NEW TRENDS IN CALORIMETRY FOR ASTROPARTICLE PHYSICS EXPERIMENTS

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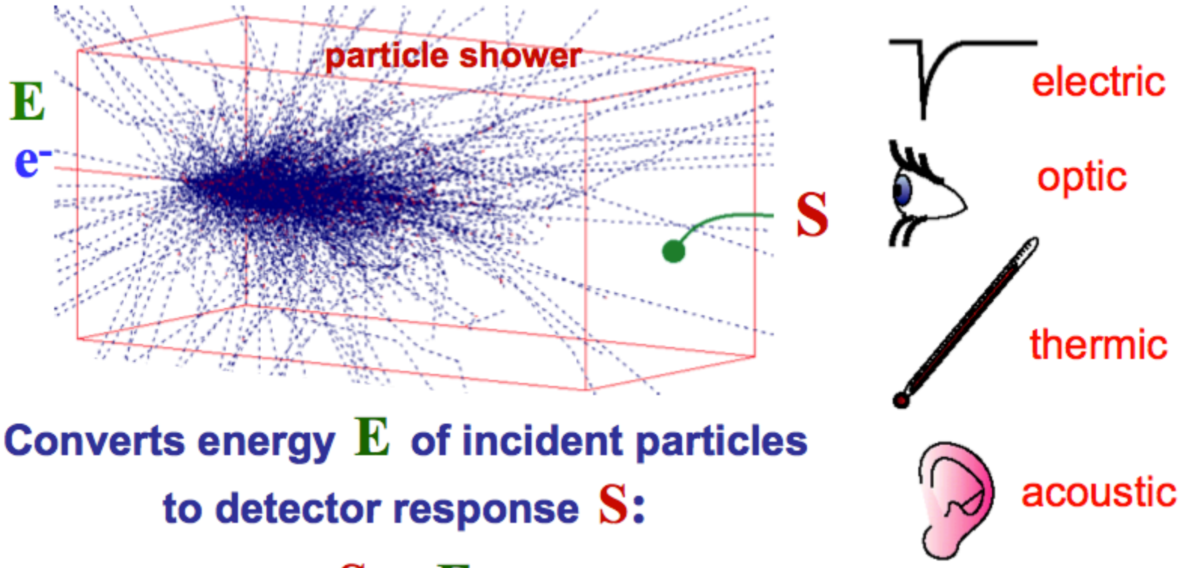
Some references (and some sources for my slides.... THANKS!!!!)

- Excellence in detectors and instrumentation techniques – EDIT2011 – CERN:
  - http://edit2011.web.cern.ch/edit2011/
- Cern Summer Student lectures:
  - http://indico.cern.ch/categoryDisplay.py?categId=345
- Giornate di studio sui rivelatori – Villa Gualino
  - http://www.gsr.unito.it/

- I will start with an introduction on calorimeter's physics with emphasis on aspects relevant for astroparticle experiments
  - Electromagnetic calorimeters
  - Hadronic caorimeters

Calorimeter: basic concept



Converts energy E of incident particles
to detector response S:

$$S \propto E$$

Calorimetry is a "destructive" method. Energy and particle get absorbed !

What should/can we measure with a calorimeter?

1. Energy
2. Impact point
3. Incident direction
4. Particle ID

And do not forget the Trigger!

Calorimeters: some features

- Detection based on stochastic processes

  precision increases with E
- Detection of both charged and neutral particles
- Dimensions necessary to containment $\propto$ lnE

  compactness
- Easy to be segmented

  measure of position and direction & particle id on topological basis
- Fast

  high rate capability, trigger

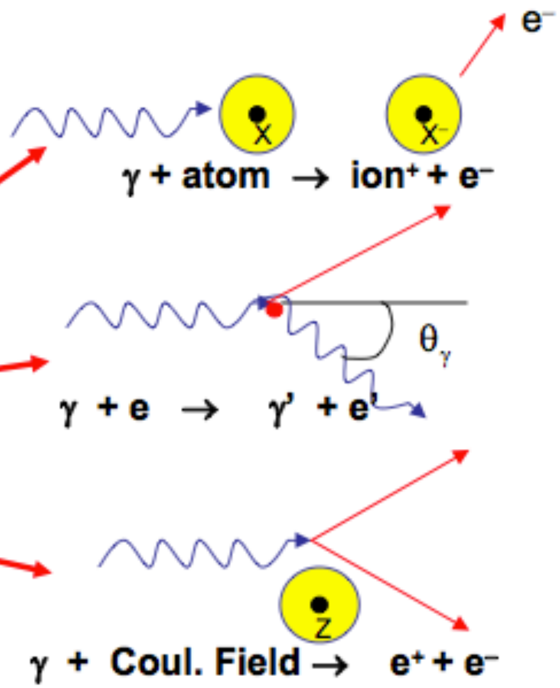
E.M. CALORIMETERS

Energy losses by e & γ

In matter electrons and photons loose energy interacting with nuclei and atomic electrons

Electrons
- ionization (atomic electrons)
- bremsstrahlung (nuclear)

Photons
- photoelectric effect (atomic electrons)
- Compton scattering (atomic electrons)
- pair production (nuclear)



Above 1 GeV radiative processes dominate energy loss by e/γ

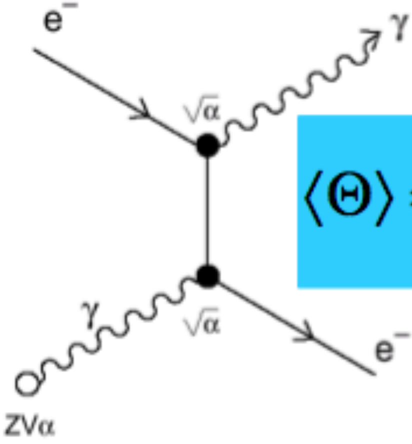
- Bremsstrahlung

$$-\frac{dE}{dx}\Big|_{rad} = \left[4n\,\frac{Z^2\alpha^3(\hbar c)^2}{m_e^2c^4}\,\ln\frac{183}{Z^{1/3}}\right]E$$

$$-\frac{dE}{dx} \propto \frac{Z^2E}{m^2}$$

$$X_0 = \left[4n\,\frac{Z^2\alpha^3(\hbar c)^2}{m_e^2c^4}\,\ln\frac{183}{Z^{1/3}}\right]^{-1}$$

$$\frac{dE}{dx} = -\frac{E}{X_0} \qquad X_0 \approx \frac{180A}{Z^2}\ g.cm^{-2}$$



$$\langle\Theta\rangle = \frac{1}{\gamma}$$

➢ $\sigma \propto Z(Z+1)$; $\sigma \propto A/X_0$ E>1 GeV, $\sigma \propto \ln E/m_e$ E<1 GeV

Radiation length: thickness of material that reduces the mean energy of a beam of high energy electrons by a factor e. For dense materials Xo ~ 1 cm.

- pair production occours if $E_\gamma > 2m_ec^2$

$$\sigma_{pair} \approx \frac{7}{9}\frac{A}{N_A}\frac{1}{X_0}$$

$\sigma \propto Z(Z+1)$; $\propto \ln E/m_e$ for E< 1GeV, constant E >1GeV

Probability of conversion in $1X_0$ is $e^{-7/9}$

Define a m.f.p. $L_{pair} = 9/7\ X_0$ (γ disappears)

- **Critical energy E_c:**

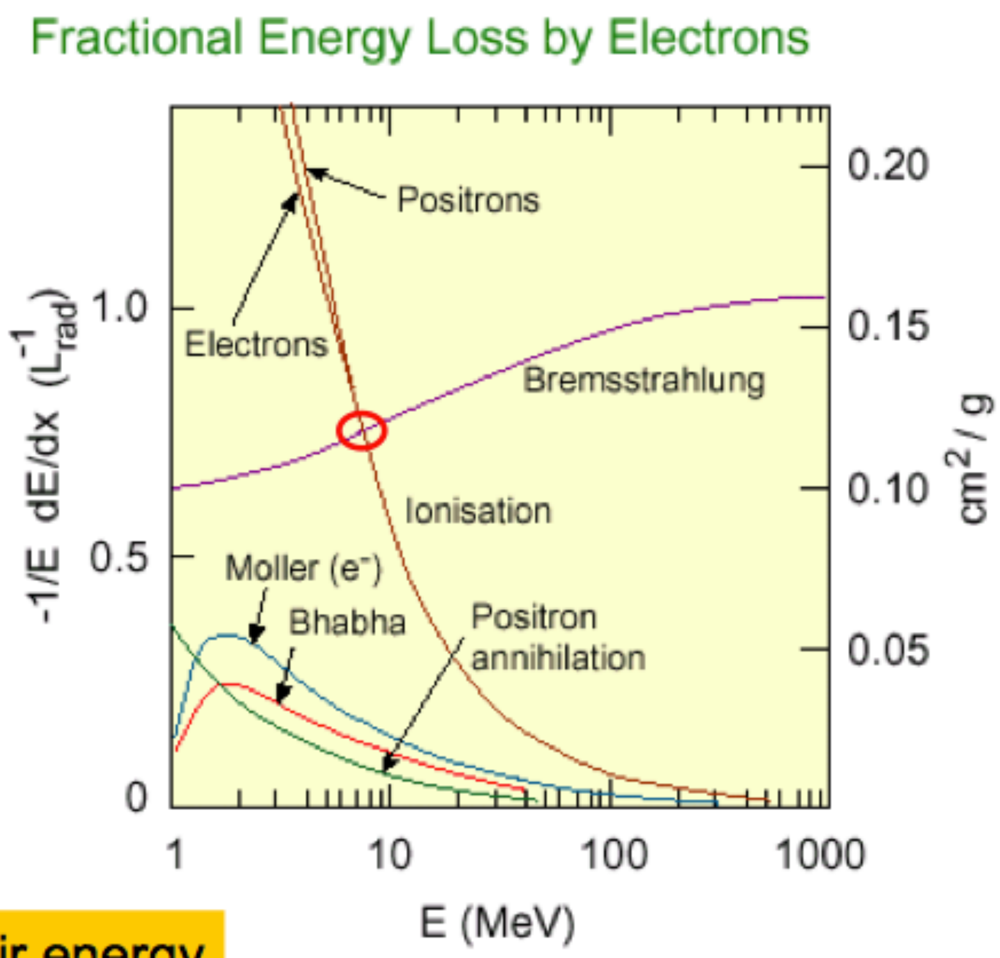
$$\frac{(dE/dx)_{rad}}{(dE/dx)_{ion}} = 1$$

$$E_c \approx \frac{610\,\mathrm{MeV}}{Z+1.24}$$

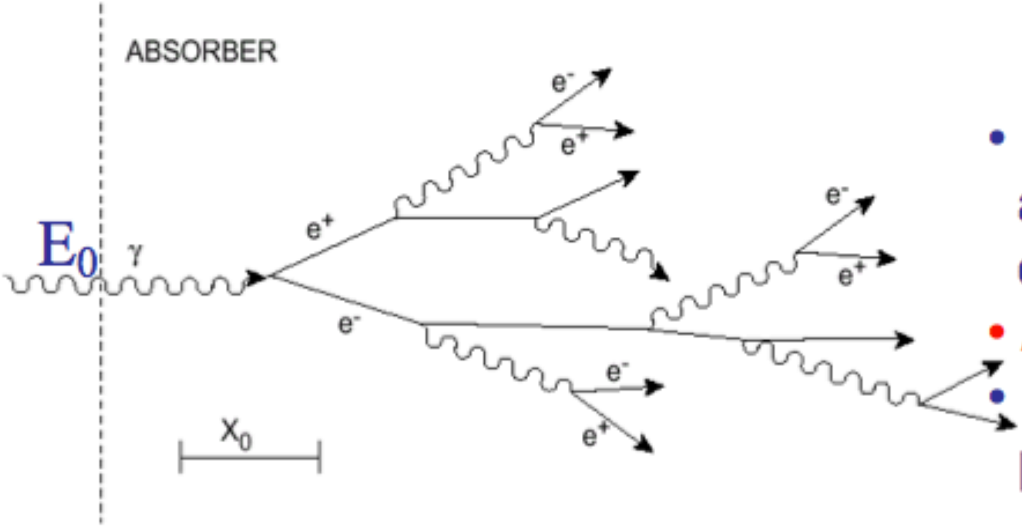
(solids, liquids)

Strongly material dependent,
it scales as 1/Z (eg. 7 MeV for lead)

Electrons irradiate photons until their energy becomes less than critical energy Ec



EM showers: a simplified model



- In $1X_0$ an e loses about 2/3 of its E and a high energy γ has a probability of 7/9 of pair conversion
- Assume X_0 as a generation length
- In each generation the number of particles increases by a factor 2

$@\Delta x = X_0 \qquad \gamma \rightarrow e+\ e- \qquad E = E_0/2$

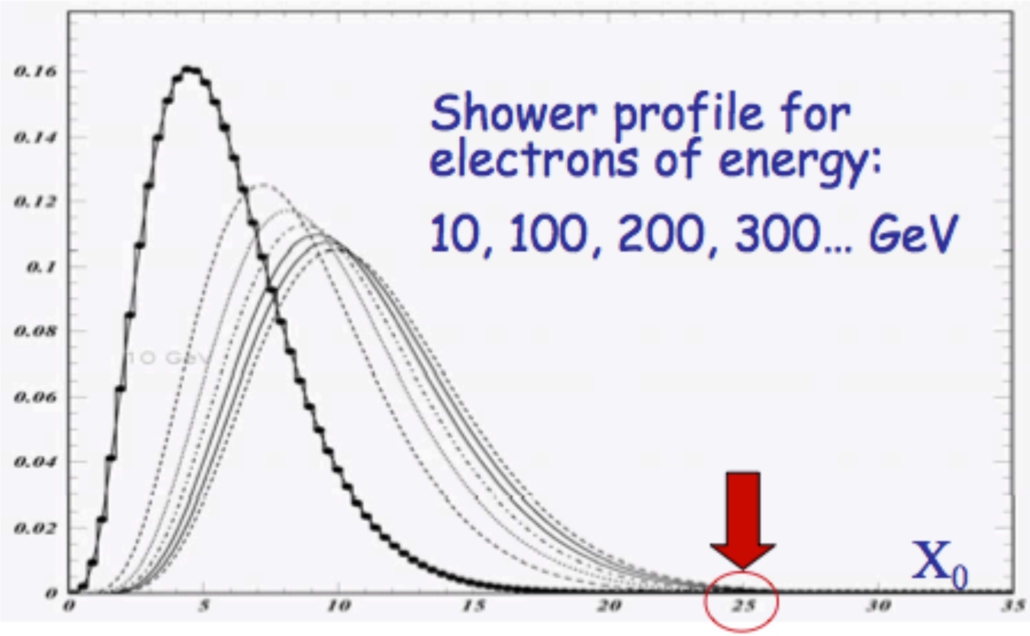
$@\Delta x = 2X_0 \qquad e \rightarrow \gamma\ e' \qquad E' = E_0/4$

$@\Delta x = tX_0 \qquad N(t) = 2^t \qquad E(t) = E_0 / 2^t$

$$E(t_{max}) = E_c \qquad E_0 / 2^{t_{max}} = E_c$$

$$\boxed{t_{max} = \ln(E_0/E_c)/\ln(2)} \qquad \boxed{N(t_{max}) \sim E_0/E_c}$$

EM showers: longitudinal profile



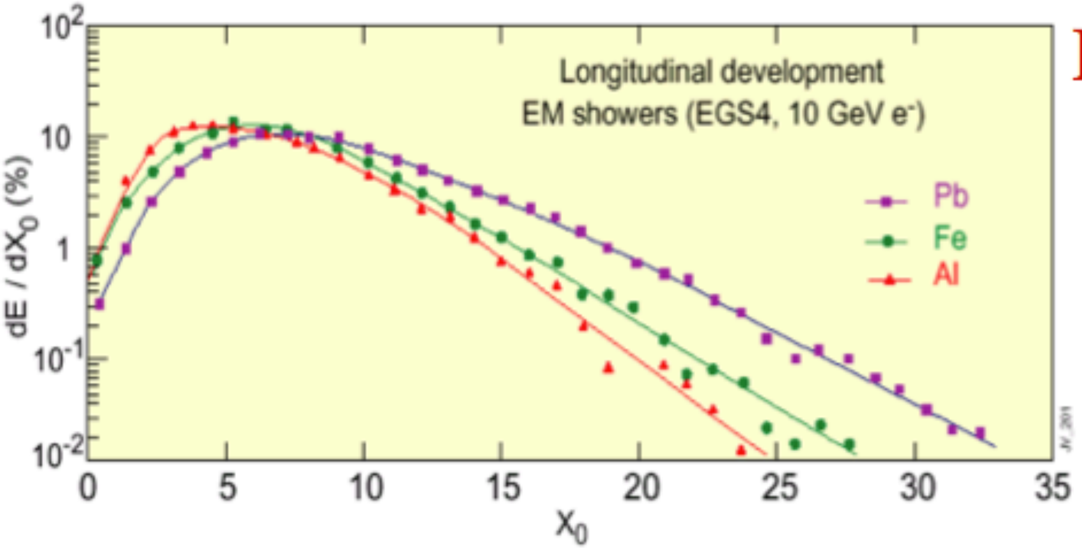
Shower energy dep parametrization:

$$\frac{dE}{dt} \propto E_0 t^{\alpha} e^{\beta t}$$

E.Longo & I.Sestili NIM 128 (1975)

