CaloCube
a new approach to calorimetry in space-based experiments for high-energy cosmic rays

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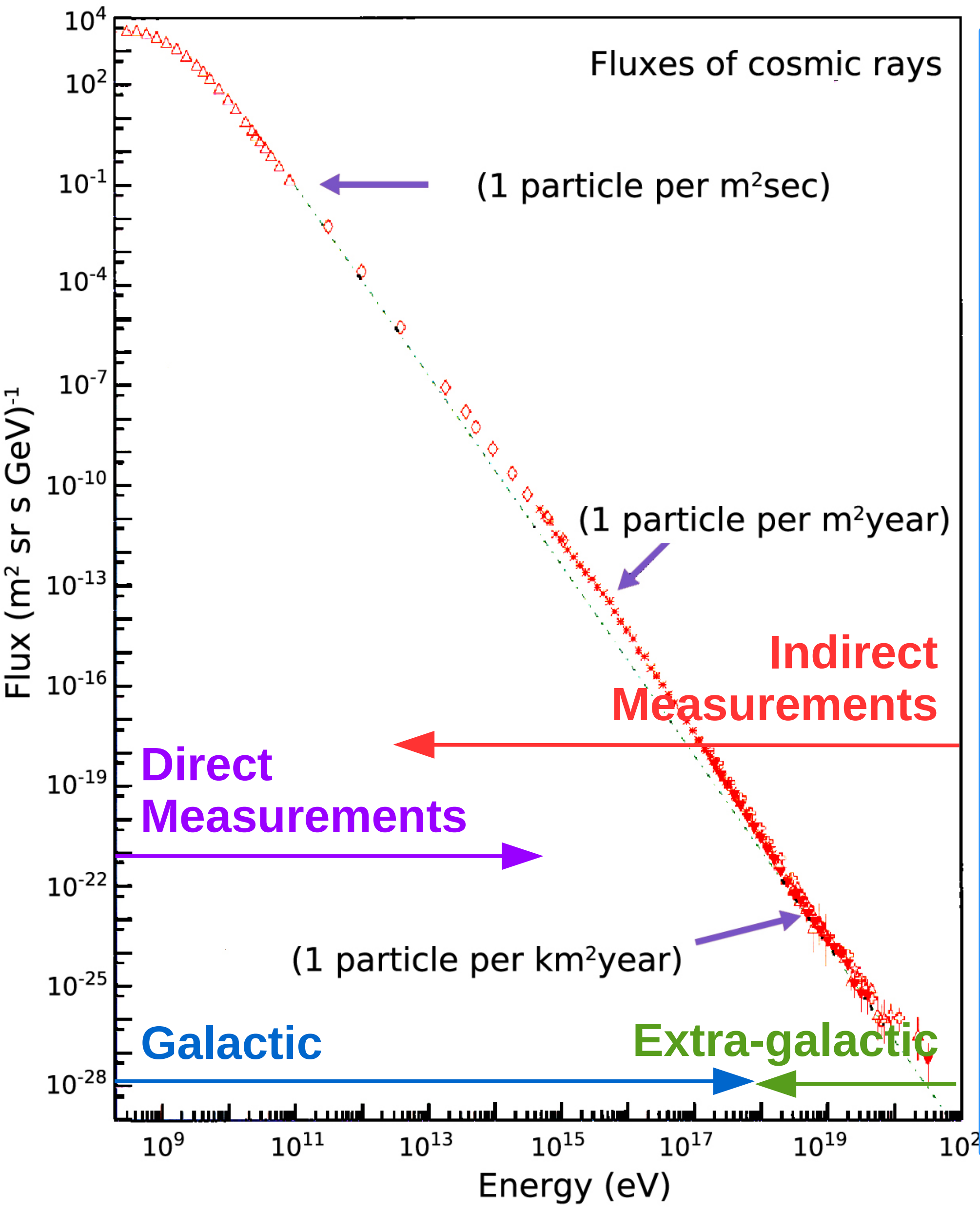
Outline

- Cosmic rays
- The Calocube project
  - Simulations
  - Prototypes
- The TIC project

Cosmic Ray physics

Cosmic rays



Open problems

- Identification of astrophysical sources responsible for acceleration
- Understanding of acceleration, propagation and interaction mechanisms
- Location of the transition region between galactic and extra-galactic origin
- Search for dark matter sources

Direct Measurements

Advantage

Individual particle identification

Disadvantage

Payload limitation
⇒small statistics

Indirect Measurements

Advantage

Large arrays
⇒large statistics

Disadvantage

Large model systematics

Satellite experiments

In order to improve past measurements and extend them to higher energy, future space experiments must fulfill several requirements

Protons and Nuclei up to 3 PeV/n

$\sigma_E/E < 40\%$

$G_{eff} \times T > 2.5\ m^2\ sr \times 5yr$

Dynamic Range $> 10^7$

$\sigma_Z < 0.2\text{-}0.3\ e$

Electrons and positrons up to 30 TeV

$\sigma_E/E < 2\%$

$G_{eff} \times T > 3.6\ m^2\ sr \times 5yr$

Dynamic Range $> 10^5$

e/p separation $> 10^6$

Geometric factor

$$G = \frac{dN_{detected}}{dt} / I$$

Typical limitations

Mass ~10^3 Kg
Power ~10^3 W
Down link ~10^2 Gb/d
Volume ~ 1 m^3

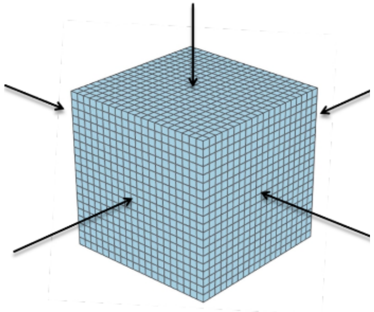
Effective geometric factor

$$G_{eff} = \epsilon_{sel}\, x\, G$$

Need to find new design for future experiments in order to fulfill requests

The Calocube project

The Calocube project



Calocube is an R&D project financed by INFN for 3+1 years in 2014

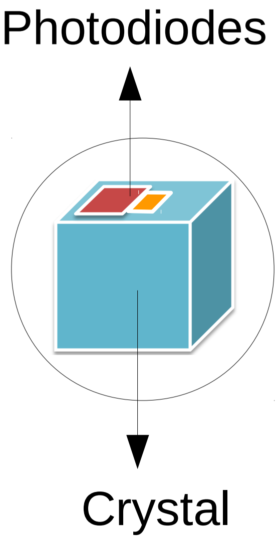
The aim of the project is the design and optimization of a ***calorimeter for the direct measurement of high-energy cosmic rays in space***

The project includes a wide range of **expertises**: calorimetry, CR physics, VLSI analog design, crystals, polymeric coatings.,,,

The **participants** to the project include several institute in Italy:

- INFN: Catania, Firenze, Milano (Bicocca), Pisa, Pavia, Trieste
- CNR-IFAC Firenze
- CNR-IMM-MATIS Catania
- IMCB-CNR Napoli

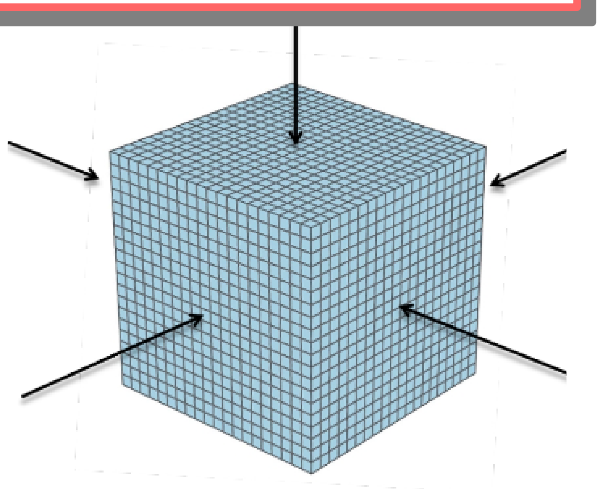
The Calocube idea



NxNxN cubic crystals with 1 Moliere radius side

Signal read by two PDs and double gain electronics

In case of CsI, N=20, side=3.6 cm, $L=39X_0$ (1.8 λ_I)



Deep homogeneous isotropic calorimeter → Good energy resolution

Cubic geometry with 5 face detection → Large geometrical acceptance

Shower imaging with 3D segmentation → Good e/p rejection, identification of shower axis and of shower starting point

Simulations

FLUKA

Implementation

Simulations of a **cubic calorimeter made of NxNxN crystals** taking into account:

- conversion of the energy deposited in the crystal to the n° of **photoelectrons** (p.e.) in the photodiode (PD) considering light yield, light collection and quantum efficiency
- estimation of the signal due to **direct ionization** in photodiodes
- energy deposited in passive layers (carbon fiber support structure)

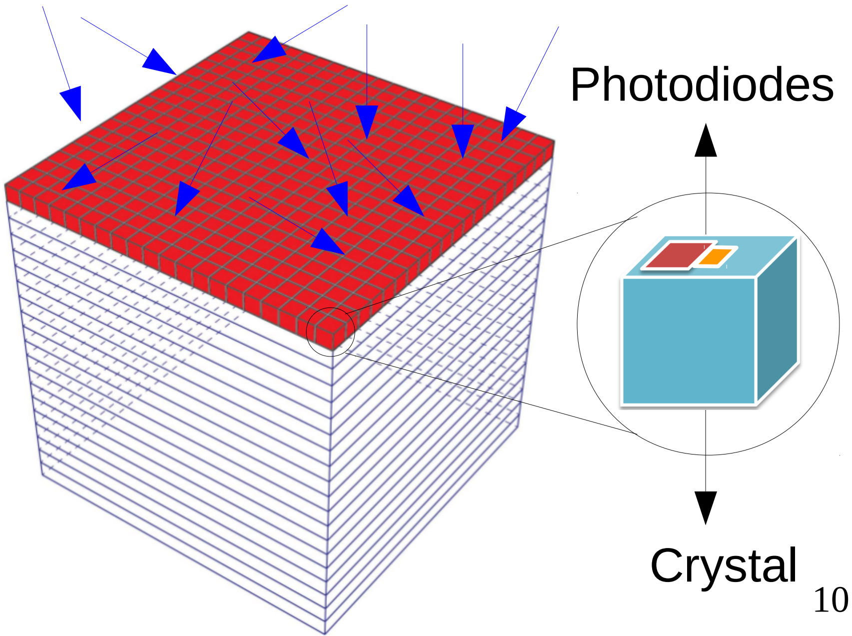
Particles are injected from top surface in an **uniform and isotropic** way:

- electrons of 100 GeV - 1 TeV
- protons of 1, 10, 100, 1000 TeV

In case of CsI:Tl

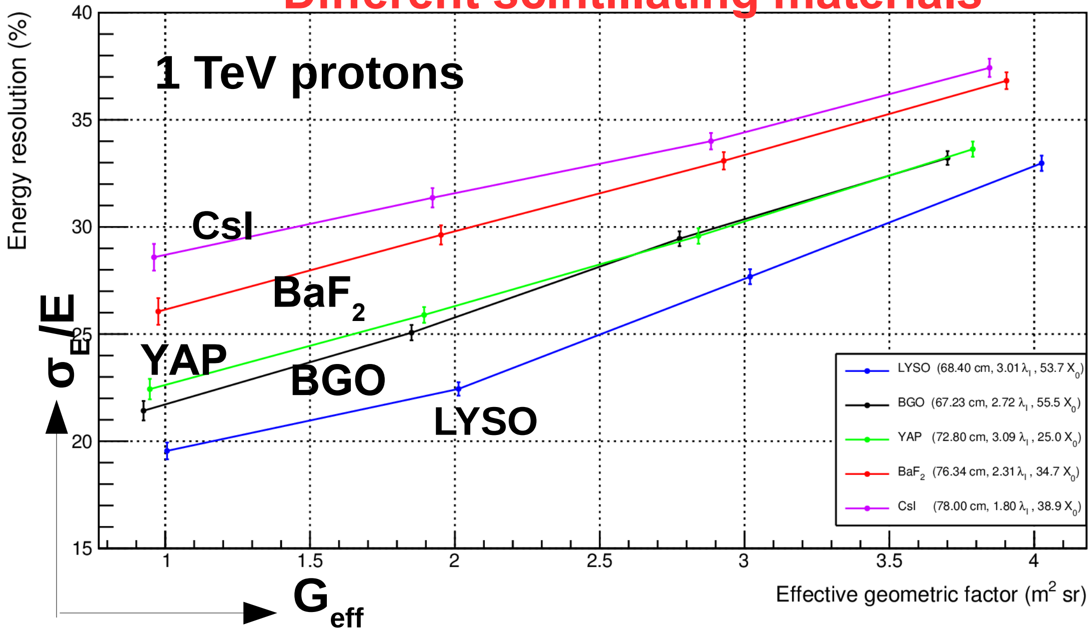
N×N×N	**20×20×20**
crystal side (cm)	3.6
crystal volume (cm³)	46.7
gap (cm)	0.3
mass (kg)	1685
number of crystals	8000
size (m³)	0.78×0.78×0.78
depth (R.L.) " (I.L.)	39×39×39 1.8×1.8×1.8
planar GF (m²sr) *	1.91

* GF only for one surface



Dependence on scintillating material and gap size

Different scintillating materials



The best value of σ_E/E is obtained using low λ_I crystals. The maximum G_{eff} has a small dependence on the material.

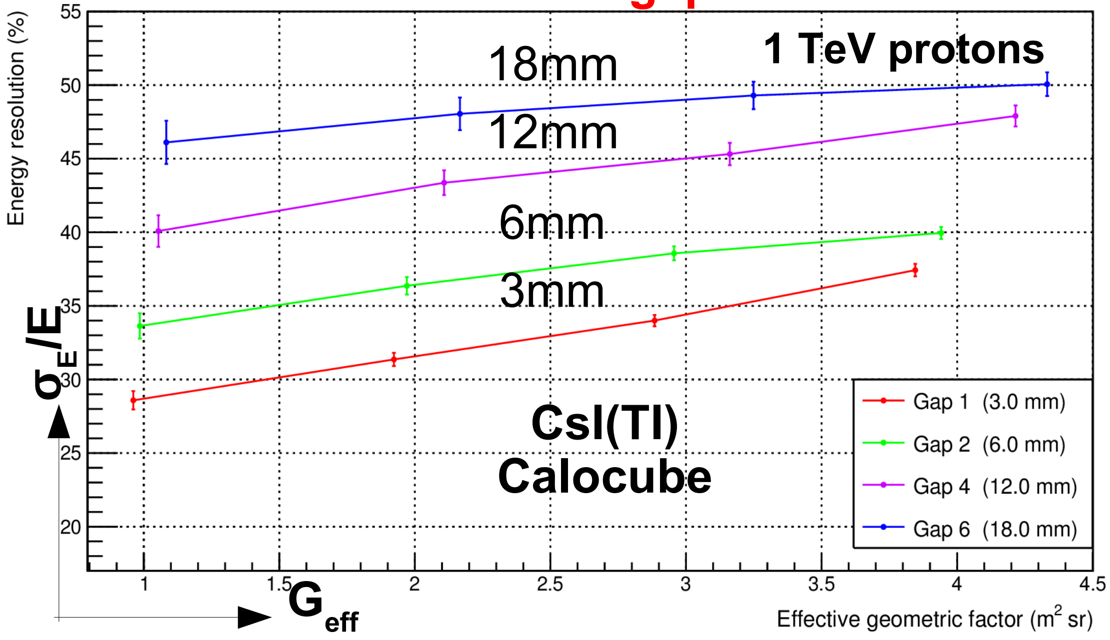
LYSO is the best candidate.

Larger gap increases G_{eff},
Smaller gap improves σ_E/E

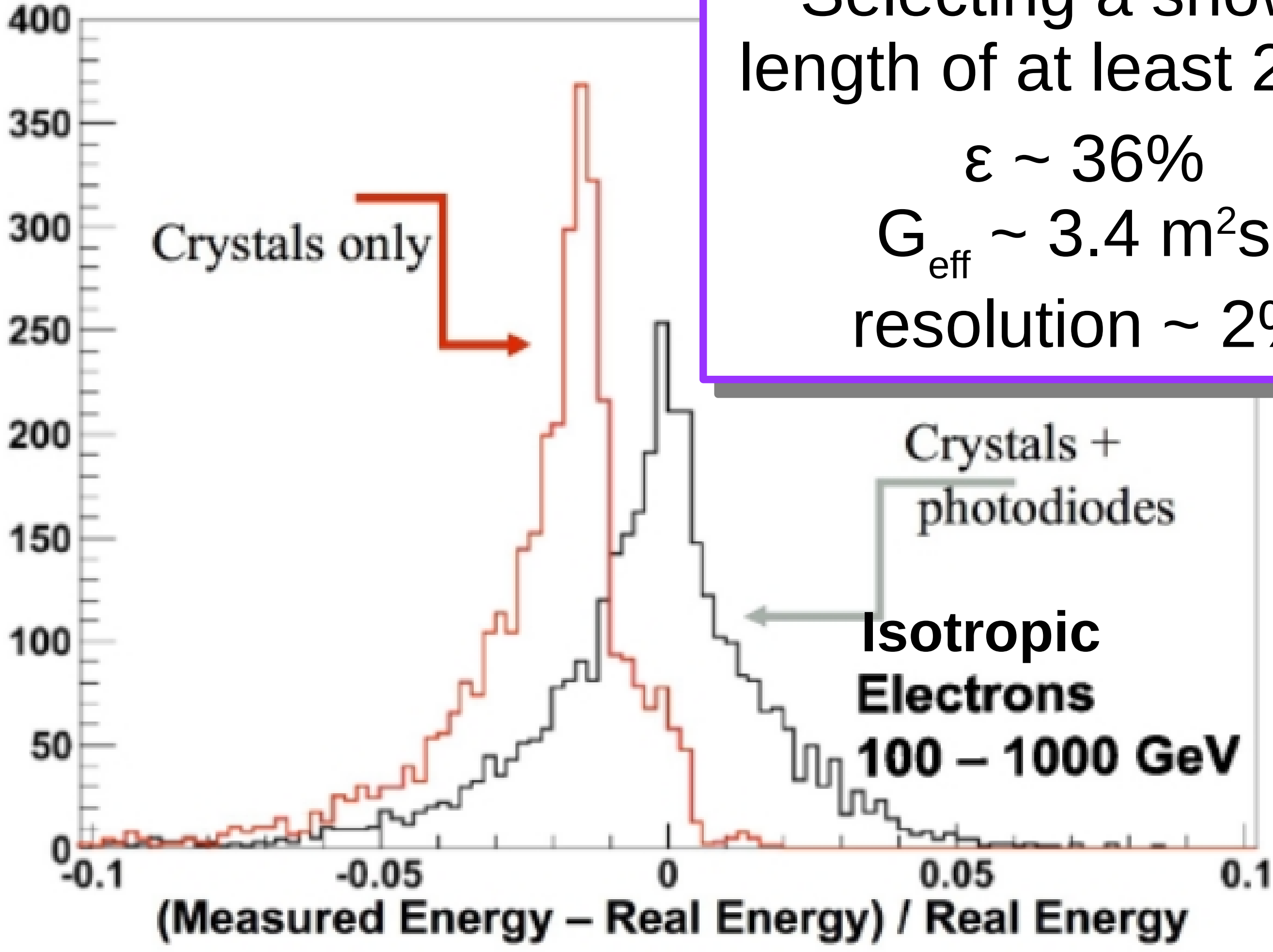
A compromise is needed.

