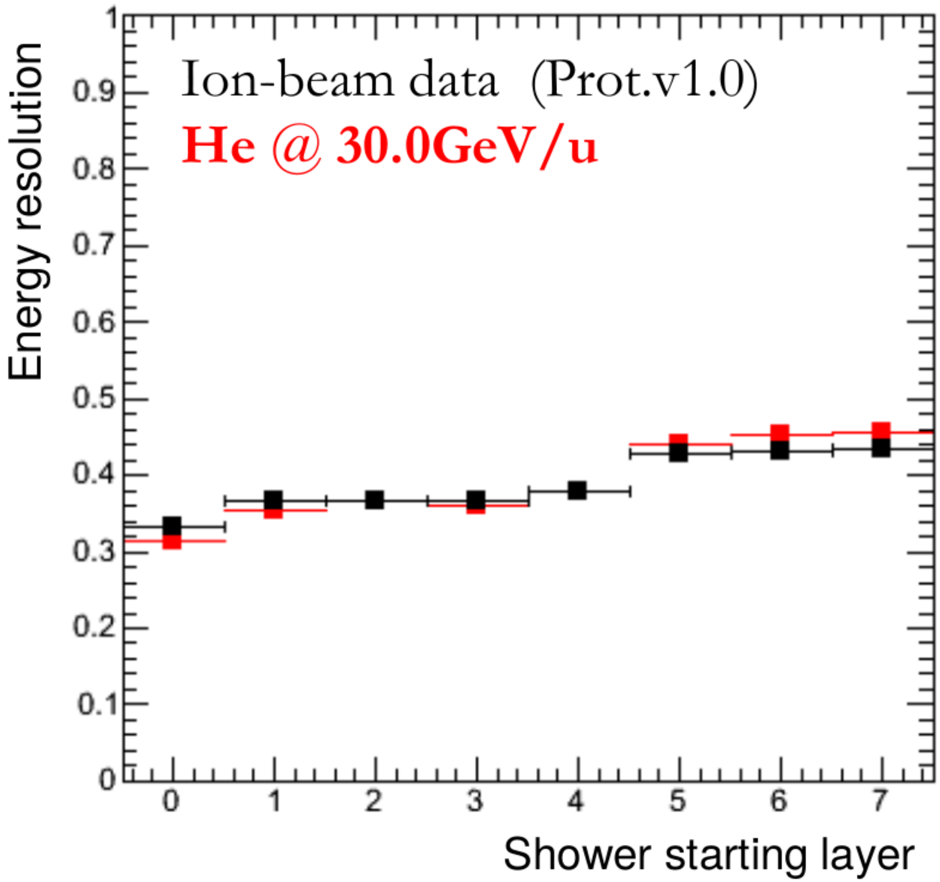
C @12.8 GeV/n



En. dep. vs shower containment

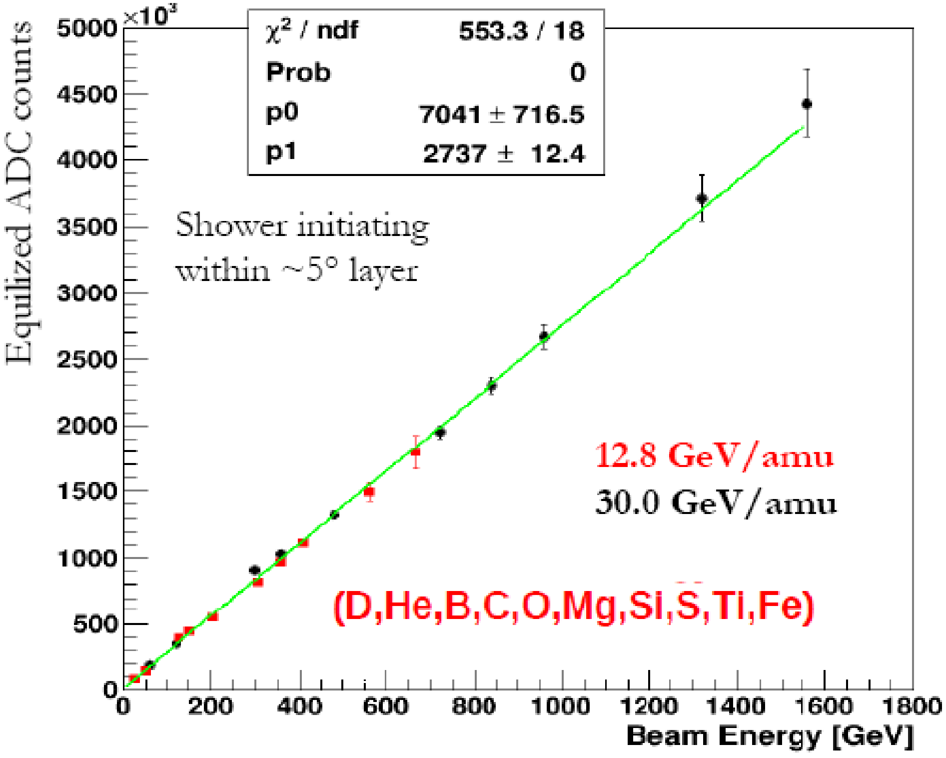
- Double thresholds algorithm is used in order to found the shower starting point