β material dependent

$t_{max} = 1.4 \ln(E_0/E_c)$ $N_{tot} \propto E_0/E_c$



$E_c \propto 1/Z$ →

- shower max
- shower tail

Longitudinal containment:

$t_{95\%} = t_{max} + 0.08Z + 9.6$

EM showers: transverse profile

Transverse shower profile

- Multiple scattering make electrons move away from shower axis
- Photons with energies in the region of minimal absorption can travel far away from shower axis

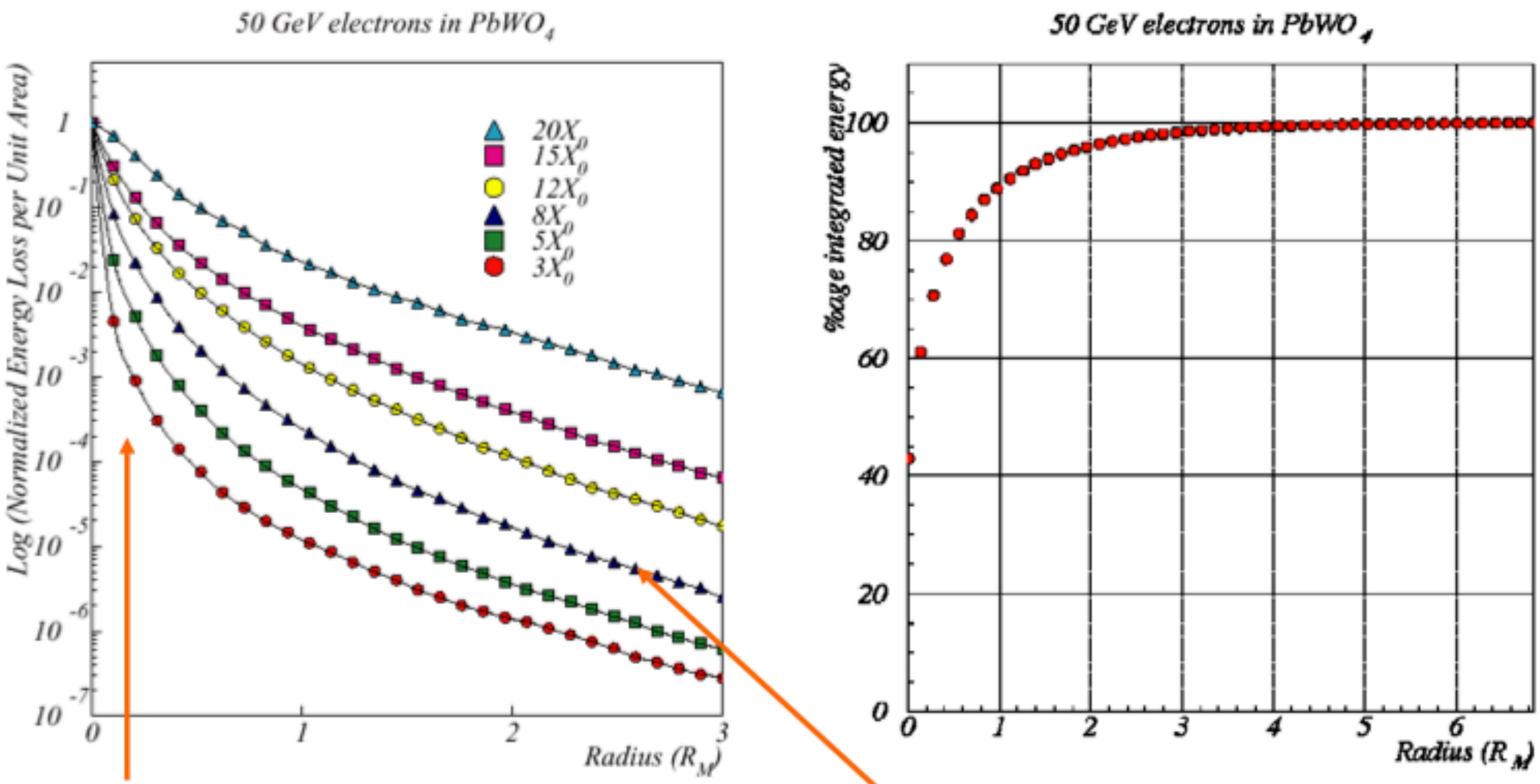
Molière radius sets transverse shower size, it gives the average lateral deflection of critical energy electrons after traversing $1X_0$

$$R_M = \frac{21\text{MeV}}{E_C} X_0$$

$$R_M \propto \frac{X_0}{E_C} \propto \frac{A}{Z} (Z >> 1)$$

90% E_0 within $1R_M$, 95% within $2R_M$, 99% within $3.5R_M$

EM showers: transverse profile



Central core: multiple scattering

Peripheral halo: propagation of less attenuated photons, widens with depth of of the shower

EM showers: energy loss detection

The energy deposited in the calorimeters is converted to active detector response

- $E_{vis} \leq E_{dep} \leq E_0$

Main conversion mechanism

- Cerenkov radiation from e
- Scintillation from molecules
- Ionization of the detection medium

Different energy threshold E_{th} for signal detectability

EM calorimeters: energy resolution

Intrinsic limit **You are not going to do better!**

Detectable signal is proportional to the total track length of e+ and e- in the active material, intrinsic limit on energy resolution is given by the fluctuations in the fraction of initial energy that generates detectable signal

$$N_{tot} \propto \frac{E_0}{E_C} \quad \xrightarrow{\text{Total track length}} \quad T_0 = N_{tot} X_0 \approx \frac{E_0}{E_C} X_0$$

Detectable track length $T_r = f_s T_0$
f_s fraction of N_{tot} with kin $E > E_{th}$
Fluctuations in track length: Poisson process

$$\rightarrow \frac{\sigma(E)}{E} \propto \frac{\sigma(T_r)}{T_r} \propto \frac{1}{\sqrt{T_r}} \propto \frac{1}{\sqrt{E_0}}$$

Fix E_0 $\rightarrow$

$$\frac{\sigma(E)}{E} \propto \frac{1}{\sqrt{f_s}} \sqrt{\frac{E_C}{X_0}} \propto \frac{1}{\sqrt{f_s}} \sqrt{\frac{Z}{A}}$$

$\rightarrow$

- maximize f_s
- minimize Z/A

EM calorimeters: homogeneous

Homogeneous calorimeters: all the energy is deposited in an active medium.
Absorber ≡ active medium → All e+e- over threshold produce a signal
Excellent energy resolution

Compare conversion processes with different energy threshold

Scintillating crystals

$$E_s \cong \beta E_{gap} \sim eV$$

$$\approx 10^2 \div 10^4 \gamma / MeV$$

$$\sigma / E \sim (1 \div 3)\% / \sqrt{E(GeV)}$$

Cherenkov radiators

$$\beta > \frac{1}{n} \rightarrow E_s \sim 0.7 MeV$$

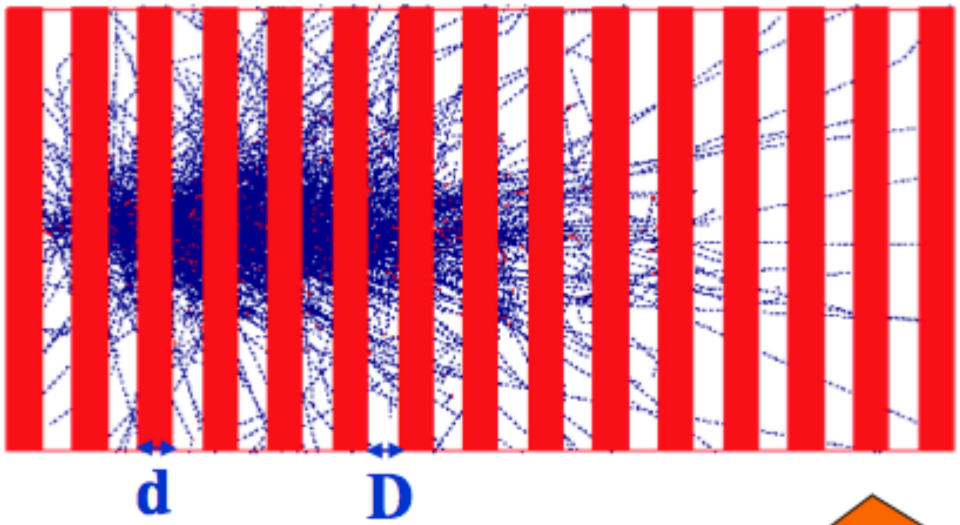
$$\approx 10 \div 30 \ \gamma / MeV$$

$$\sigma / E \sim (5 \div 10)\% / \sqrt{E(GeV)}$$

Lowest possible limit in em calorimetry

EM calorimeters: sampling

Sampling calorimeters: shower is sampled by layers of active medium (low-Z) alternated with dense radiator (high-Z) material.



- Limited energy resolution
- Detailed shower shape information
- Cost

absorber=shower generator
active layers (scintillators, wire chambers…) negligible in the shower development

- only a fraction of the shower energy is dissipated in the active medium
- energy resolution is dominated by fluctuations in energy deposited in active layers: sampling fluctuations
- intrinsic resolution irrelevant

$$\sigma / E \sim (10 \div 20)\% / \sqrt{E(GeV)}$$

EM calorimeters: energy resolution

Energy resolution of a calorimeter can be parameterized as

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

$\oplus$ means sqrt (quadratic sum)

- **a** the *stocastic term* accounts for any kind of Poisson-like fluctuations
  - natural merit of homogeneous calorimeters
  - several contributions add to the "intrinsic one"
- **b** the *noise term* responsible for degradation of low energy resolution
  - mainly the energy equivalent of the electronic noise
  - contribution from pileup: the fluctuation of energy entering the measurement area from sources other than the primary particle
- **c** the *constant term* dominates at high energy
  - its relevance is strictly connected to the small value of **a**
  - it is mostly dominated by the stability of calibration
  - contributions from energy leakage, non uniformity of signal generation and/or collection, loss of energy in dead materials,…

Crystals for homogeneous EM Calorimeters

	NaI(Tl)	CsI(Tl)	CsI	BGO	$PbWO_4$
Density (g/cm^3)	3.67	4.53	4.53	7.13	8.28
X_0 (cm)	2.59	1.85	1.85	1.12	0.89
R_M (cm)	4.5	3.8	3.8	2.4	2.2
Decay time (ns)	250	1000	10	300	5
slow component			36		15
Emission peak (nm)	410	565	305	410	440
slow component			480		
Light yield γ/MeV	4×10^4	5×10^4	4×10^4	8×10^3	1.5×10^2
Photoelectron yield (relative to NaI)	1	0.4	0.1	0.15	0.01
Rad. hardness (Gy)	1	10	10^3	1	10^5

Barbar@PEPII, 10ms interaction rate, good light yield, good S/N

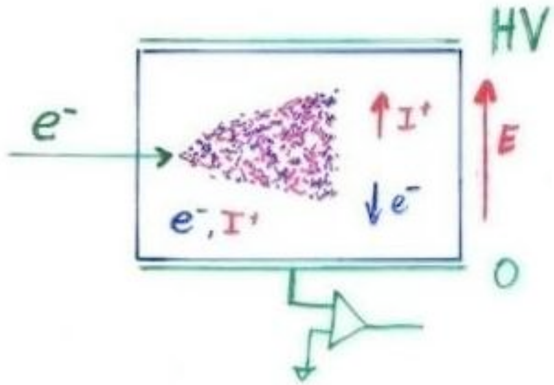
KTeV@Tevatron, High rate, Good resolution

L3@LEP, 25us bunch crossing, Low radiation dose

CMS@LHC, 25ns bunch crossing, high radiation dose

Noble Liquids for Homogeneous EM Calorimeters

	Ar	Kr	Xe
Z	18	36	58
A	40	84	131
X_0 (cm)	14	4.7	2.8
R_M (cm)	7.2	4.7	4.2
Density (g/cm^3)	1.4	2.5	3.0
Ionization energy (eV/pair)	23.3	20.5	15.6
Critical energy ϵ (MeV)	41.7	21.5	14.5
Drift velocity at saturation (mm/μs)	10	5	3



When a charge particle traverses these materials, about half the lost energy is converted into ionization and half into scintillation.

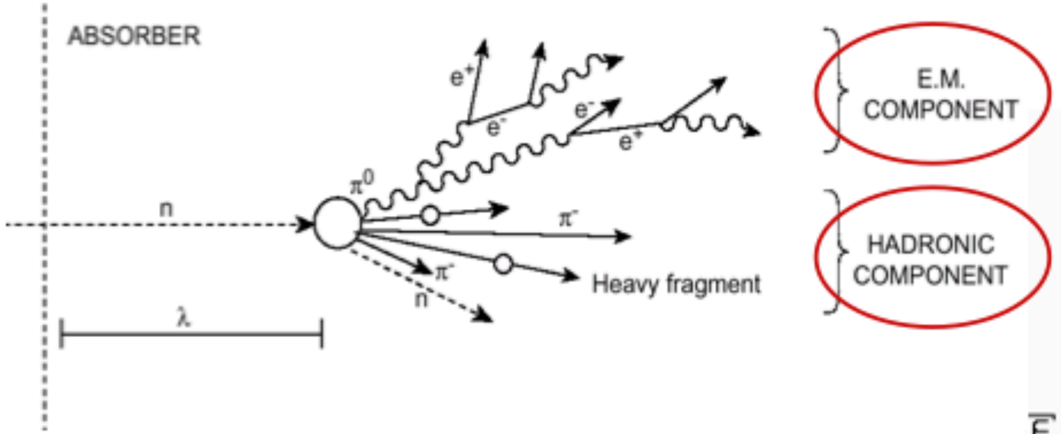
The best energy resolution would obviously be obtained by collecting both the charge and light signal. This is however rarely done because of the technical difficulties to extract light and charge in the same instrument.

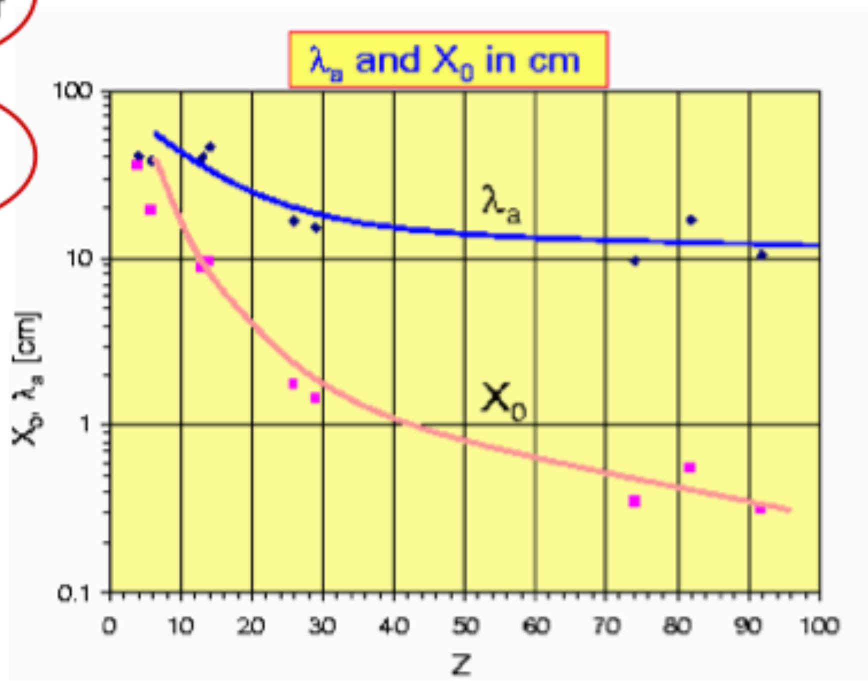
Krypton is preferred in homogeneous detectors due to small radiation length and therefore compact detectors. Liquid Argon is frequently used due to low cost and high purity in sampling calorimeters (see later).

