PROPOSAL FOR AN HOMOGENEOUS, ISOTROPIC CALORIMETER FOR SPACE EXPERIMENTS

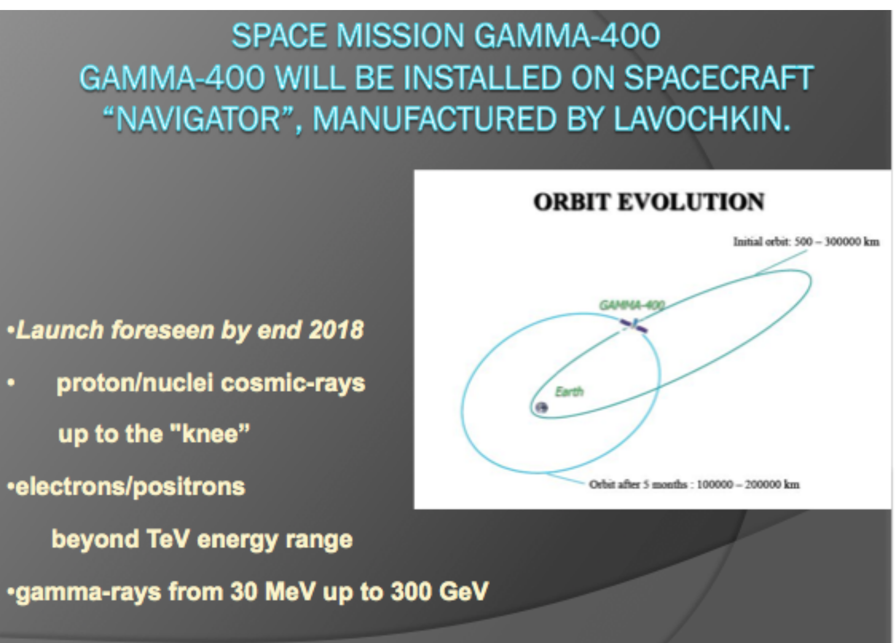
Oscar Adriani
INFN and University of Florence
On behalf of the Florence Cosmic Rays group

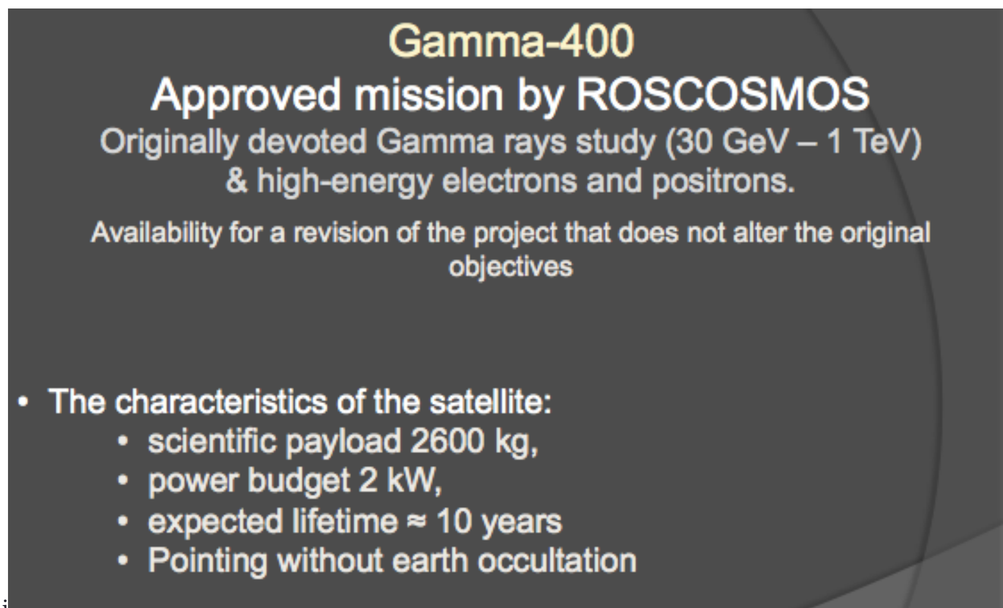
Beijing, October 17th, 2012

The First International Workshop on the High Energy cosmic-Radiation Detection

Background

- We are developing this calorimeter for the Gamma-400 project, planned to be installed on a Russian satellite
- I would like to present you this idea, to look for possible sinergies with HERD project





Which are the most important aspects of a calorimeter for high energy cosmic rays – space based experiment?

Physics goal:

- High energy (~ TeV) electron to search for structures in the spectrum and to study close-by sources
- High energy (>10^{14} eV) proton and nuclei to study the knee region

Requirements

1. Very large geometrical factor (few m^2 sr)
2. Good electron and hadron energy resolution (~1-2% for e, ~30% for hadrons)
3. Excellent electron/hadron separation (>10^5 rejection factor)
4. Reduced weight and power consumption (depend on the launch vehicle)

Our proposal: a cubic, homogeneous, isotropic calorimeter (I)

- We propose a large cubic homogeneous calorimeter, made with many small cubes. The detector would thus be able to contain and measure showering particles impacting on all sides.

1. The Geometrical factor is multiplied by 5 wrt the traditional 'top style' geometry!!!!
   - This idea is especially suited to a calorimeter which is the heaviest sub-detector in the complete experiment.
   - 'Ancillary' detectors are necessarily placed around the calorimeter, but these are extremely lightweight compared to the calorimeter itself ! (e.g. a charge measuring and trigger system).
   - The small separation gaps in between the calorimeter cubes increase the size and hence the geometrical factor without increasing the weight, at the price of a small degradation in energy resolution.
   - The bottom side can be used for mechanical support.

Our proposal: a cubic, homogeneous, isotropic calorimeter (II)

3. Good electron and hadron energy resolution can be accomplished because of:
   - Homogeneous detector (scintillating crystals)
   - Very deep calorimeter for full e.m. shower containment up to very high energies
4. Excellent electron/hadron separation reached thanks to:
   - Very fine granularity in every direction
   - Small cube size ~ Moliere radius
5. Adjustable weight and power consumption:
   - They can be easily adjusted to the launch vehicle limit simply rescaling the size (always keeping in mind the necessary depth for full shower containment!!!

Additional details….

- Exercise made on the assumption that the detector's only weight is ~ 1600 kg (Gamma-400 driven idea)
  - Mechanical support is not included in the weight estimation
- The optimal material is CsI(Tl)

Density:	4.51 g/cm^3
X_0:	1.85 cm
Moliere radius:	3.5 cm
λ_I:	37 cm
Light yield:	54.000 ph/MeV
τ_{decay}:	1.3 μs
λ_{max}:	560 nm

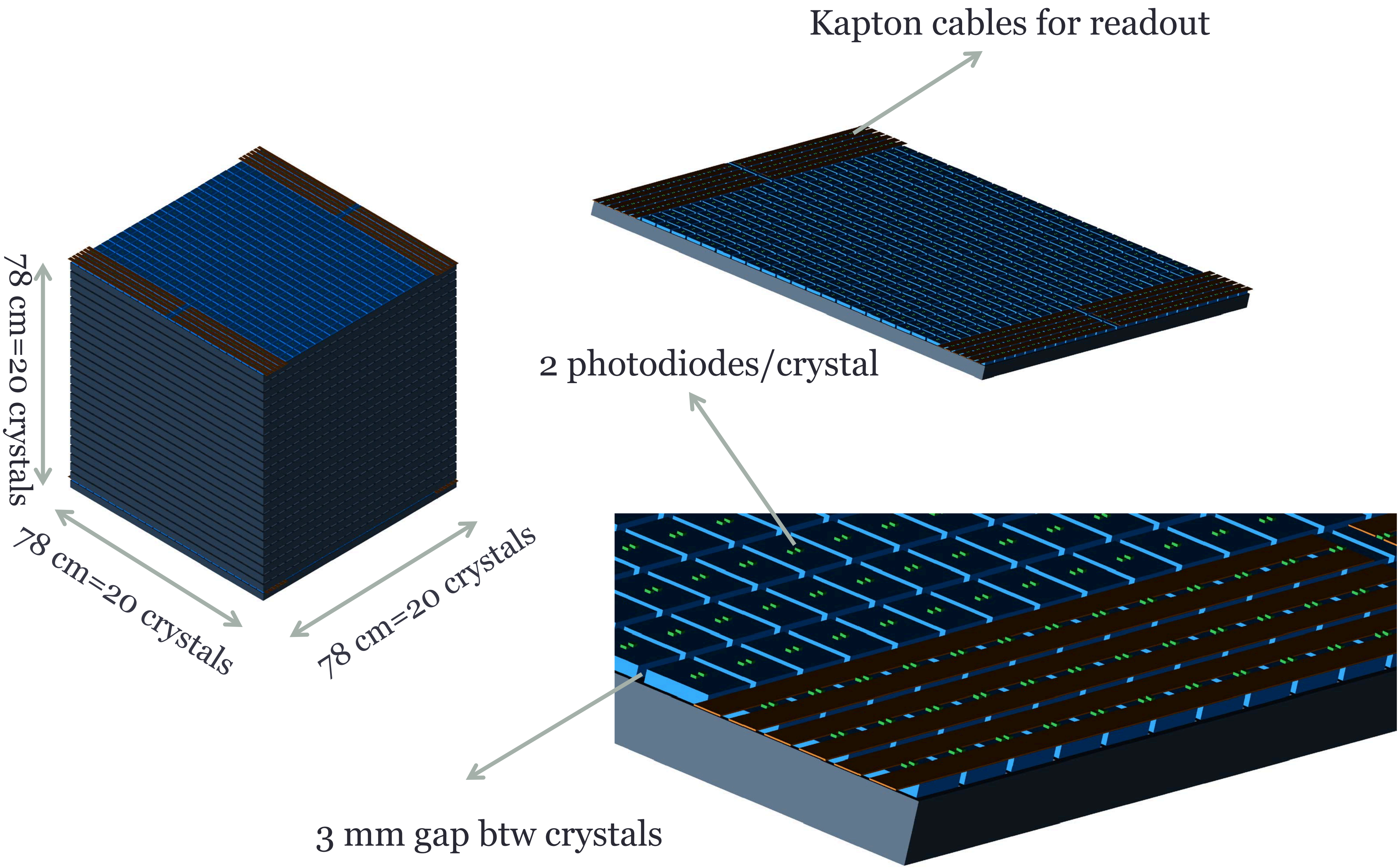
- Simulation and prototype beam tests used to characterize the detector

The proposed configuration:
CsI(Tl) ~ 1680 kg

	Cubes
N×N×N	**20×20×20**
L of small cube (cm)	3.6*
Crystal volume (cm^3)	46.7
Gap (cm)	**0.3**
Mass (Kg)	1683
N.Crystals	8000
Size (cm^3)	78.0×78.0×78.0
Depth (R.L.) " (I.L.)	39×39×39 1.8×1.8×1.8
Planar GF (m^2sr) **	1.91

Very deep!!!!

(* one Moliere radius)
(** GF for only one face)


Kapton cables for readout
2 photodiodes/crystal
78 cm=20 crystals
78 cm=20 crystals
78 cm=20 crystals
3 mm gap btw crystals

The readout sensors

- Minimum 2 Photo Diodes are necessary to cover the whole huge dynamic range
- 1 MIP→10^7 MIPS, since E_{max} in one crystal ~ 0.1 E_{tot}

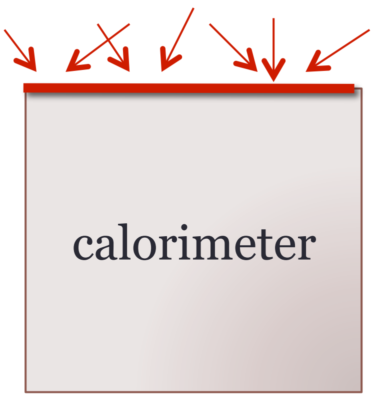
- Large Area Excelitas VTH2090 9.2 x 9.2 mm^2 for small signals → Inserted in the simulation!
- Small area 0.5 x 0.5 mm^2 for large signals

- Two independent readout channels will be used
- Details later on!