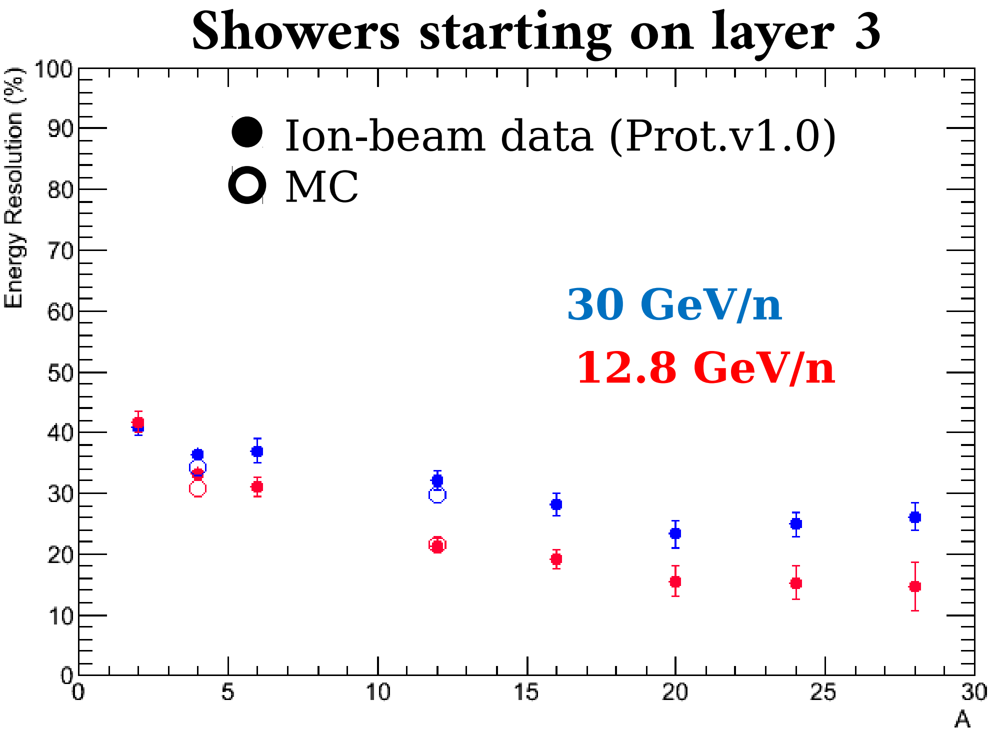


Linearity vs beam energy

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

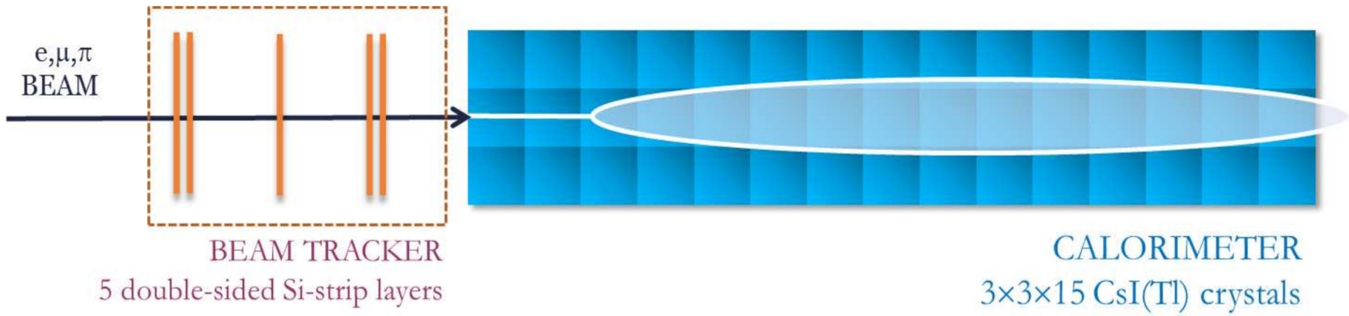


Energy resolution improves with A. Good agreement between data and MC



Beam test with electrons

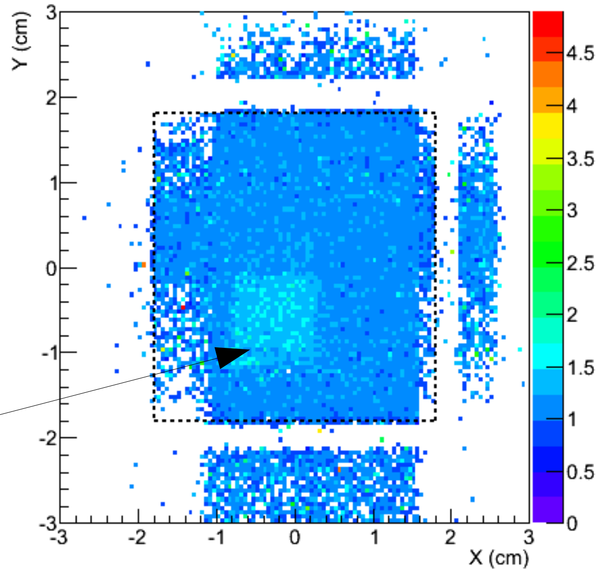
- CERN, SPS, H8 area, Electron from 50 GeV to 200 GeV
- Tracking is performed with ADAMO, 5 layer of silicon micro-strip detector, double sided (X,Y)



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

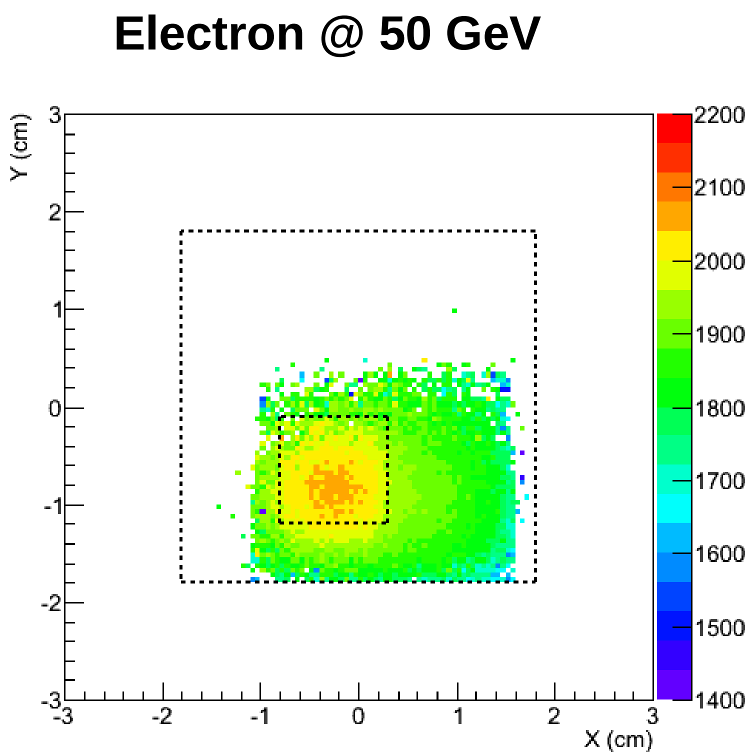
Good identification of crystals positions