The points corresponds to different selection efficiency

Different gaps



Electron performances



Selecting a shower length of at least 22 X_0:
$\varepsilon \sim 36\%$
$G_{eff} \sim 3.4\ m^2sr$
resolution ~ 2%

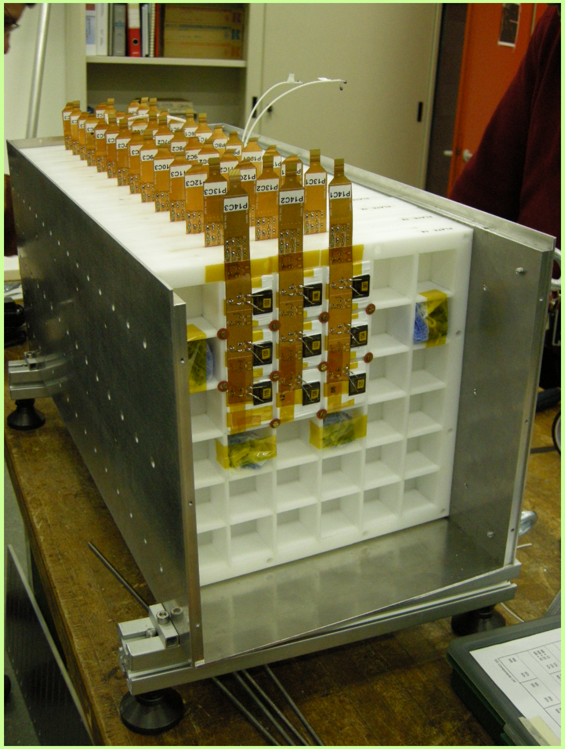
Direct ionization in photodiodes is about 1.7% of the total signal

Prototypes

Main versions

2012

Prototype v0



2013

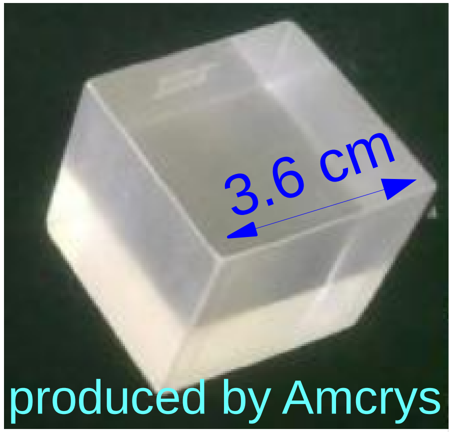
Prototype v1

2016

Prototype v2

Different prototypes have been built among the years, both increasing the size and upgrading the system

CsI:Tl scintillator

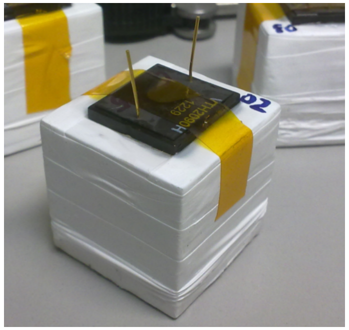


Density	4.51 g/cm³
Wavelength @max	550 nm
Light output	54 ph/keV (45 % of NaI(Tl))
Primary decay time	**1.25 μs**

Good compromise between acceptance and resolution

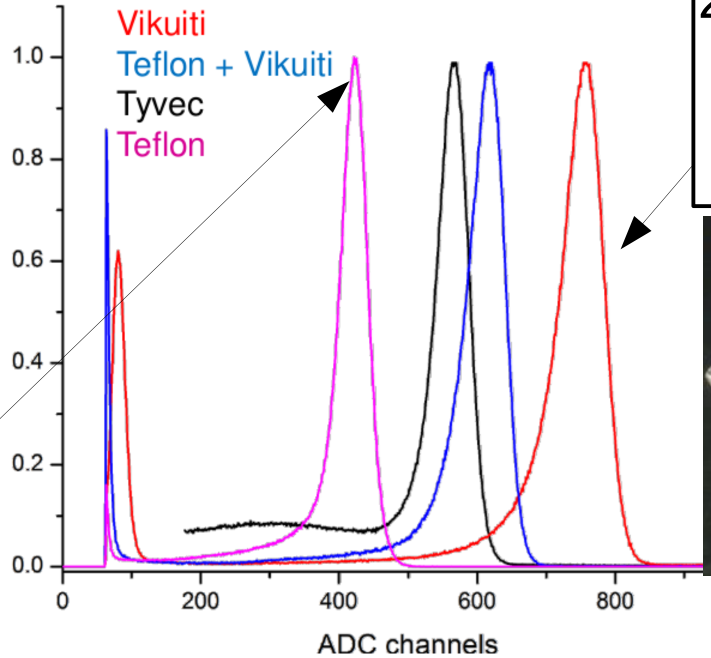
Good to be read making use of photodiodes sensors

Good intensity of the light signal (1 MIP ~ 20 MeV ~ 10^6 photons)



2012 prototype and 2013 prototype

Am 5.5 MeV α

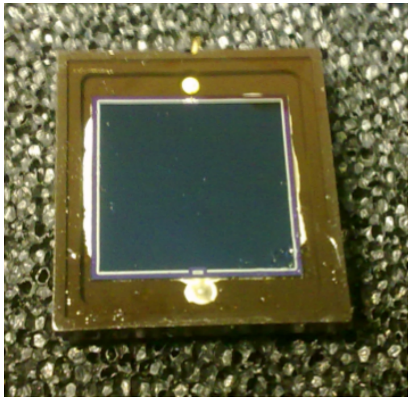


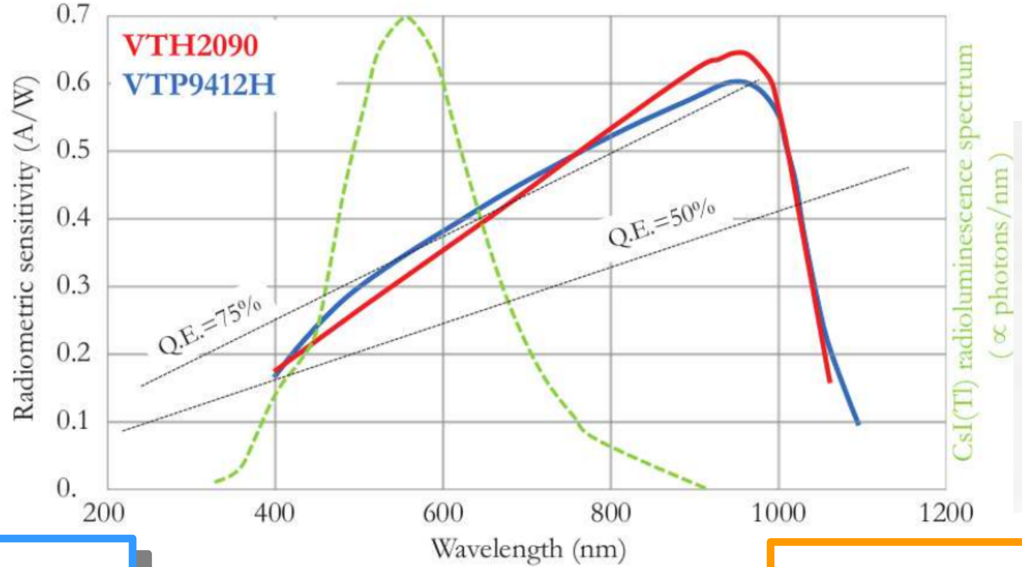
2013 upgrade and 2016 prototype

Vikuiti ensures the best light collection efficiency

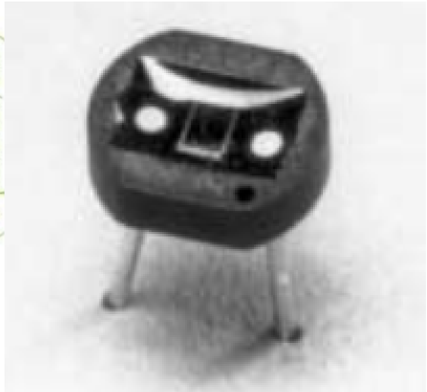
Photodiodes

LARGE PD





SMALL PD



VTH2090
Area ~ 86.64 mm^2
MaxSignal ~ 30 nC

Maximum detectable energy release in the crystal is ~ 30 GeV

The combination of photodiodes ensures a dynamic range of ~ 10^6

VTP9421H
Area ~ 1.6 mm^2
MaxSignal ~ 0.3 nC

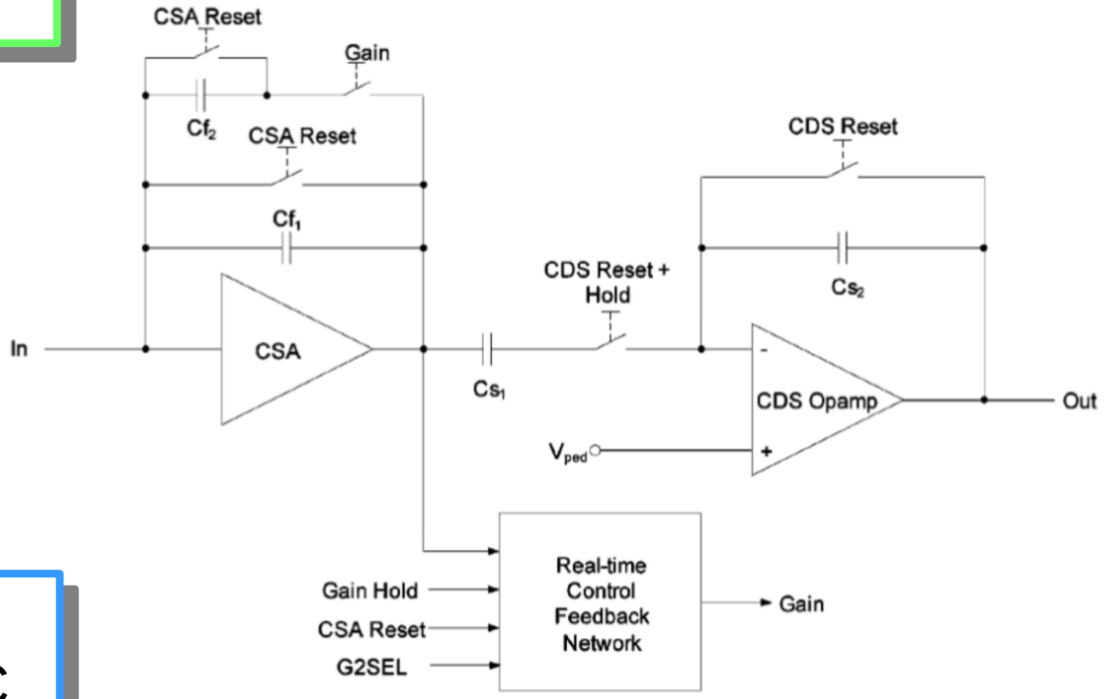
Maximum detectable energy release in the crystal is ~ 3 TeV

Front-end electronics

CASIS (HIDRA) chip
- R&D project by INFN
- Developed by INFN-Trieste
- Designed for silicon calorimetry in space

Specification
- 16 (28) channels
- charge sensitive amplifier + correlated double sampling
- double gain (1:20)
- automatic gain control

Performances
- High Dynamic range = 52.6 pC
- Low ENC = 2280e$^-$ + 7.6e$^-$ /pF
- Low Consumption = 2.8 mW/ch



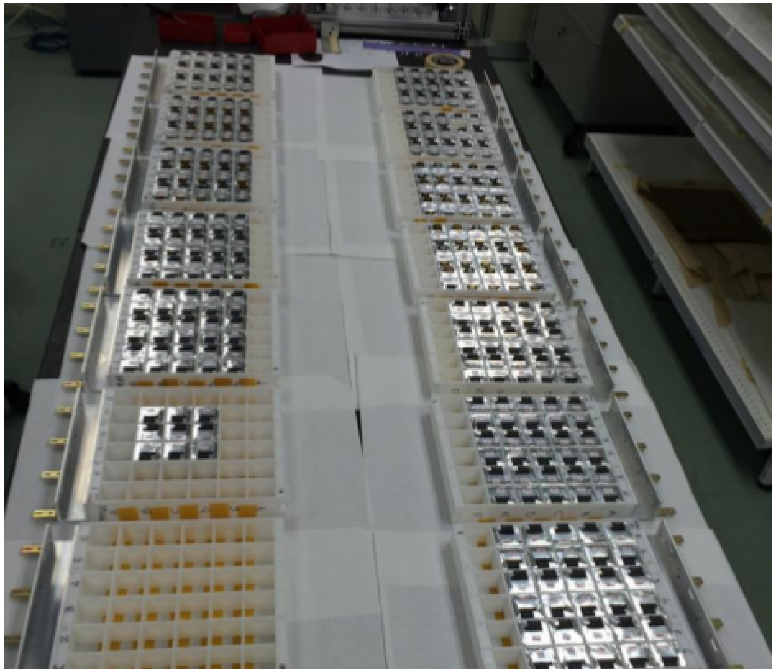
Prototype v2

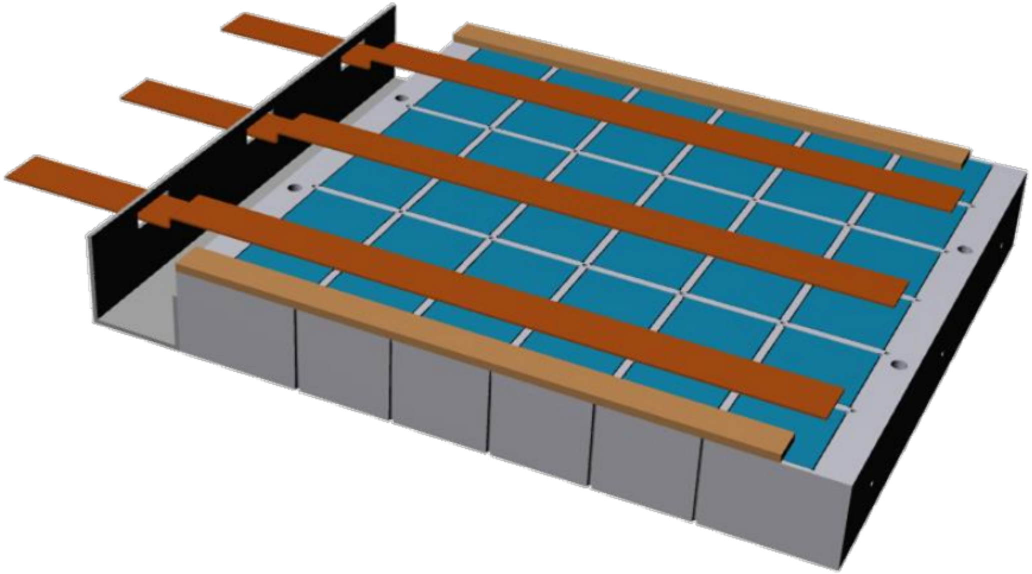
Geometry
- 18 layers of 5x5 CsI:Tl cubes
- Scintillators wrapped in Vikuiti
- Light collected by Small and Large PD

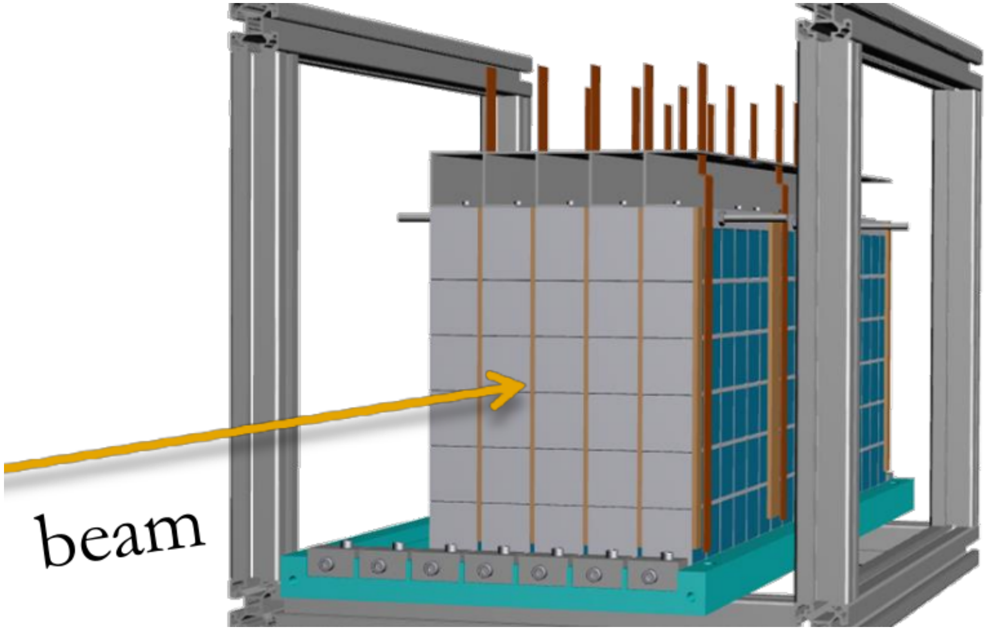
Shower containment
- 2.5 Moliere radius
- 35 X_0
- 1.6 λ_I