Simulation

- FLUKA based simulation
- Planar generation surface on one of the 5 faces
- Results valid also for the other faces!
- Carbon fiber in between crystals (3 mm gaps)
- Large photodiode is inserted on the crystal in the simulation
  - We take into account also the energy release in the Photodiode itself!
  - Results are valid for every face since scintillation light is isotropically emitted
- Electrons: 100 GeV – 1 TeV range
- Protons: 100 GeV – 100 TeV range
- ~ 100 – 10.000 events for each energy
- No mis-calibration effects are included in the simulation
- Light collection efficiency and PD quantum efficiency are included in the simulation
- For the moment we have very low statistics for high energy particles (huge computing time is necessary….)

Electrons



Very simple geometrical cuts:

- The track should point to a fiducial surface (two crystals on the side are eliminated)
- The maximum of the shower should be well contained in the fiducial volume
- The length of the shower should be at least 40 cm (~21 X_0)

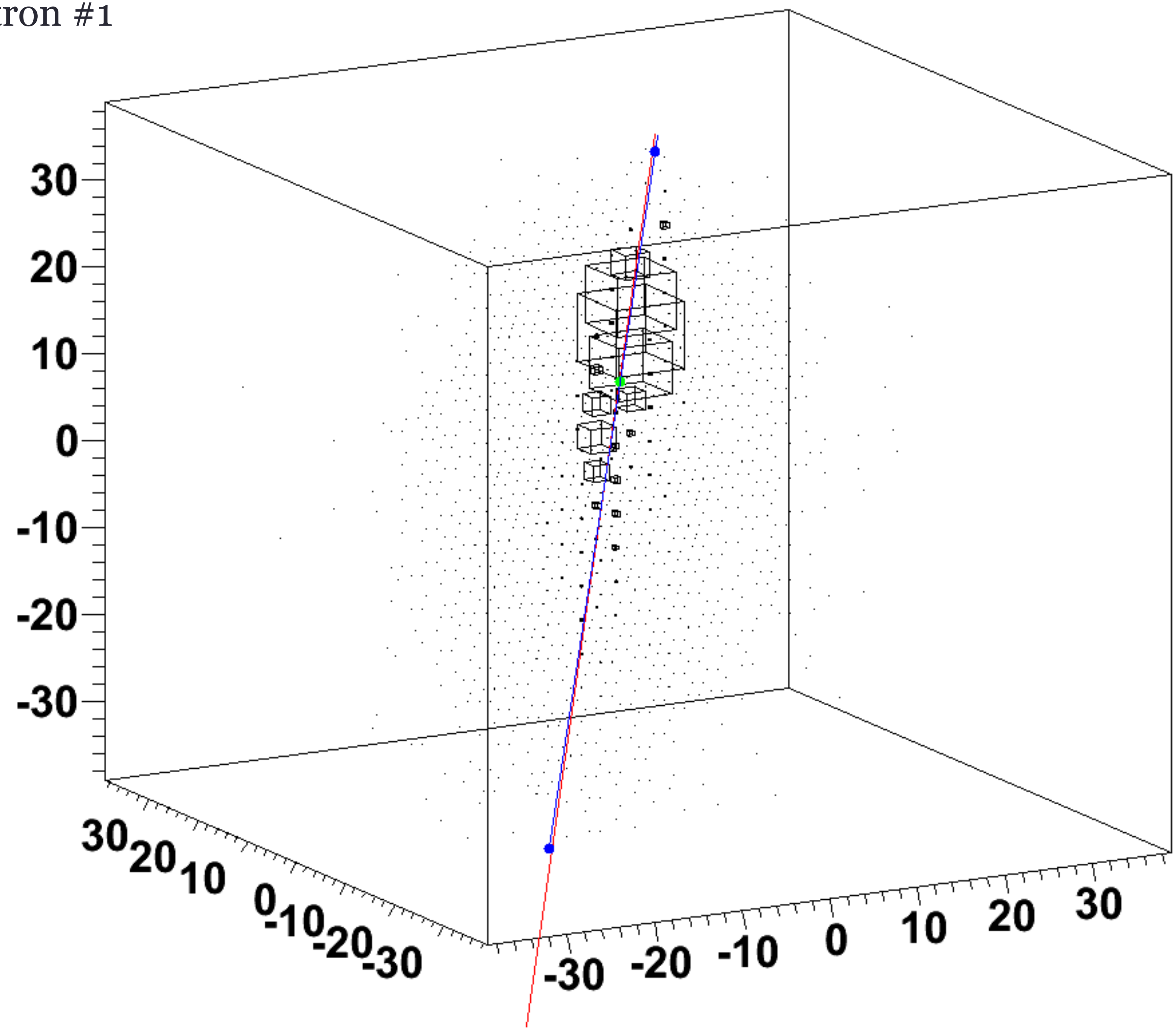
Efficiency of these cuts~ 36%

Effective geometrical factor ~

$(0.78*0.78*\pi)*5*\varepsilon$ m² sr= $9.55*\varepsilon$ m² sr

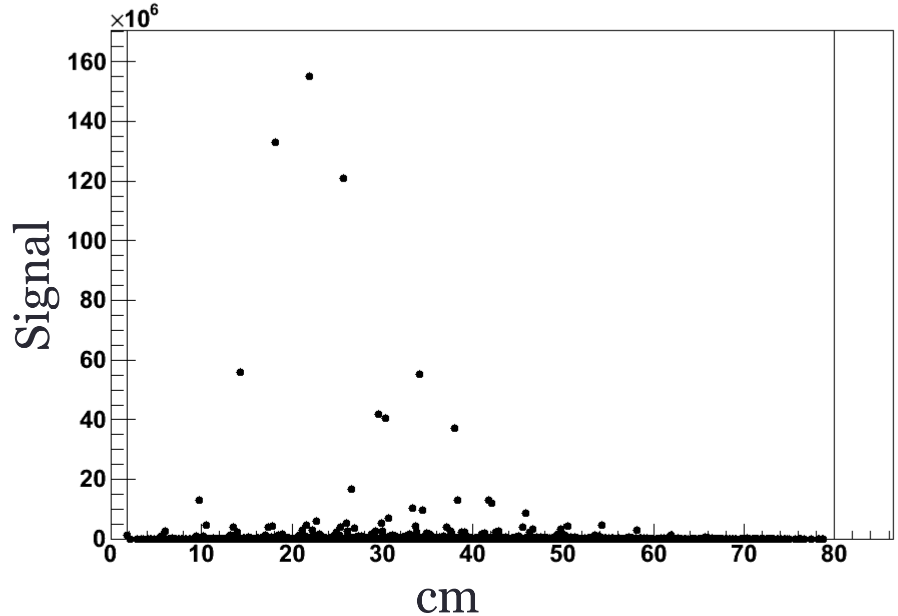
Gf_{eff}~3.4 m²sr (including the efficiency)