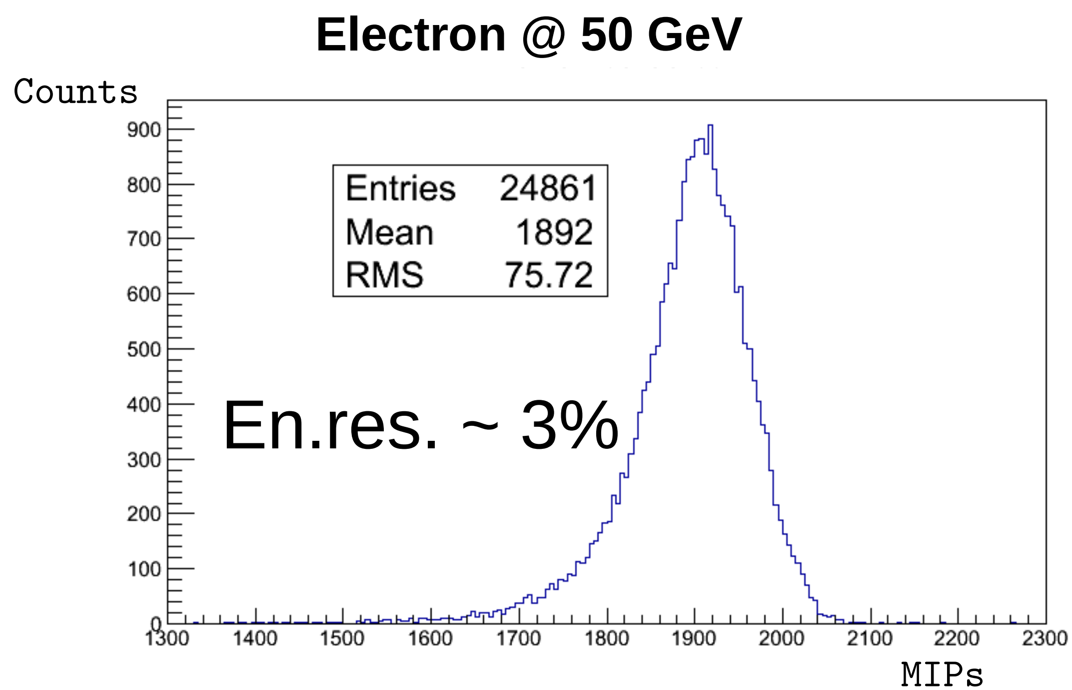
Reconstruction of PD position is also possible because of direct ionization



Energy deposit by electron

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



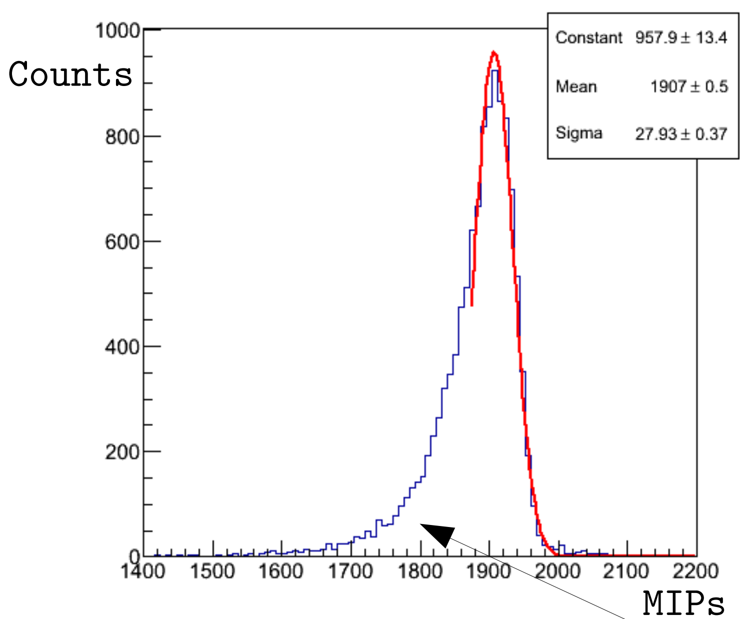


- In order to study the prototype performance a FLUKA based simulation with detailed prototype geometry was developed

MC data vs beam data

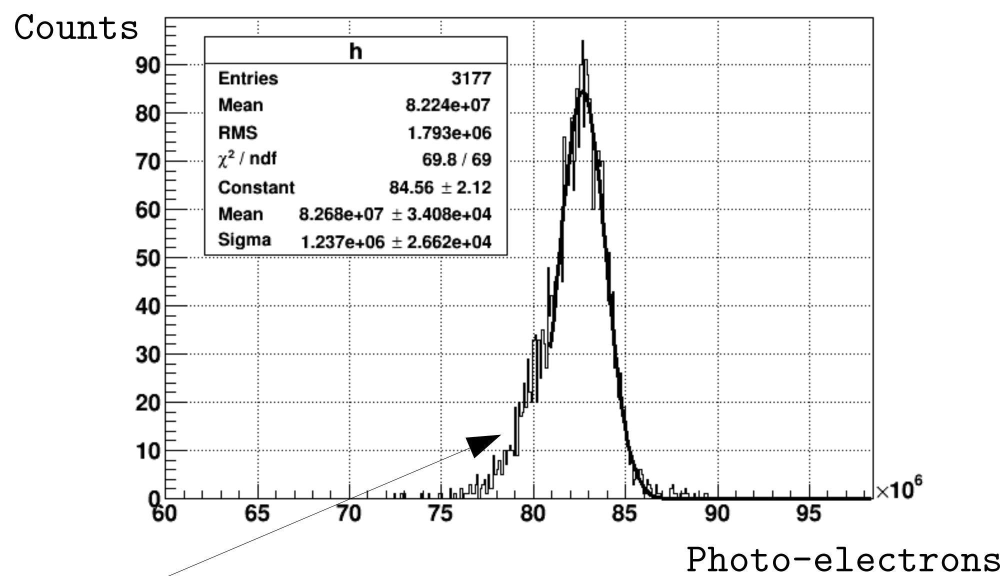
- Electrons @ 50 GeV energy deposit after geometrical selection of events with direction that does not intercept the PD (both in simulation and beam data)