Beam tests

Sep 2016	v2.0	μ, π, e 50-75-150-180 GeV
Aug 2017	v2.1	μ, π, e + Ions

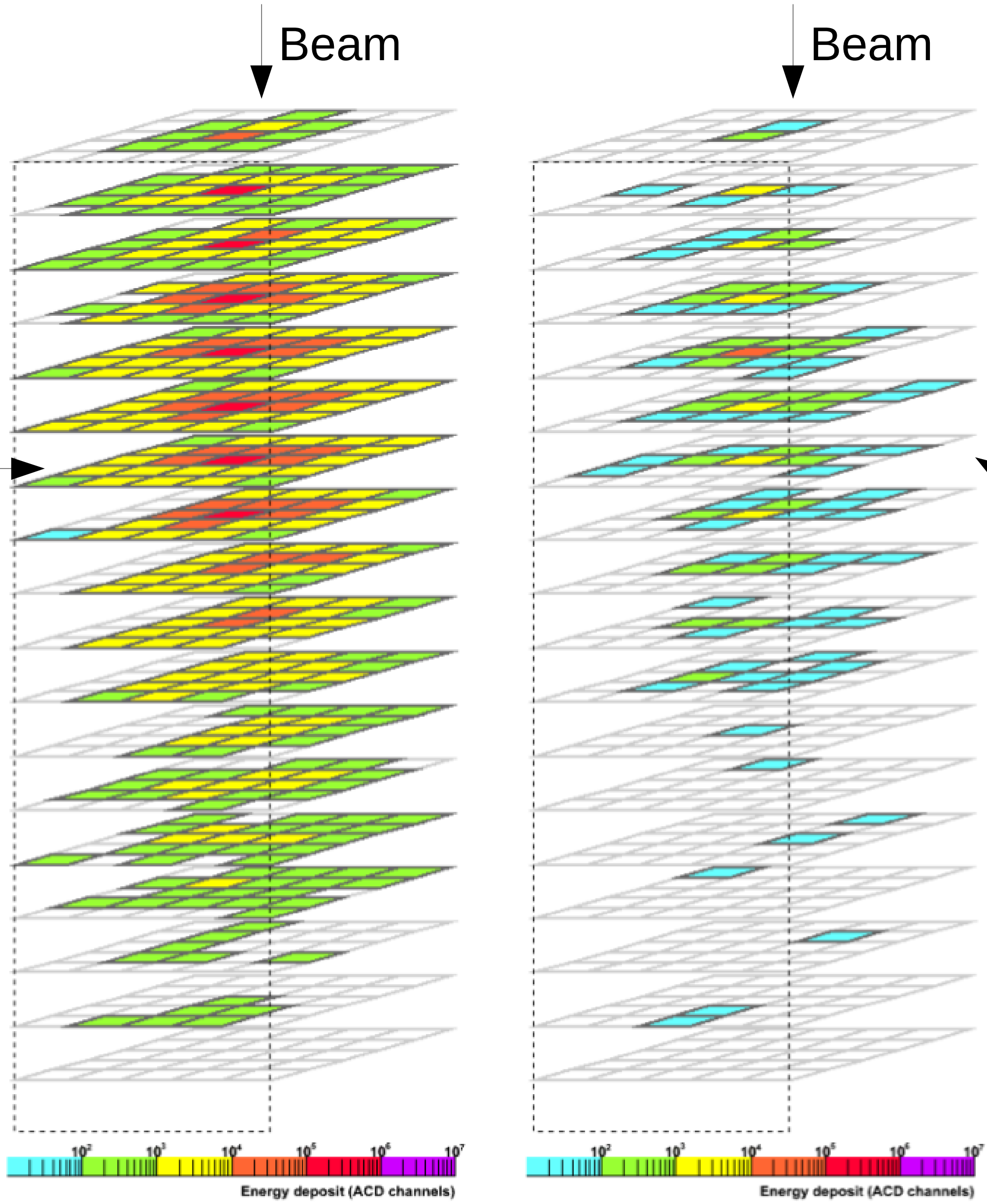






Prototype v2

Event view of a 200 GeV electron



Saturation in crystals where shower development is maximum

Large PDs

Combining the Large and Small PDs we can improve the linearity and resolution

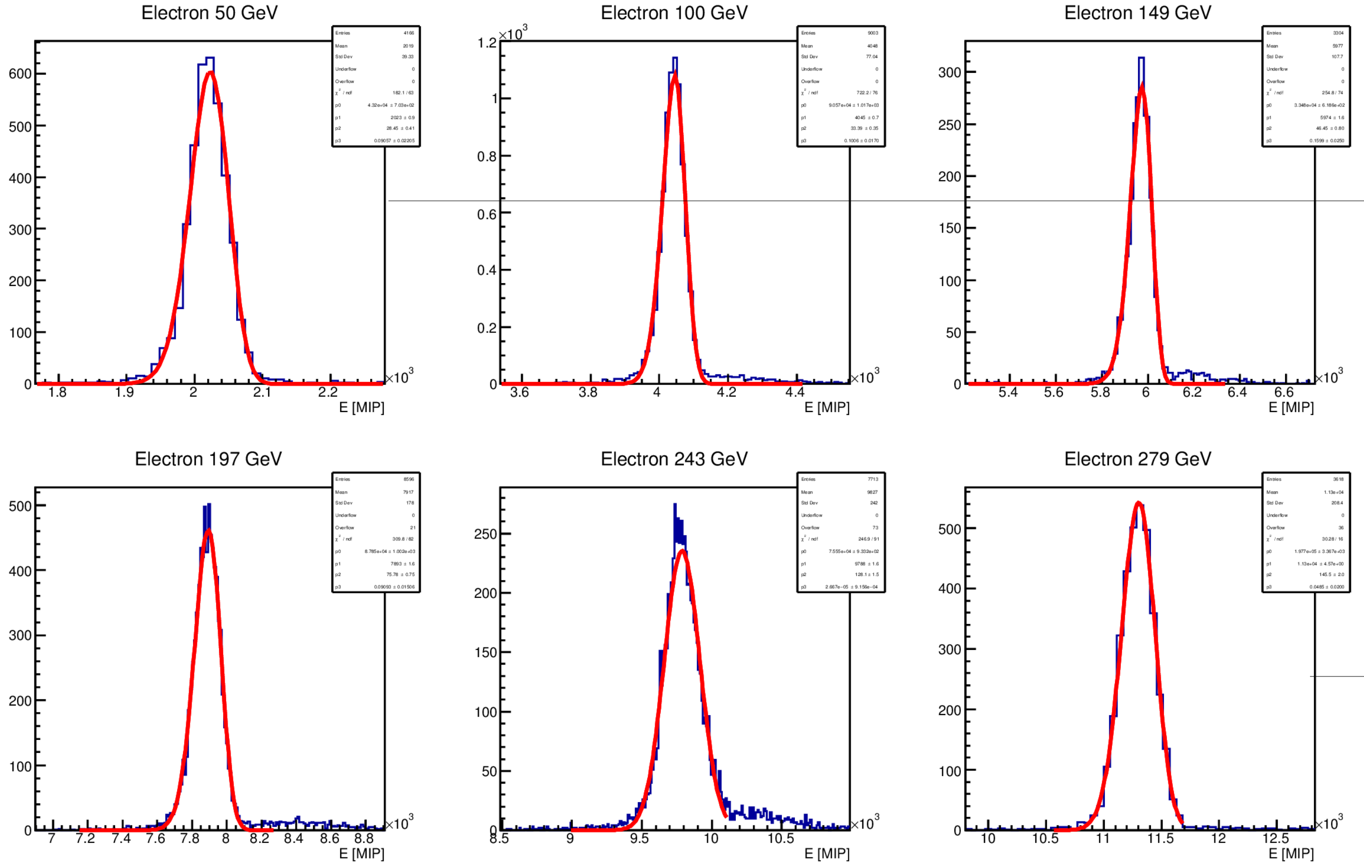
The information of Large PDs saturated channels can be recovered using Small PDs

Small PDs

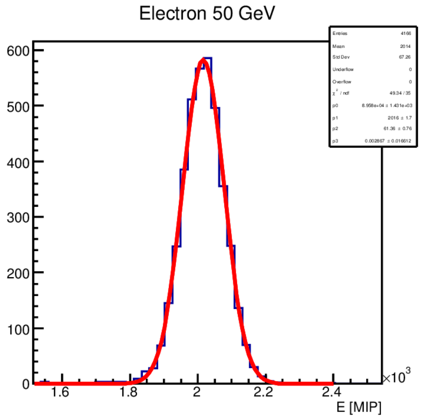
Prototype v2

Electron deposit

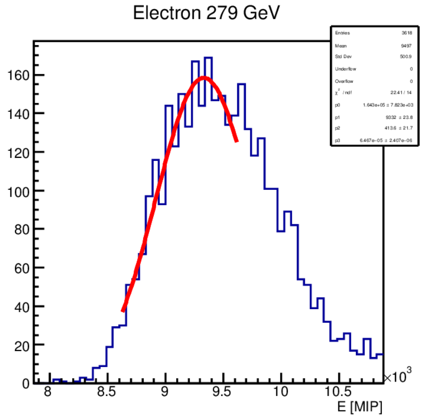
Combined PDs



Small PDs

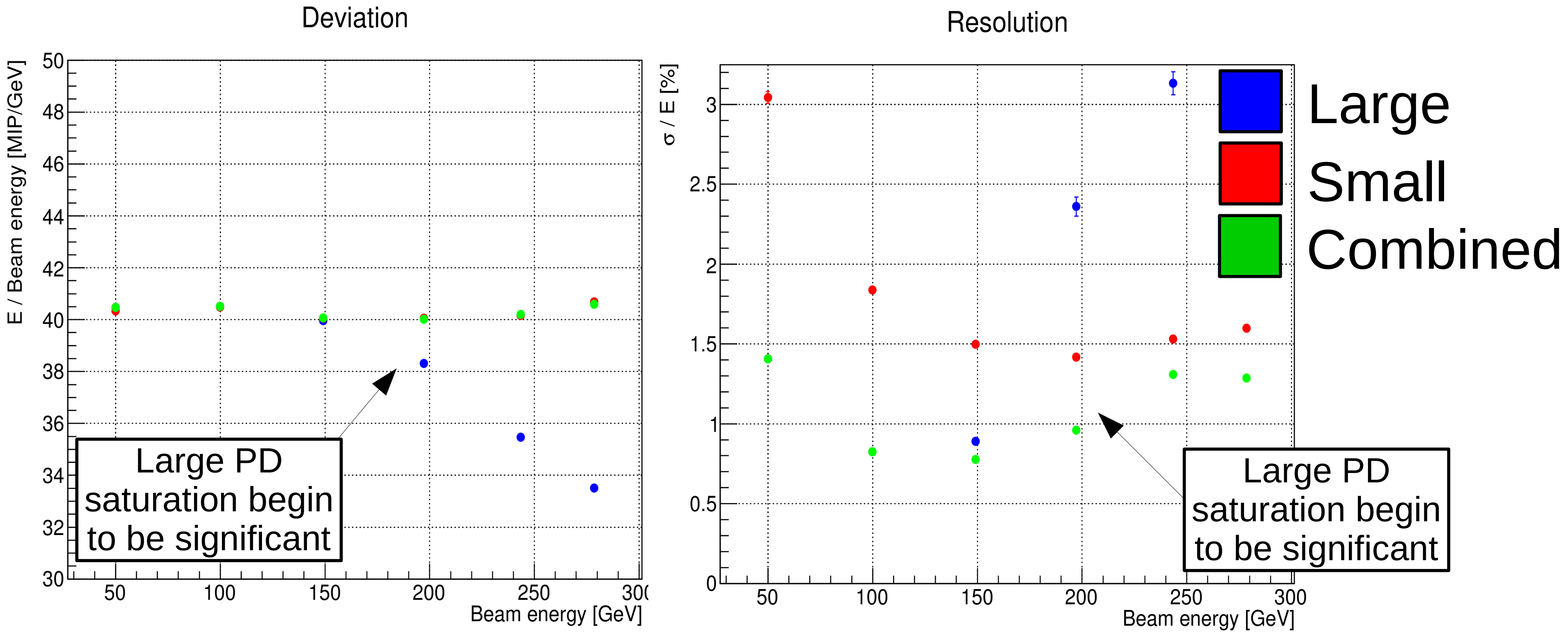


Large PDs



Prototype v2

Electron performances



Large PD saturation begin to be significant

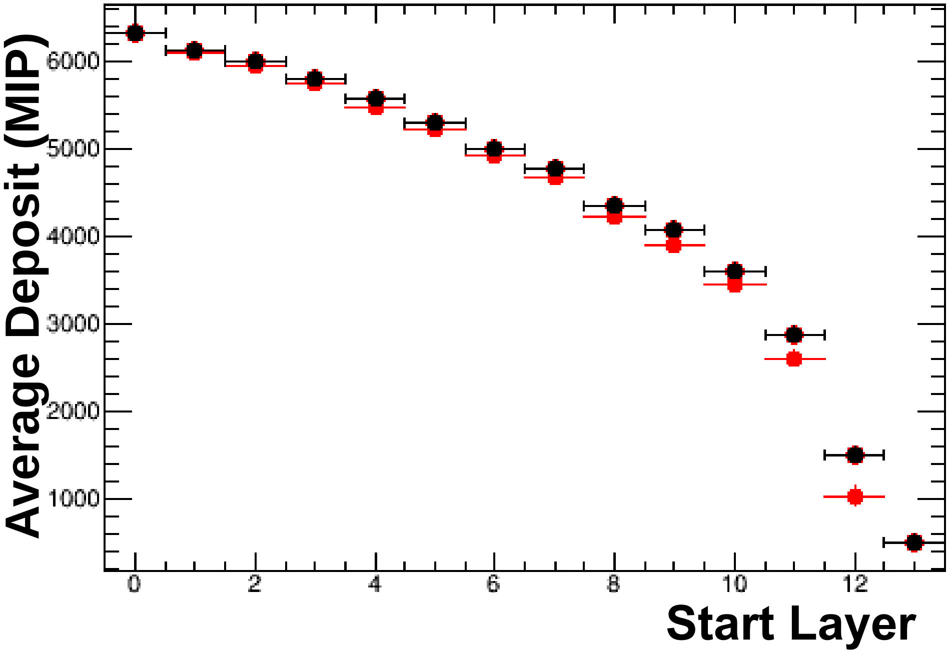
Large PD saturation begin to be significant

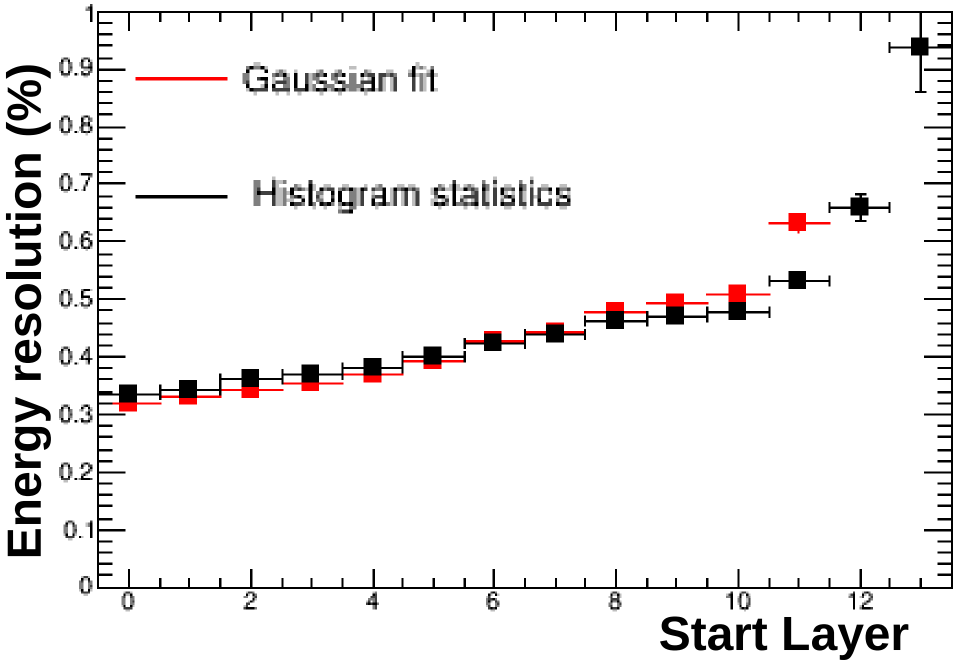
By combining the information of Large and Small PDs:

- non-linearity ~ 1%
- resolution < 1.5%

Prototype v2

Hadron performances
350 GeV proton beam

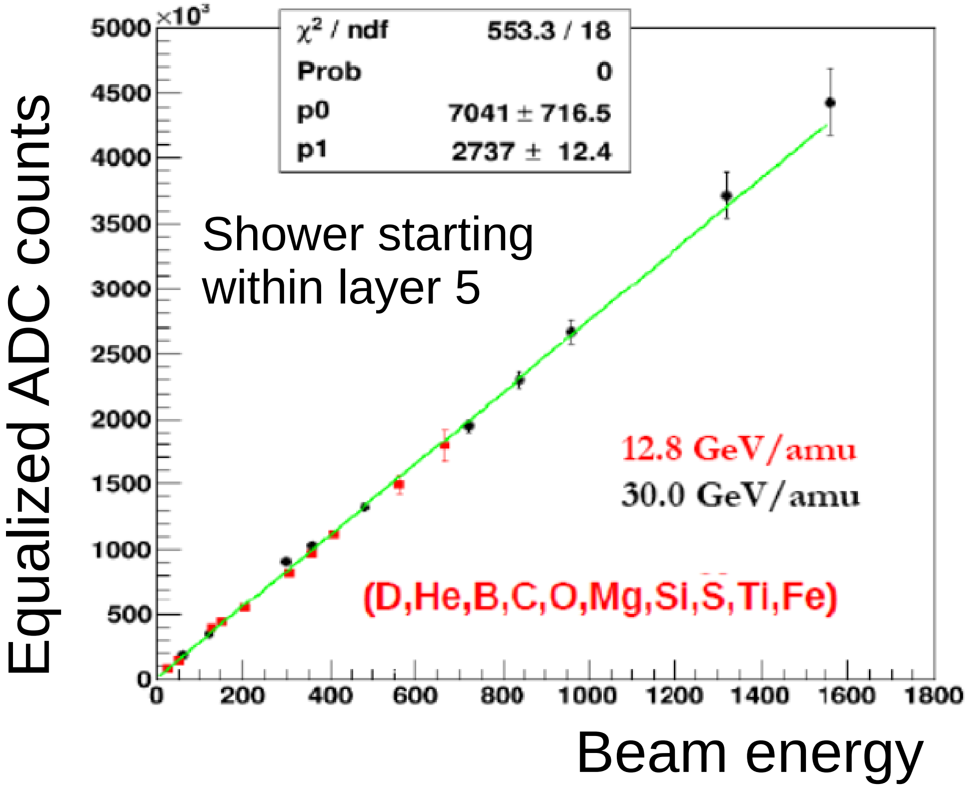


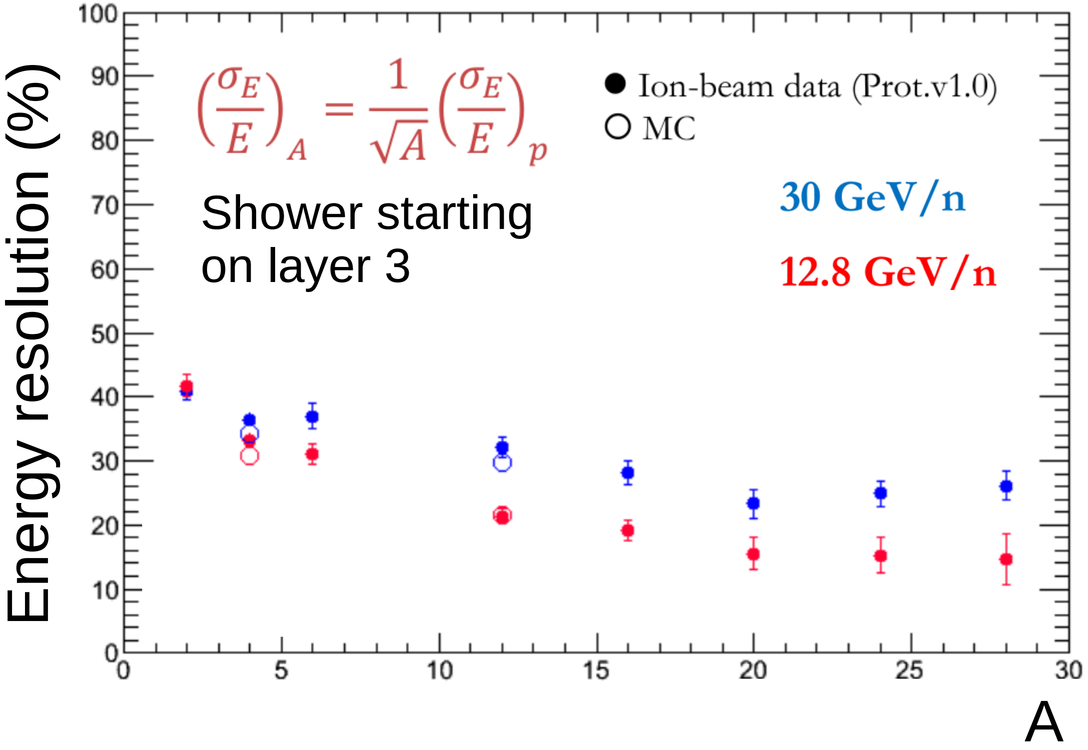


By selecting showers started in the first 3 layers we have a resolution better than 40%

Similar performances found for 30 GeV/n ions with resolution improvement from 40% to 20% when considering A going from 2 (D) to 28 (Si)

Energy resolution for hadrons





Quite good linearity
up to 1.6 TeV ion energy

Quite good agreement between
between data and MC

Instrumental effects (optical cross-talk) were mostly understood and corrected starting from prototype v1.1

The TIC project

The TIC project

TIC is an R&D project financed by INFN for 1 years in 2017

The aim of the project is the design and optimization of a ***tracker integrated inside the calorimeter (Tracker In Calorimeter)***

In a large space satellite experiment, we are interested in collecting signals from **different channels**: electron, proton, nuclei and γ-rays.

CaloCube was optimized for charged particles: **how about γ-rays**?