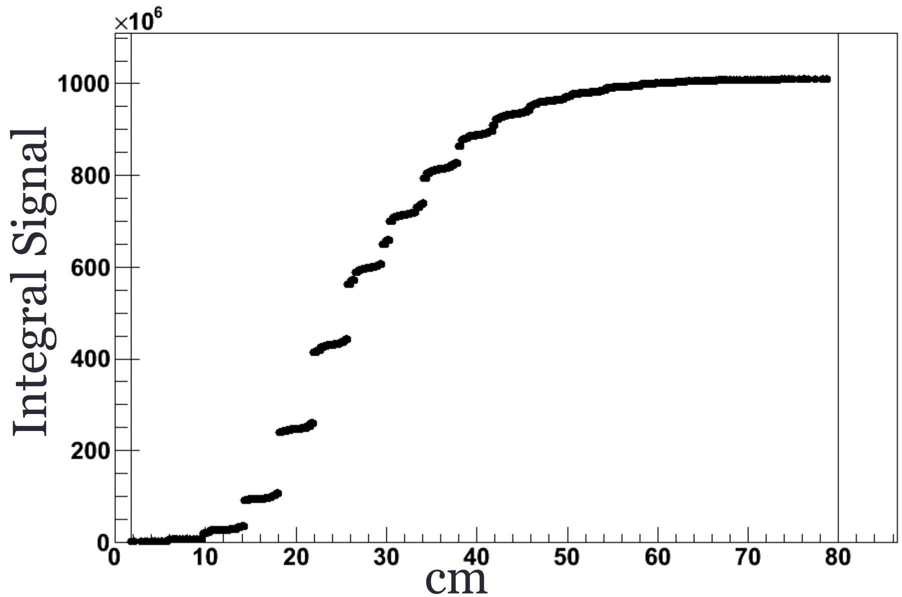
Electron #1

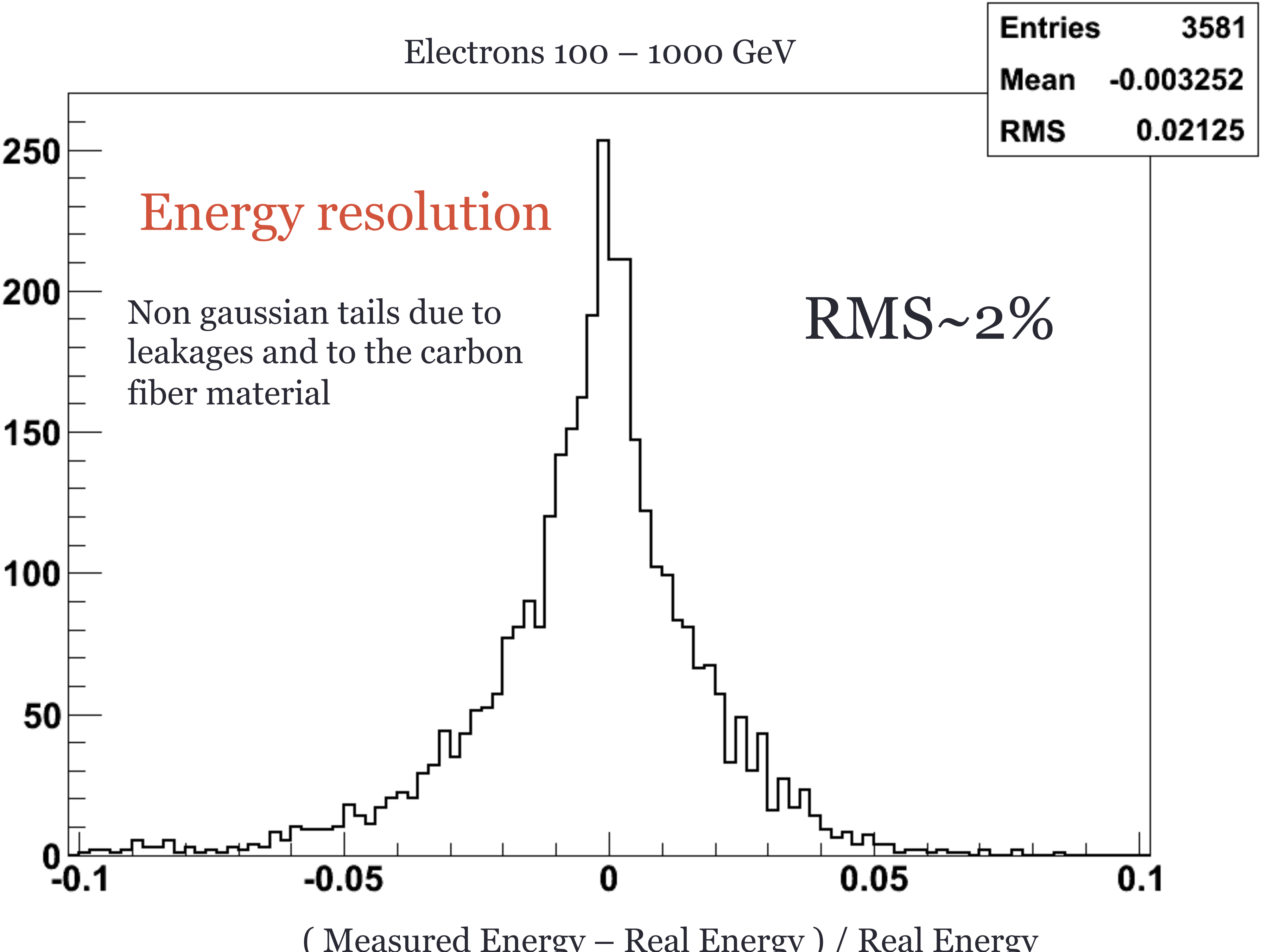


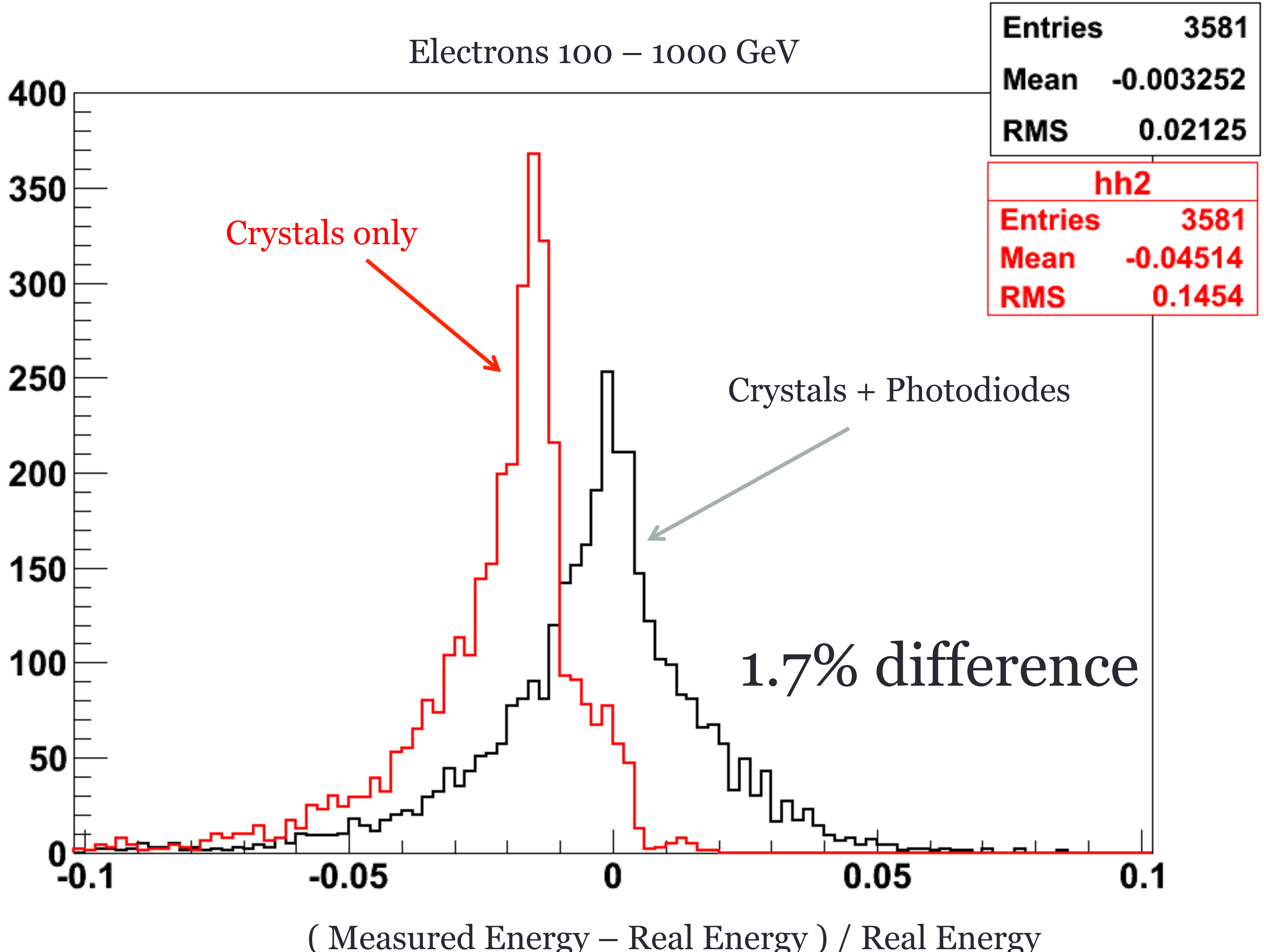
Electron #1

Longitudinal profile

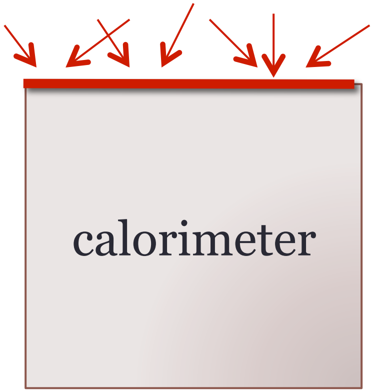





Electrons 100 – 1000 GeV
Entries 3581
Mean -0.003252
RMS 0.02125
Energy resolution
Non gaussian tails due to leakages and to the carbon fiber material
RMS~2%
250
200
150
100
50
0
-0.1
-0.05
0
0.05
0.1
(Measured Energy – Real Energy) / Real Energy

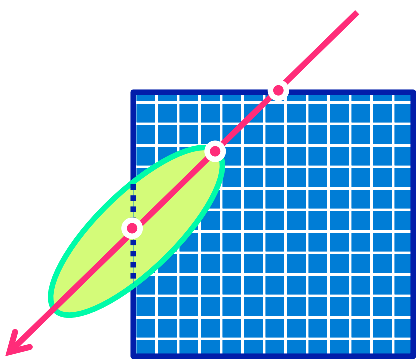

Electrons 100 – 1000 GeV
Entries 3581
Mean -0.003252
RMS 0.02125
hh2
Entries 3581
Mean -0.04514
RMS 0.1454
Crystals only
Crystals + Photodiodes
1.7% difference
400
350
300
250
200
150
100
50
0
-0.1
-0.05
0
0.05
0.1
(Measured Energy – Real Energy) / Real Energy

Protons



Very simple geometrical cuts:

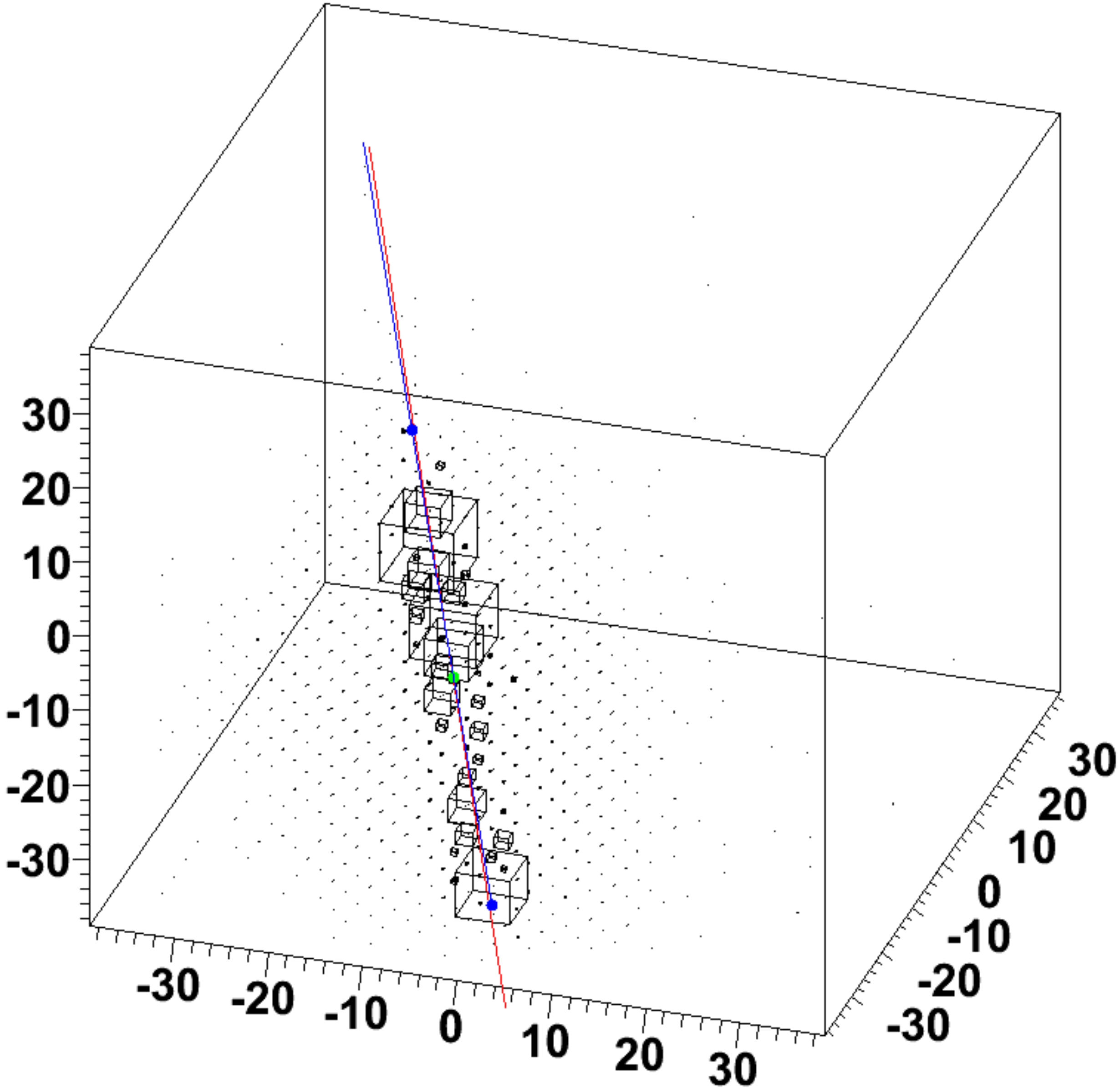
- A good reconstruction of the shower axis
- At least 50 crystals with >25 MIP signal



- Energy is reconstructed by using the shower length measured in the calorimeter, since leakage are important (1.8 λ_I for perpendicular incidence)