Beam data: Electron @ 50 GeV



En. Res. ~ 1.5%

MC data: Electron @ 50 GeV

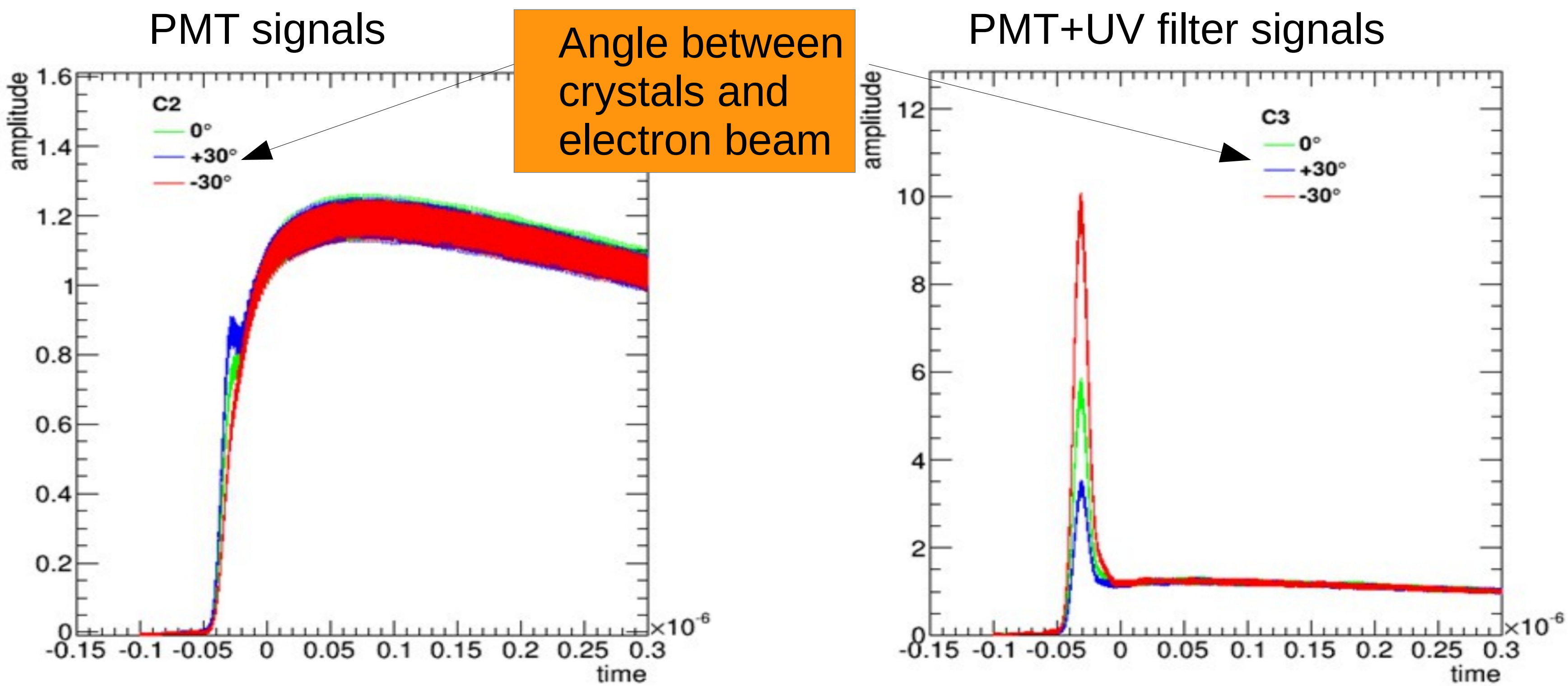


En. Res. ~ 1.5%

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

Cherenckov Light in CsI(Tl)

- Simultaneous detection of Cherenkov and scintillation light could be useful to increase performance.
- Test performed at BTF-Frascati (460MeV e -): we found that the Cherenkov is visible even in CsI(Tl)



Conclusion

- CaloCube R&D project, financed by INFN (Italy), was presented.
- The performances of the calorimeter was studied with MonteCarlo simulation, FLUKA based, for electrons and protons.
- Material and geometry optimization for protons was discussed.
- A prototype of CsI(Tl) has been constructed and tested both with electrons and nuclei.
- Beam test data are in good agreement with the simulation results
- We also investigated the dual readout technique using Cherenckov light in CsI(Tl) (some additional informations are in backup slides)

NEW PROTOTYPE (v 2.0)

- 18 Layer of 6 x 6 crystals of CsI(Tl) (**35 X_0 <--> 1.75 λ_I**)
- 2 PD for each crystals and new mechanical structure