Need a good compromise between

good angular resolution for γ-rays

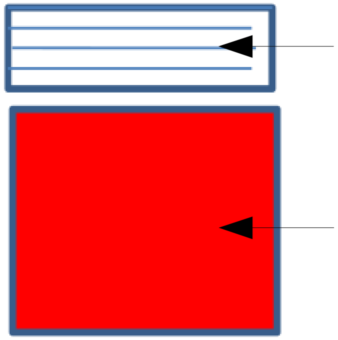
large acceptance for charged particles

Tracker design

The angle can be measures using two different approaches

Standard approach

Exploiting conversion of γ in e^+e^- pair in W

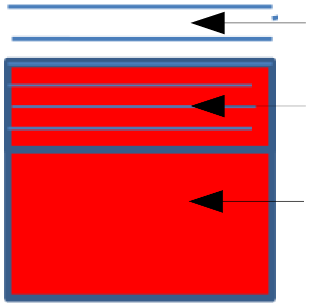


Tracker (Si + W)

Calorimeter (LYSO)

TIC approach

Exploiting transverse profile of shower



Charge identifier (Si only)

Tracker (Si + LYSO)

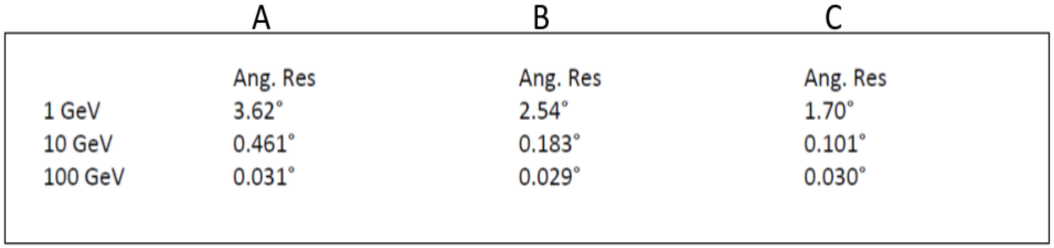
Calorimeter (LYSO)

Advantages of TIC design

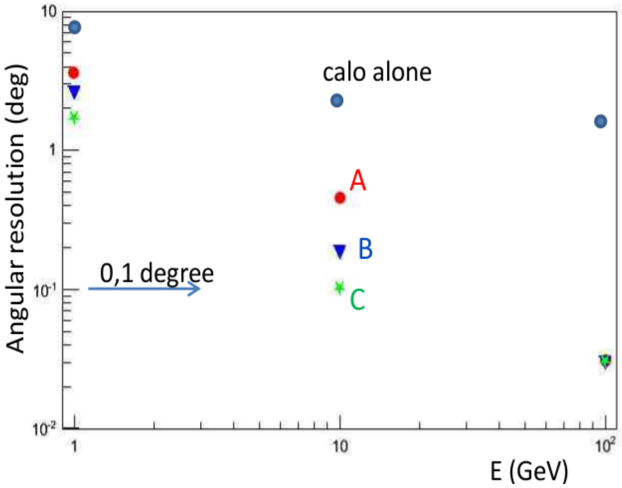
- decrease the amount of mass used for passive material (W)
- reduce hadron fragmentation in passive material
- increase the geometric acceptance

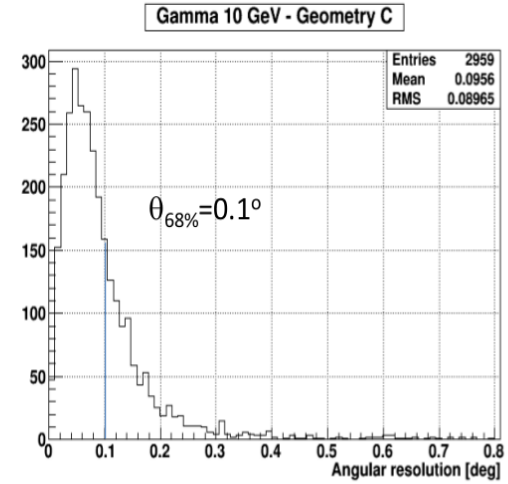
GEANT4

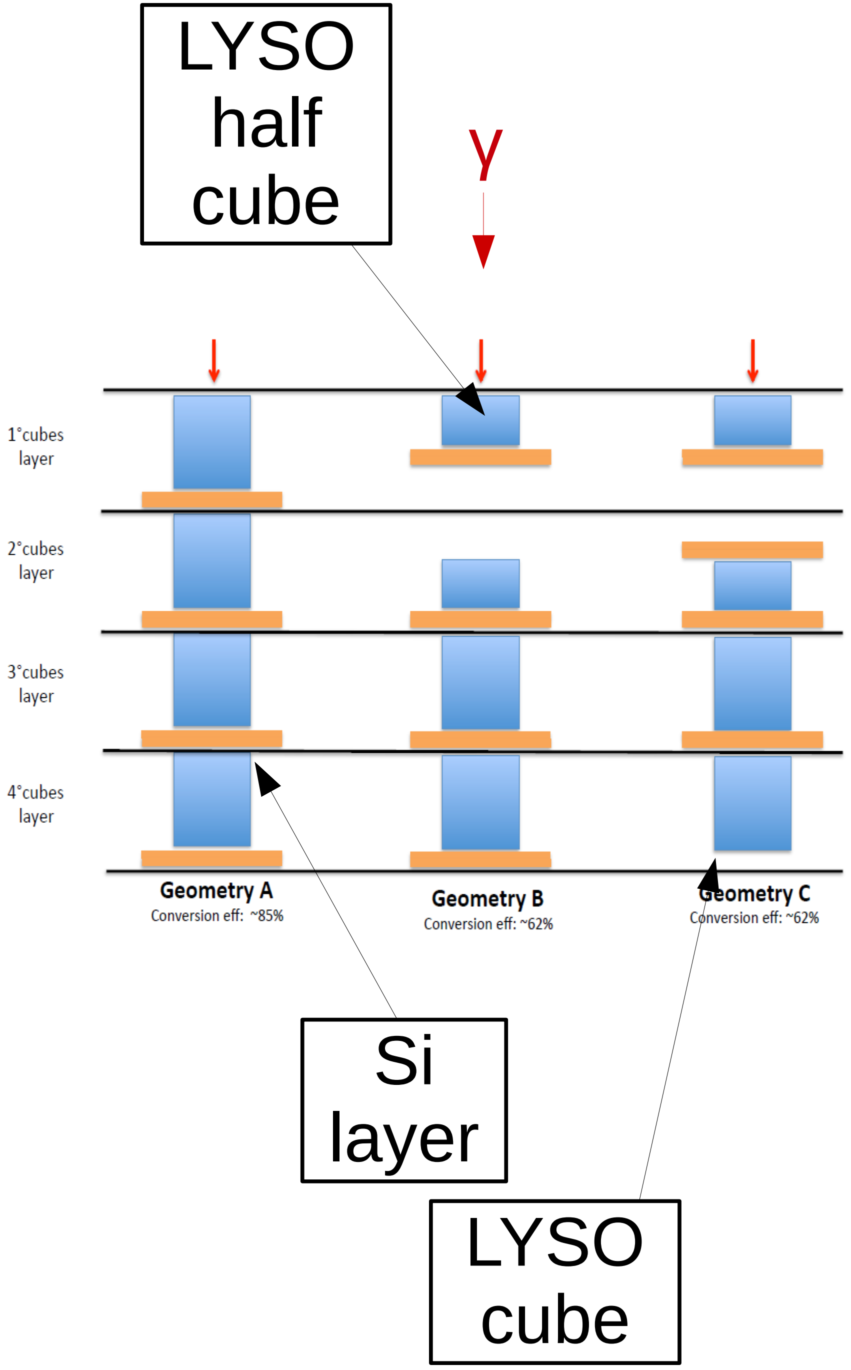
Simulation



	A	B	C
	Ang. Res	Ang. Res	Ang. Res
1 GeV	3.62°	2.54°	1.70°
10 GeV	0.461°	0.183°	0.101°
100 GeV	0.031°	0.029°	0.030°







LYSO half cube

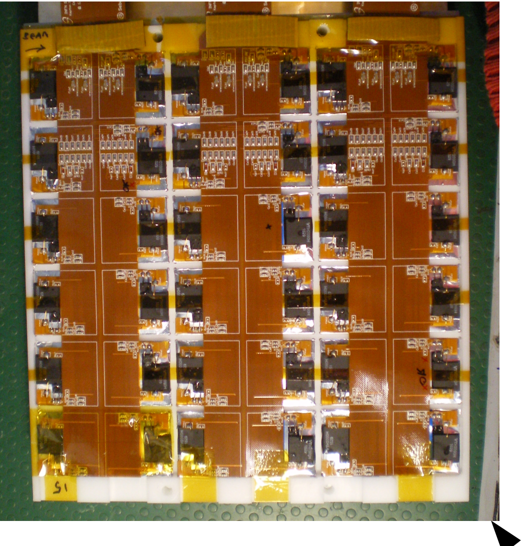
Si layer

LYSO cube

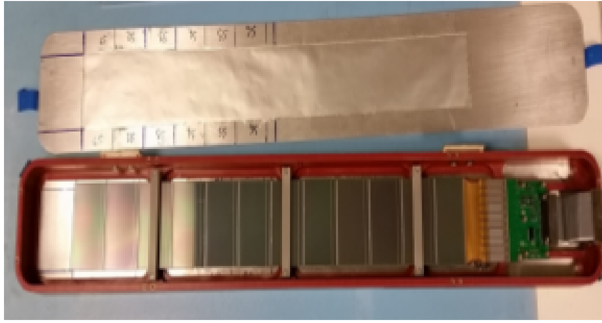
Using full information both from calorimeter and silicon tracker, angular resolution for vertical γ is better than 0.1° above 10 GeV (comparable to Fermi-LAT)

TIC Prototype

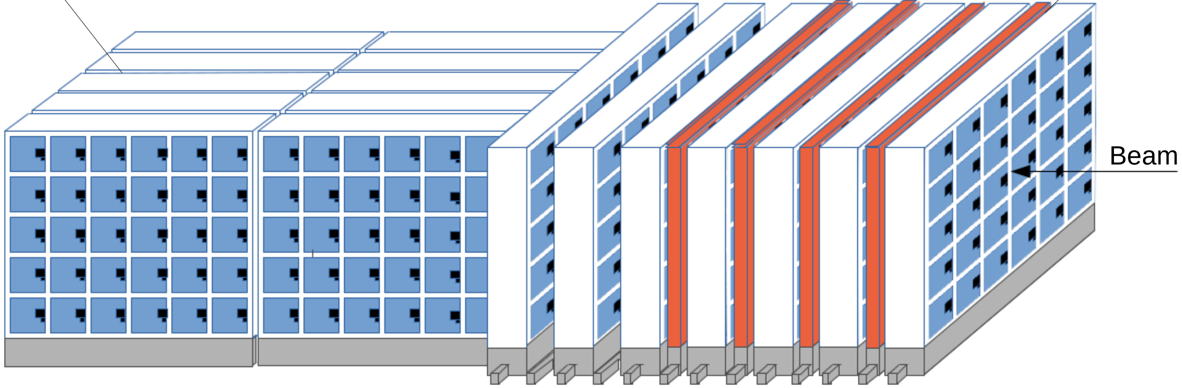
CsI layers



Si layers



From simulation we expect an angular resolution for vertical γ better than 0.1-0.5° above 10 GeV



A **TIC prototype** have been realized integrating several **DAMPE spare silicon layers inside the Calocube prototype**.

The prototype is currently under **beam test at the CERN PS+SPS with 1-100 GeV electrons** at different incident angles

Summary

The **CaloCube R&D project** aims to develop a novel design calorimeter intended for the measurement of high-energy cosmic rays in space.

MC simulations were used to optimize the design of the detector in order to satisfy the scientific requirements on geometric factor and energy resolution of:

- G_{eff} ~ 3.4 m^2sr and $\sigma_E/E < 2\%$ for electrons
- G_{eff} ~ 4 m^2sr and $\sigma_E/E < 40\%$ for protons

Several prototypes made of CsI(Tl) crystals have been built and tested, obtaining results mostly consistent with MC simulations:

- $\sigma_E/E < 1.5\%$ for electrons up to 280 GeV
- $\sigma_E/E < 35\%$ for ions up to 30 GeV / n

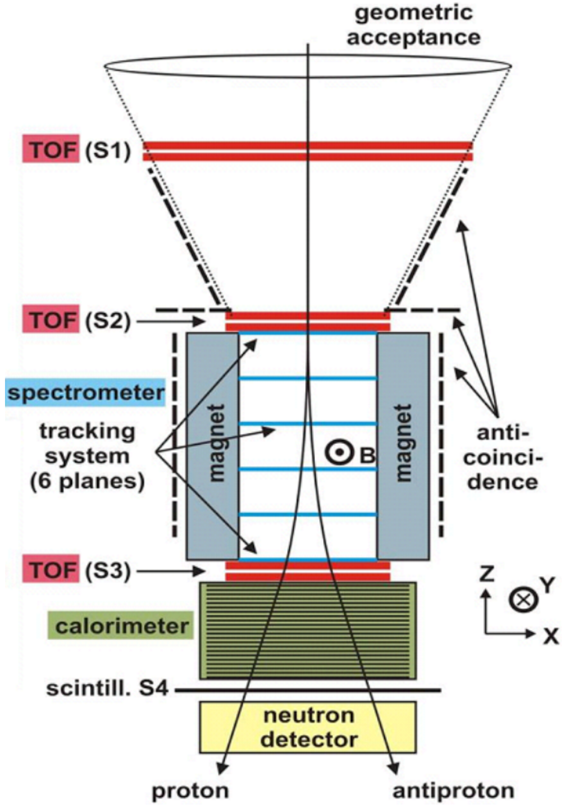
The **TIC R&D project** is ongoing to study a new tracker configuration that allows good reconstruction performances both for charged particles and γ-rays.

Back Up

Past vs Future experiments

Past experiments

based on ***magnetic spectrometer***



$$\sigma_E/E \propto E$$

because of rigid geometry it can measure particles from one direction only

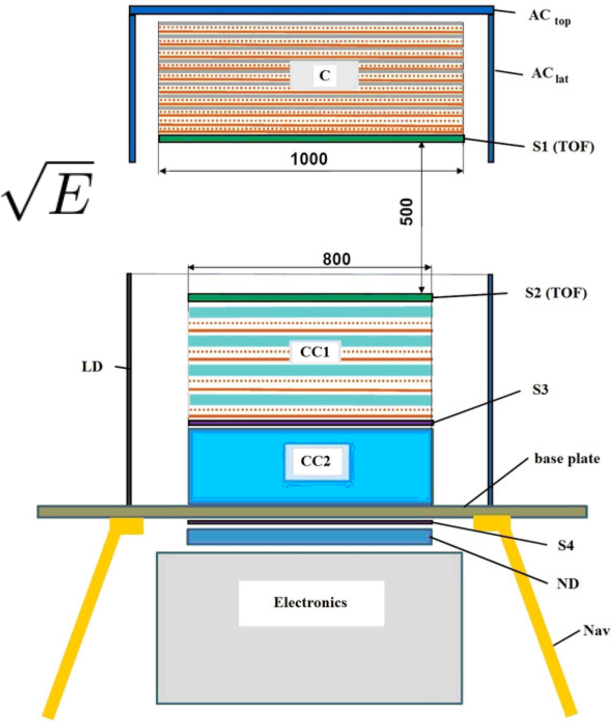
Future experiments

based on ***calorimeter***

better resolution at high energy

$$\sigma_E/E \propto 1/\sqrt{E}$$

better geometrical acceptance

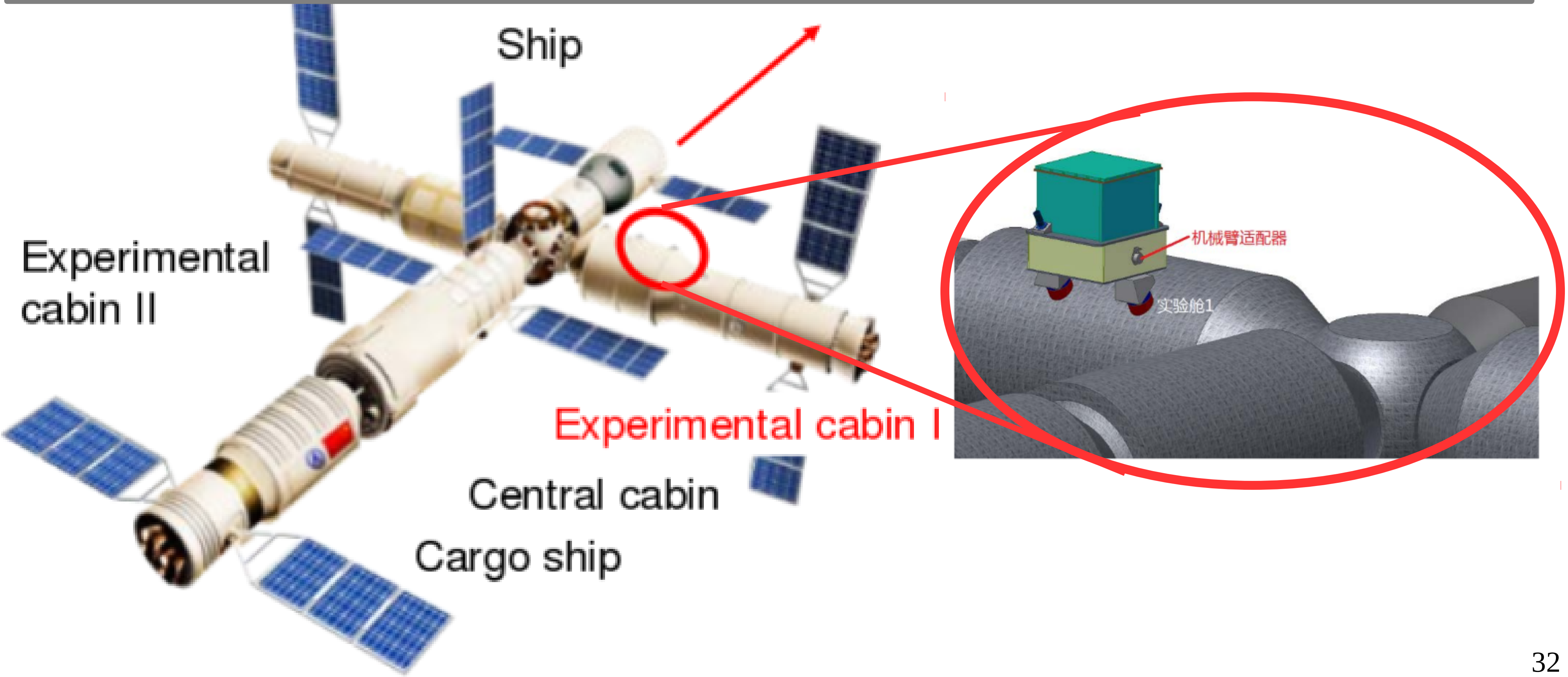


because of flexible geometry it can detect particles from more faces

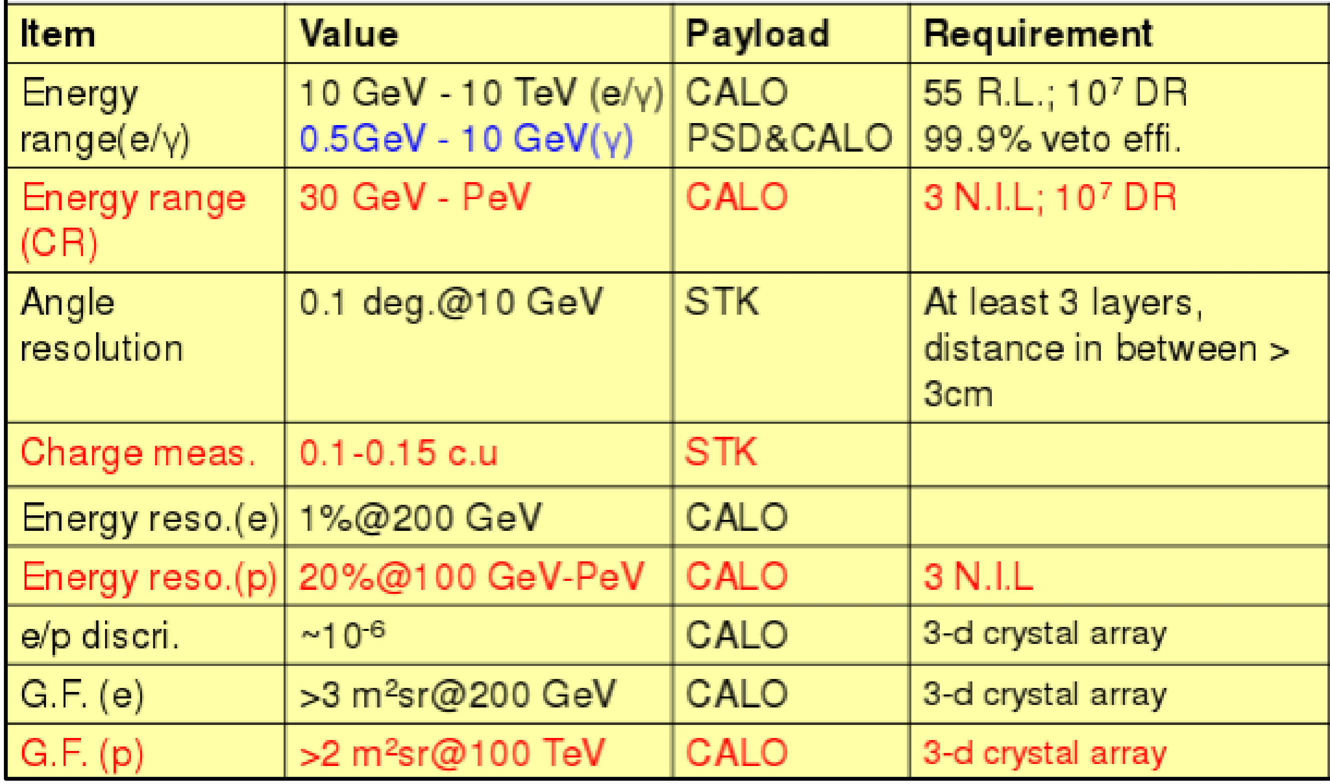
For example in the case of PAMELA
$G = 20.5$ cm^2 sr
$\sigma_p/p \sim 15\%$ for 100 GeV p
MDR = 740 GV/c

HERD (High Energy cosmic Radiation Detector)

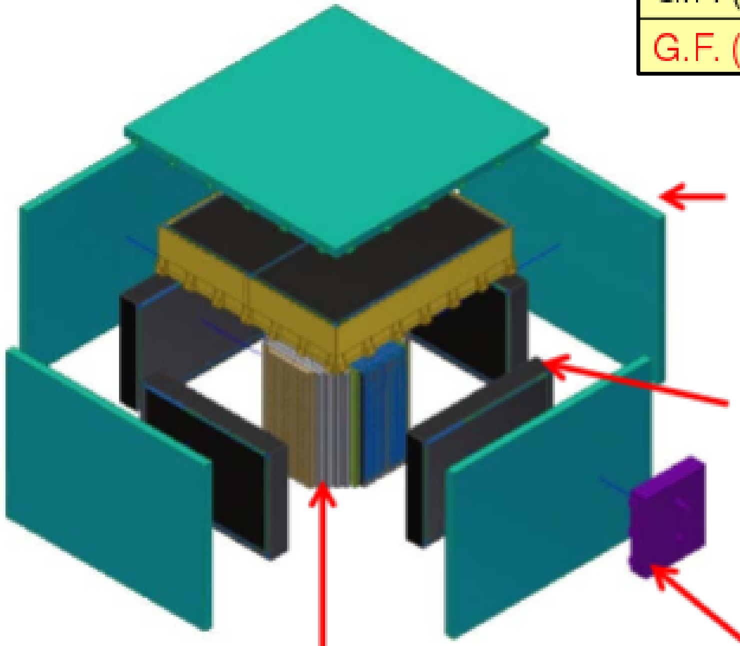
Chinese Space Station will be constructed before 2022.
It will house the HERD payload for the detection of cosmic rays.
Several universities and institutes are interested in the project.
Main countries involved are China, Italy, Switzerland and Spain.