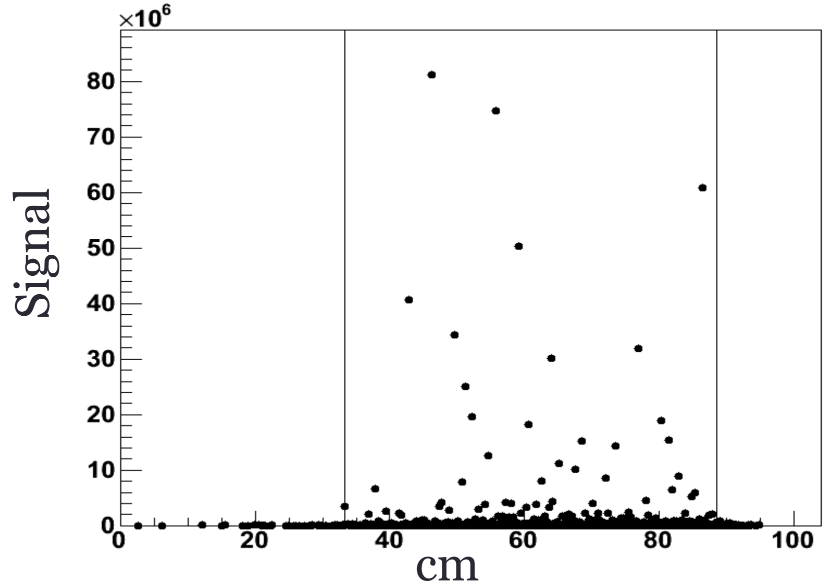
Image

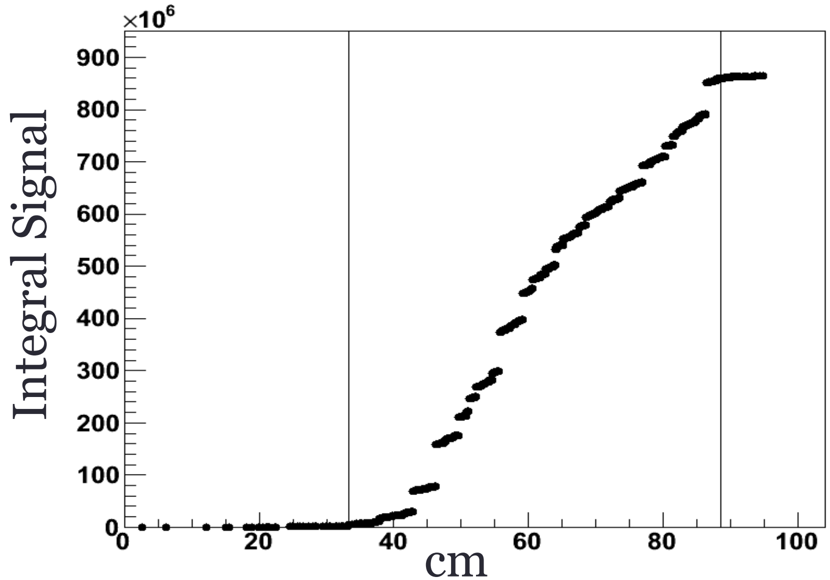
Proton #1



Proton #1

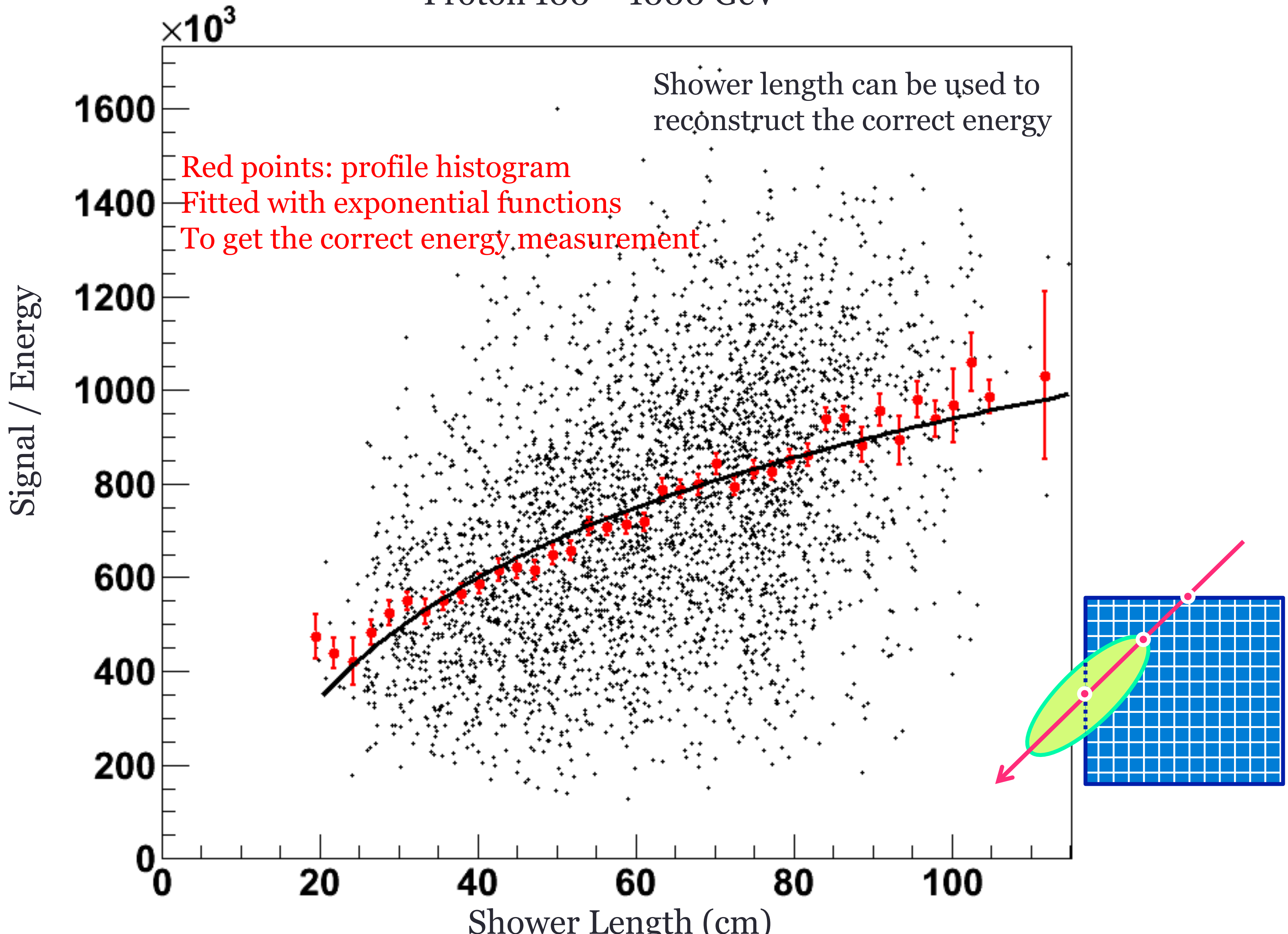
Longitudinal profile





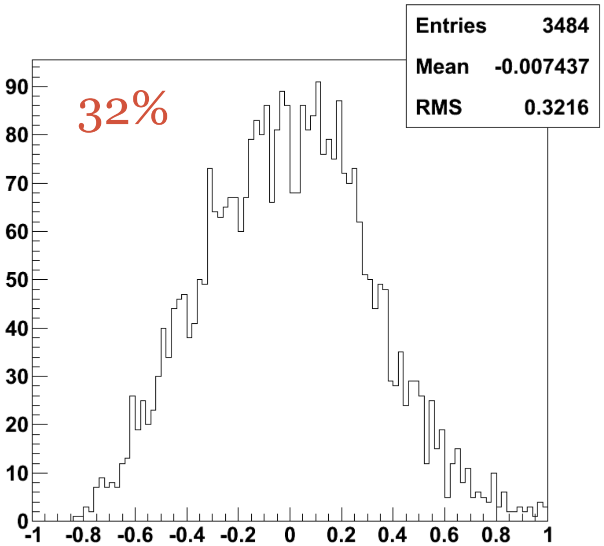
Shower starting point is identified with ~1 cm resolution

Proton 100 – 1000 GeV

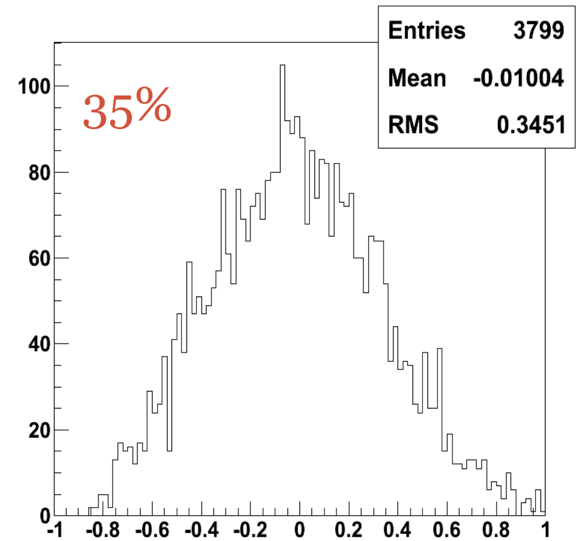


Proton energy resolution

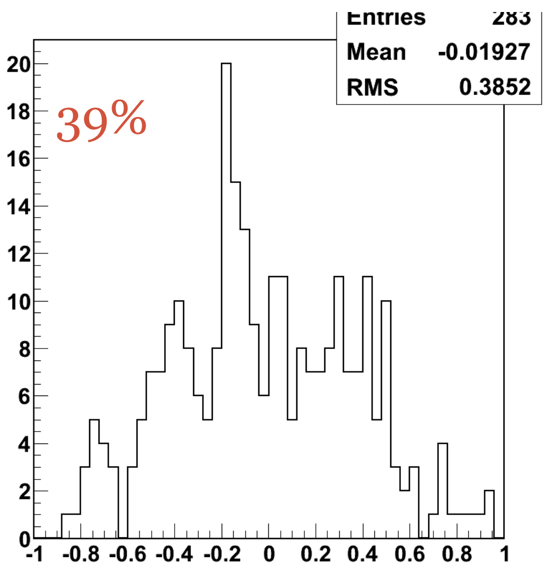
100 –
1000 GeV



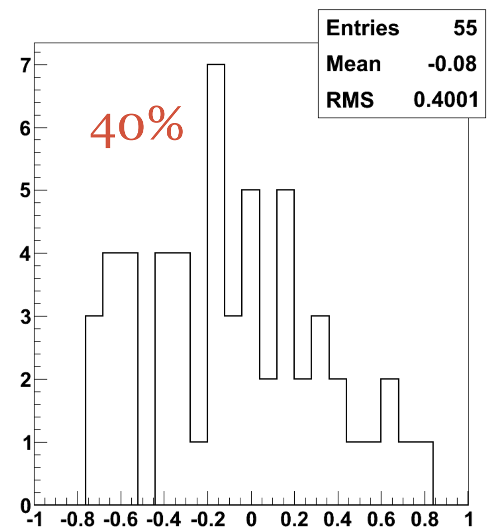
1 TeV



10 TeV



100 TeV



(Measured Energy – Real Energy) / Real Energy

Efficiencies and Geometrical factors

GF(1 face) = $0.78*0.78*\pi$ m^2 sr= 1.91 m^2 sr

GF(5 faces)= 1.91*5 m^2 sr = 9.55 m^2 sr

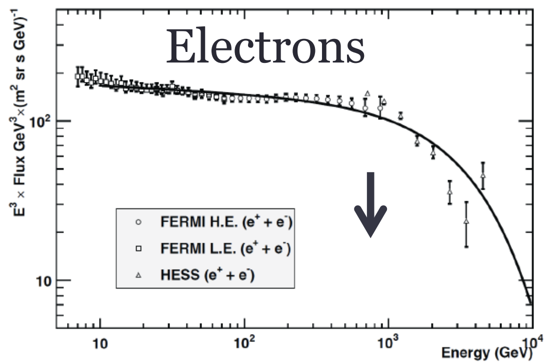
Energy	ε	Energy resolution	Gfeff (m^{2}sr)
100-1000 GeV	35%	32%	3.3
1 TeV	41%	34%	3.9
10 TeV	47%	38%	4.5

Selection cuts can be tuned to optimize the parameters
Roughly speaking: GF>3 m^{2}sr with good energy resolution!!!!

What we can reach with this calorimeter?

Assumptions:

- 10 years exposure
- No direct closeby sources for electrons
- Polygonato model for protons/nuclei



Electrons

Gf_{eff} ($m^2 sr$)	ΔE/E	Depth (X_0)	e/p rej. factor	E>0.5 TeV	E>1 TeV	E>2 TeV	E>4 TeV
3.4	2%	39	$>10^5$	~2.10⁵	~4.10⁴	~6.10³	~7.10²

~ knee

Protons and Helium

Gf_{eff} ($m^2 sr$)	ΔE/E	Depth (λ_I)	E>100 TeV		E>500 TeV		E>1000 TeV		E>2000 TeV		E>4000 TeV	
			p	He	p	He	p	He	p	He	p	He
~4	40%	1.8	2.8×10^4	2.7×10^4	1.7×10^3	1.8×10^3	4.4×10^2	5.5×10^2	1.0×10^2	1.6×10^2	1.7×10^1	3.6×10^1

Some caveats….

- Please note:
  - The theoretical previsions for the knee region are really very much spread out!
  - Pre-PAMELA-ATIC-CREAM scenarium: simple single power low up tp the knee region
  - Post-PAMELA_ATIC_CREAM scenarium: the models have to exaplain the change in slope around 200 GV/c, and the different slopes btw protons and helium
  - Differents sources, different injectiuon spectra, closeby sources,,non standard propagation scenarium….