HADRONIC CALORIMETERS

Hadron showers (a complicated story)

- Strong interaction is responsible for shower development
- A high energy hadron interacting with matter leads to multi-particle production, typically mesons $\pi^{\pm}$, π^{o}, K etc., these in turn interact with further nuclei
- Nuclei breakup leading to spallation neutrons/protons
- Multiplication continues until the pion production threshold, $E \sim 2m_{\pi} = 0.28$ GeV





Nuclear interaction length:

$$\lambda_{int} = \frac{A}{N_A \sigma_{int}} \propto A^{1/3}$$

$\lambda \sim 35\ A^{1/3}$ g cm^{-2}

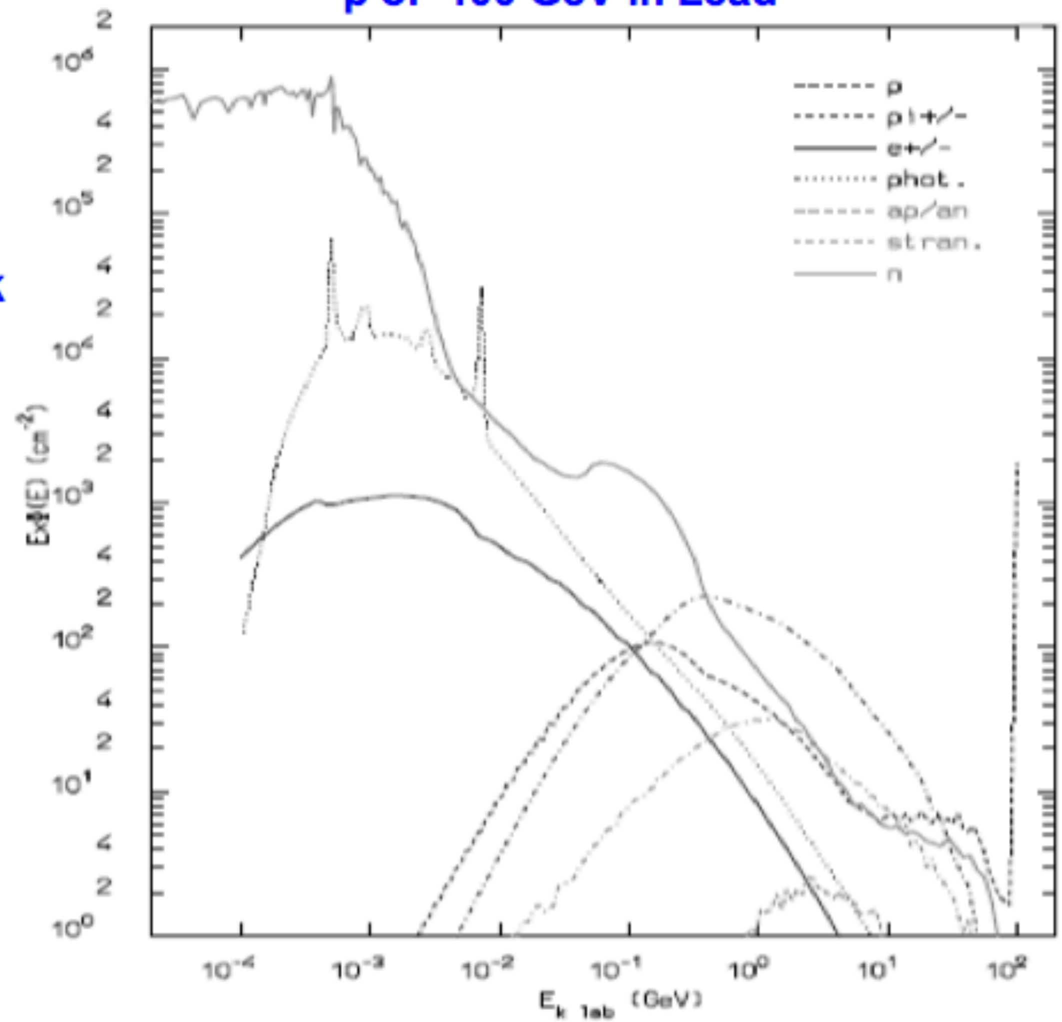
$$\sigma_{int} = \pi R^2 \ \alpha \ A^{2/3}$$

Hadron showers

Hadron shower induced by a 100 GeV proton in Lead: energy spectra of the major shower components weighted by their track lenght in the shower (average)

- **Soft spectra dominated by neutrons and photons**
- **Hard spectra dominated by charged pions**

p of 100 GeV in Lead



Hadron showers

All the fluctuations described in em case plus more and more significant

- Breakdown of ***non-em*** energy deposit in lead absorber:
  - *Ionizing particles* *56%* (2/3 from spallation protons)
  - *Neutrons* *10%* (37 neutrons per GeV!)
  - *Invisible* *34%*

  Spallation protons carry typically 100 MeV,
  Evaporation neutrons 3 MeV

An important fraction of energy goes in nuclear binding: not detectable!

FLUCTUATIONS OF E_{vis} : INTRINSIC LIMIT TO HADRONIC ENERGY MEASUREMENT

- Hadron showers contain em component (π^o, η)
- Size of em component F_{em} is mainly determined by the first interaction
- On average 1/3 of mesons produced in the 1° interaction will be a π^o, this fraction fluctuates in a significant way
- The 2° generation $\pi^\pm$ will produce π^o if enough energetic

An important fraction of energy goes in em deposits and strongly varies

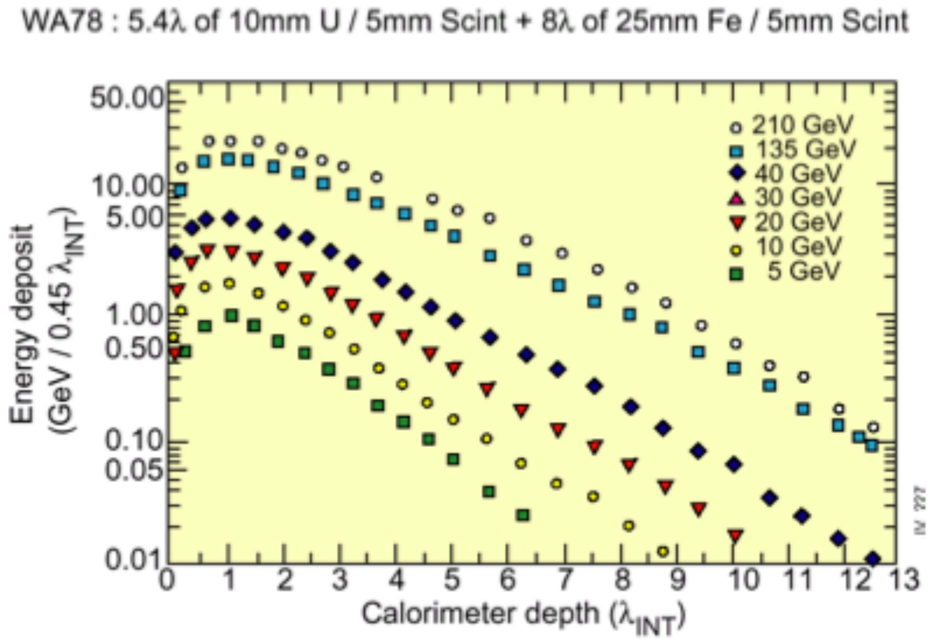
Hadron shower profile

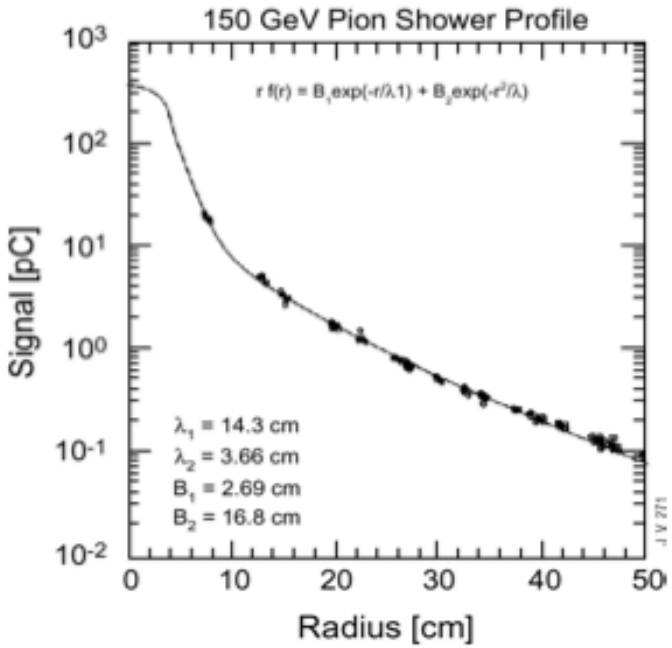
LONGITUDINAL

- Sharp peak from π^o from the 1° interaction
- Gradual extinction with typical scale λ_{int}

LATERAL

- Average p_t secondaries ~ 300 MeV
- Typical transverse scale λ_{int}
- Dense core due to π^o





~10 λ needed to contain 99% E of 200 GeV π
(about 1 – 2 m of heavy absorber)

Transverse radius for
95%E containment ~1λ

Need to sample

Hadron showers

- A priori e and h in a calorimeter give a different response, e.g. e/h > 1
- The fluctuations in the fraction of energy deposited by e and h limitis resolution moreover in average this fraction is energy dependent (non linearity in detector response)

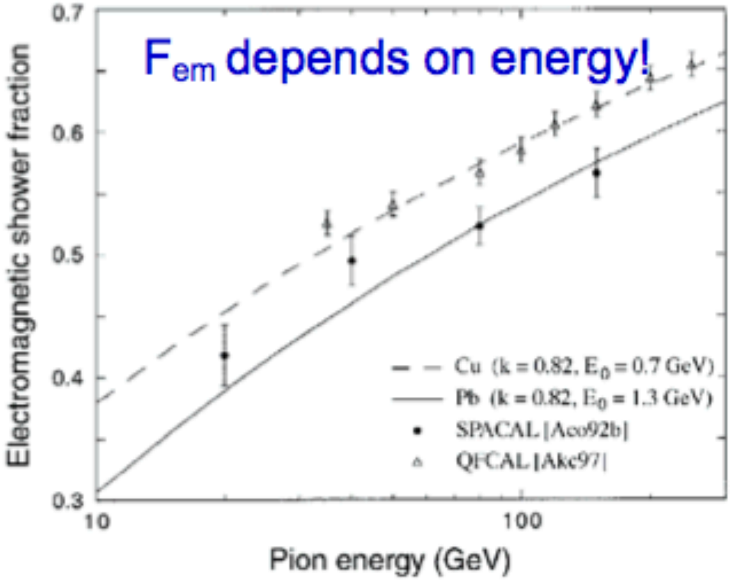


FIG. 2.22. Comparison between the experimental results on the em fraction of pion-induced showers in the (copper-based) QFCAL and (lead-based) SPACAL detectors. Data from [Akc 97] and [Aco 92b].

Elements to obtain e/h=1 (compensation)

- **Suppress em component (high Z abs.)**
- **enhance n production through fission**
- **enhance response to n using active materials hydrogen reach**

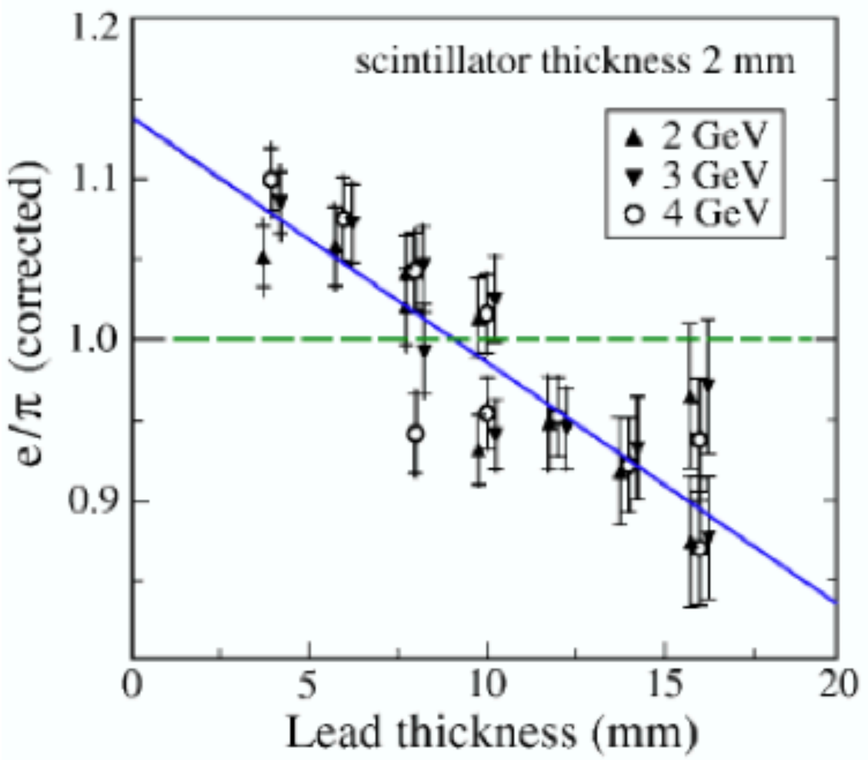
Intrisic hadronic resolution due to fluctuations of invisible energy and electromagnetic component (no compensation):

$$\sigma / E \sim (20 \div 40)\% / \sqrt{E(GeV)}$$

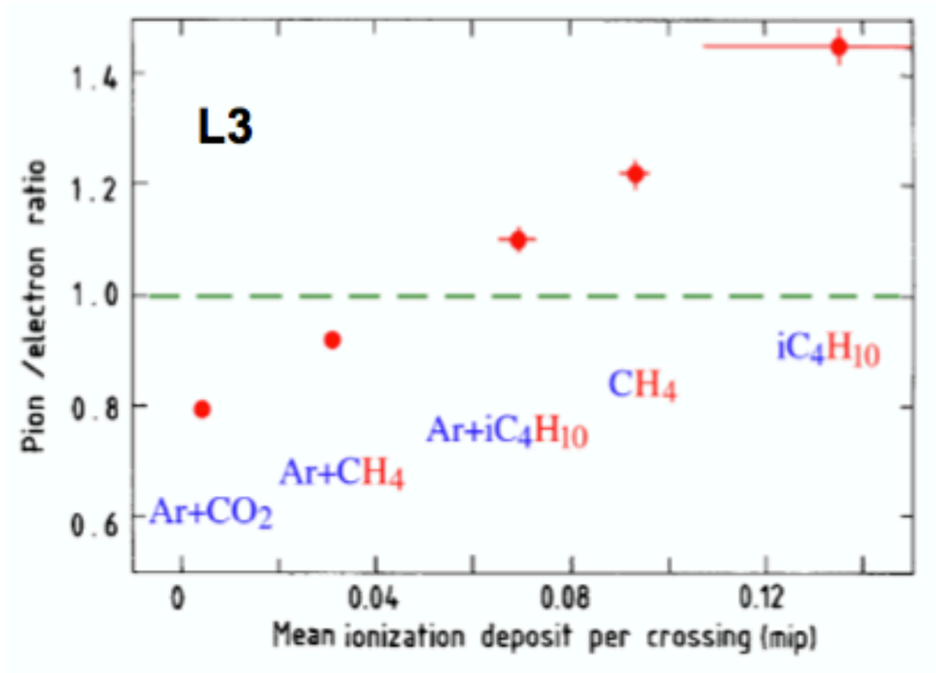
+ sampling…+…

Compensation

Pb/Scintillator



Hydrogen in active material (gas mixture)



Sampling fraction can be tuned to achieve compensation

Elastic n-p scattering: efficient sampling of neutrons through the detection of recoiling protons!

Ideas in hadron calorimetry (Dual Redout)

How to improve energy measurement in hadron calorimetry?