Current proposal of the HERD detector



Item	Value	Payload	Requirement
Energy range(e/γ)	10 GeV - 10 TeV (e/γ) 0.5GeV - 10 GeV(γ)	CALO PSD&CALO	55 R.L.; 10^7 DR 99.9% veto effi.
Energy range (CR)	30 GeV - PeV	CALO	3 N.I.L; 10^7 DR
Angle resolution	0.1 deg.@10 GeV	STK	At least 3 layers, distance in between > 3cm
Charge meas.	0.1-0.15 c.u	STK	
Energy reso.(e)	1%@200 GeV	CALO	
Energy reso.(p)	20%@100 GeV-PeV	CALO	3 N.I.L
e/p discri.	~10^{-6}	CALO	3-d crystal array
G.F. (e)	>3 m^2sr@200 GeV	CALO	3-d crystal array
G.F. (p)	>2 m^2sr@100 TeV	CALO	3-d crystal array



PSD, five sides
LE Gamma identification
Charge

STK(SSD),five sides
Charge
Trajectory
Gamma tracking

TRD
TeV proton calibration

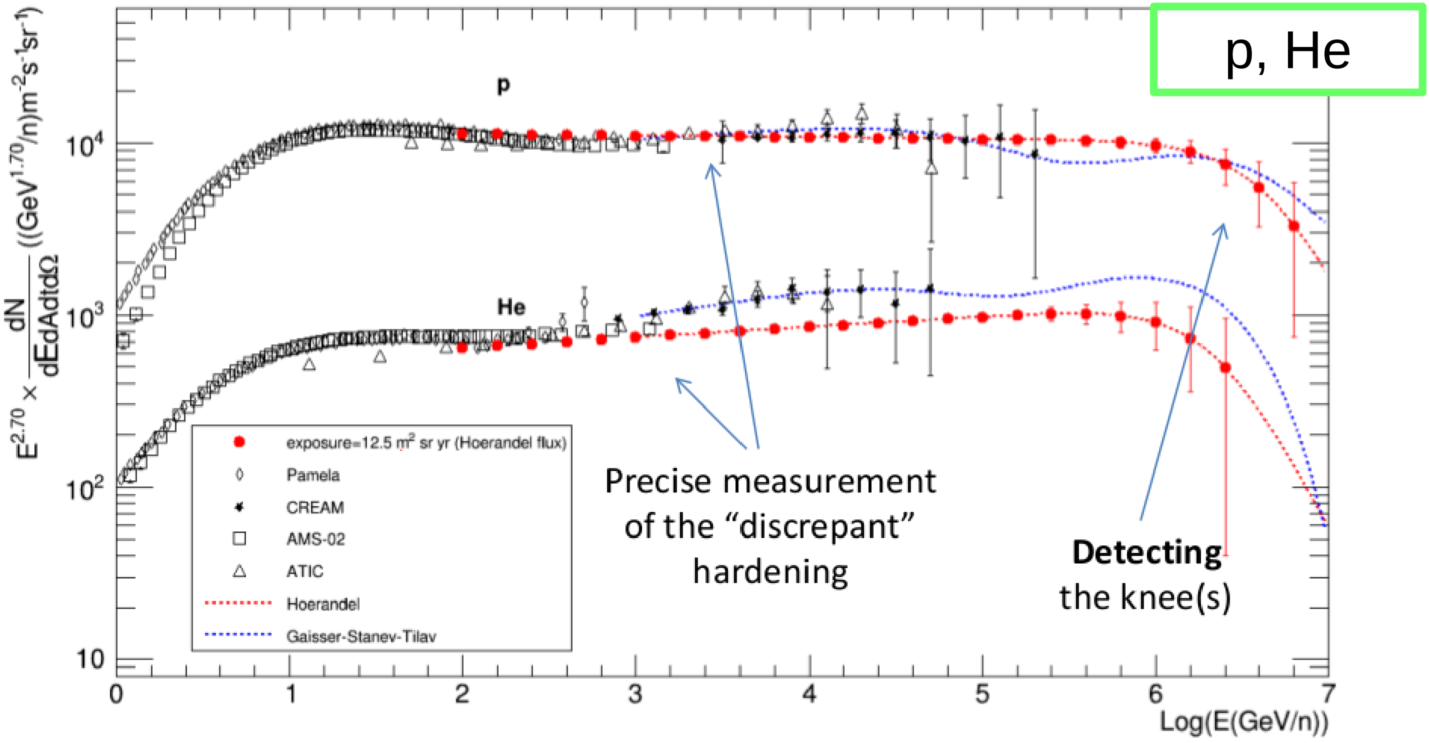
LYSO array
Trigger sub-system
ISCMOS sub-system

CALO, 3-d
e/G/CR energy
e/p discrimination

The design of the HERD detector is going to be optimized starting from this year

Expected spectra with the HERD detector in five years

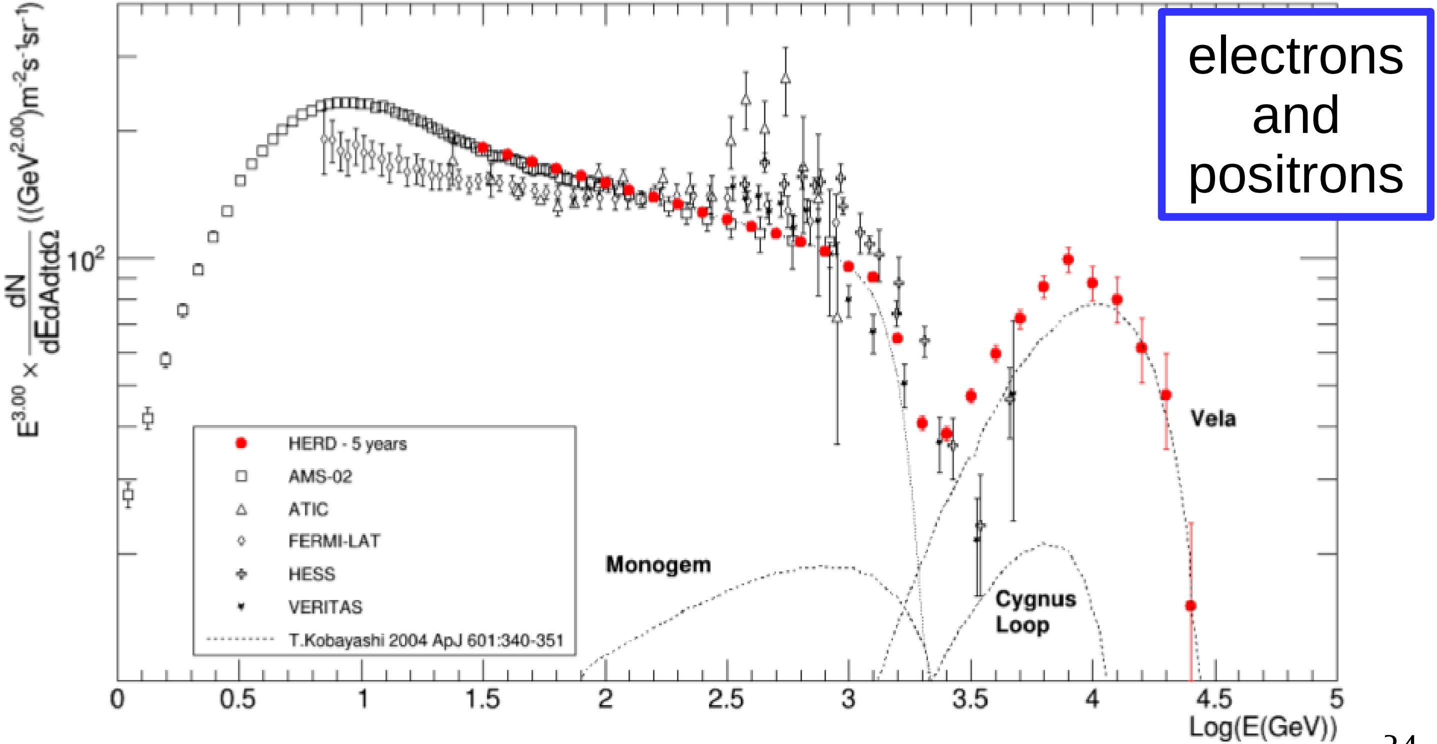
from Ivan De Mitri 2017 HERD workshop



p, He

Precise measurement of the “discrepant” hardening

Detecting the knee(s)

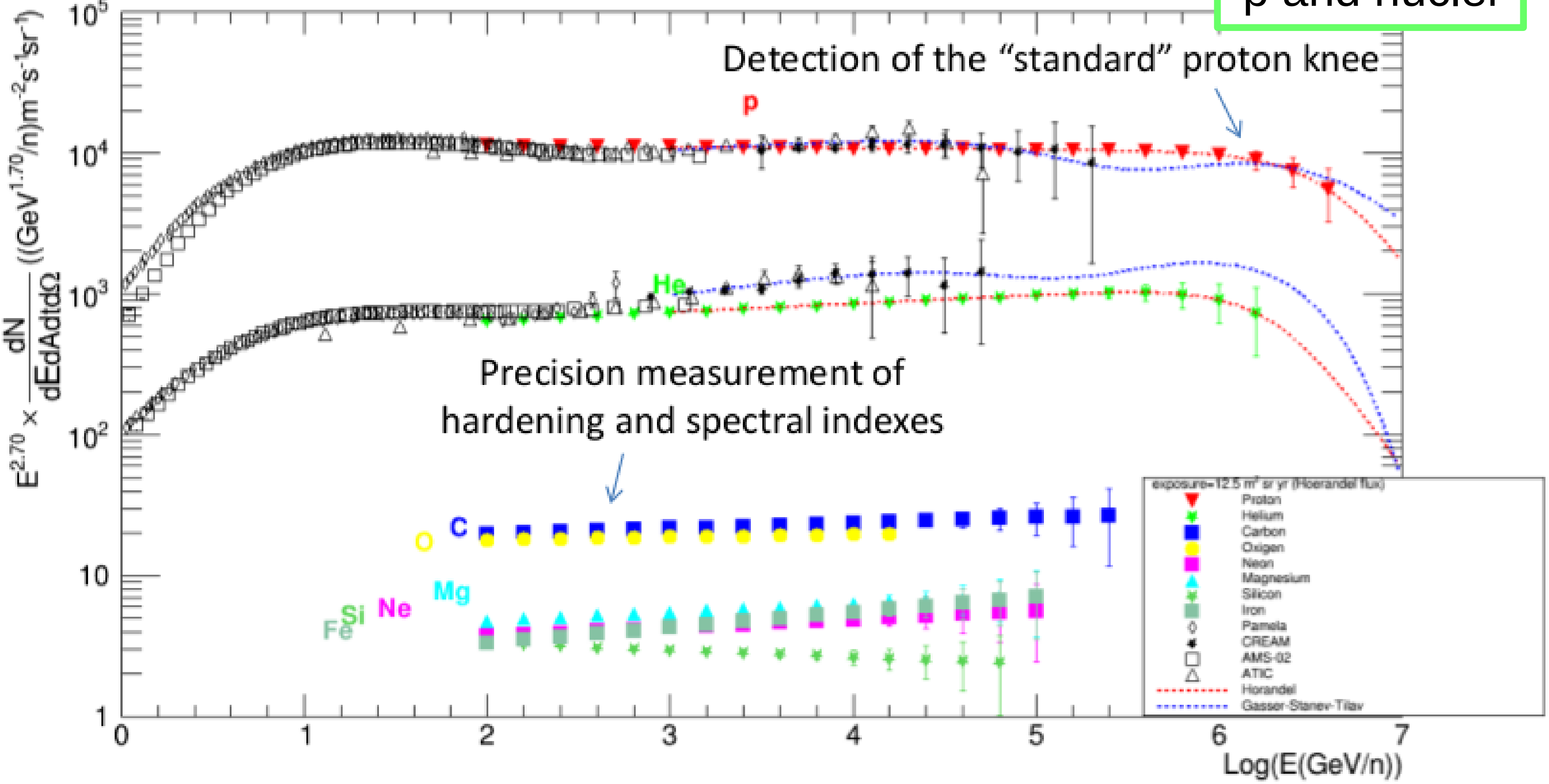


electrons and positrons

Expected spectra with the HERD detector in five years

from Ivan De Mitri
2017 HERD
workshop

p and nuclei



Detection of the “standard” proton knee

Precision measurement of hardening and spectral indexes

Choice of Calocube layout

Different Calocube layout have been tested fixing

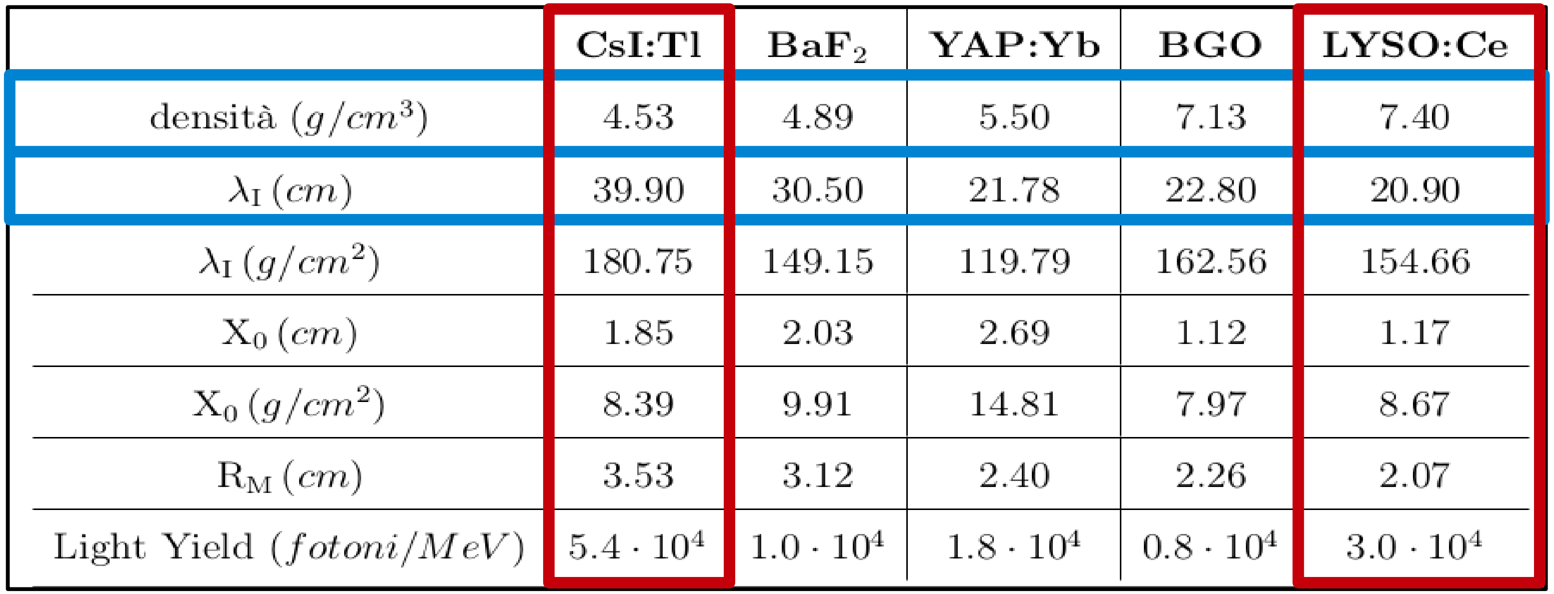
- total mass of detector = 2 x 10^3 kg
- crystal size = 1 Moliere radius
- gap size = 0.3 cm for CsI:Tl

  scaled according to the crystal size otherwise

...and using **different materials** as scintillator

The ideal material is a trade-off between **density** (i.e. detector acceptance) and **interaction length** (i.e. energy resolution)

Properties of crystals



	CsI:Tl	**BaF$_2$**	**YAP:Yb**	**BGO**	**LYSO:Ce**
densità (g/cm^3)	4.53	4.89	5.50	7.13	7.40
λ_I (cm)	39.90	30.50	21.78	22.80	20.90
λ_I (g/cm^2)	180.75	149.15	119.79	162.56	154.66
X_0 (cm)	1.85	2.03	2.69	1.12	1.17
X_0 (g/cm^2)	8.39	9.91	14.81	7.97	8.67
R_M (cm)	3.53	3.12	2.40	2.26	2.07
Light Yield ($fotoni/MeV$)	$5.4 \cdot 10^4$	$1.0 \cdot 10^4$	$1.8 \cdot 10^4$	$0.8 \cdot 10^4$	$3.0 \cdot 10^4$