- Many works have been published in the last few years:
  - Thoudam and Horandel
  - Zatsepin, Panov, Sokolskaya.
  - Bernard, Delahaye, Keum, Liu, Salati, Taillet
  - Yuan, Zhang, Bi
  - Tomassetti
  - Blasi, Amato, Donato, Serpico

I can give you references if you are interested

- As a results, the expected spectrum around knee is unclear, and probably higher than the one expected up to few years ago
- Possible structures may arise?
- Direct measurementes are really essential!
- With the propsed calorimeter, we could measure well above the knee

The prototype

- We are building a small scale prototype to verify the performances and check that no weak points exist in the project
- First pre-prototype already constructed
  - 12 CsI(Tl) crystals 2.5x2.5x2.5cm^3 (Thanks to Y.F. Wang!!!!!)
  - 6 layers with with a 3x3 matrix, with Iron cubes where CsI is not available
- Goal of the pre-prototype: test beam at Cern-SPS before the Cern accelerator shutdown for ~2 years
- The test has been completed on October 14!!!
- A more complete 144 3.6x3.6x3.6 cm^3 prototype will be built in the next few months


VTH2090H
1229

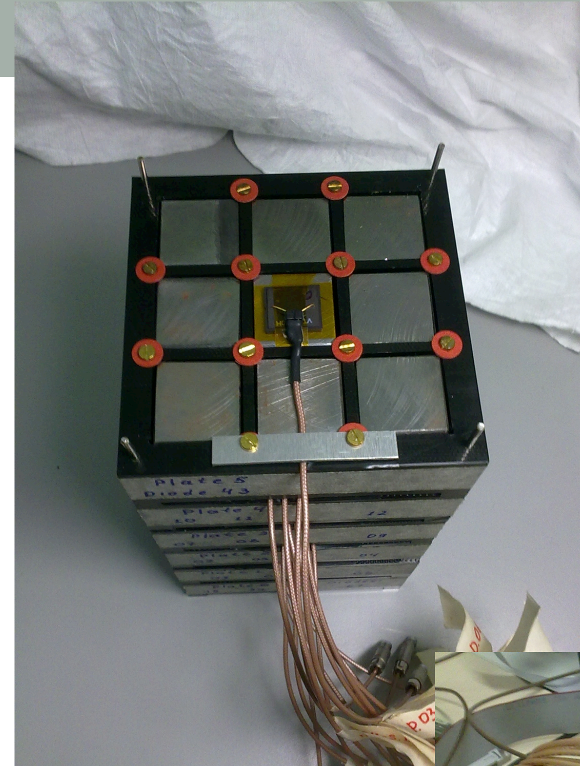


Plate 5
Diode 43

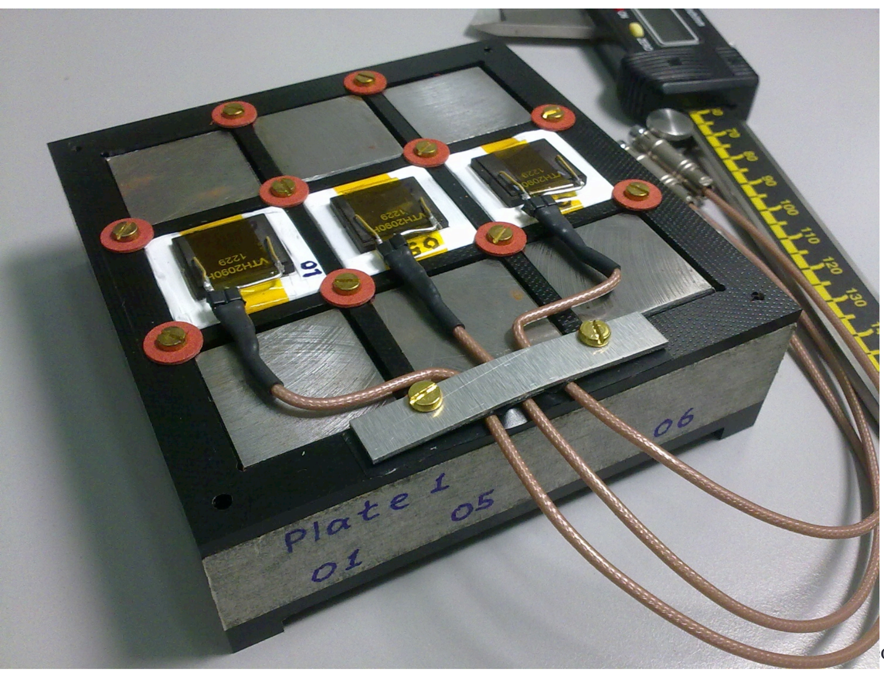
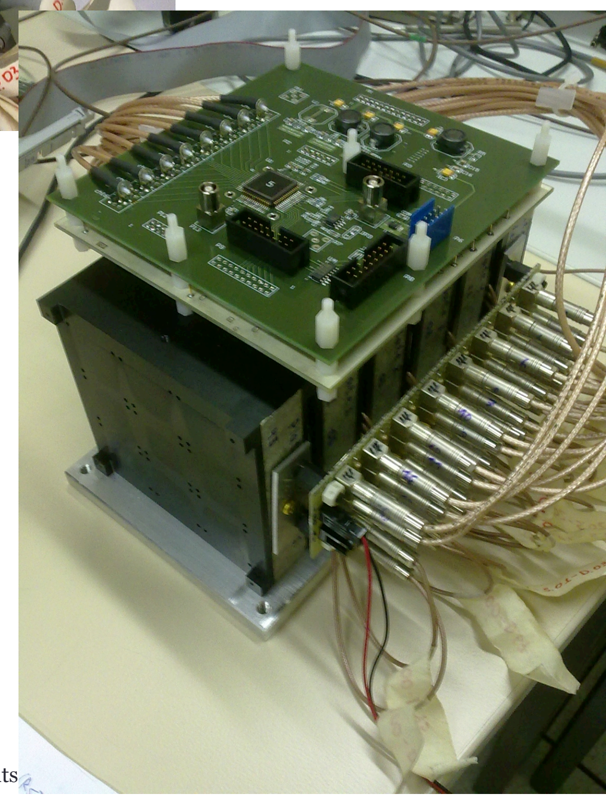


Plate 1
01
05
06



Some comments on the required dynamic range

CsI(Tl)

- 1 MIP/cm = 1.25 MeV/(g/cm^2)*4.5 g/cm ^{3} = 5.62 MeV/cm
- 1 MIP (for cube 3.6 cm) = 5.62 *3.6 = 20 MeV
- Light yield = 54 000 ph/MeV
- Light yield for cube = 54 000*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 = 28.10^3 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)

By using two different PD we could well see MIP, and we could avoid saturation in one crystal provided we can find a suitable preamplifier chip (64pC/2fC=3.10^4 dynamic range)

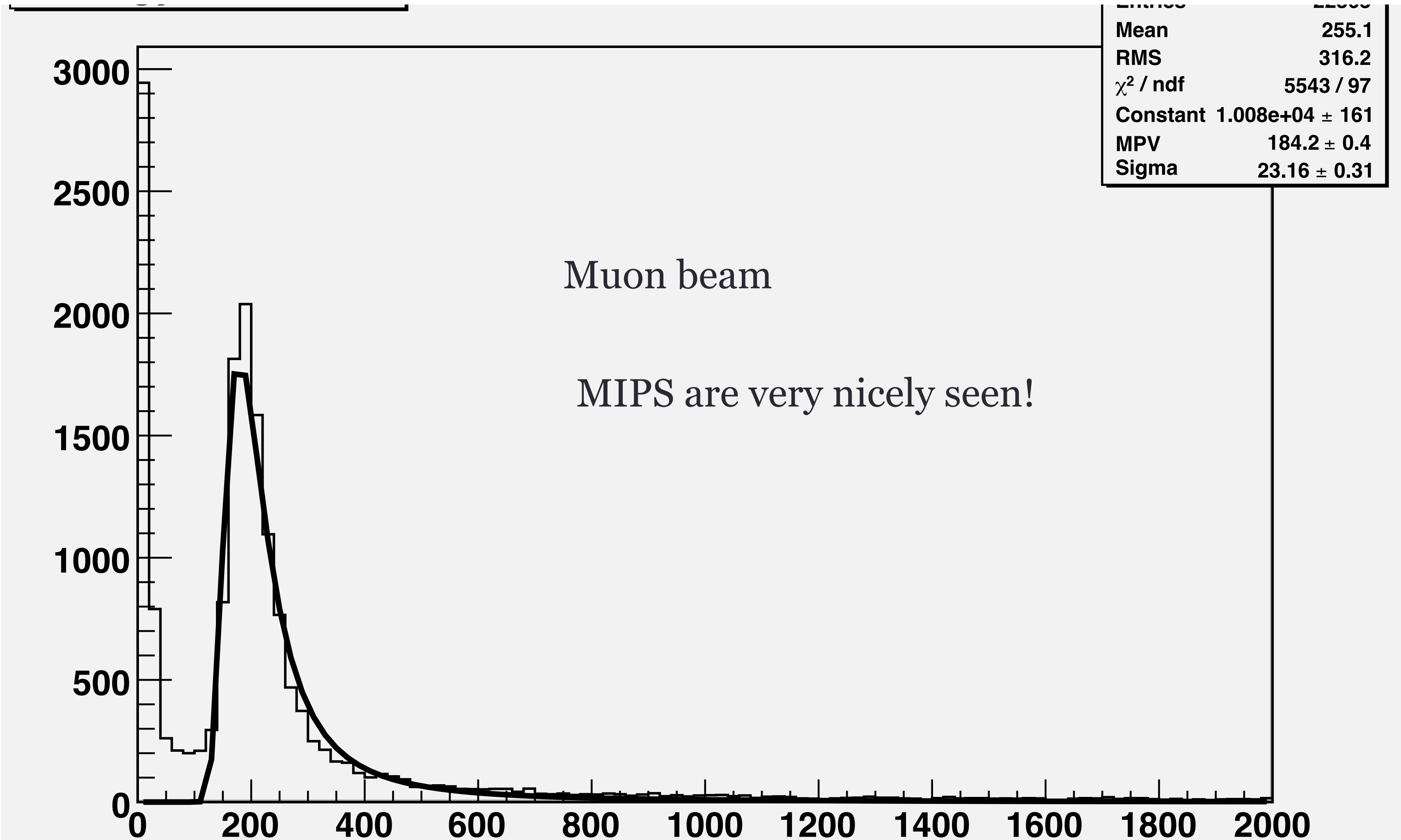
The CASIS chip

IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 57, NO. 5, OCTOBER 2010

- The CASIS chip, developed in Italy by Trieste, is very well suited for this purpose
- 16 channels, Charge Sensitive Ampl and Correlated Double Sampling
- Automatic switching btw low and high gain mode
- 2.8 mW/channel
- 3.10^3 e^- noise for 100 pF input capacitance
- 53 pC maximum input charge