Thanks to the organizers for this opportunity

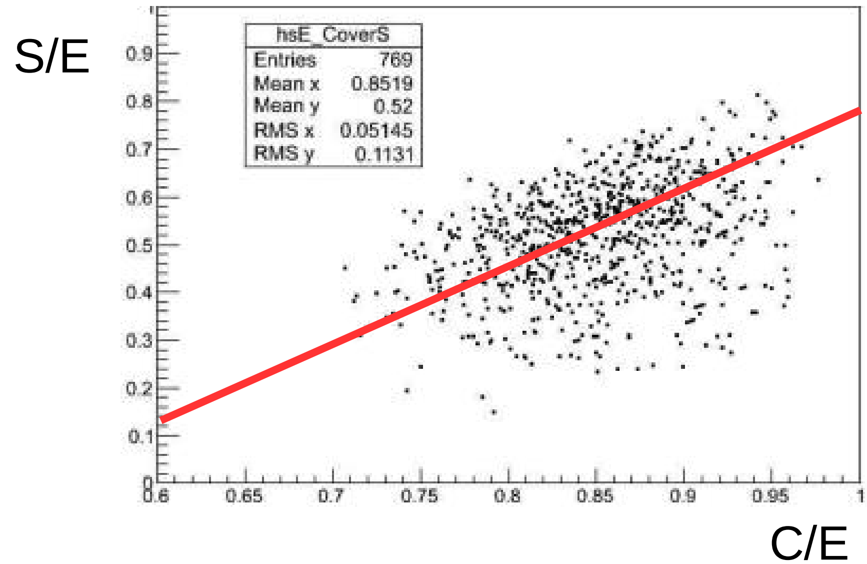
Backup slides

1) Dual readout in Calocube
2) Direct/Indirect measurements
3) Proton event selections
4) Ion beam calibration
5) Ion beam data vs MC
6) MC simulation: electron beam
7) Local energy resolution for electrons @ 50 GeV
8) Proton energy resolution @ 1 TeV

Dual readout

- Scintillation is considered strictly proportional to the total ionization
- The fluctuations of the e.m. fraction of the shower dominate the energy resolution for protons and nuclei
- Cherenkov light response to e.m. fraction is different with respect to scintillation
- Simultaneous detection of Cherenkov and scintillation light useful to event-by-event correction for fluctuations in shower e.m.-fraction

Protons @ 100 GeV

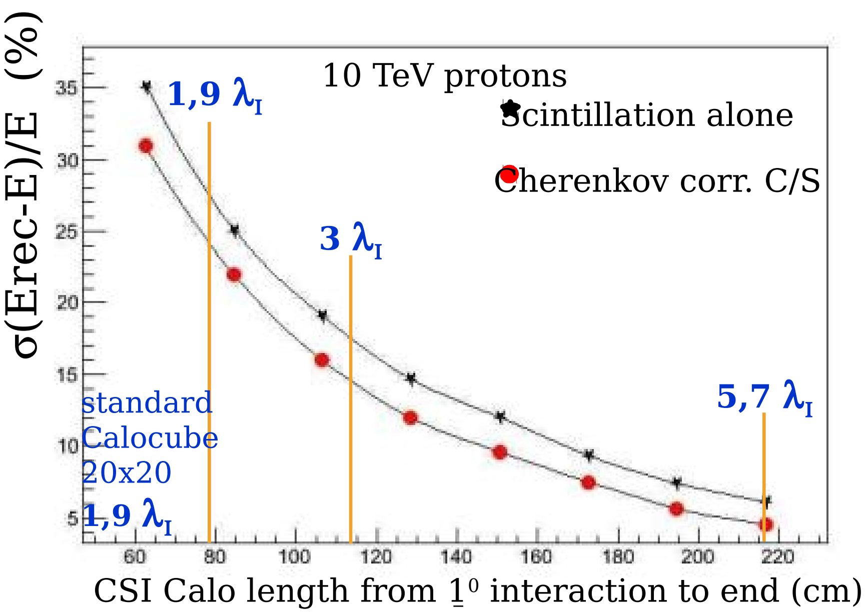


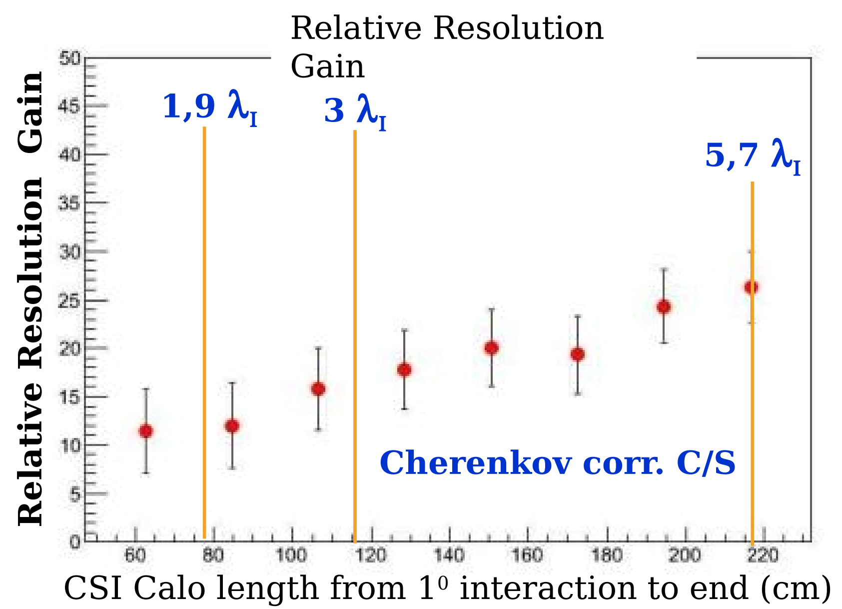
S/E = scintillation signal divided by proton energy
C/E = Cherenkov signal divided by proton energy

Combination of S/E and C/E allow to reconstruct the proton energy
(see: arXiv:1210.2334v2 , D.Groom)

Dual readout in CaloCube

- Simulation of a large CaloCube: 60x60x60 CsI(Tl) crystals
- Resolution improvement increasing for increasing depth





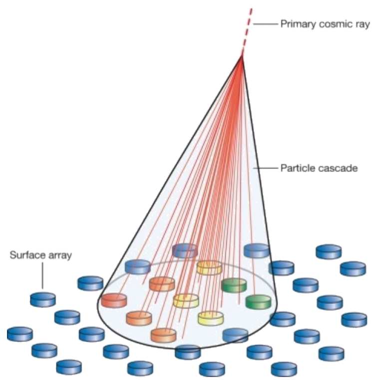
- Only moderate improvement for CaloCube standard geometry (10%)
- Cherenkov could provide cross-calibration of the calorimeter response, very important features for space-born detector