Measure F_{em} event by event using Čerenkov light emission

Čerenkov light emission threshold: $\beta > 1/n$
e.g. quartz n=1.45 E_{th} = 0.2 MeV for electrons, 400 MeV for protons
Enhance electromagnetic response (in a quartz fiber calorimeter e/h ~ 5)

DUAL READOUT

$f = F_{em}$

Cerenkov radiator:
sample em part of the shower

Scintillator:
sample all components

Take electrons signal as reference

$$\boxed{C = [f + c(1-f)]\,E} \quad c = (h/e)_C$$

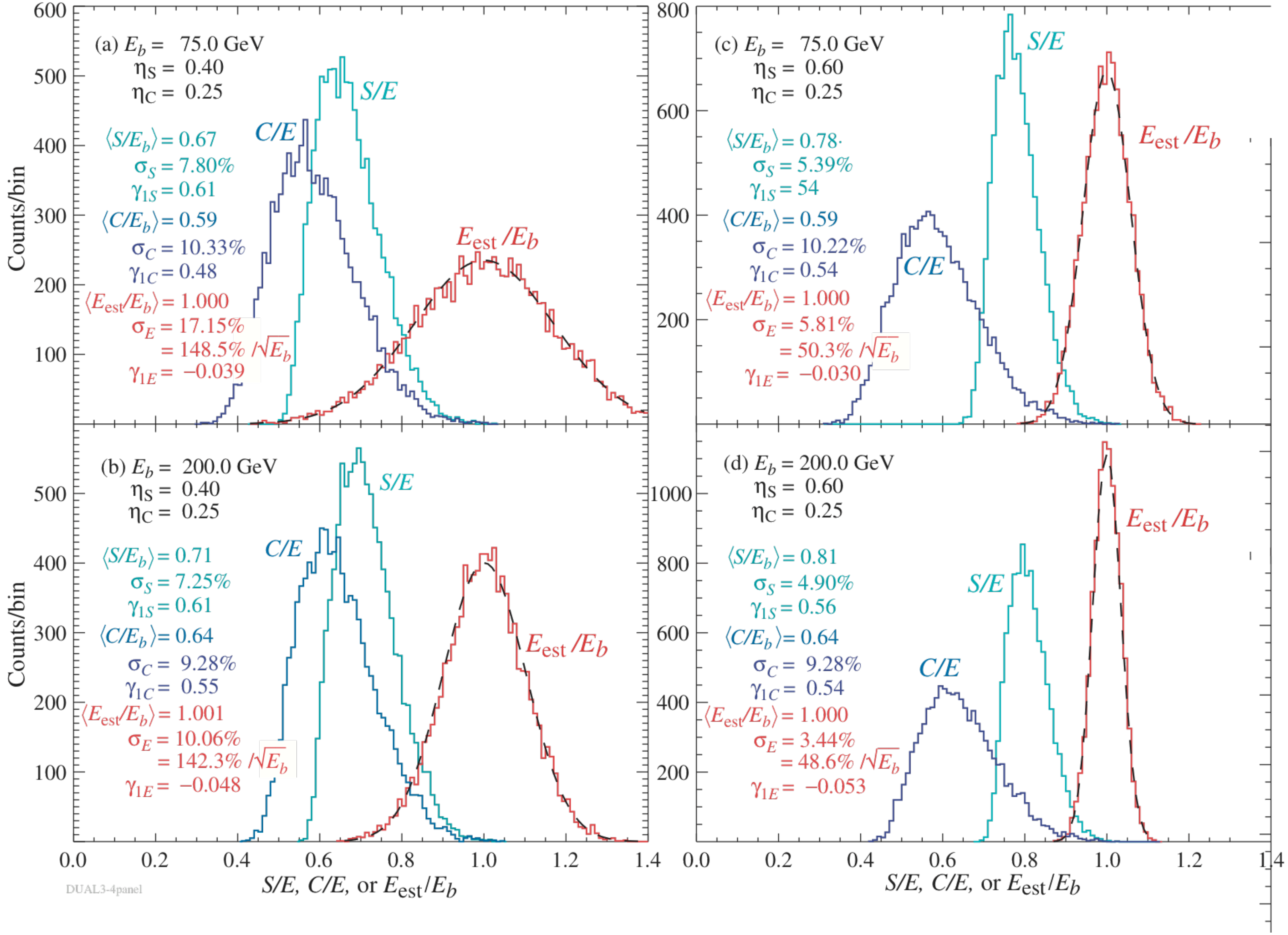
$$\boxed{S = [f + s(1-f)]\,E} \quad s = (h/e)_S$$

Combine information and get F_{em} (f) and E !

$$f = \frac{c - s(C/S)}{(C/S)(1-s) - (1-c)} \qquad E = \frac{S - \lambda C}{1 - \lambda}$$

$$\lambda = \frac{1-s}{1-c}$$

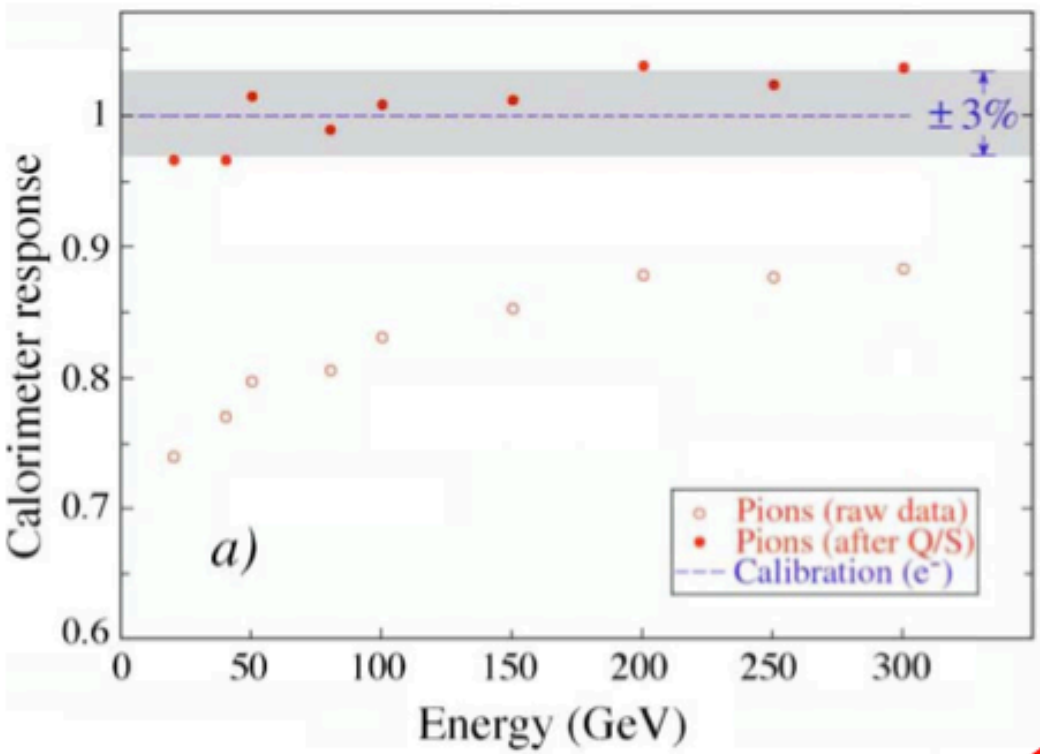
Constant of the calorimeter

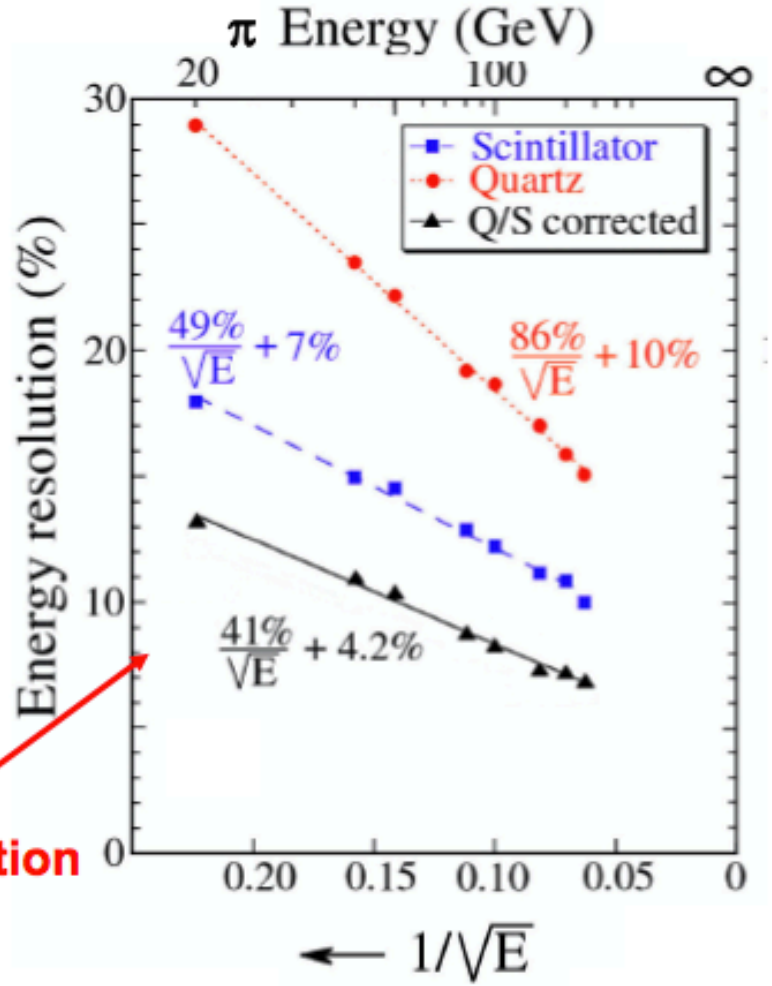


If S/E is significantly different from C/E → Good energy resolution!

Dual readout: DREAM

Hadronic response after C/S correction





NB contains leakage contribution

NICE IDEAS AND STUDIES GOING ON, NEXT STEP TRANSITION TO A SYSTEM?

Position resolution - EM

- Reconstruction of invariant masses of particles decaying into photons, electron identification using match with track measured in tracking devices
- Impact position of showers is determined using the transverse (and longitudinal) energy distribution in calorimeter cells
- Method based on center of gravity (COG) calculation
  - works for projective geometry and particles coming from the interaction vertex
  - calorimeter cell size $d \leq 1R_M$
- Typical resolutions: few mm/$\sqrt{E}$

An example of high precision device: LHCf

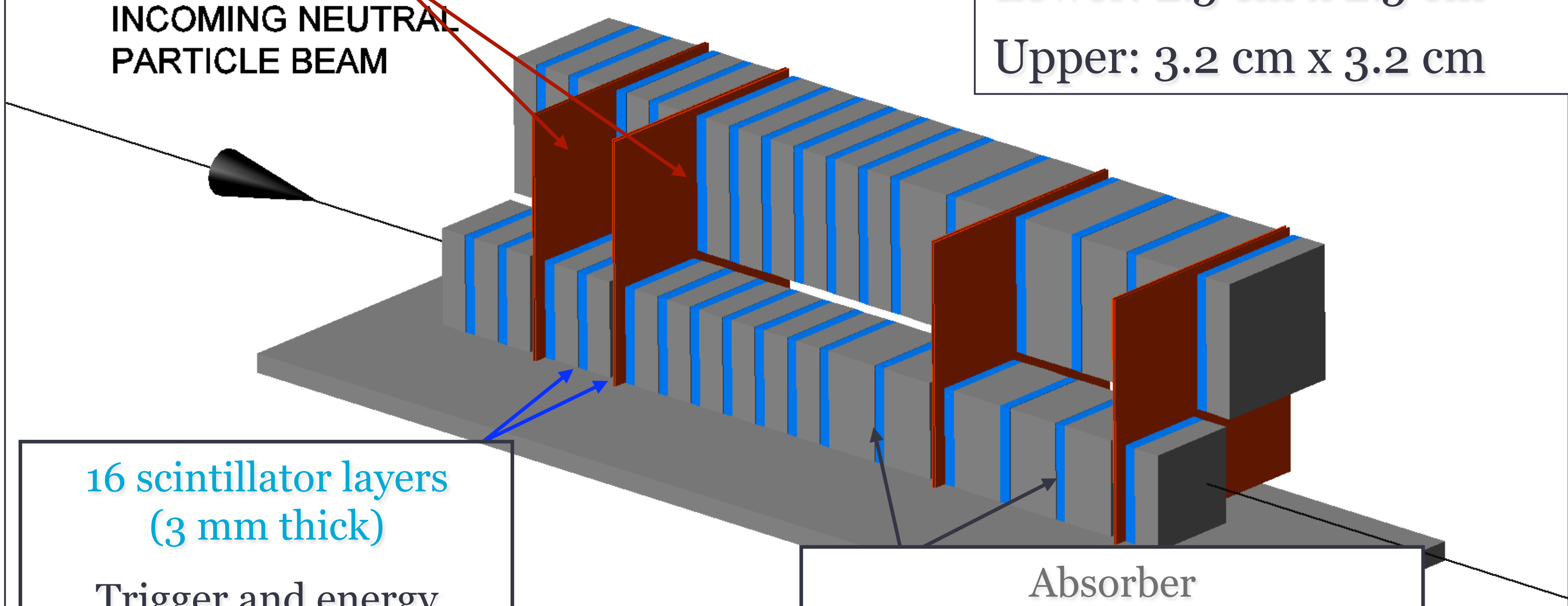
Impact point (η)

4 pairs of silicon microstrip layers
(6, 12, 30, 42 r.l.) for tracking purpose
(X and Y directions)

2 towers 24 cm long stacked on their edges and offset from one another

Lower: 2.5 cm x 2.5 cm

Upper: 3.2 cm x 3.2 cm



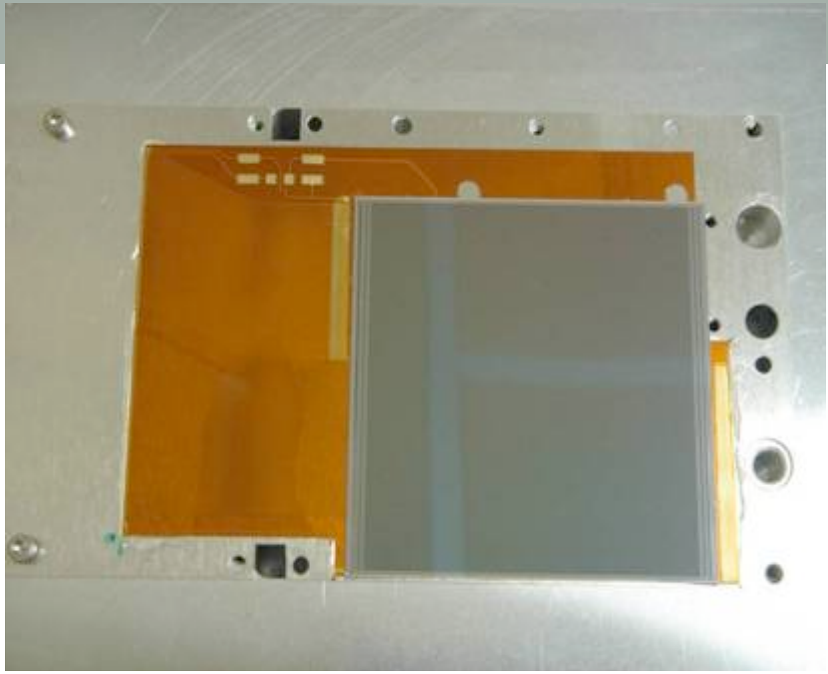
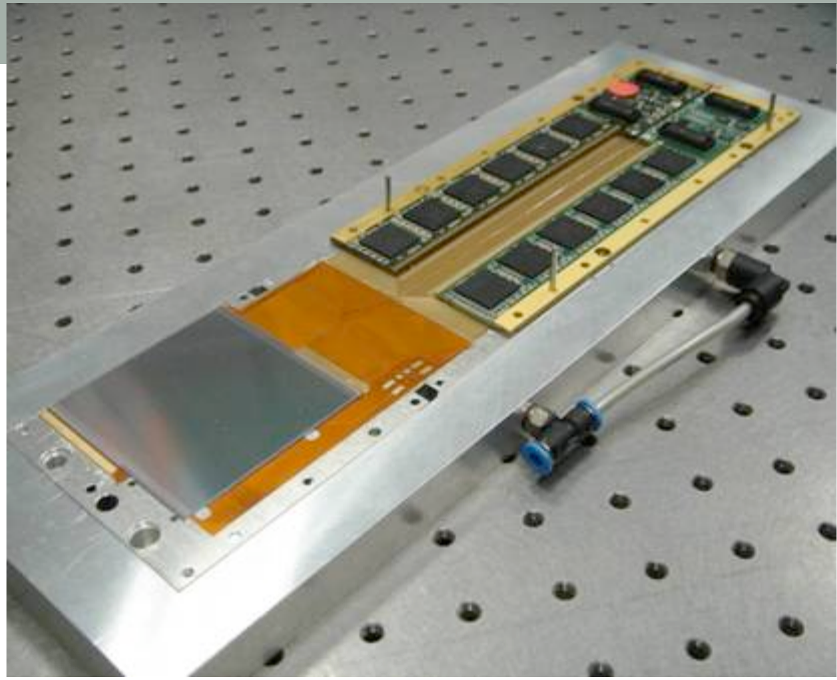
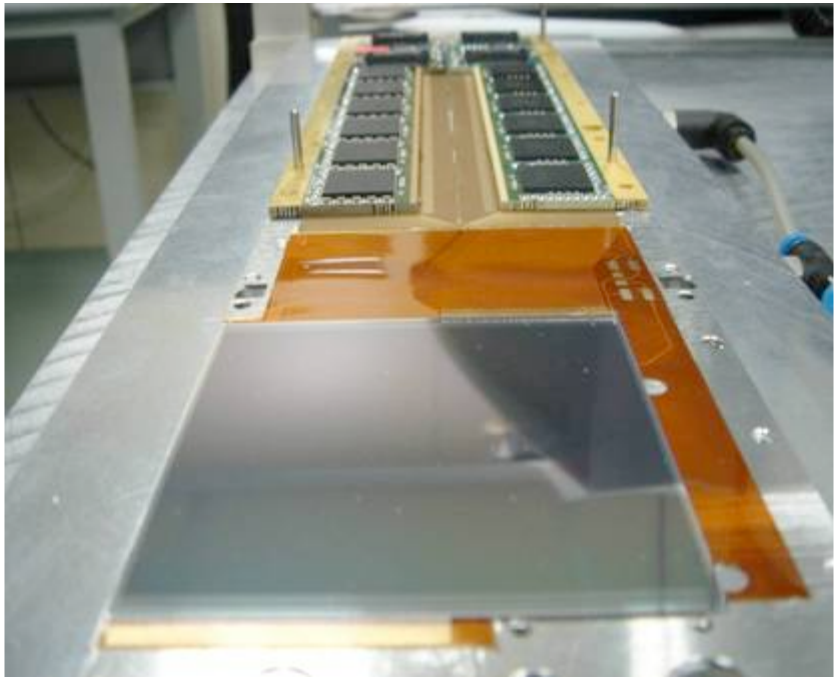
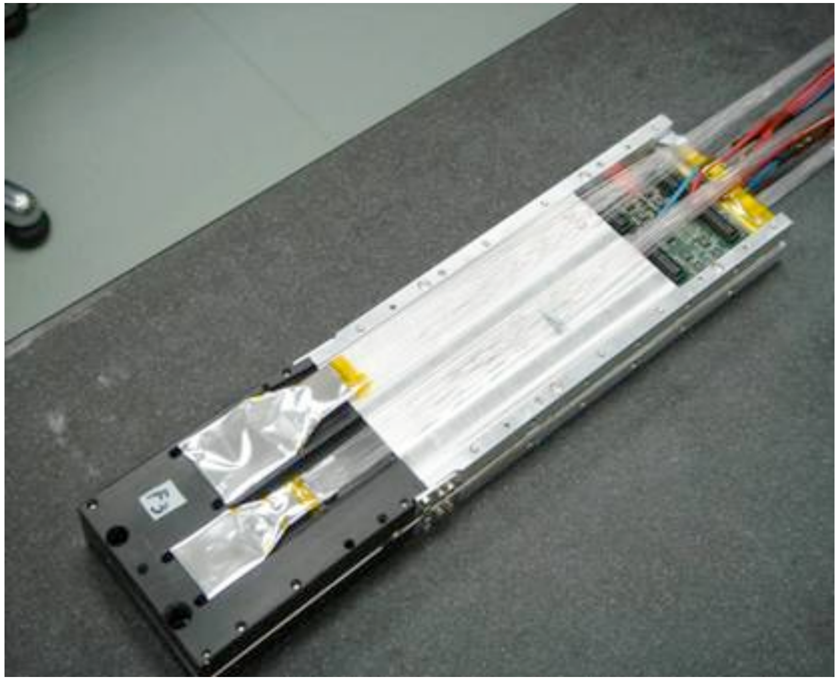
16 scintillator layers
(3 mm thick)