- The CASIS chip has been successfully used for the pre-prototype

A spot on the pre-prototype test beam

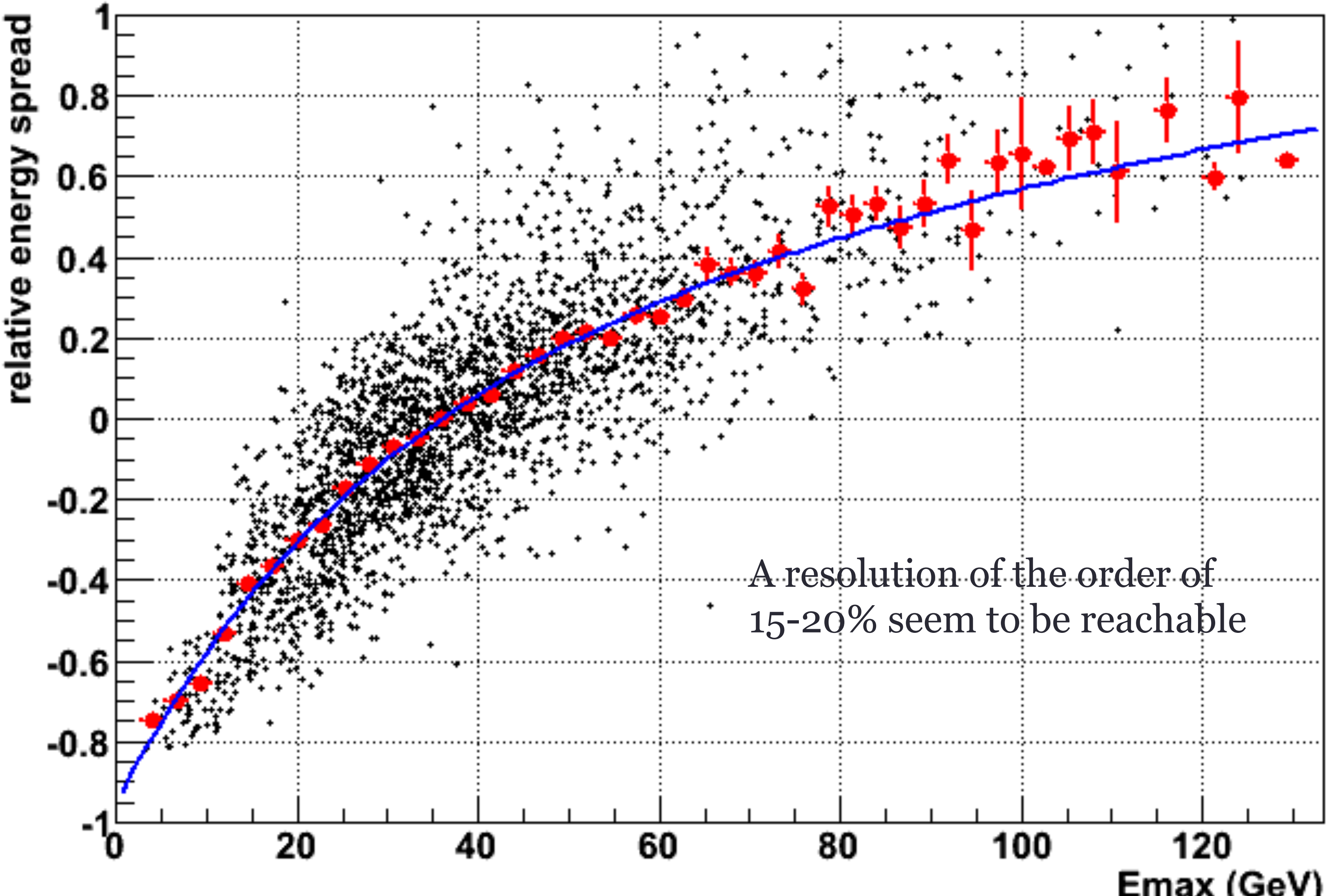


How to improve the calorimeter performances?

- We could try to see the Cherenkov light produced in the crystals by the electromagnetic component of the shower
  1. Improvement of the e/p rejection factor
  2. Improvement of the hadronic energy resolution (DREAM project)

- Problem: different response to electromagnetic and hadronic particles (e/h>1)
- Effect: worsening of energy resolution
- Solution: try to compensate the hadronic response to make it equal to electromagnetic one
  - 'Software compensation' developed in the last few years
  - Hardware compensation (~late 1980)

Software compensation



A resolution of the order of 15-20% seem to be reachable

Hardware compensation

- Dual readout –> CsI: scintillation + Cherenkov
- Scintillation is sensitive to the overall energy release
- Cherenkov is sensitive to electromagnetic component
- Idea: measure Cherenkov light event by event, and use this info to correct the measured energy
- Pro: Possibility to use the timing information to discriminate btw scintillation (slow) and Cherenkov (fast) component
- Contro: Cherenkov light is a small fraction of the scintillaton light, compatible with the direct energy release in the PD….
- A dedicated R&D is still necessary

Dual-readout calorimetry with a full-size BGO electromagnetic section

N. Akchurin[a], F. Bedeschi[b], A. Cardini[c], R. Carosi[b], G. Ciapetti[d], R. Ferrari[e], S. Franchino[f], M. Fraternali[f], G. Gaudio[e], J. Hauptman[g], M. Incagli[b], F. Lacava[d], L. La Rotonda[h], T. Libeiro[a], M. Livan[f], E. Meoni[h], D. Pinci[d], A. Policicchio[h,1], S. Popescu[a], F. Scuri[b], A. Sill[a], W. Vandelli[i], T. Venturelli[h], C. Voena[d], I. Volobouev[a], R. Wigmans[a,*]

Dual readout –> BGO: scintillation + Cherenkov

Filter: 250 ÷ 400 nm for Cherenkow light
>450 nm for Scintillator light

Hardware compensation

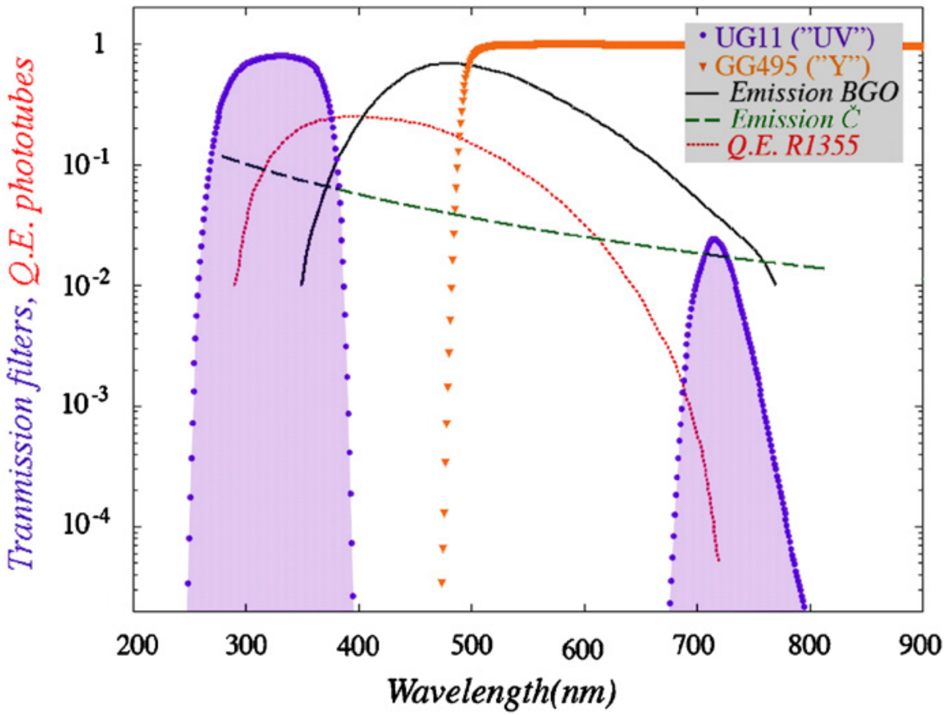
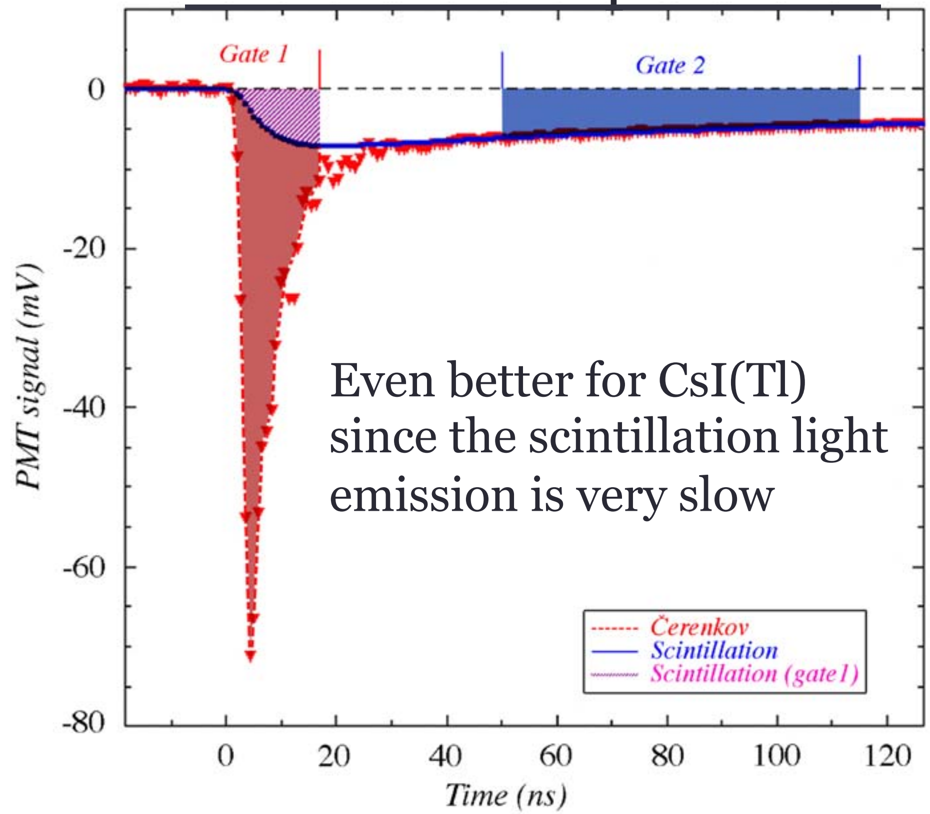


Fig. 14. Light transmission as a function of wavelength for the two filters used to read out the BGO crystal. The light emission spectrum of the crystal, the spectrum of the Cherenkov light generated in it and the quantum efficiency of the PMTs used to detect this light are shown as well. The vertical scale is absolute for the transmission coefficients and the quantum efficiency, and constitutes arbitrary units for the light spectra.



Even better for CsI(Tl) since the scintillation light emission is very slow

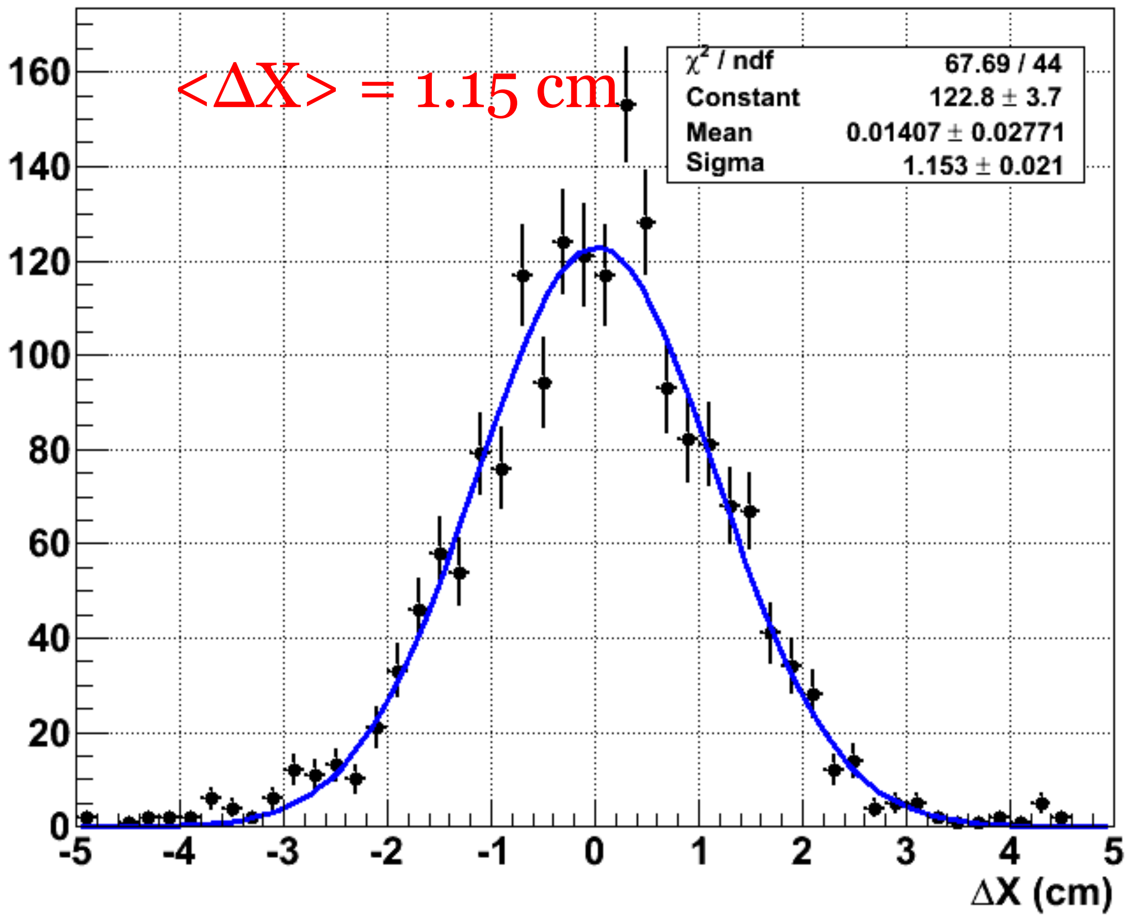
Fig. 5. The time structure of a typical shower signal measured in the BGO em calorimeter equipped with a UV filter. These signals were measured with a sampling oscilloscope, which took a sample every 0.8 ns. The UV BGO signals were used to measure the relative contributions of scintillation light (gate 2) and Cherenkov light (gate 1).