Direct/indirect measurenemnts

DIRECT MEASURENMENTS

- Precise measurements using spectrometers and/or calorimeters
- Good individual particle identification
- Limit in energy due to small acceptance:
  - Nuclei below 100 TeV/n
  - Electron+positron below 1 TeV

INDIRECT MEASURENMENTS



- High acceptance, high statistics
- Good measurement of all-particle spectra
- Systematics due to simulation approximations
- Difficult in composition measurements

Proton: event selections

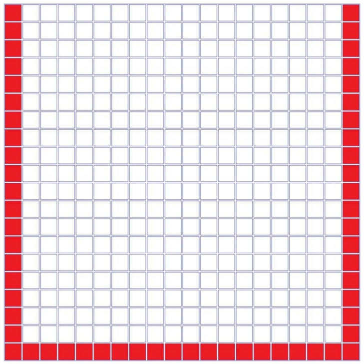
Selection criteria:

1)Interacting protons: 100 crystals with signals > 15 MIP

2)Maximum point containment: the crystals with maximum signal is in "fiducial area"

3)Minimum shower length

Red cubes is out of the fiducial area



- Simulated protons @ 1 TeV, 10 TeV, 100 TeV, 1 PeV
- The efficiency of selections (1) and (2) is 35% - 40%

$\varepsilon_{S.L.}$ = Efficiency of minimum shower length selection

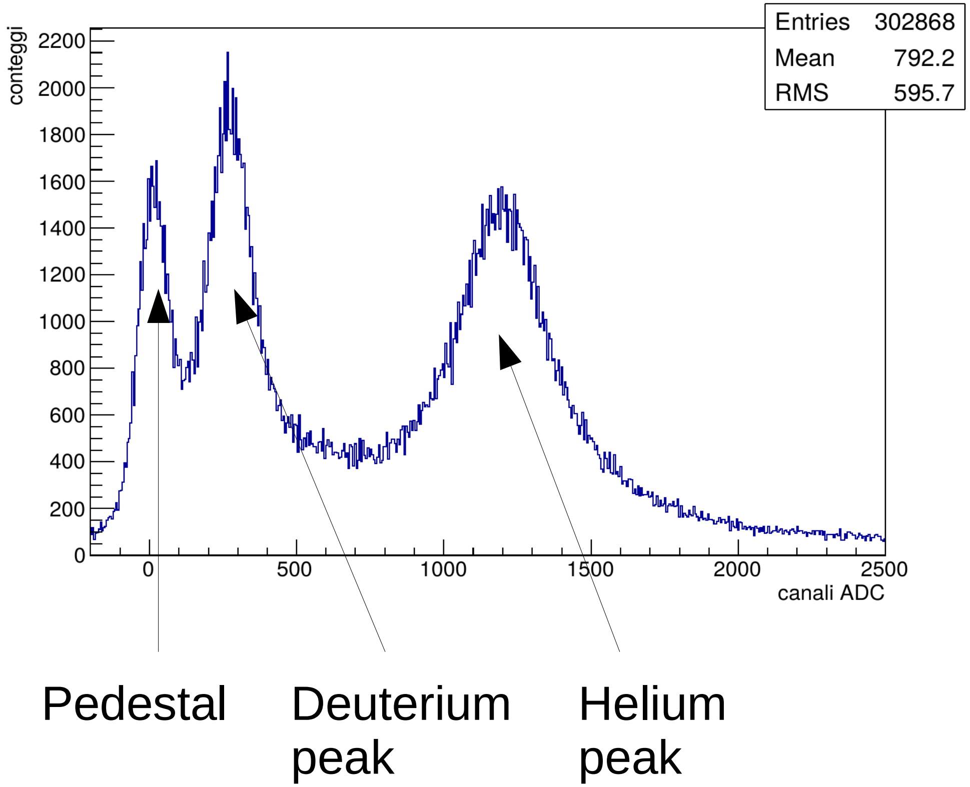
- 4 different selections of minimum shower length:

$\varepsilon_{S.L.}$ = 100%,75%,50%,25%

Ion beam: calibration

- Identification of non interacting deuterium and helium signals for channels equalization