Trigger and energy
profile measurements

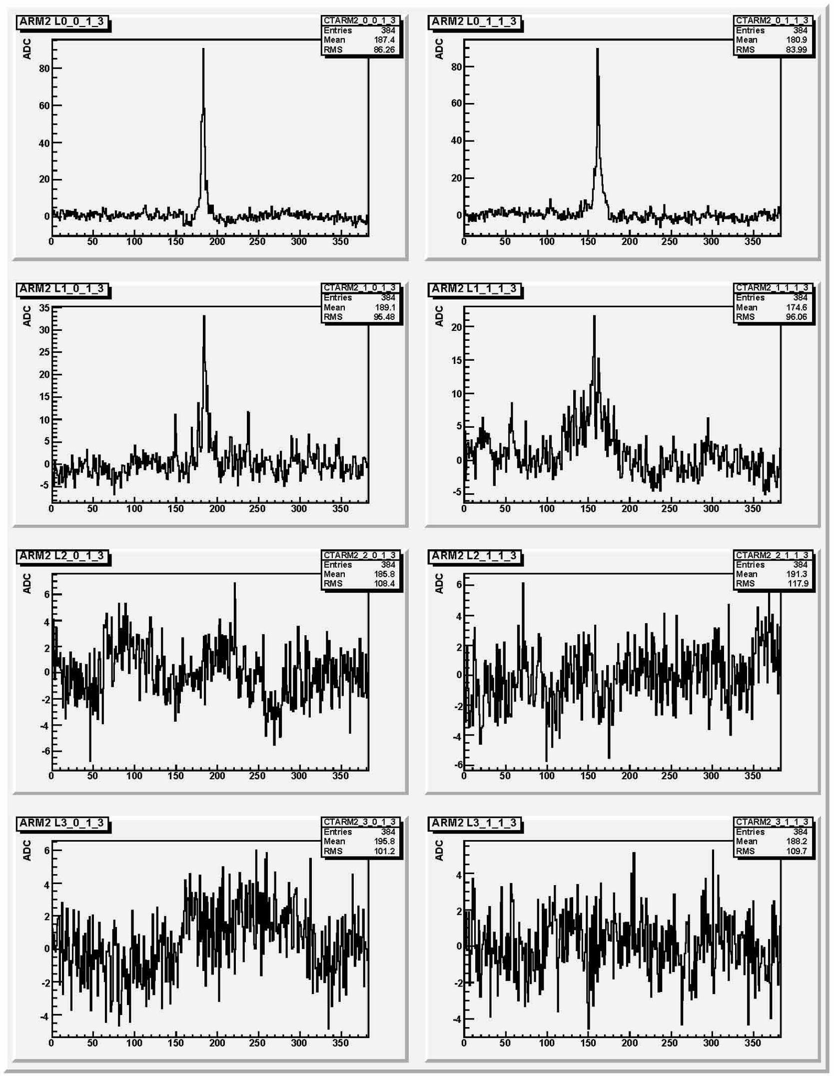
Absorber

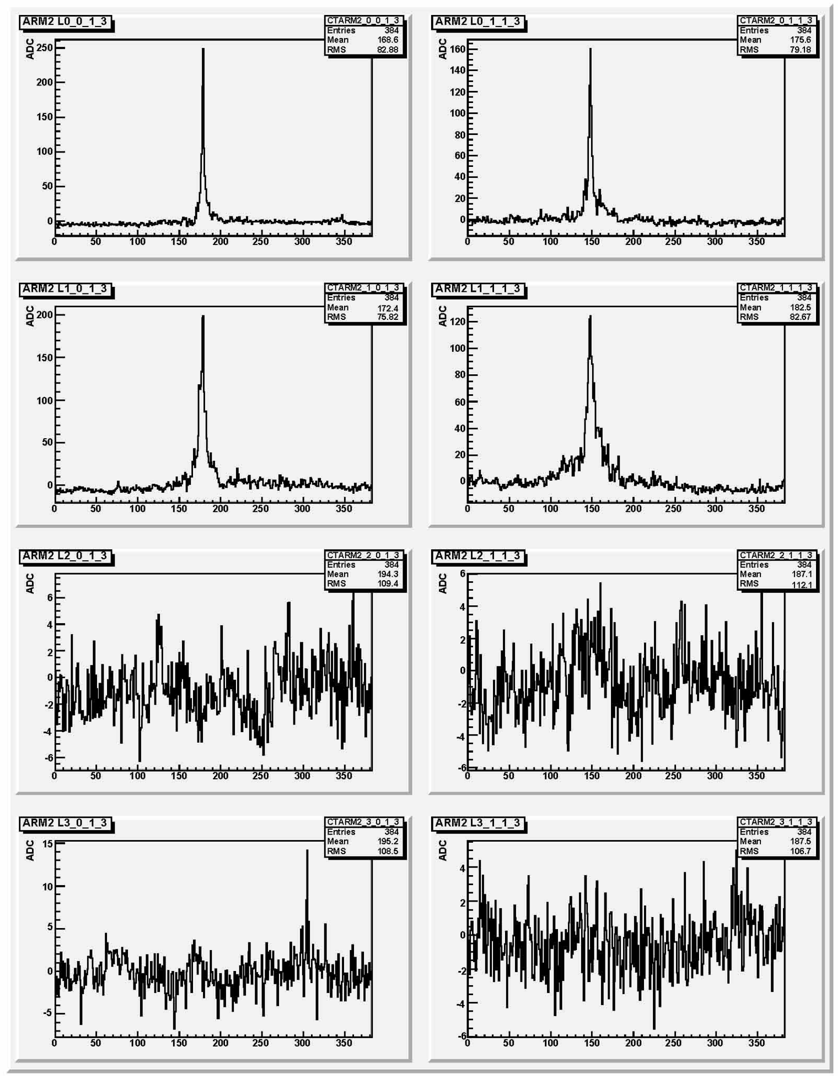
22 tungsten layers
7mm – 14 mm thick (2-4 r.l.)
(W: X_0 = 3.5mm, R_M = 9mm)