Conclusion

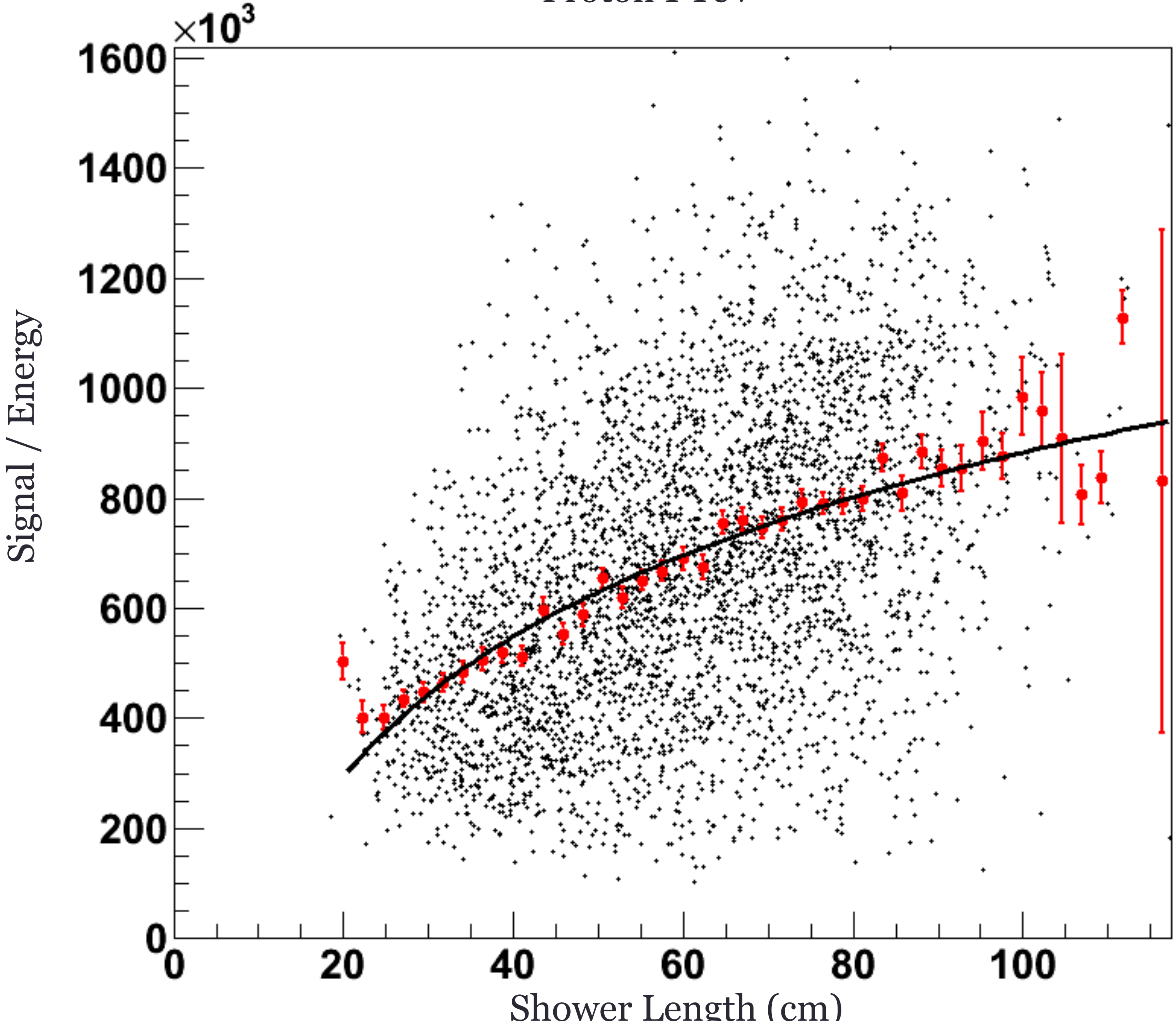
- An homogeneous, isotropic calorimeter look to be an optimal tool for space experiments dedicated to high energy electrons and protons/nuclei
- The idea is under development for the Gamma-400 project, but could be eventually investigated for HERD?
- The status of the project is quite advanced:
  - Simulation
  - Prototype
  - Test beam
- We are available for any further discussion on this idea!!!

BACKUP

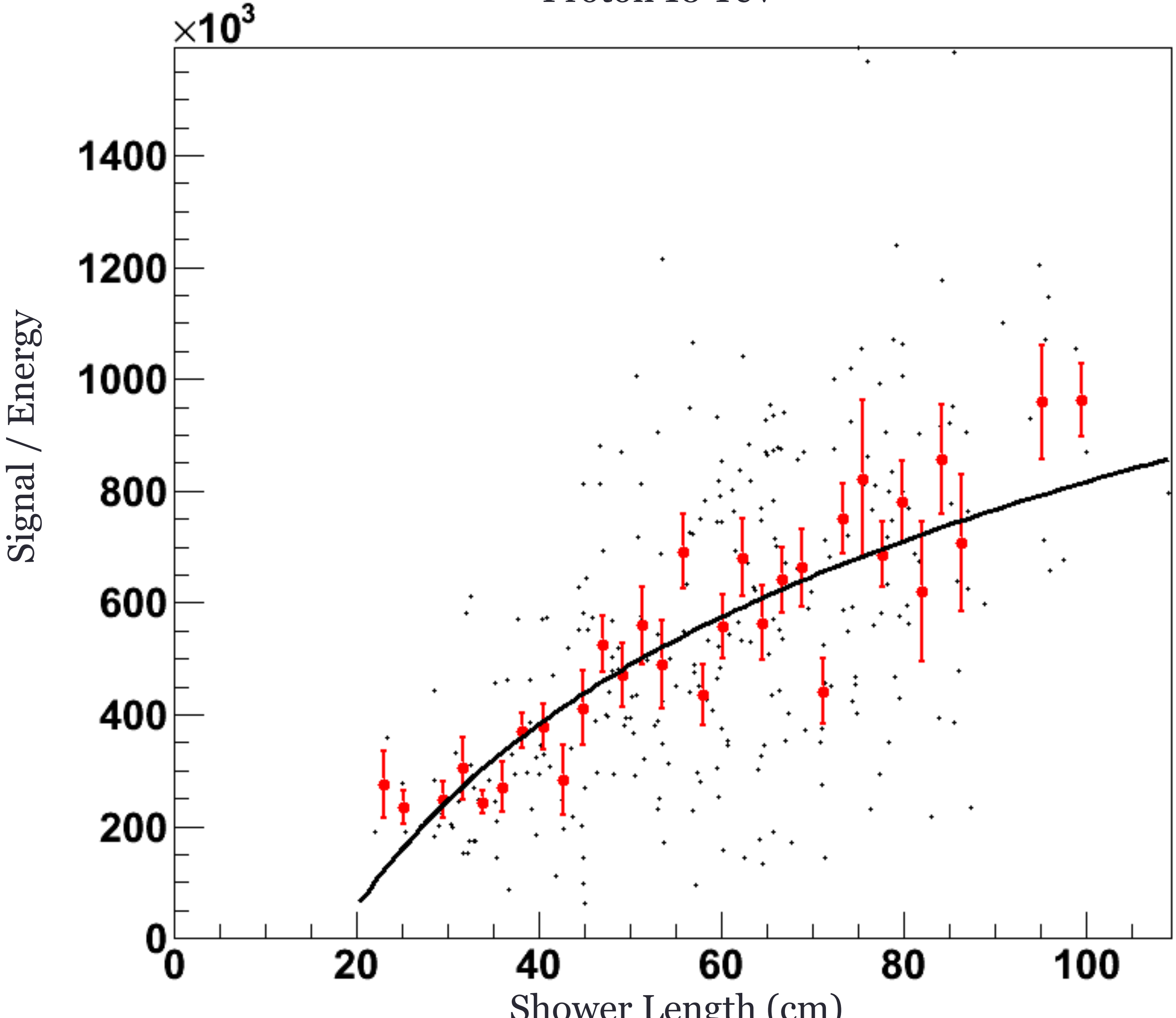
Shower starting point resolution

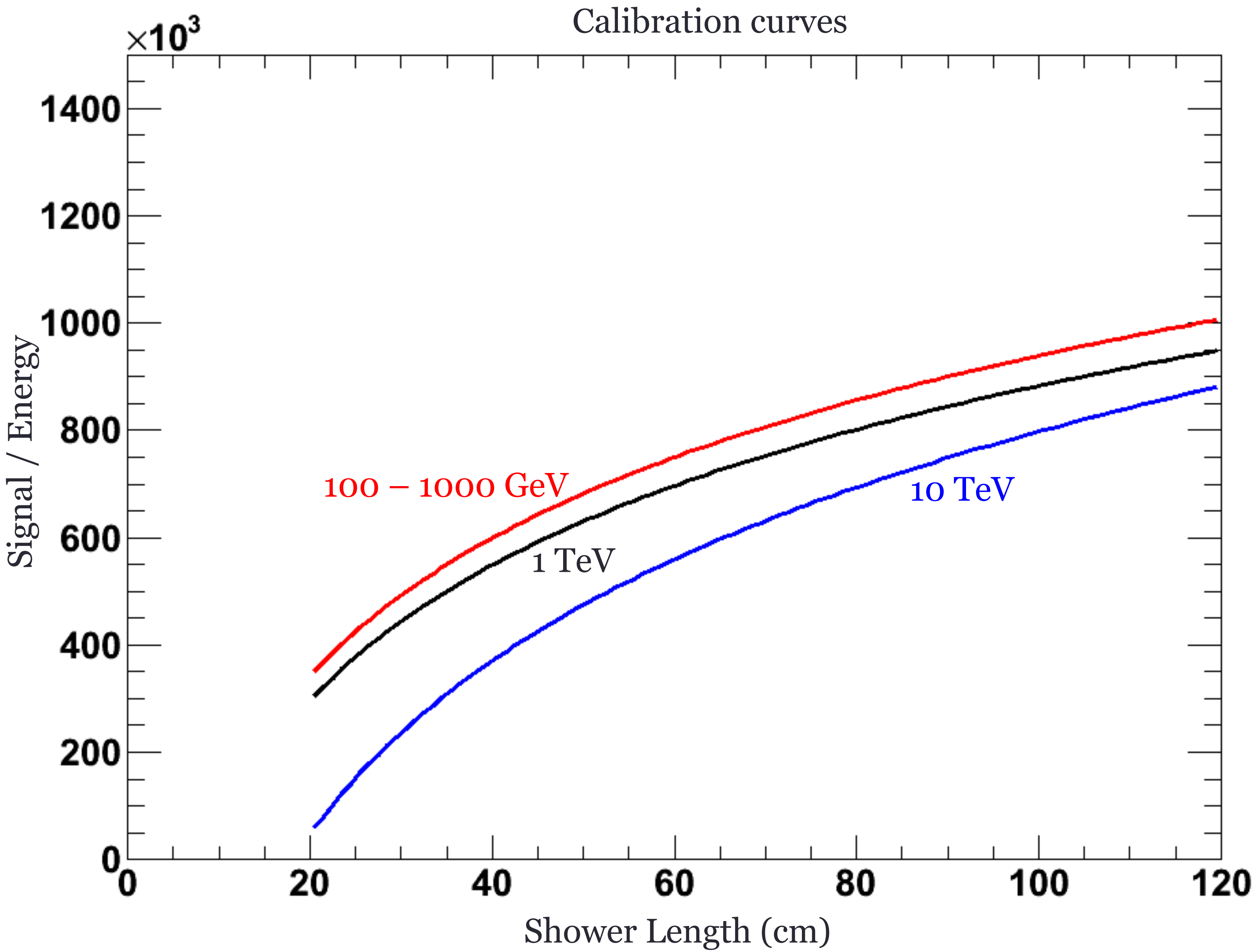


Proton 1 TeV


×10³
1600
1400
1200
1000
800
600
400
200
0
Signal / Energy
0
20
40
60
80
100
Shower Length (cm)