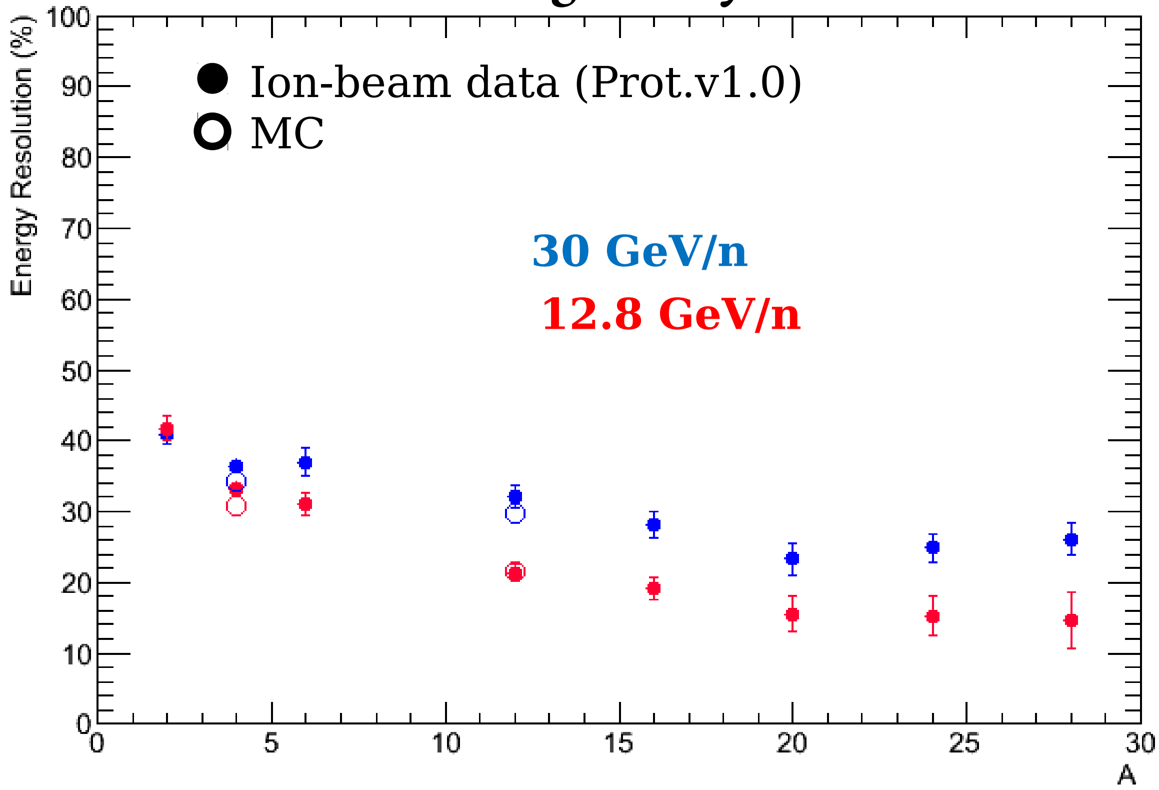
Signals central cube, first layer



Ion beam: data vs MC en. res.

- Energy resolutions increases with A
- **Difference between MC simulations and data are few percent**
- Instrumental effects not implemented in simulations: optical crosstalk (14%), gaussian spread to single crystal (4.5%)
- No crosstalk in v1.1 (Tedlar) and v1.2 (Vikuiti)

Showers starting on layer 3

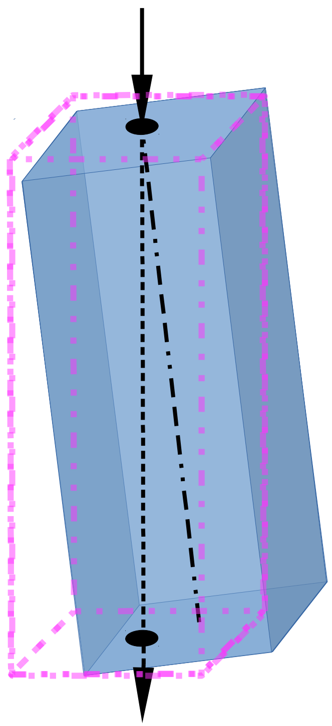


In a full containment calorimeter →

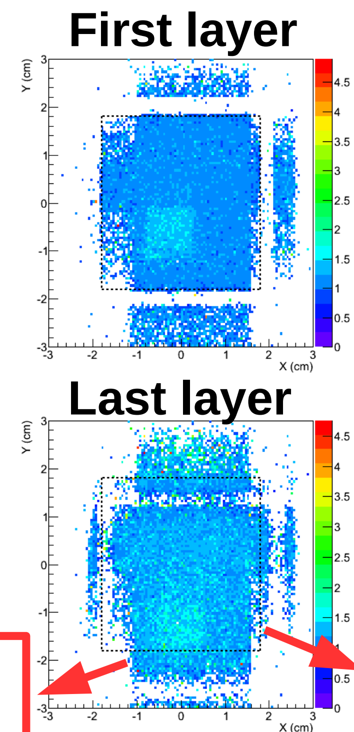
$$\left(\frac{\sigma_E}{E}\right)_A = \frac{1}{\sqrt{A}}\left(\frac{\sigma_E}{E}\right)_p$$

MC simulations: electron beam

- In order to study the prototype performances a FLUKA based simulation with details prototype geometry was developed
- The angle between the calorimeter and the electron beam was implemented in simulation
- This angle was measured using muons data
- Very good agreement between beam data and MC data was found (see next slide)