Energy

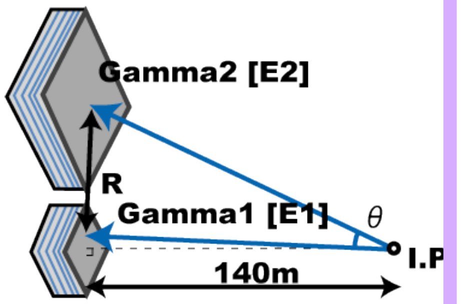
50 GeV e^- 200 GeV e^-

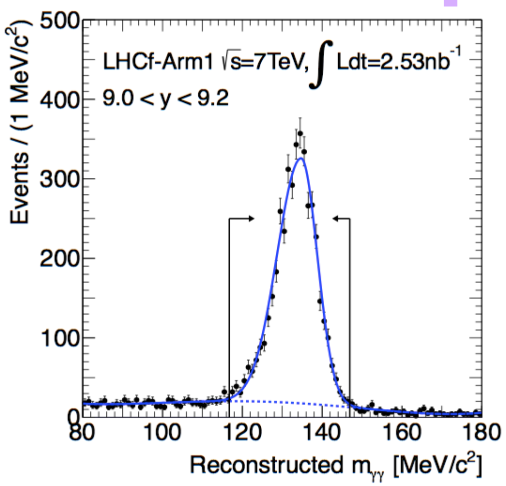


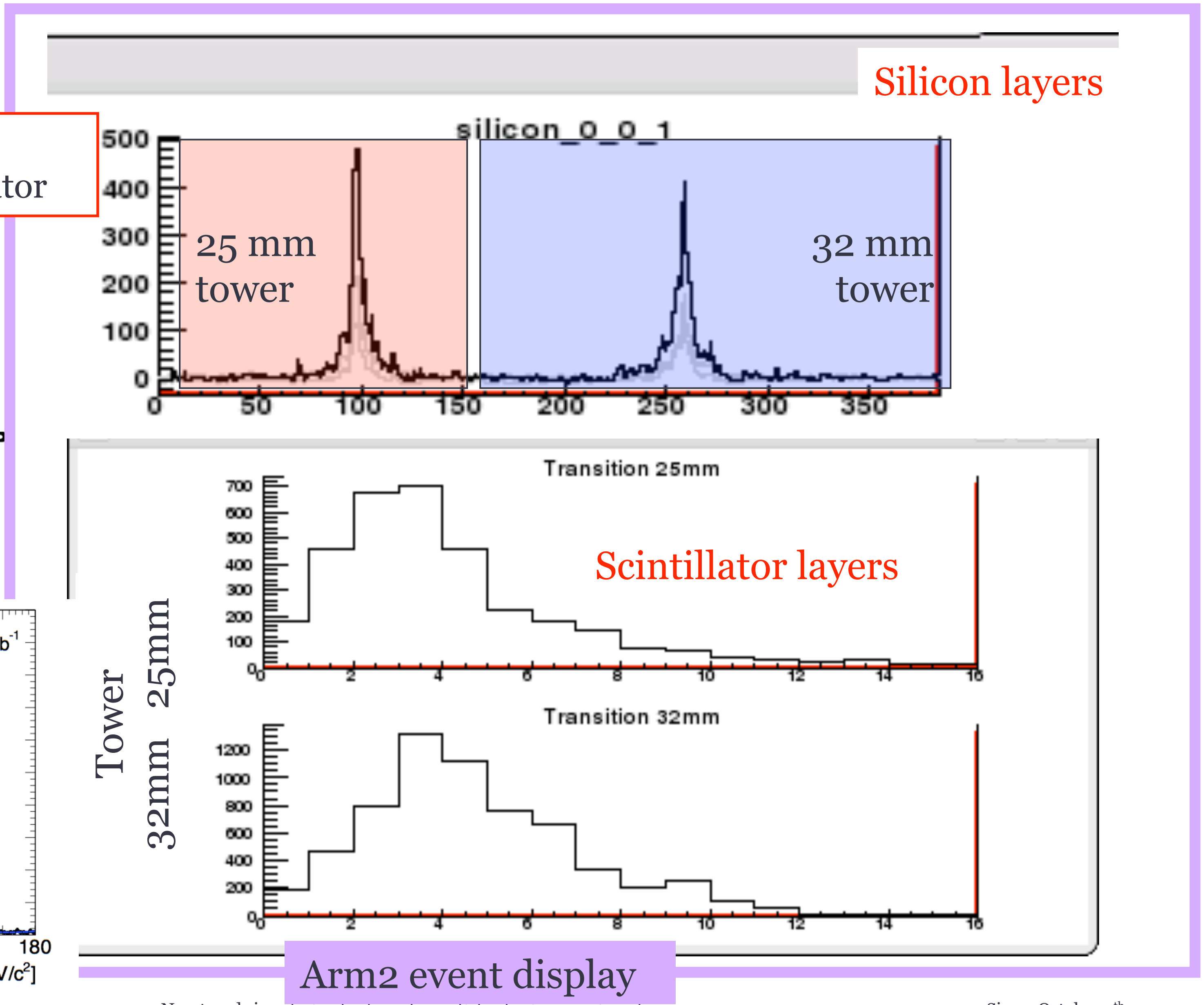


π^0 at 7 TeV as seen by LHCf

- Robust sample
- Good energy calibrator

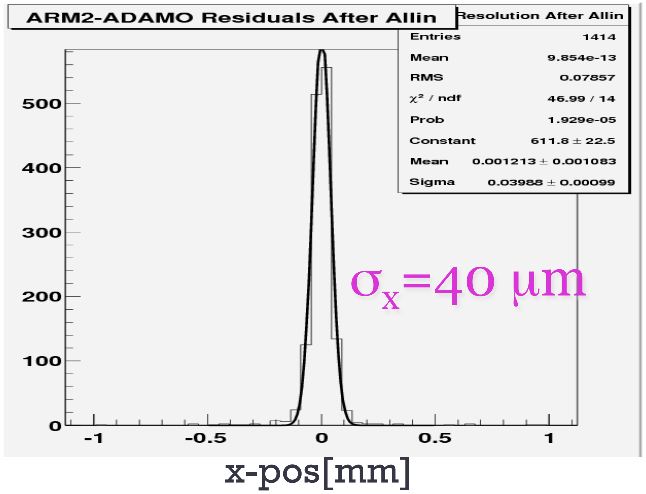


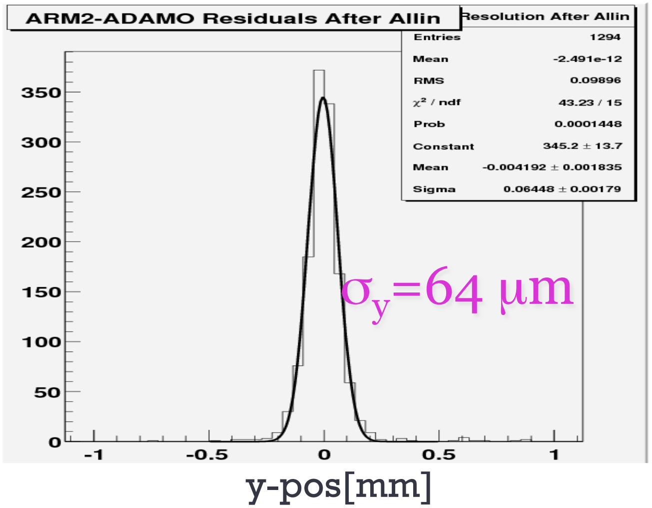


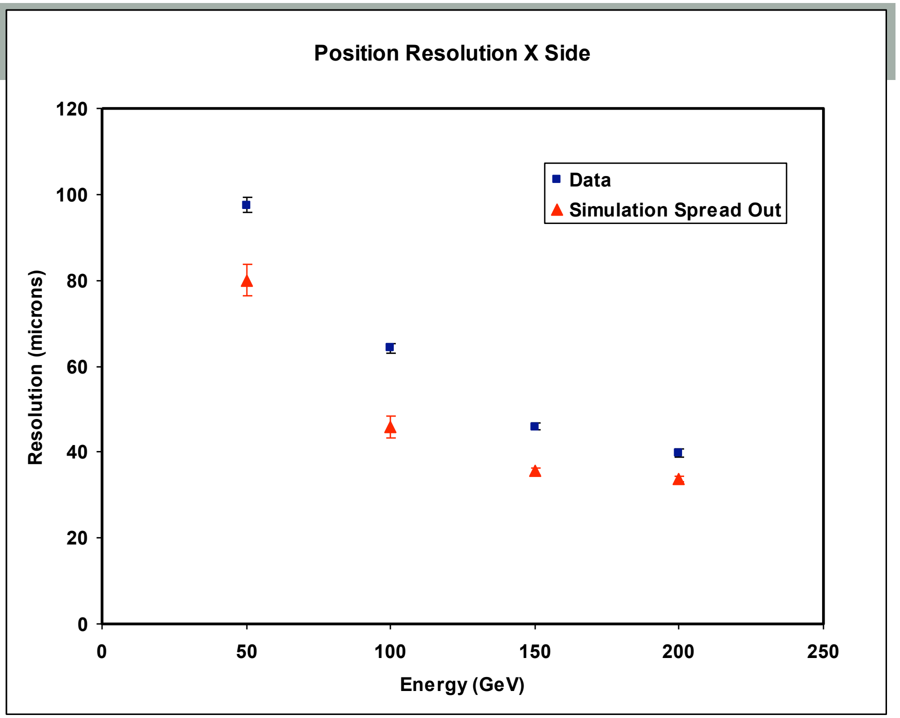


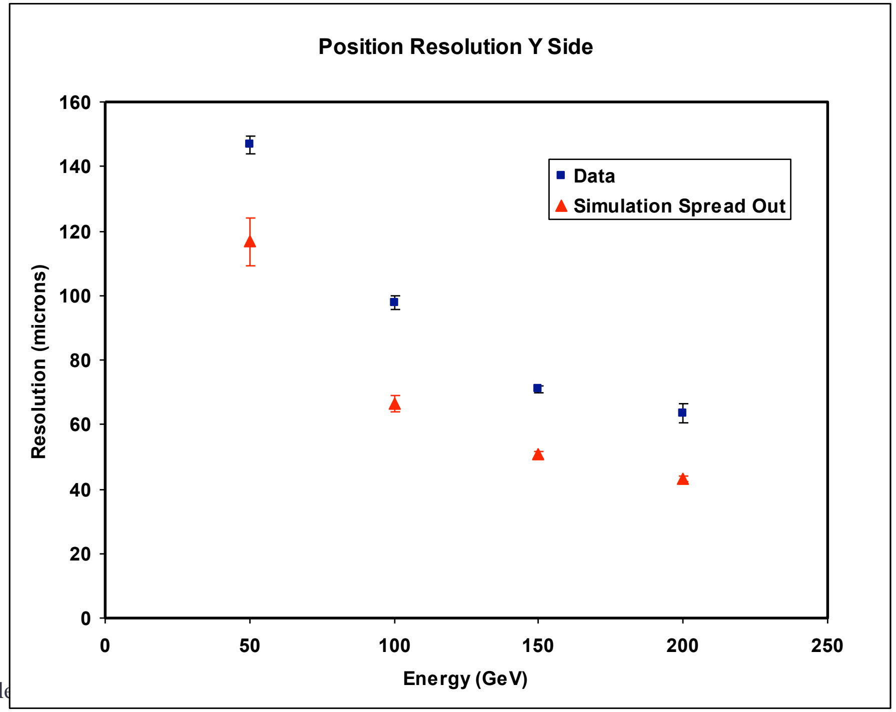
LHCf Position Resolution

200 GeV electrons









Alignment has been taken into account

In summary

Electromagnetic calorimetry

Homogeneous, if well done a ~ 3% (take care of c!)

Sampling, if well done a ~ 10%

Hadron calorimetry (non compensating)

a ~ 50%-100%

Thick HCAL

Hadron calorimetry (compensating)

a ~ 35%

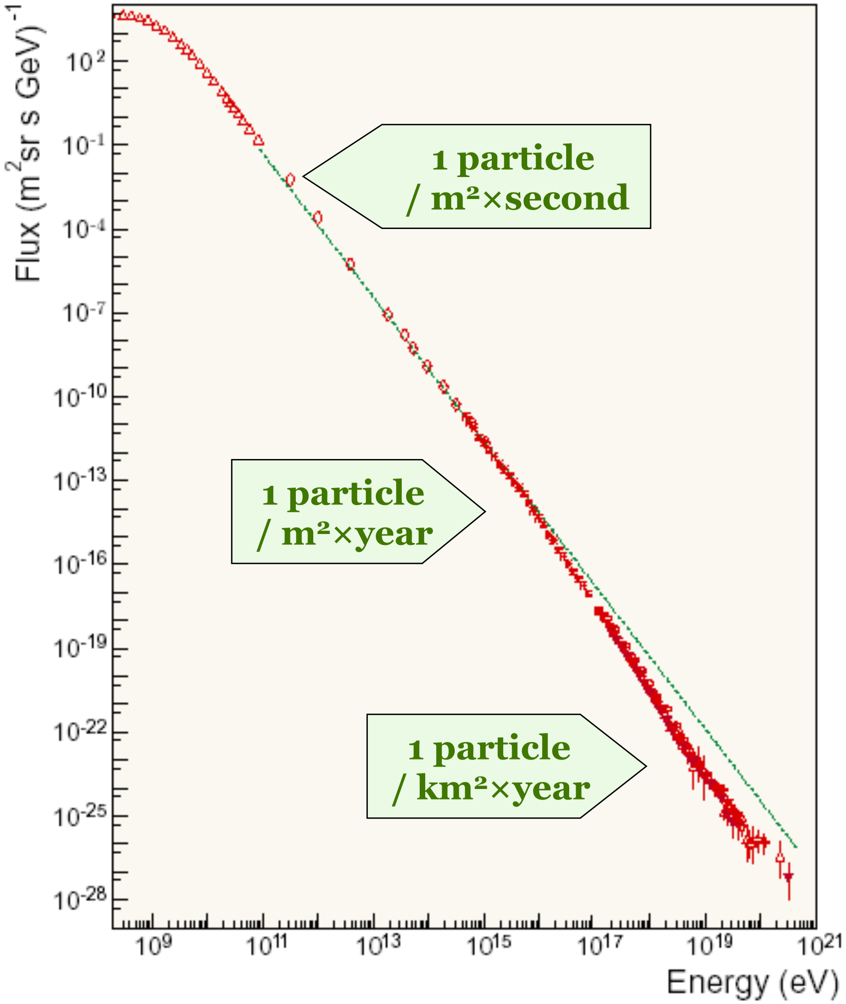
Dual Readout (R&D) calorimetry

a ~ 15% (potentially)

AND NOW… A SPECIFIC APPLICATION FOR AN ASTROPARTICLE EXPERIMENT IN SPACE

The CaloCube concept

Some of the Cosmic-Ray 'mysteries'



High energy nuclei

- **"Knee" structure around ~ PeV**
  - Upper energy of galactic accelerators (?)
  - Energy-dependent composition
- **Structures in the GeV – TeV region recently discovered for p and He**
  - Composition at the knee may differ substantially from that at TeV
- **Spectral measurements in the knee region up to now are only indirect**
  - Ground-based atmospheric shower detectors
  - High uncertainties

A direct spectral measurement in the PeV region requires great acceptance (few m^{2}sr) and good energy resolution for hadrons (at least 40%)

High energy Electrons+Positrons

- **Currently available measurements show some degree of disagreement in the 100 GeV – 1 TeV region**
- **Cutoff in the TeV region?**

Direct measurements require excellent energy resolution (~%), a high e/p rejection power (> 10^5) and large acceptance above 1 TeV

Main issues for a space based calorimeter

1. Very large geometrical factor (few m^2 sr)
2. Good electron and γ energy resolution for source studies (~1-2%)
3. Good hadron energy resolution (~30%) to investigate structure in the knee region
4. Excellent electron/hadron separation (>10^5 rejection factor)
5. Excellent angular resolution for γ source pointing
6. Reduced weight and power consumption (depend on the launch vehicle)
7. Rad hard technology

But please note that:

a full containment hadron calorimeter is IMPOSSIBLE!

CaloCube: a cubic, homogeneous, isotropic calorimeter (I)

- A large cubic homogeneous calorimeter, made with many small cubes would 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.

CaloCube: 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….

See for example:
N. Mori, et al.,
Homogeneous and isotropic calorimetry for space experiments
NIMA (2013)
http://dx.doi.org/10.1016/j.nima.2013.05.138i

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

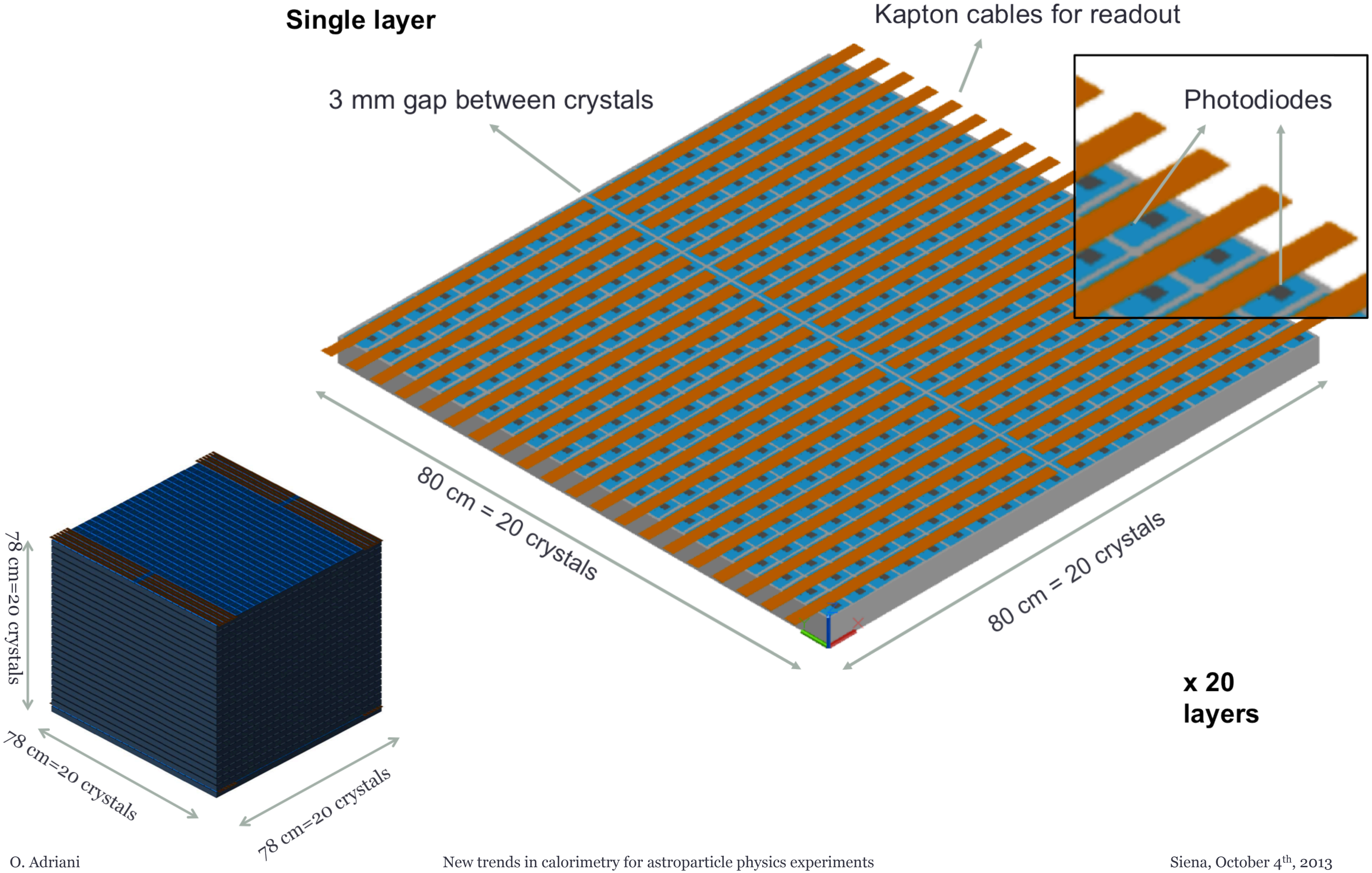
Density:	4.51 g/cm^3
X_0:	1.85 cm
Moliere radius:	3.5 cm
λ_I:	37 cm
Light yield:	54.000 ph/MeV
τ_{decay}:	1.3 μs
λ_{max}:	560 nm

- Simulation and prototype beam tests used to characterize the detector

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

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

Mechanical idea



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

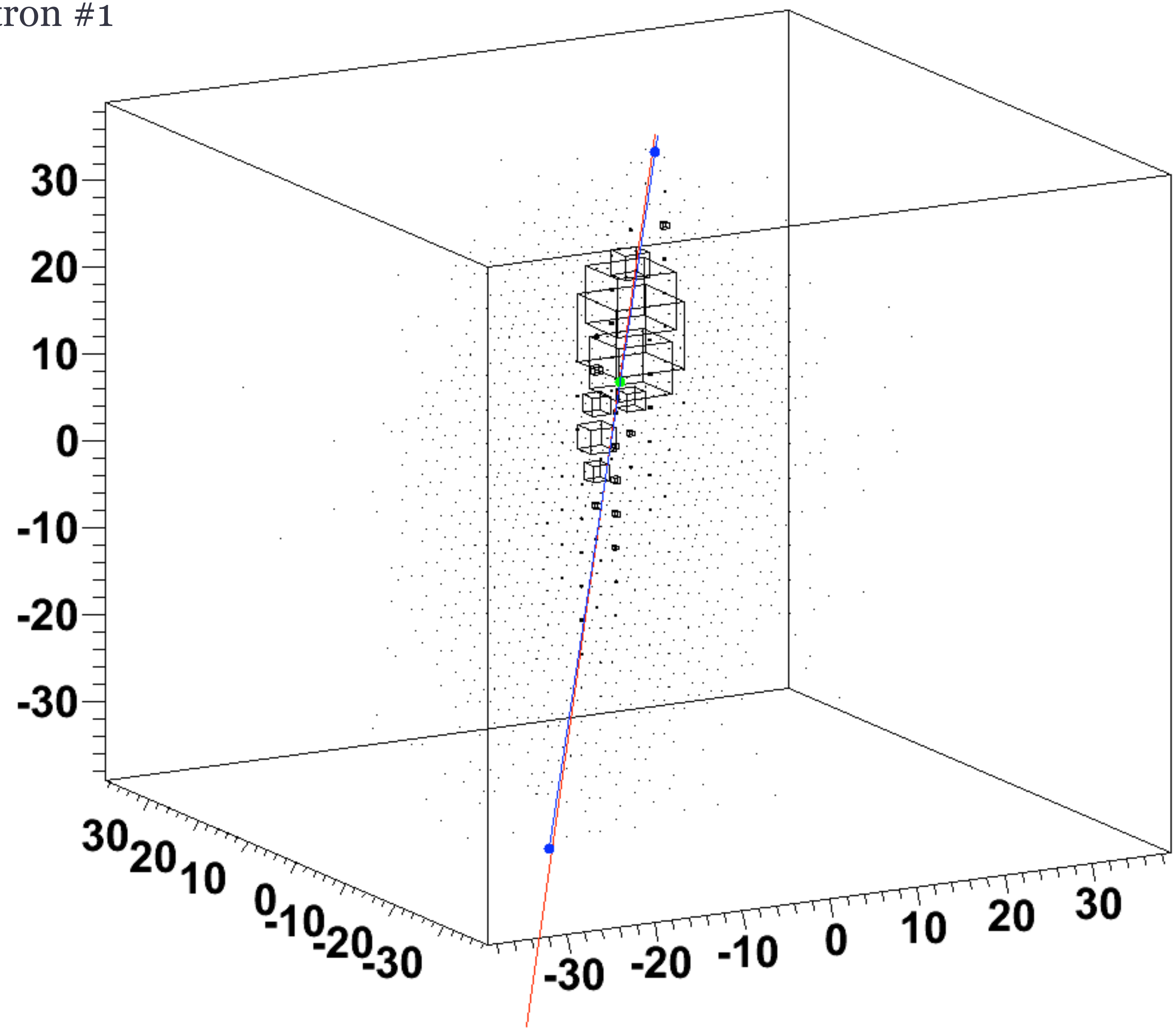
- The CASIS chip, developed in Italy by Trieste, is very well suited for this purpose
- 16 channels, Charge Sensitive Ampl and Correlated Double Sampling
- Automatic switching btw low and high gain mode
- 2.8 mW/channel
- 3.10^3 e^- noise for 100 pF input capacitance
- 53 pC maximum input charge