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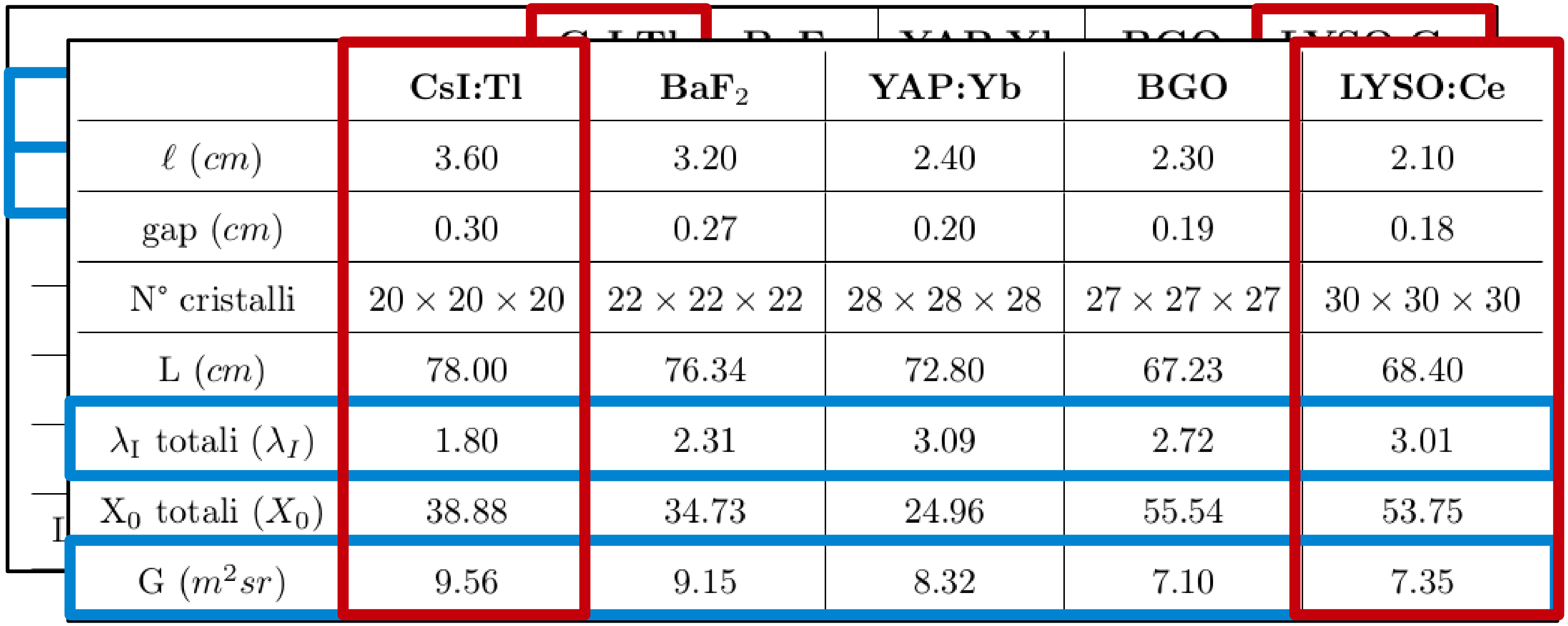
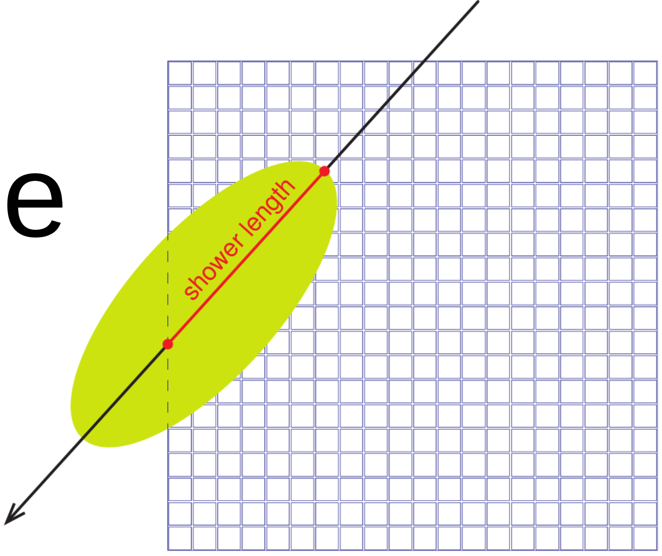
Properties of CaloCube



	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

For a planar surface A, the geometric factor is **G = πA**
In our case this is multiplied by number of active faces (**5**)

Resolution vs Acceptance

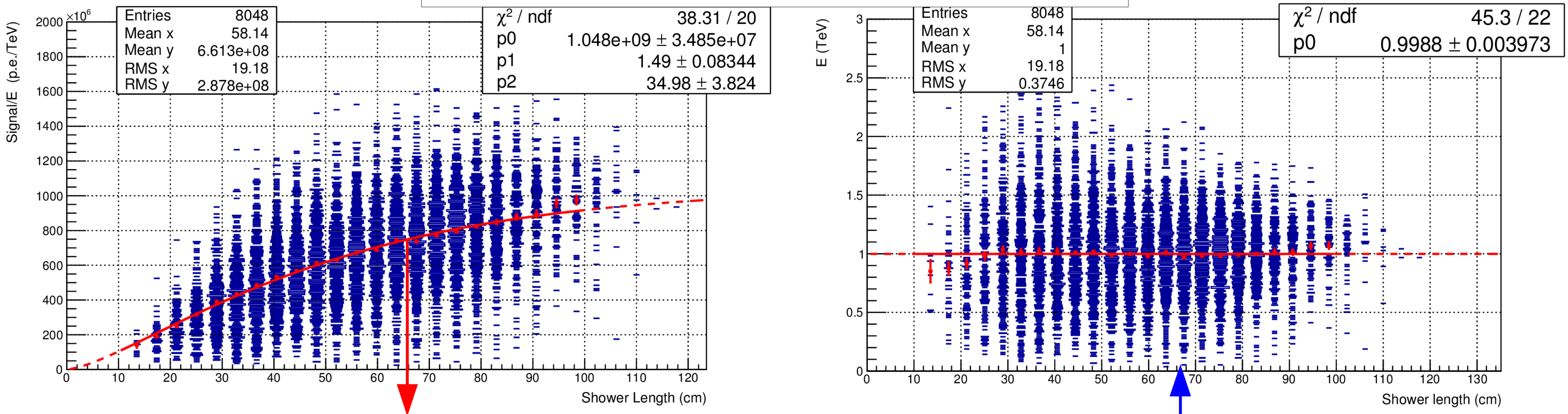


In case of no-full-shower-containment the resolution is spoiled by fluctuations of the **shower length**

Selecting only events with large shower length improves **resolution** but decreases the **acceptance**

Making use of integrated gamma function, it is possible to correct the energy deposit for the shower length event by event

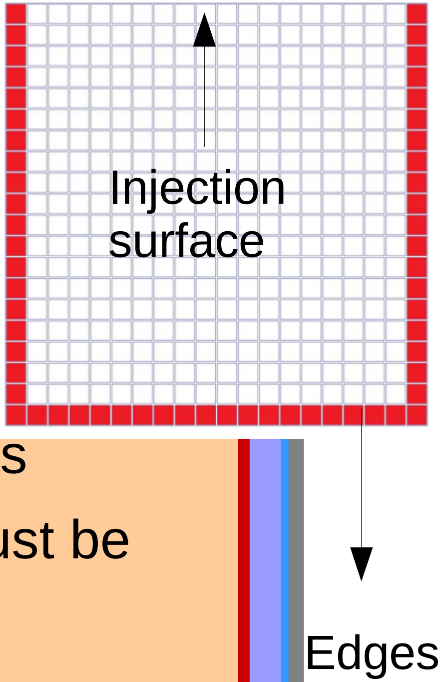
1 TeV protons in a CsI:Tl Calocube



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

$$E_m \, [TeV] = \frac{S \, [\mathrm{p.e.}]}{F(x,E) \, [\mathrm{p.e/TeV}]}$$

Event selection



Important quantities

- **Hit** in crystal *i*

  $dE_i > n \times \mathrm{MIP}$ where n= 0.80-0.85

- **Shower starting point**

  crystal *i* having $dE_i > 15$ MIP

- **Shower maximum**

  crystal *i* having maximum dE_i

Basic event selection

- shower maximum must be outside of edges
- shower starting point must be defined
- $N_{hit} > 100$

The efficiency of this selection is

$$\boldsymbol{\varepsilon_{BS} = 40\text{-}55\%}$$

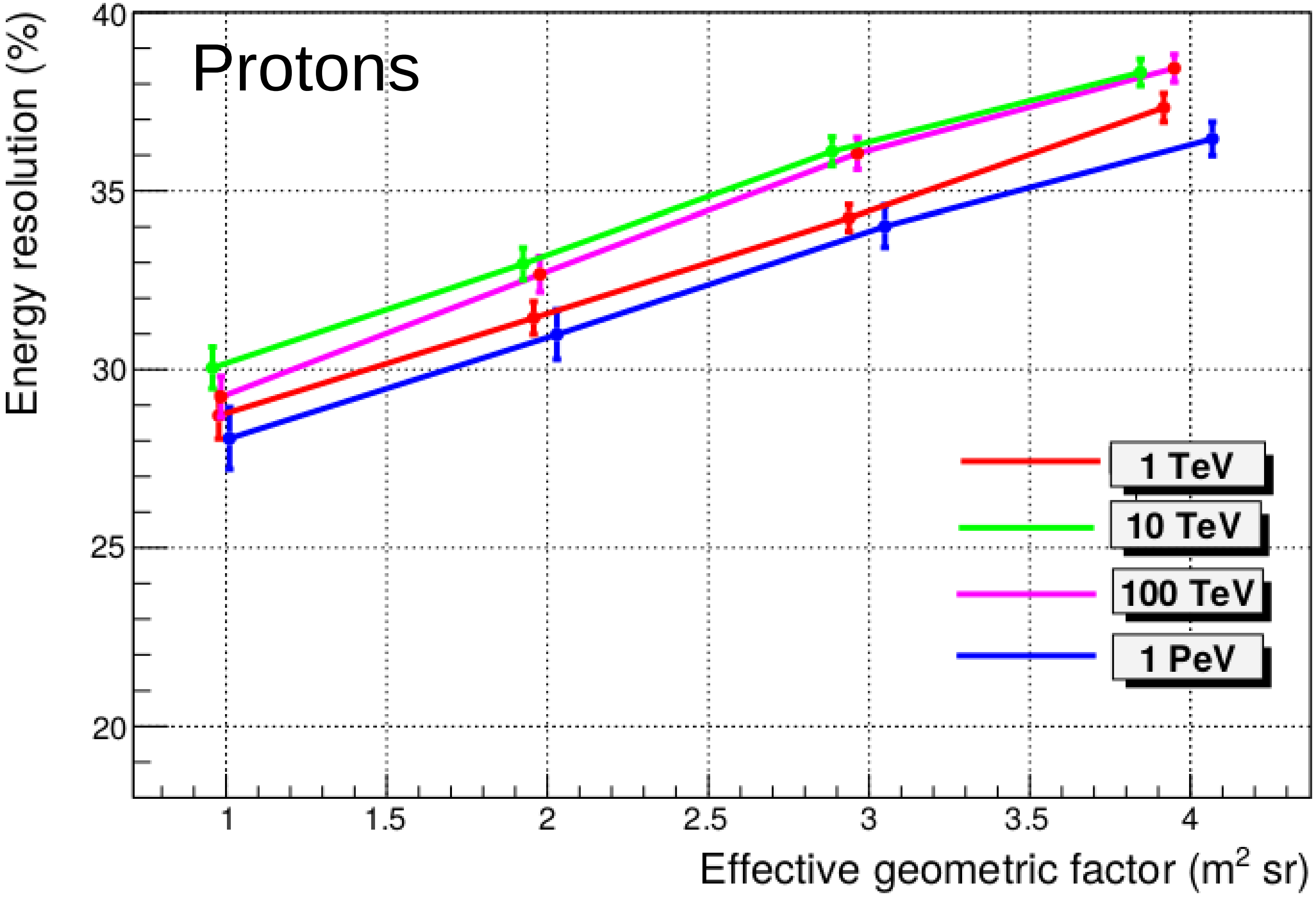
Because *Resolution vs Acceptance* depends on shower length, 4 different cases have been investigated, corresponding to a minimum value of shower length that ensures an additional event selection with an efficiency

$$\boldsymbol{\varepsilon_{SL} = 25, 50, 75, 100\%}$$

The **effective geometric factor** is therefore given by

$$\boldsymbol{G_{eff} = G \times \varepsilon_{BS} \times \varepsilon_{SL}}$$

Dependence on the primary energy



σ_E/E is mostly independent on the primary energy

Prototype v1

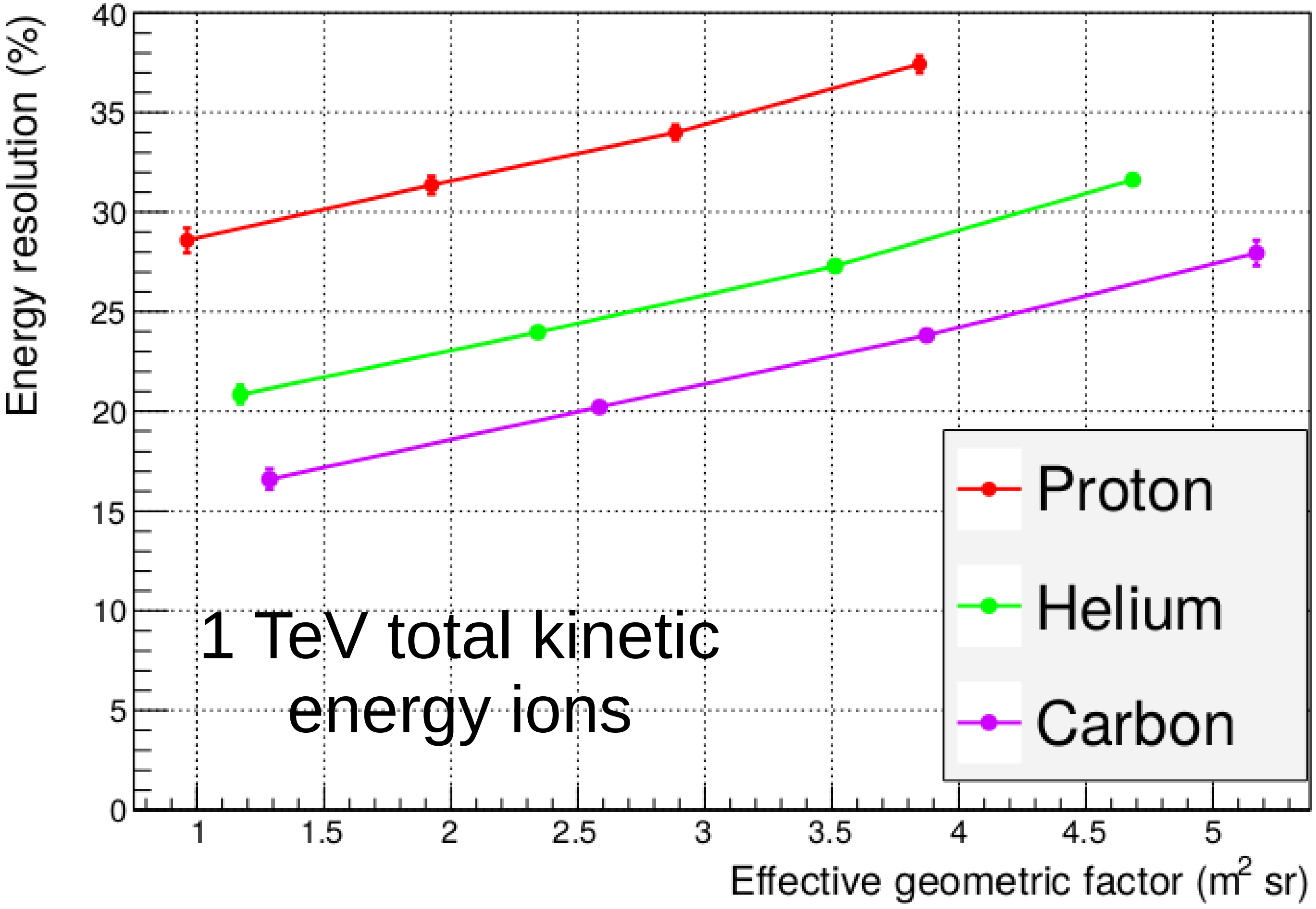
Geometry
- 15 layers of 3x3 CsI:Tl cubes
- Scintillators wrapped in Teflon
- Light collected by Large PD (small PD tested on only 3 cubes)

Shower containment
- 1.5 Moliere radius
- 28.4 X_0
- 1.35 λ_I

Beam tests

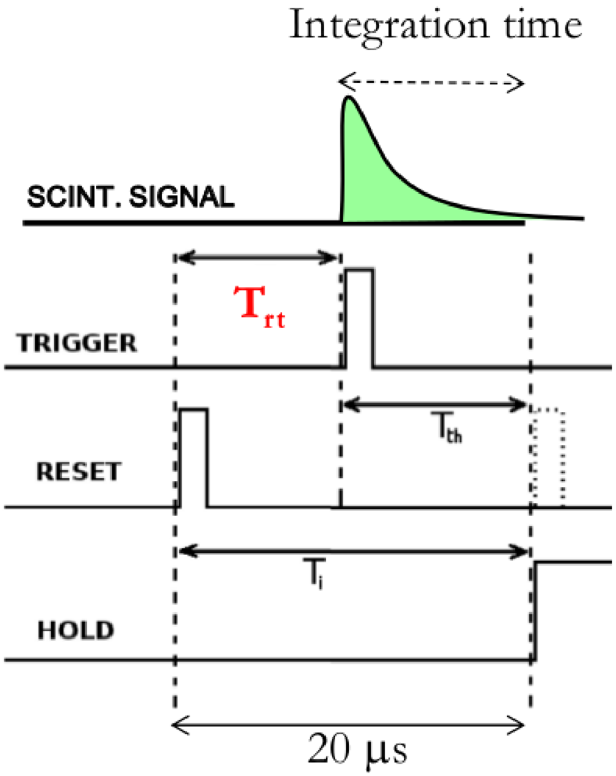
Feb 2013	v1.0	Ions Pb+Be 13-30 GeV/u
Mar 2015	v1.1	Ions Ar+Poly 13-30 GeV/u
Aug/Sep 2015	v1.2	μ, π, e 50-75-150-180 GeV