Proton 10 TeV

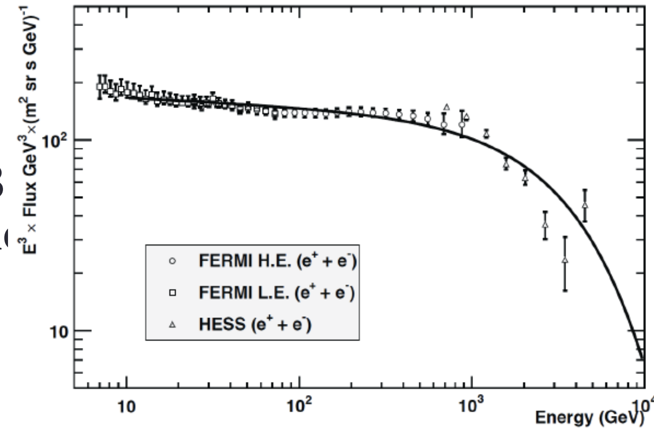




Calibration curves
×10^3
1400
1200
1000
800
600
400
200
0
0
20
40
60
80
100
120
Signal / Energy
Shower Length (cm)
100 – 1000 GeV
1 TeV
10 TeV

Counts estimation, *electrons*

G400 configuration: CsI(Tl), 20x20x20 crystals
Size: 78.0x78.0x78.0 cm³ – gap 0.3
Taking into account: geometrical factor and exp. durati
selection efficiency 80%



Experiment	Duration	Planar GF (m² sr)	Calo σ (E)/E	Calo depth	e/p rejection factor	E > 0.5 TeV	E > 1 TeV	E > 2 TeV	E > 4 TeV
CALET	5 y	0,12	~2%	30 X_0	10^5	3193	611	95	10
AMS02	10 y	0,5**	~2%	16 X_0	10^3 **	26606	5091	794	84
ATIC	30 d	0,25	~2%	18 X_0	10^4	109	21	3	0
FERMI	10 y	1,6@300 GeV * 0,6@800 GeV *	~15%	8,6 X_0	10^4	59864	2545	0	0
G400	**10 y**	**8,5**	**~0,9%**	**39 X_0**	**10^6**	**452303**	**86540**	**13502**	**1436**

* efficiencies included ** calorimeter standalone

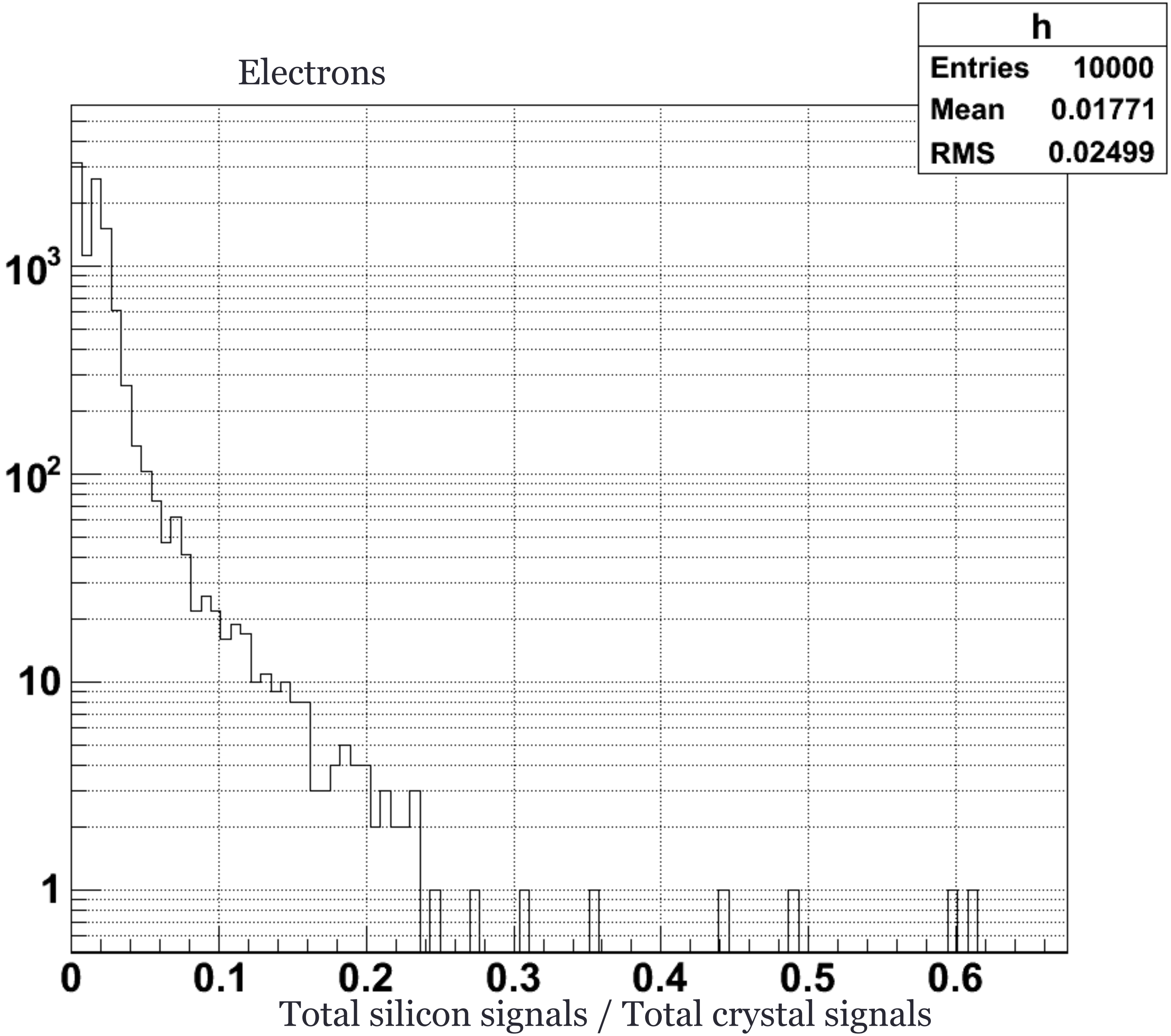
Counts estimation, protons and helium nuclei

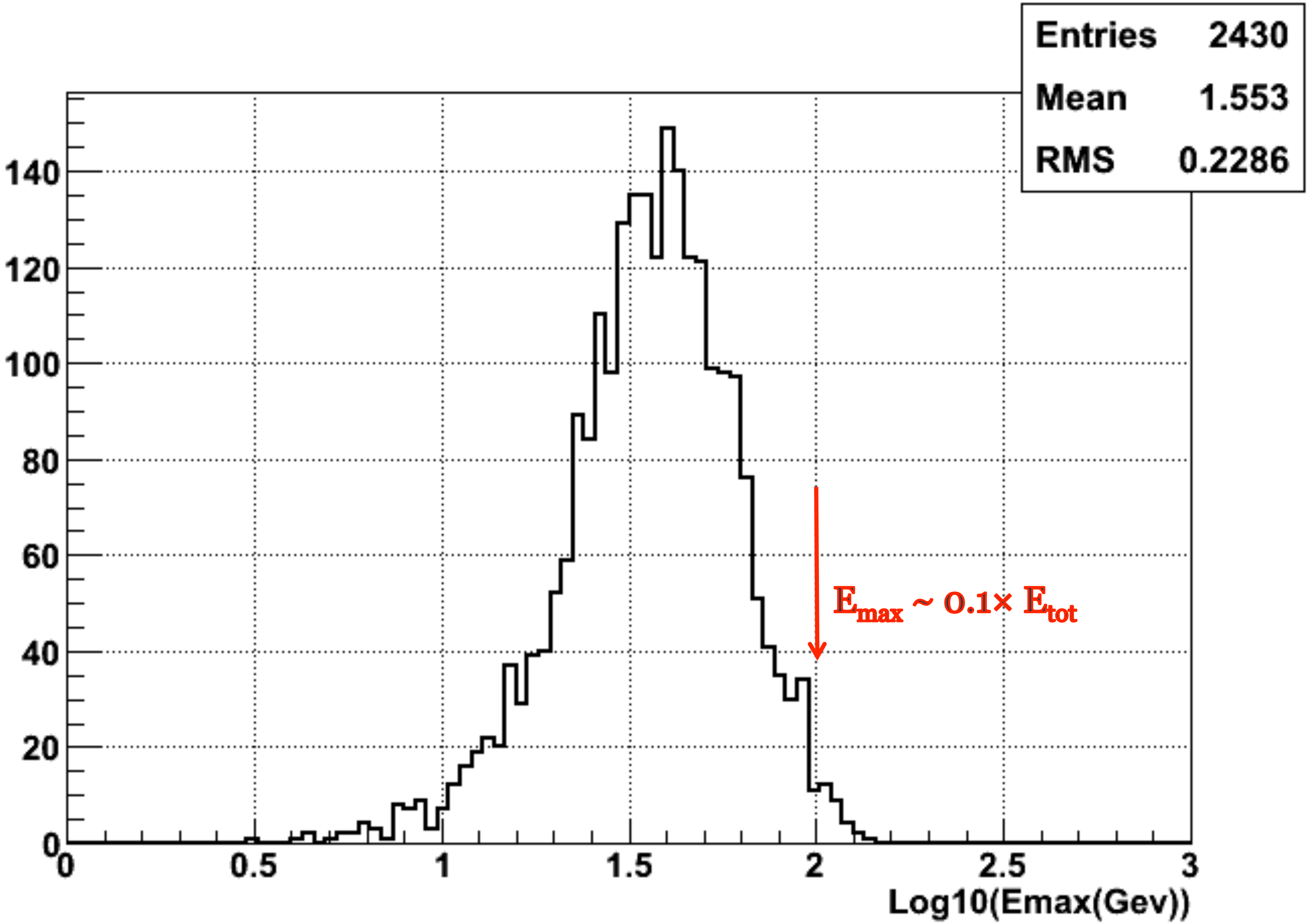
Polygonato model
G400 configuration: CsI(Tl), 20x20x20 crystals
Size: 78.0x78.0x78.0 cm^3 – gap 0.3 cm
Taking into account: geometrical factor and exp. duration + selection efficiency 80%

~ knee

Experiment	Duration	Planar GF (m^2 sr)	ε sel	ε conv	Calo σ(E)/E	Calo depth	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
CALET	5 y	0,12	0,8	0,5	~40%	$30 X_0$ $1,3 \lambda_0$	146	138	9	10	2	3	1	1	0	0
CREAM	180 d	0,43	0,8	0,4 CT*	~45%	$20 X_0$ $1,2 \lambda_0$	41	39	3	3	1	1	0	0	0	0
ATIC	30 d	0,25	0,8	0,5 CT*	~37%	$18 X_0$ $1,6 \lambda_0$	5	5	0	0	0	0	0	0	0	0
G400	**10 y**	**8,5**	**0,8**	**0,4**	**~17%**	$\mathbf{39 X_0}$ $\mathbf{1,8 \lambda_0}$	**16521**	**15624**	**979**	**1083**	**261**	**326**	**60**	**92**	**10**	**21**

* carbon target


Electrons
h
Entries 10000
Mean 0.01771
RMS 0.02499
10^3
10^2
10
1
0
0.1
0.2
0.3
0.4
0.5
0.6
Total silicon signals / Total crystal signals



Entries 2430
Mean 1.553
RMS 0.2286
140
120
100
80
60
40
20
0
0
0.5
1
1.5
2
2.5
3
Log10(Emax(Gev))
E_max ~ 0.1× E_tot

Energy resolution