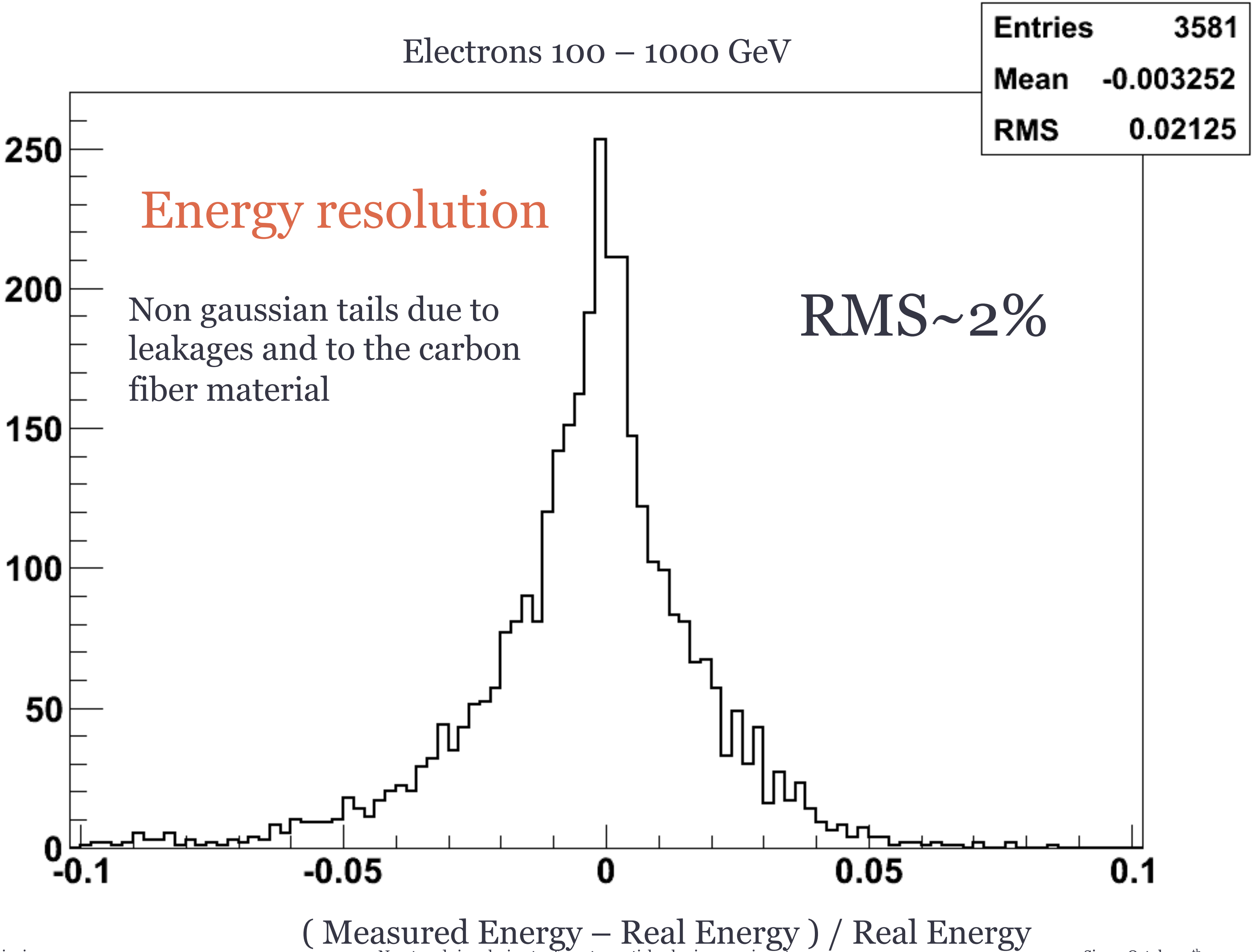
- The CASIS chip has been successfully used for the pre-prototype

MC simulations

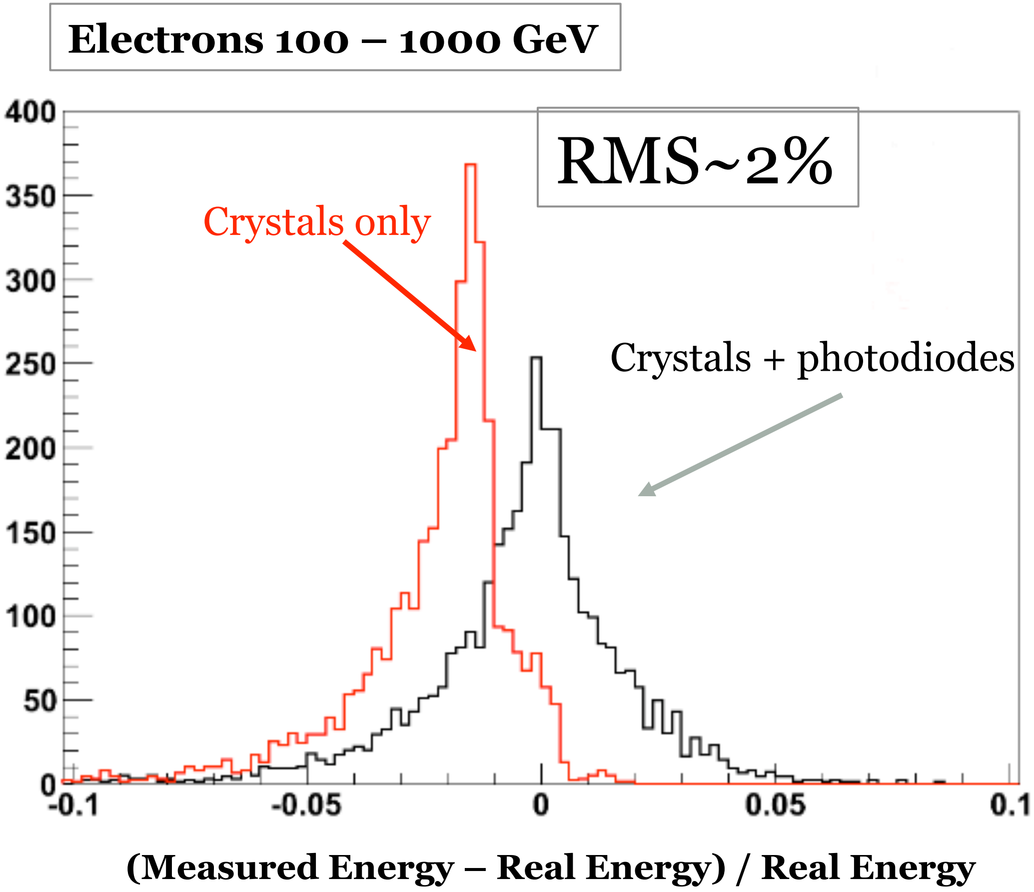
- **Fluka-based MC simulation**
  - Scintillating crystals
  - Photodiodes
    - Energy deposits in the photodiodes due to ionization are taken into account
  - Carbon fiber support structure (filling the 3mm gap)
- **Isotropic generation on the top surface**
  - Results are valid also for other sides
- **Simulated particles:**
  - Electrons: 100 GeV → 1 TeV
  - Protons: 100 GeV → 100 TeV
  - about $10^2 - 10^5$ events per energy value
- **Geometry factor, light collection and quantum efficiency of PD are taken into account**
- **Requirements on shower containment (fiducial volume, length of reconstructed track, minimum energy deposit)**
  - Nominal GF: $(0.78*0.78*\pi)*5*\varepsilon\ m^2sr = 9.55*\varepsilon\ m^2sr$

Electron #1




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



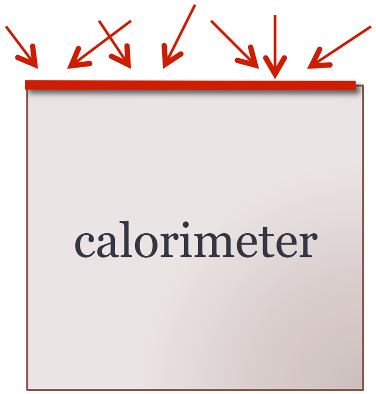
Selection efficiency:
$\varepsilon \sim 36\%$

$GF_{eff} \sim 3.4\ m^2sr$

Non-gaussian tails due to leakages and to energy losses in carbon fiber material

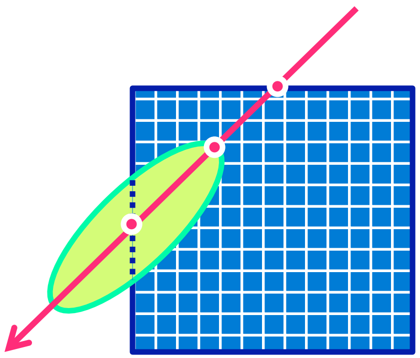
<u>Ionization effect on PD: 1.7%</u>

Protons



Very simple geometrical cuts:

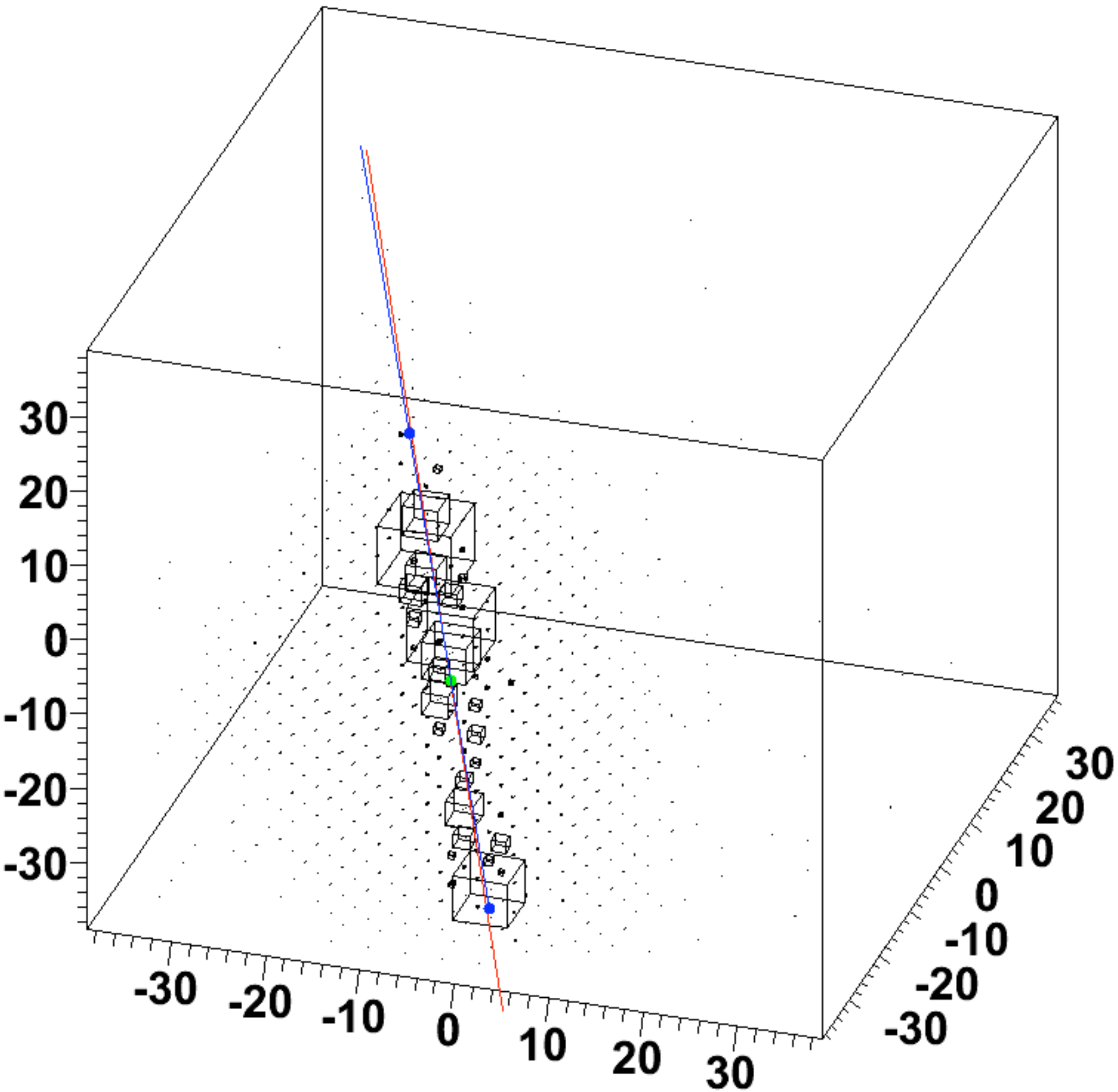
- A good reconstruction of the shower axis
- At least 50 crystals with >25 MIP signal