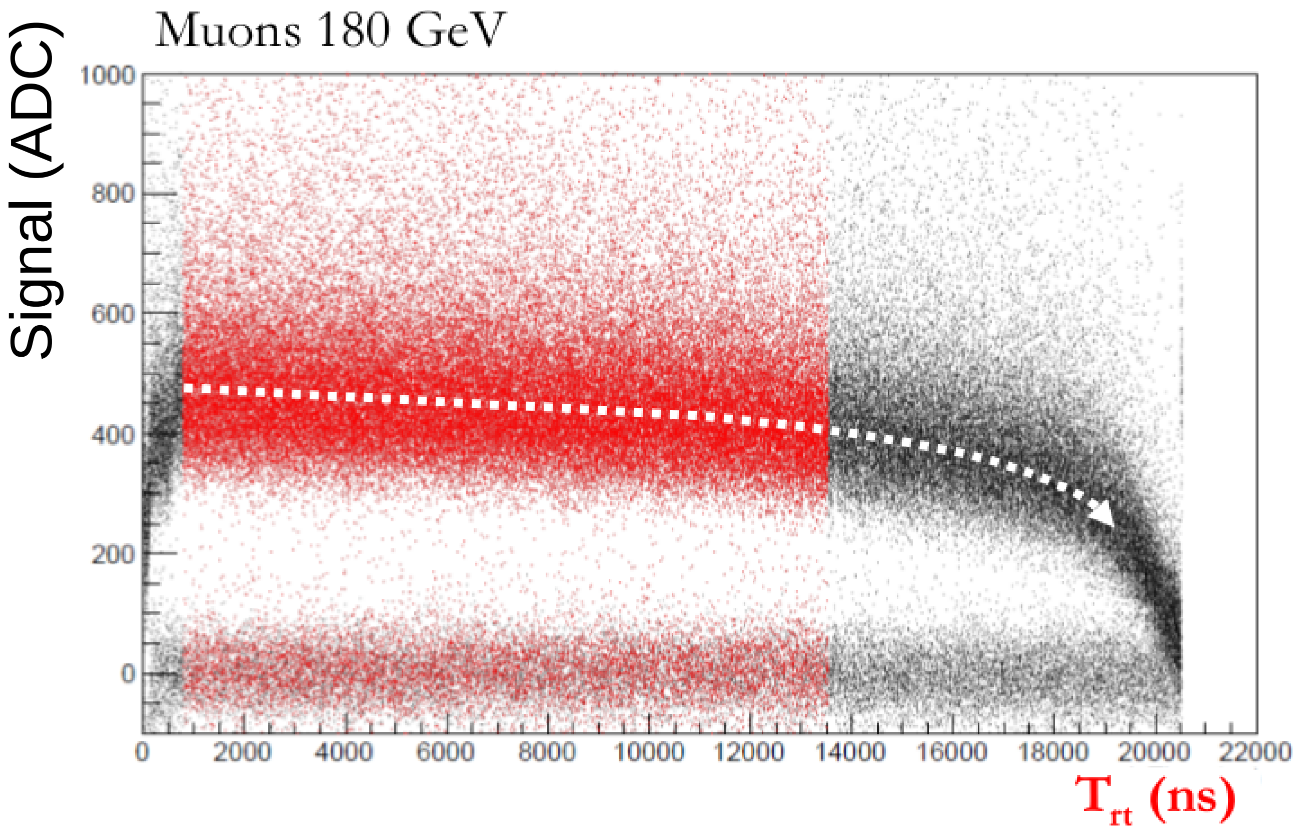
Depedence on the ion: CsI:Tl Calocube



1 TeV total kinetic energy ions

Signal dependence from integration time



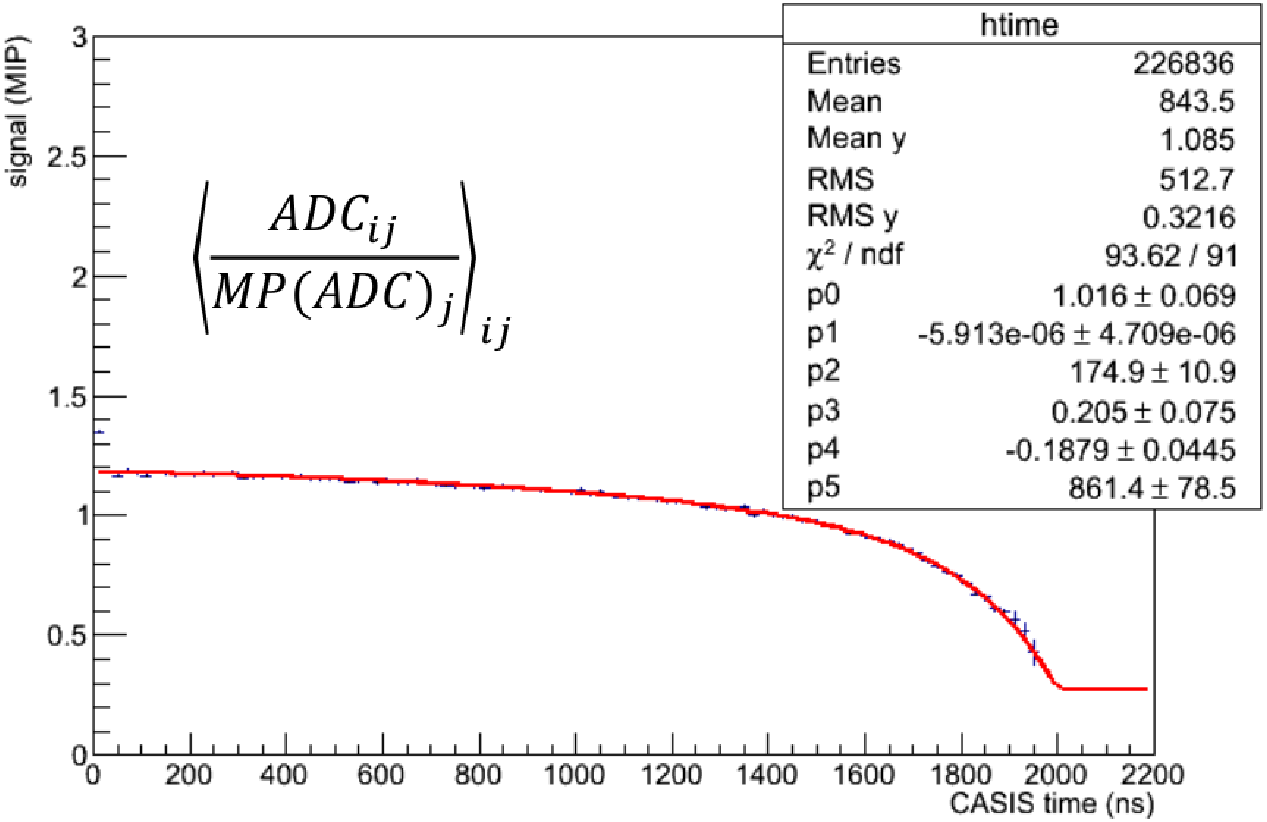


Signal attenuation consistent with 30% of slow scintillation component having τ = 8 µs

Computation of time correction factor

For each scintillation component

$$S(t_C)_{CsI(Tl)} = \int_0^{T_i - t} I_0 e^{t/\tau} dt = I_0 \tau (1 - e^{-T_i/\tau} e^{t/\tau})$$



$$\left\langle \frac{ADC_{ij}}{MP(ADC)_j} \right\rangle_{ij}$$

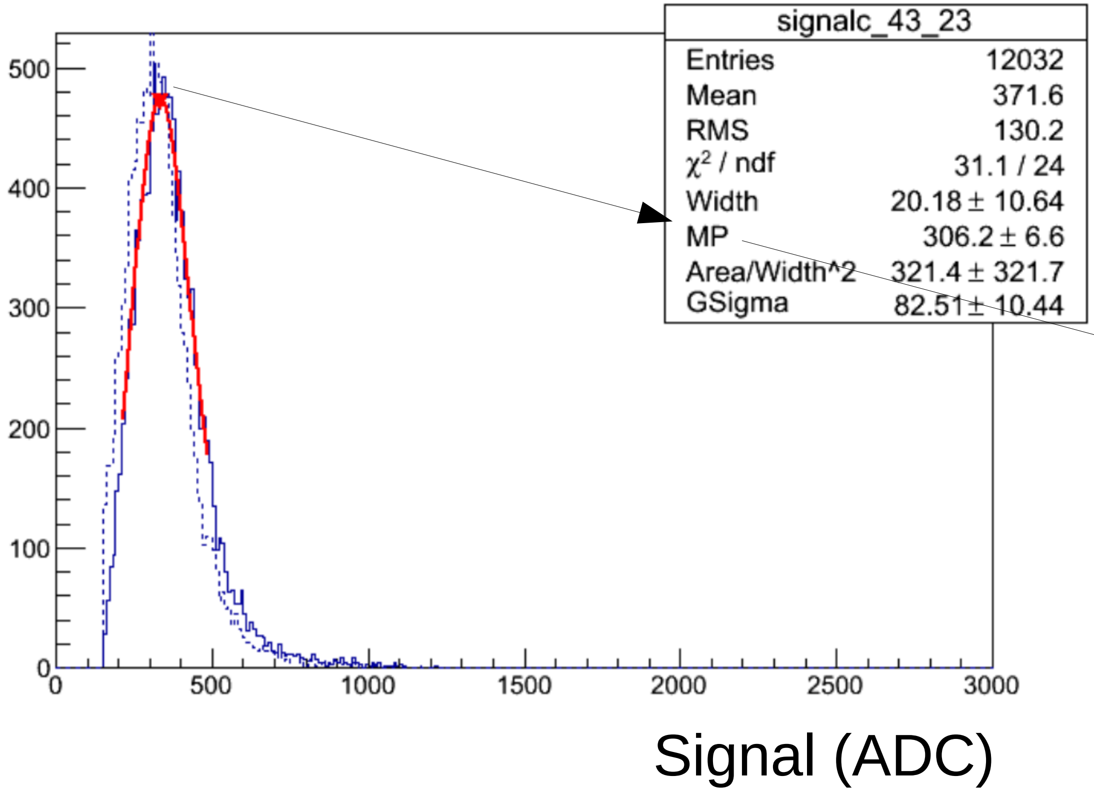
Cumulative distribution of all signals belonging to the central column normalized to the corresponding most probable value (MP)

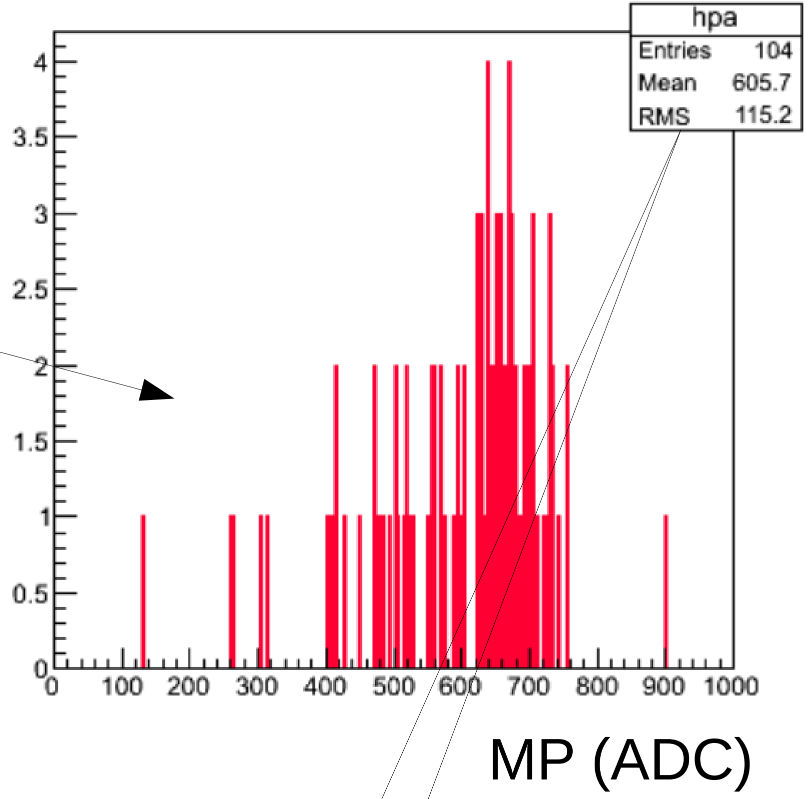
$$f(t) = P_0 \cdot \left(1 + P_1 \cdot e^{t/P_2}\right) + P_3 \cdot \left(1 + P_4 \cdot e^{t/P_5}\right)$$

$$\text{Time correction} \longrightarrow \frac{f(0)}{f(t)}$$

Equalization of channels using muons beam

Cumulative distribution of MP for all layers invested by muons beam



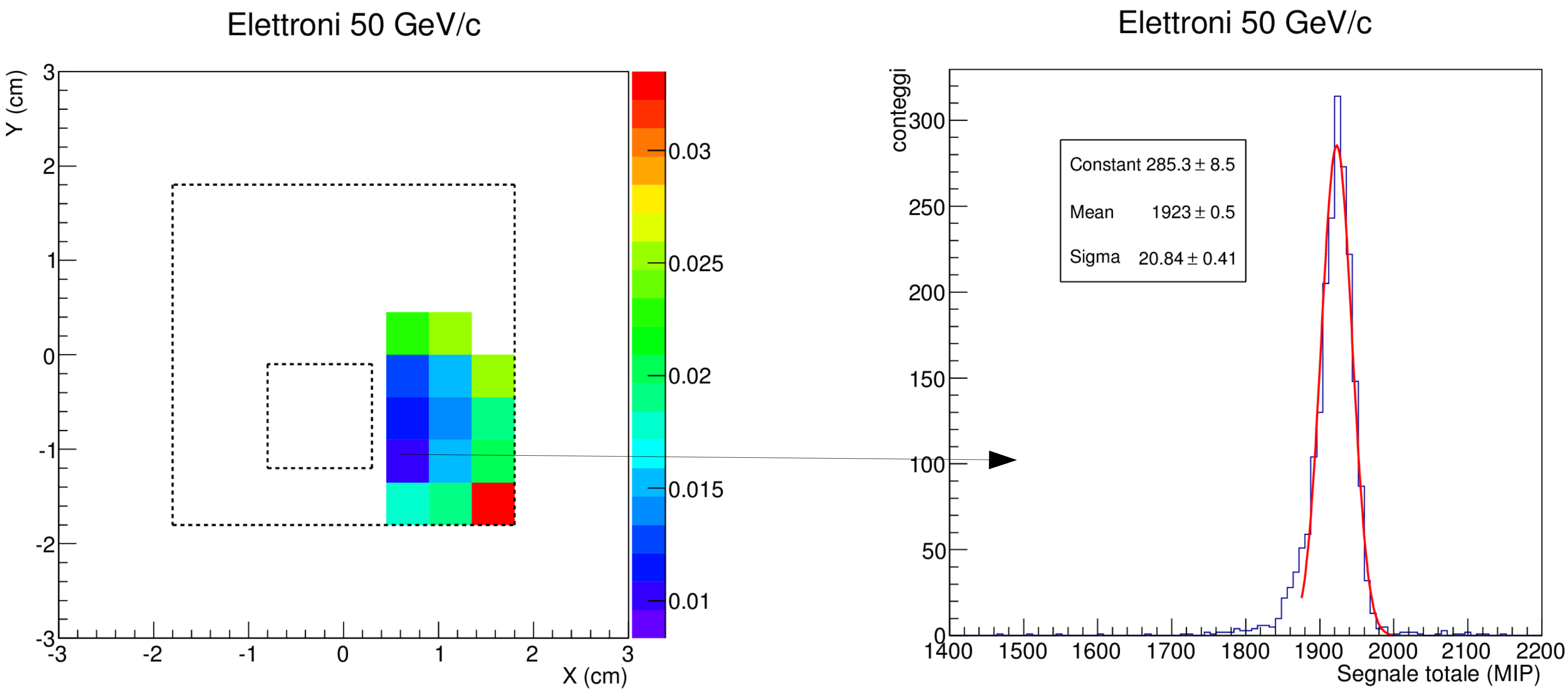


Gain dispersion among crystals ~ 19%

RMS$_{noise}$ ~ 60/80 ADC

Signal/Noise ~ 10

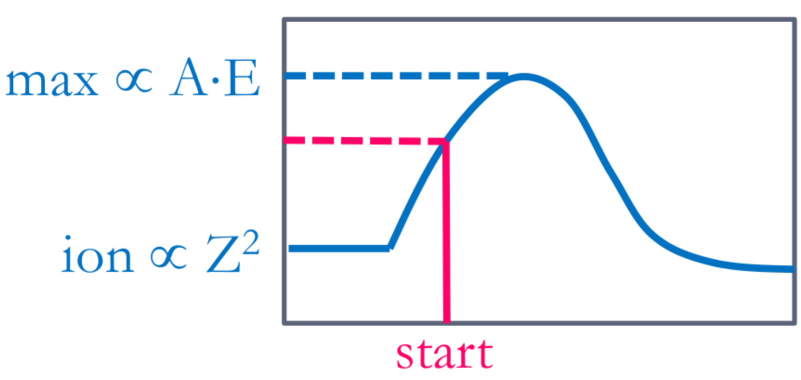
Energy resolution with electrons: Prototype v1.3



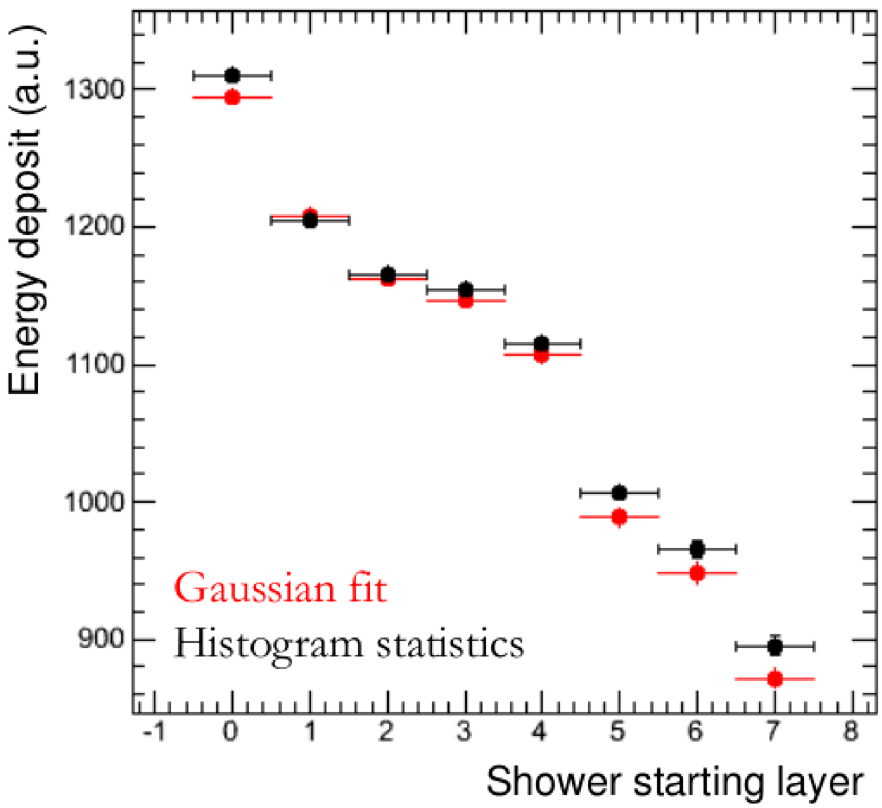
Energy resolution as a function of impact position shows strong dependence of performances on the region of the crystal

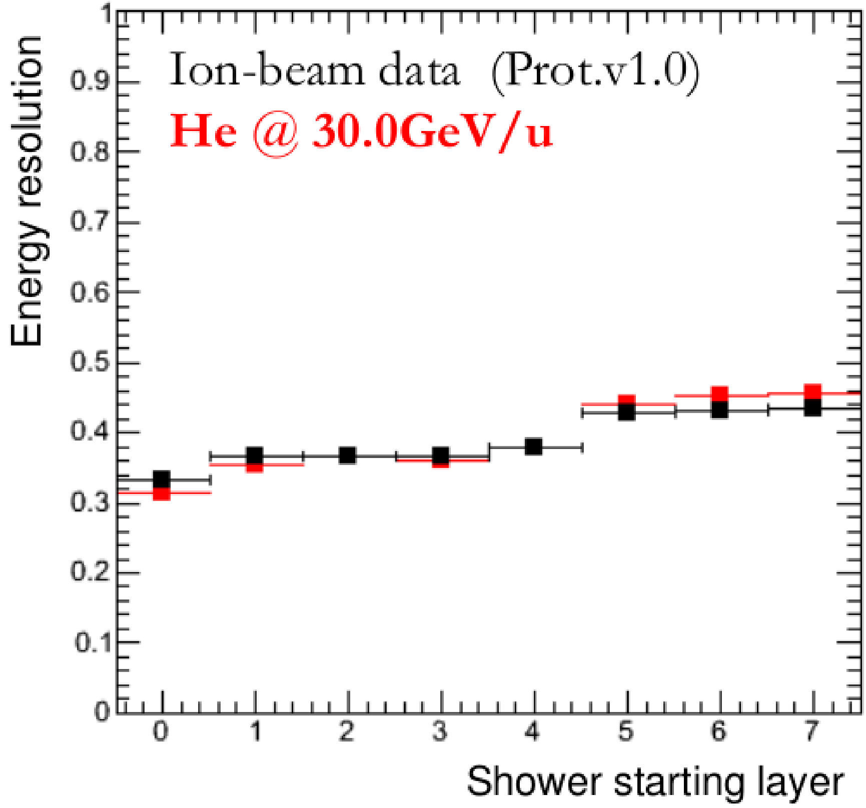
Total signal in the crystal region having best resolution gives a value of this parameter of 1.1% for 50 GeV electrons