Misalignment measurements

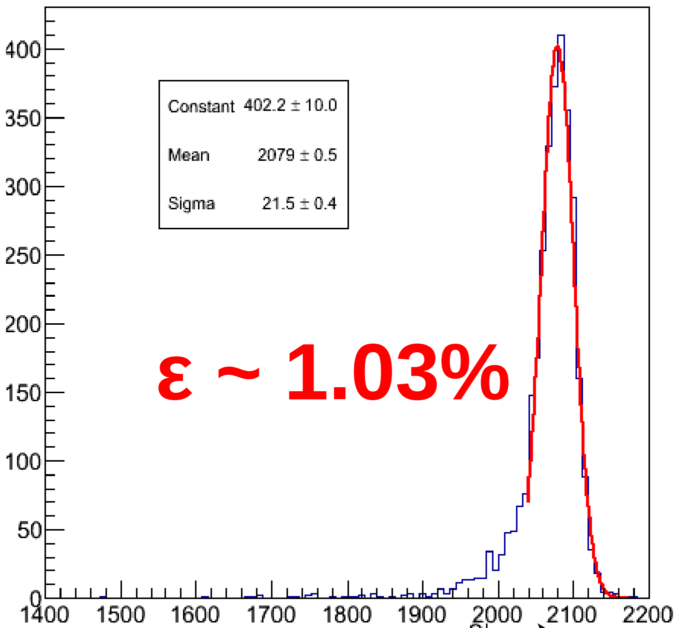


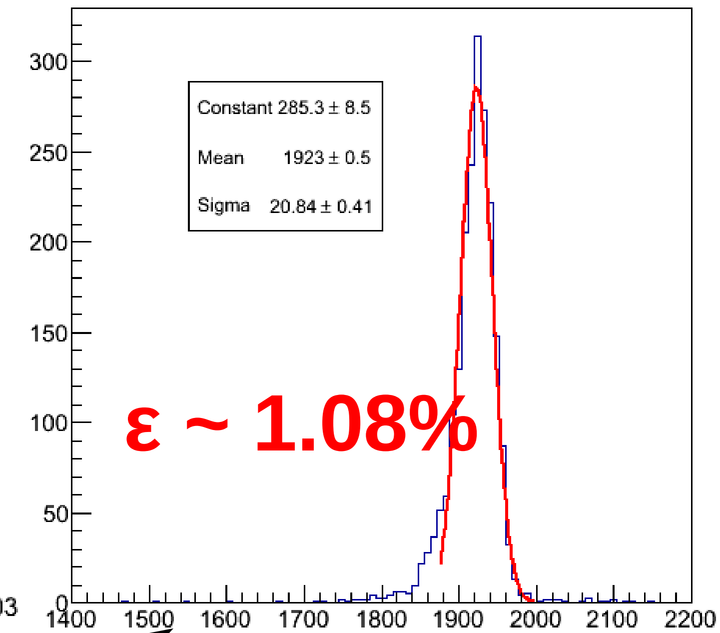
ΔX ~ 6mm
↓
θ ~ 0.6°

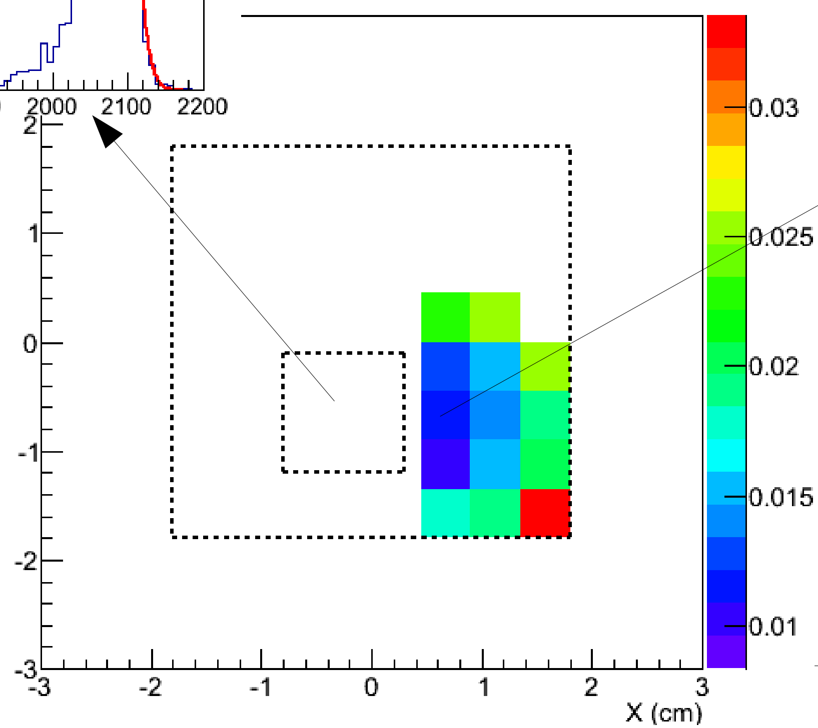
ΔY ~ 2mm
↓
φ ~ 0.2°

Electron @ 50 GeV

e^+
@ 50GeV/c







Energy distribution for events in PD active area

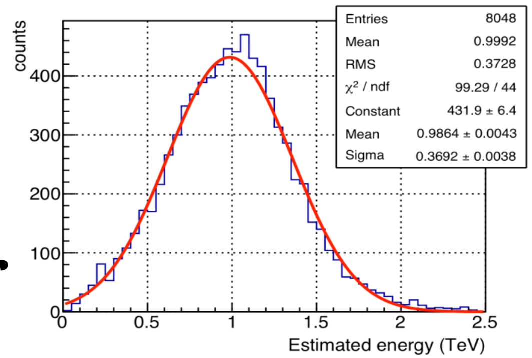
Energy distribution for a local area ($0.45x0.45cm^2$) far from PD and cube edge

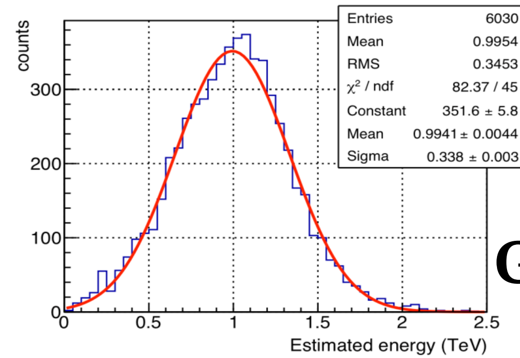
Proton @ 1 TeV

$$\frac{\Delta E}{E} = (37.4 \pm 0.4)$$

$\varepsilon_{S.L.}$ = 100%

GF_{eff} = 3.8 m^2str





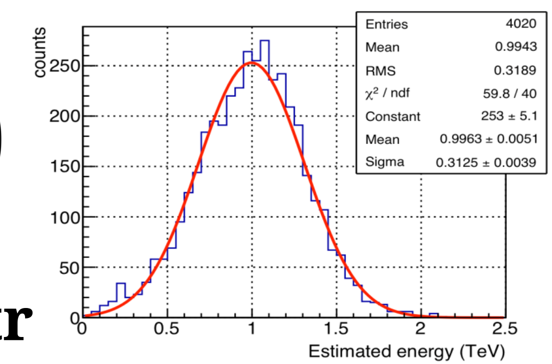
$\varepsilon_{S.L.}$ = 75%

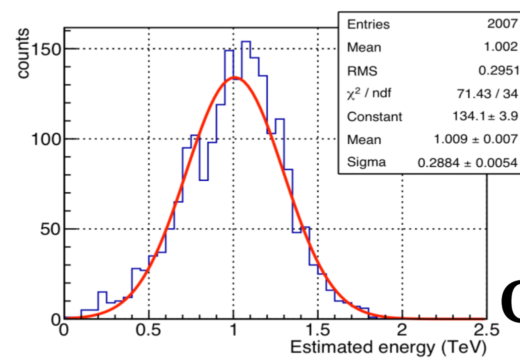
GF_{eff} = 2.9 m^2str

$$\frac{\Delta E}{E} = (31.4 \pm 0.5)$$

$\varepsilon_{S.L.}$ = 50%

GF_{eff} = 1.9 m^2str





$$\frac{\Delta E}{E} = (28.6 \pm 0.6)$$

$\varepsilon_{S.L.}$ = 25%

GF_{eff} = 0.95 m^2str