Shower classification

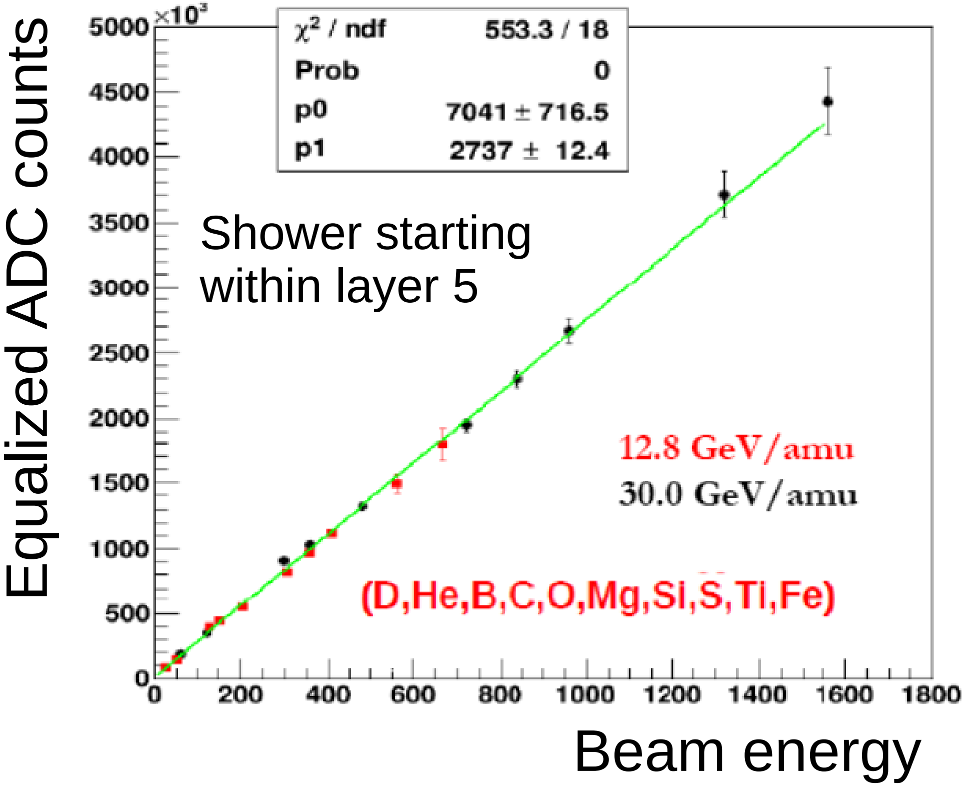


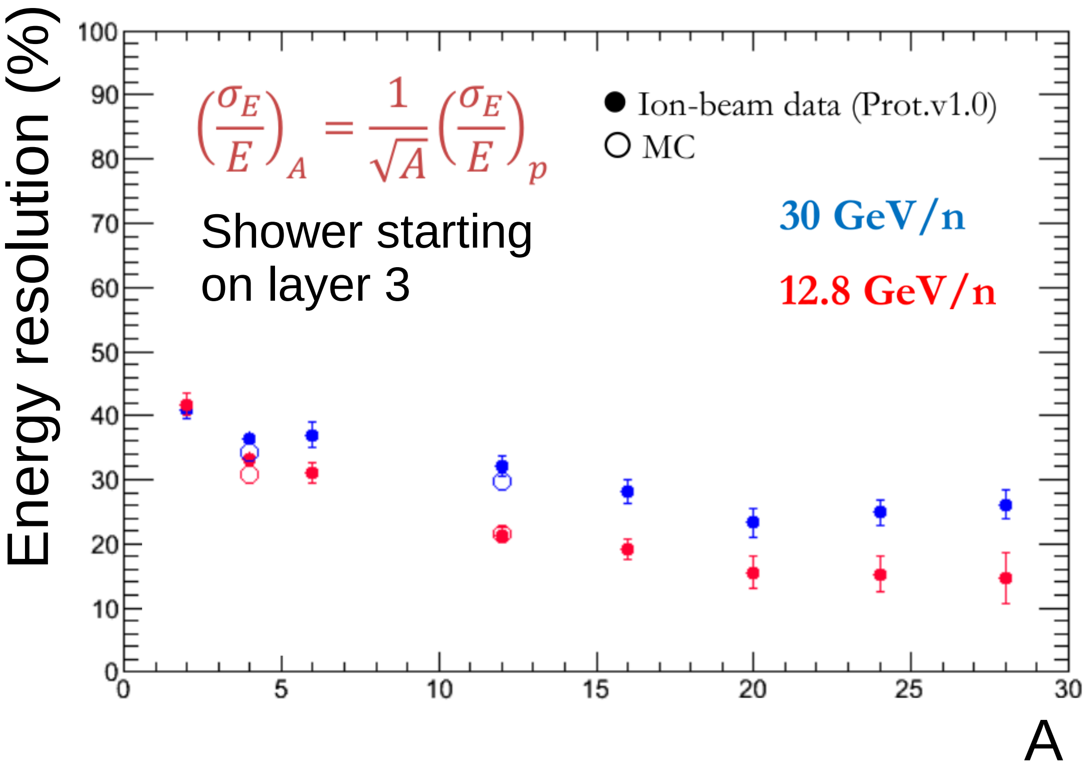
Showers are classified according to the **starting layer** representing the first interaction point





Energy resolution for hadrons



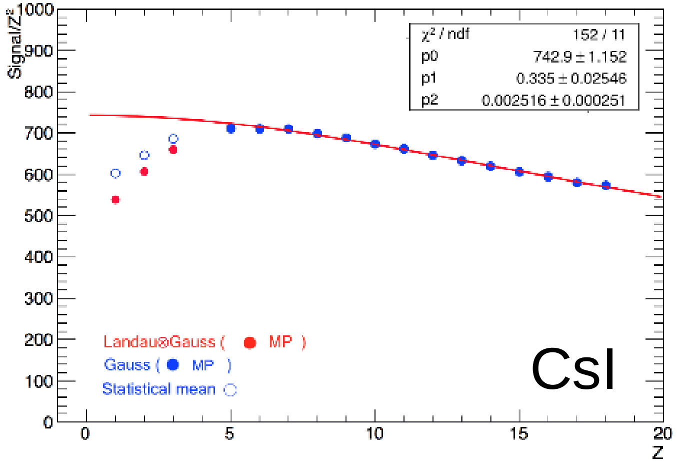


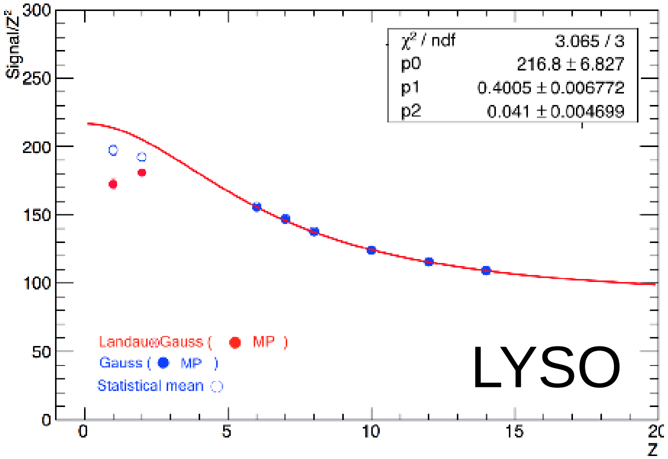
Quite good linearity
up to 1.6 TeV ion energy

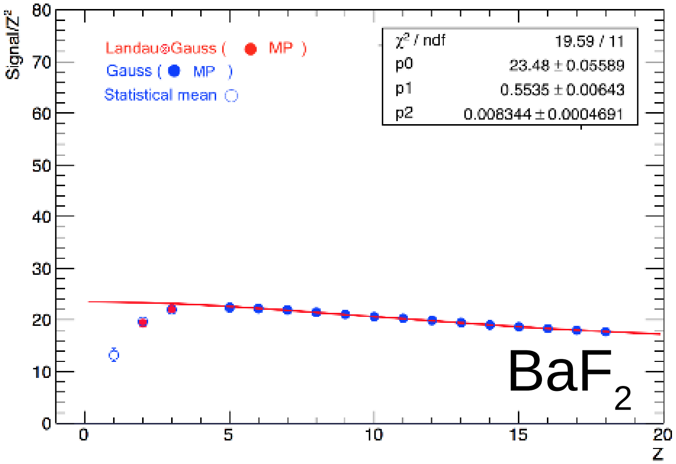
Quite good agreement between
between data and MC

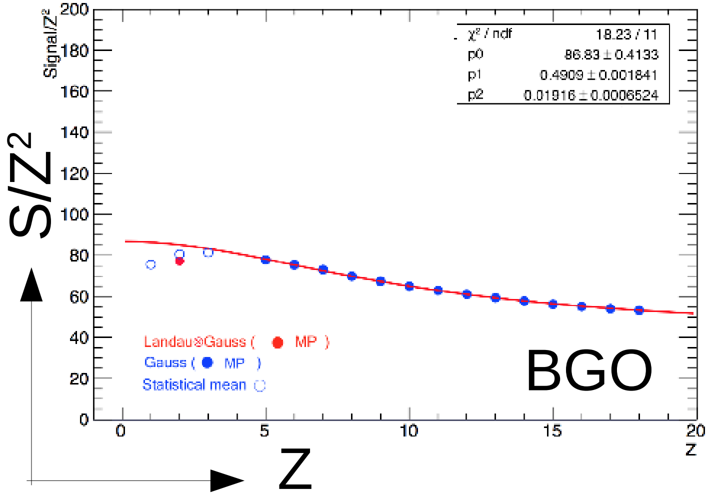
Instrumental effects (optical cross-talk) were mostly understood and corrected starting from prototype v1.1

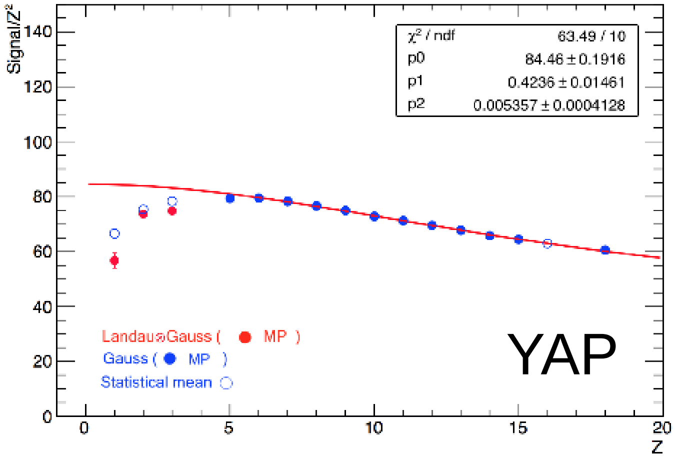
Crystal linearity











Tarlé model

$$\frac{dL}{dx} = K\{\frac{(1-F_s)dE/dx}{1+B(1-F_s)dE/dx} + F_s\frac{dE}{dx}\}$$

Fit function

$$\frac{S}{Z^2} = p_0\{\frac{(1-p_1)}{1+p_2(1-p_1)Z^2} + p_1\}$$

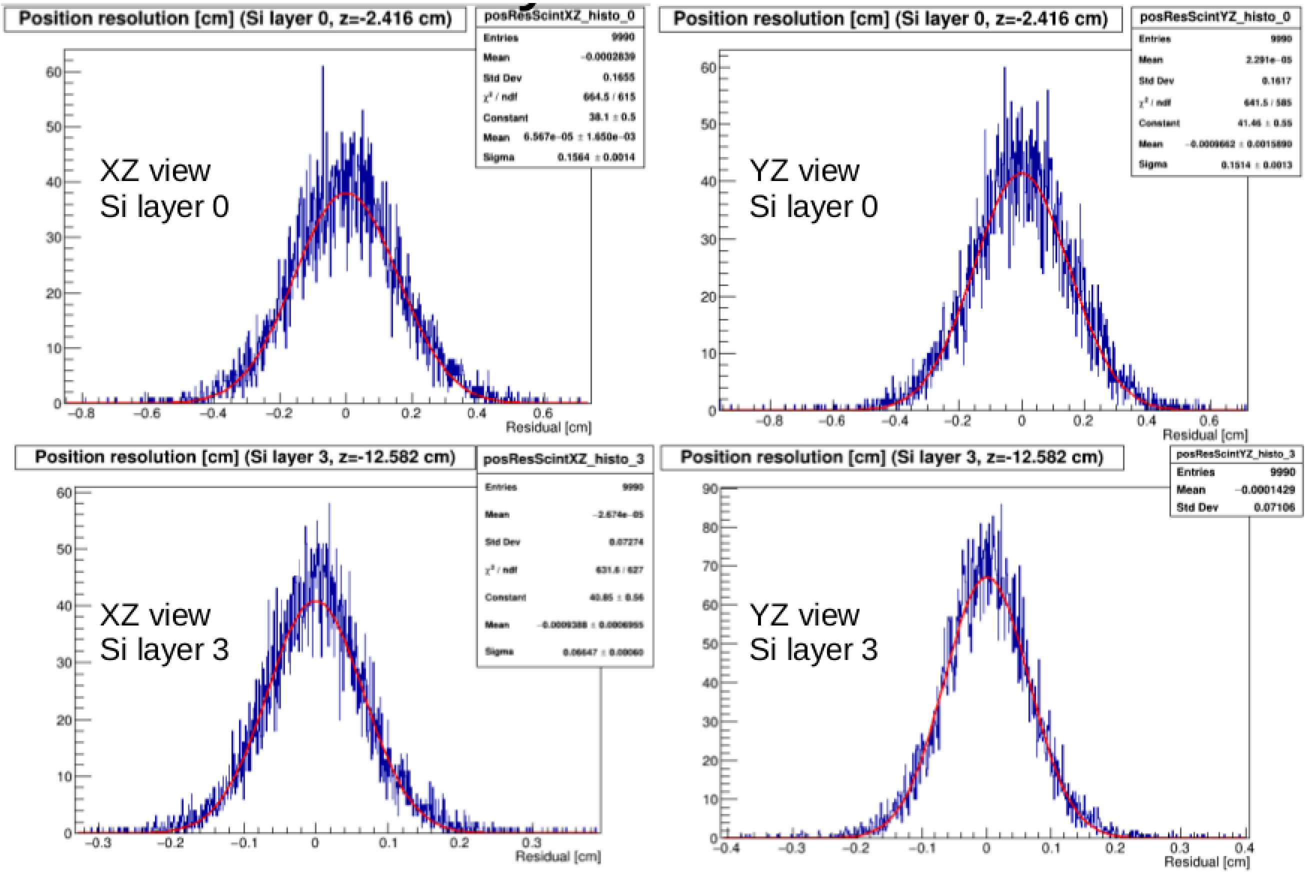
The non linear regime starts for $Z^2 = p_2 = 1/Z_0^2$

CsI:Tl has the largest Z_0

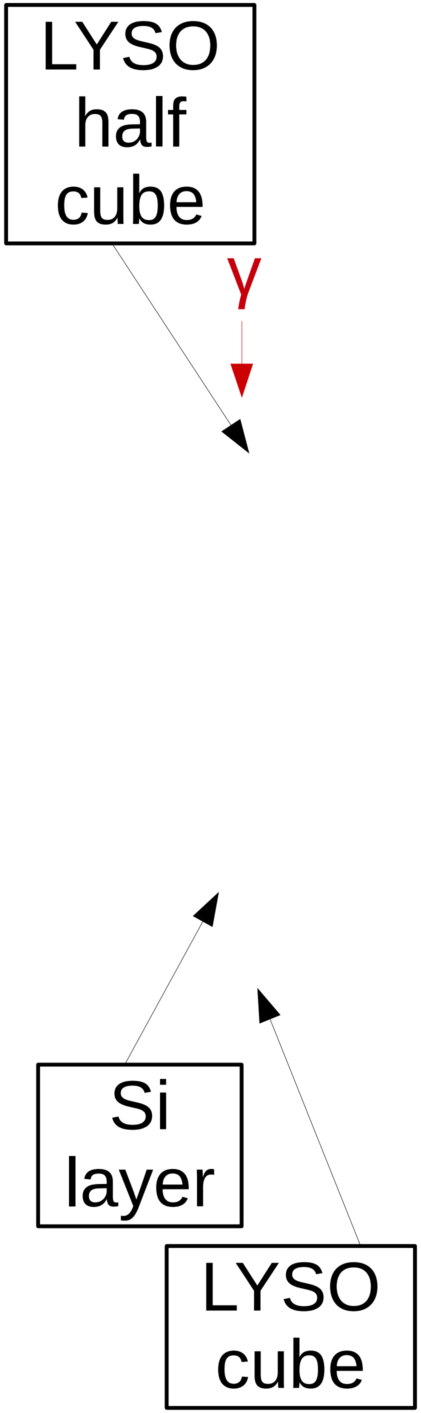
LYSO has the smallest Z_0

GEANT4

Simulation



Using full information both from calorimeter and silicon tracker, angular resolution for vertical γ is better than 0.1-0.5° above 10 GeV



LYSO half cube

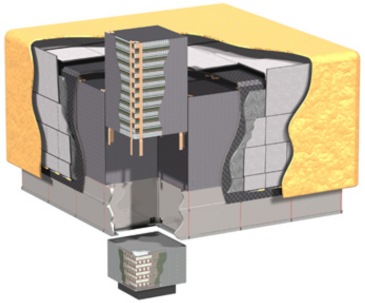
γ

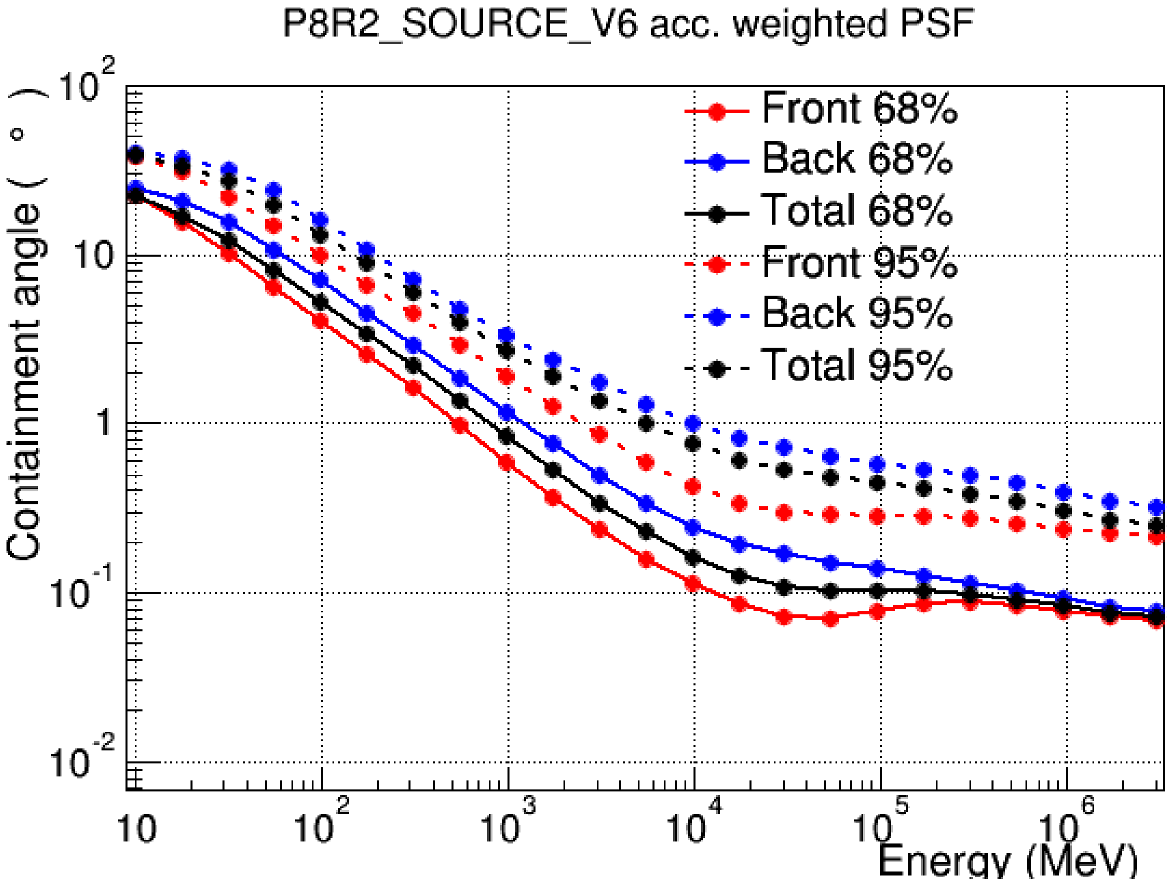
Si layer

LYSO cube

http://www.slac.stanford.edu/exp/glast/groups/canda/lat_Performance.htm

Fermi-LAT angular resolution





"Starting from the front of the instrument, the LAT tracker (TKR) has 12 layers of 3% radiation length tungsten converters (THIN or FRONT section), followed by 4 layers of 18% r.l. tungsten converters (THICK or BACK section). These sections have intrinsically different PSF due to multiple scattering with the PSF for FRONT events being approximately a factor of two better than the PSF for BACK events."

Calocube angular resolution