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

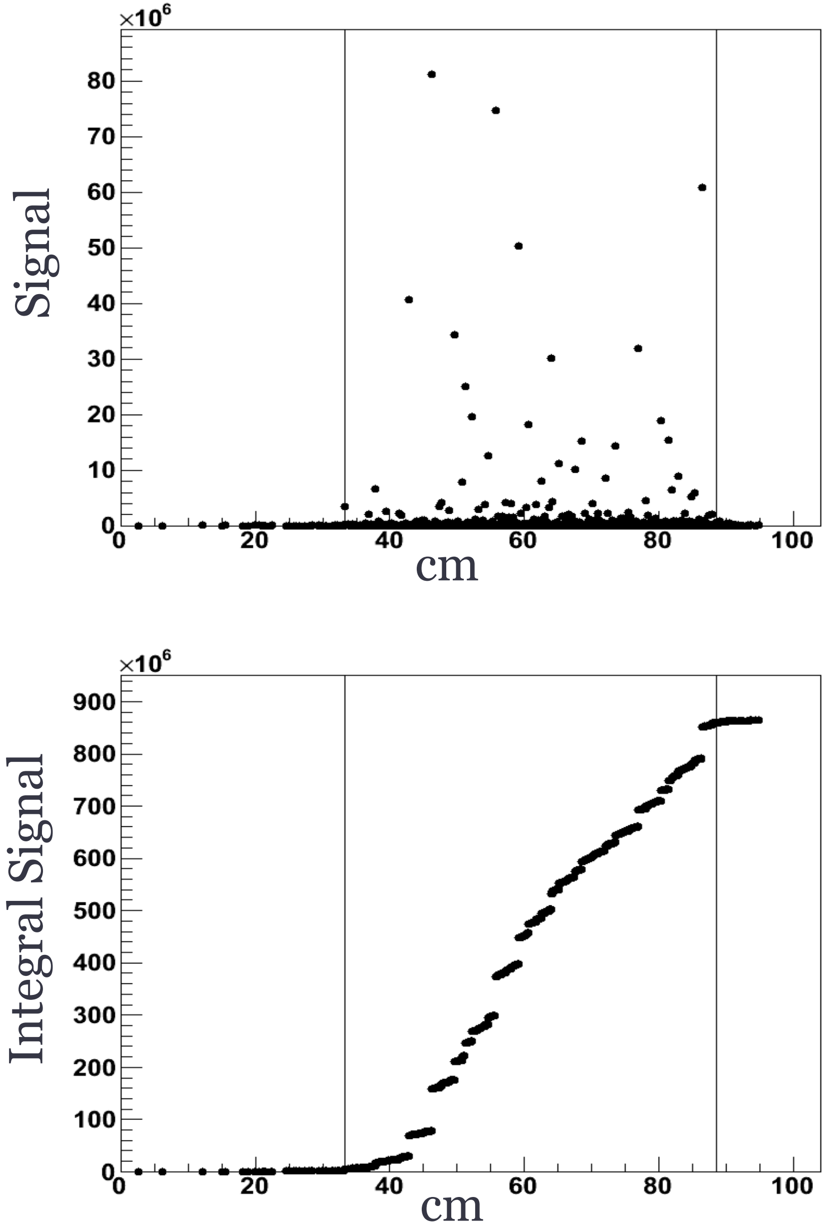
Image

Proton #1



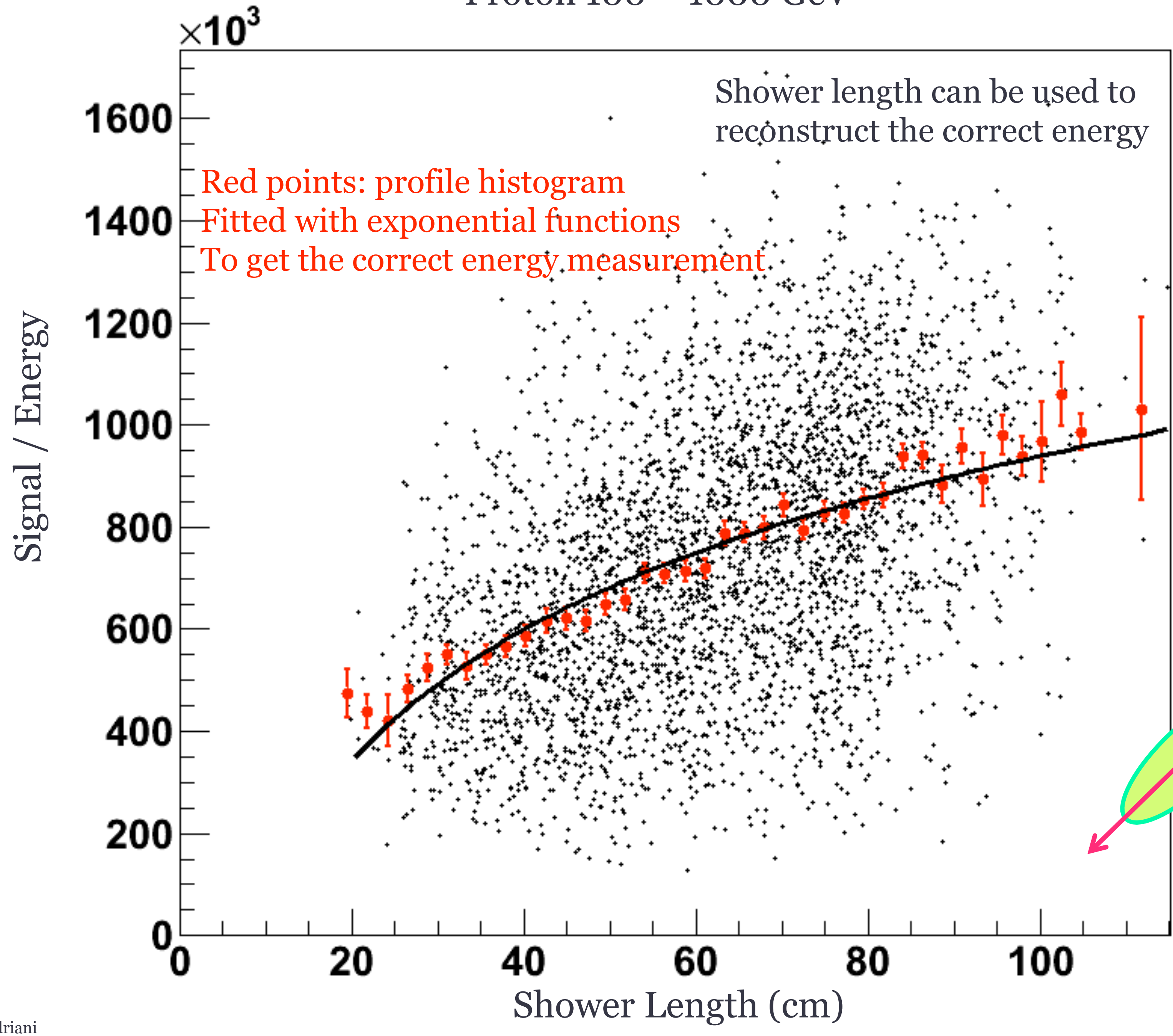
Proton #1

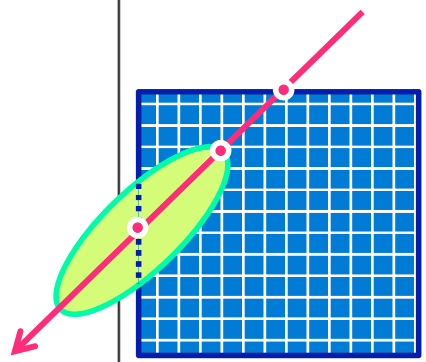
Longitudinal profile



Shower starting point is identified with ~1 cm resolution

Proton 100 – 1000 GeV

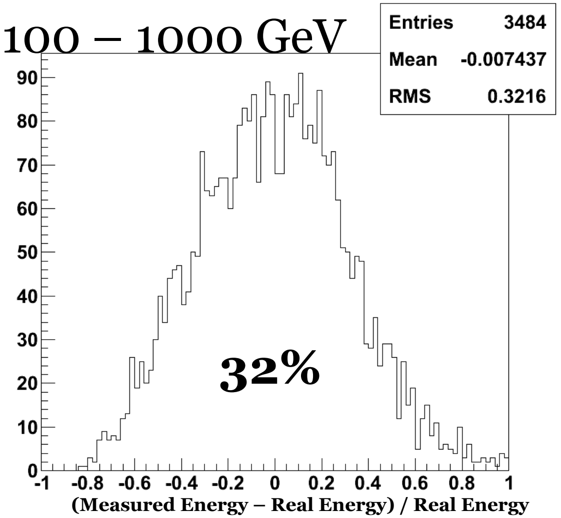




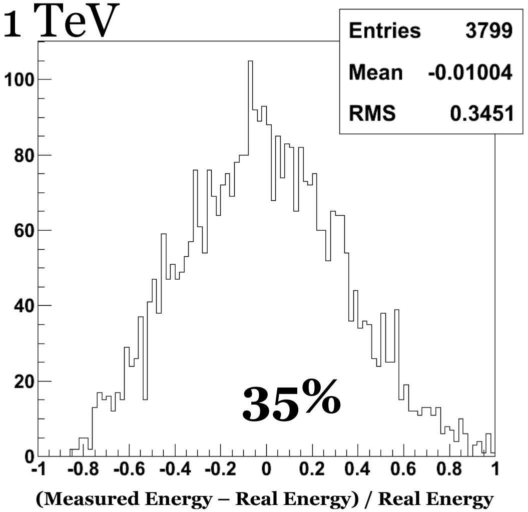
Protons

Energy resolution (correction for leakage by looking at the shower starting point)

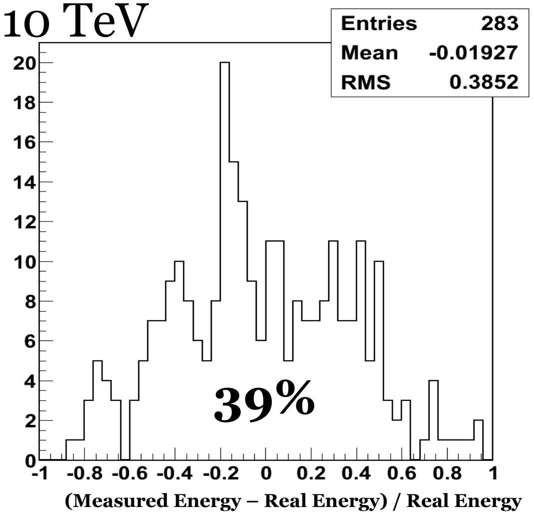
100 – 1000 GeV



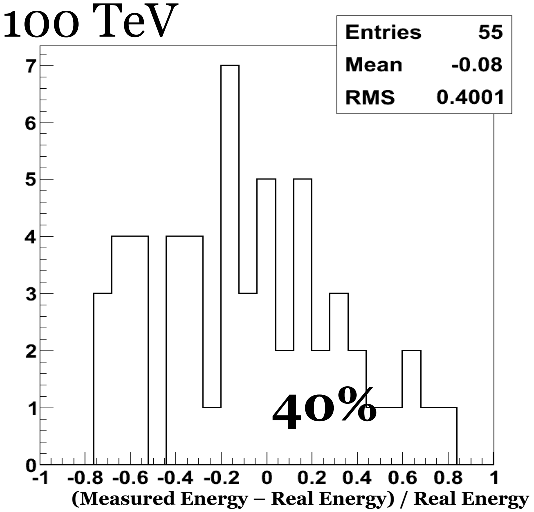
1 TeV



10 TeV



100 TeV



Selection efficiencies:

$\varepsilon^{0.1\text{-}1TeV} \sim 35\%$

$\varepsilon^{1TeV} \sim 41\%$

$\varepsilon^{10TeV} \sim 47\%$

$GF_{eff}^{0.1\text{-}1TeV} \sim 3.3\ m^2sr$

$Gf_{eff}^{1TeV} \sim 3.9\ m^2sr$

$Gf_{eff}^{10TeV} \sim 4.5\ m^2sr$

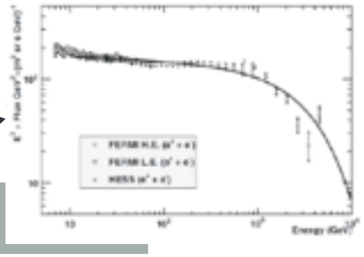
Proton rejection factor with simple topological cuts:

2.10^5-5.10^5 up to 10 TeV

Expected number of events

Assumptions:

- 10 years exposure
- p/e rejection factor ~ 10^5
- Depth: 39 X_0 – 1.8 λ



Electrons

Effective GF (m^2 sr)	$\sigma(E)/E$	E>0.5 TeV	E>1 TeV	E>2 TeV	E>4 TeV
3.4	~1%	181.10^3	35.10^3	5.10^3	6.10^2

Knee

Protons and Helium – Polygonato Model

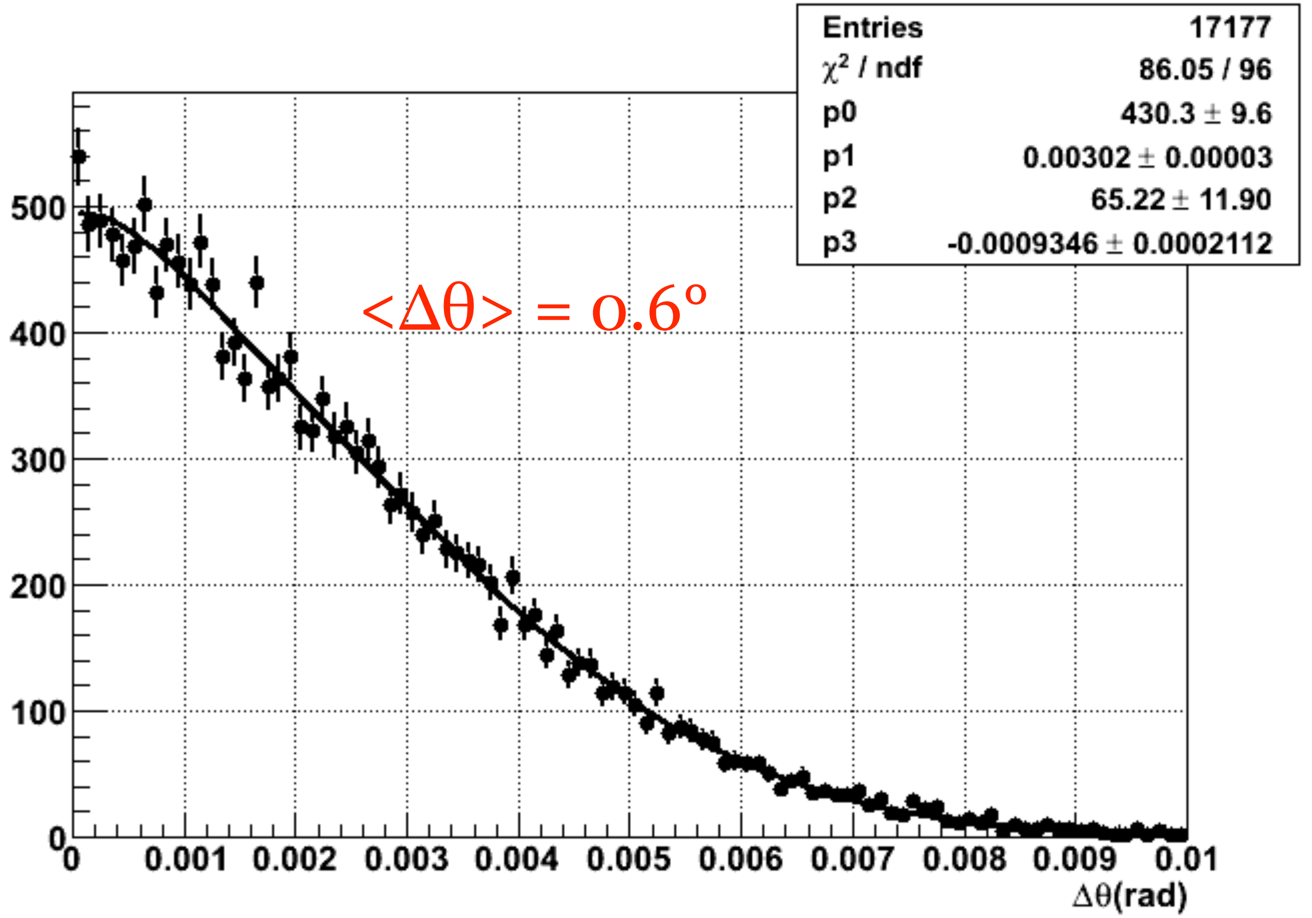
Effective GF (m^2 sr)	$\sigma(E)/E$	E>0.1 PeV		E>0.5 PeV		E>1 PeV		E>2 PeV		E>4 PeV	
		P	He	P	He	P	He	P	He	P	He
~4.0	35%	$7.8.10^3$	$7.4.10^3$	$4.6.10^2$	$5.1.10^2$	$1.2.10^2$	$1.5.10^2$	28	43	5	10

Heavier Nuclei (2<Z<25)– Polygonato Model

Effective GF (m^2 sr)	$\sigma(E)/E$	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
~4.8	32%	$4.3.10^3$	$4.5.10^3$	$3.0.10^2$	$3.2.10^2$	$1.0.10^2$	$1.0.10^2$	29	34	8	10

Angular resolution

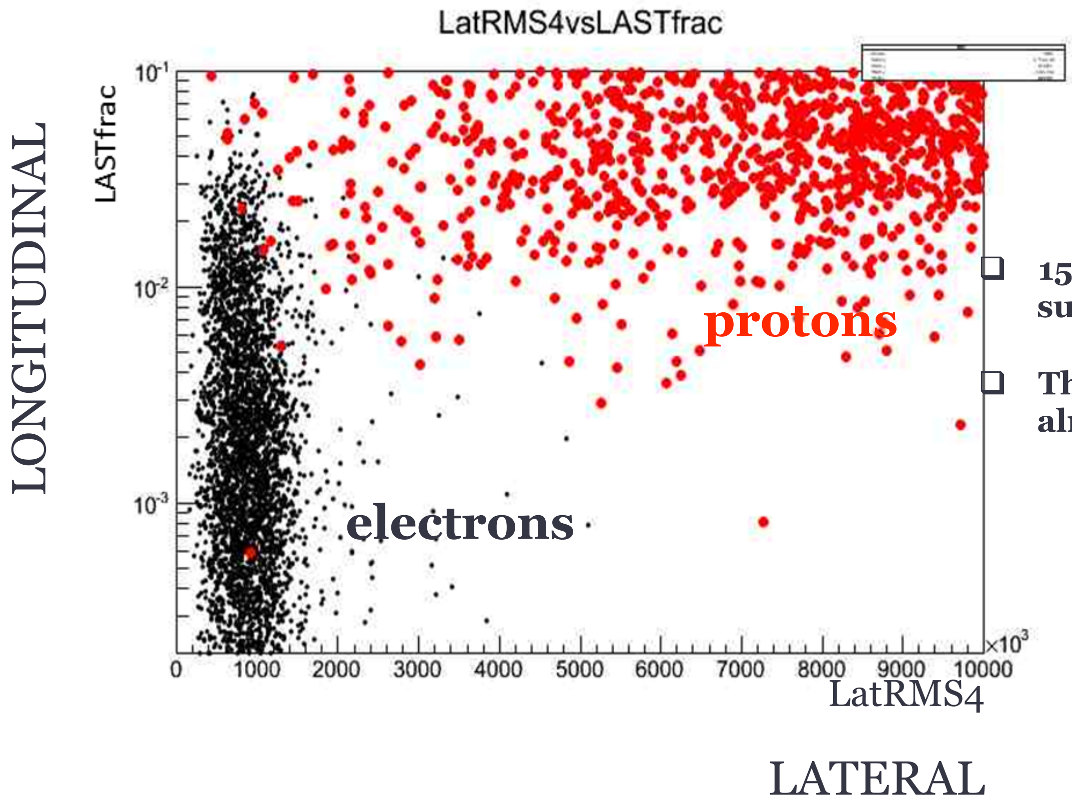
Shower direction can be nicely reconstructed thanks to the high granularity
Fit on the shower shape



Top & bottom fiducial containment

e/p rejection factor

The proton background is much higher that the electron flux (>10^4)
Very large e/p rejection factor is mandatory
Topological cuts are the best solution → Calocube is optimal!



- 155.000 protons simulated at 1 TeV : only 1 survive the cuts
- The corresponding electron efficiency is 37% and almost constant with energy above 500gev

The CaloCube prototypes and the test beams

- Two prototypes have been built at INFN Florence, with the help of INFN Trieste, INFN Pisa and University of Siena.

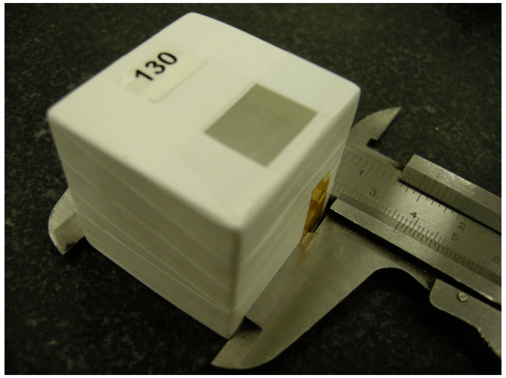
- A small, so called "pre-prototype", made of 4 layers with 3 crystals each
  - 12 CsI(Tl) crystals, 2.5x2.5x2.5 cm^3

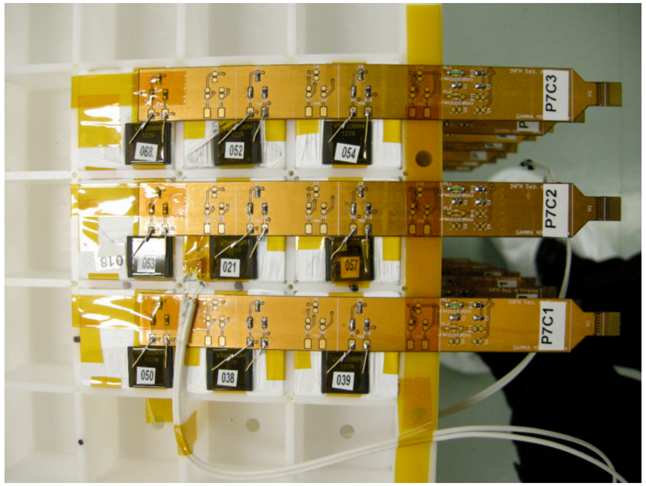
- A bigger, properly called "prototype", made of 14 layers with 9 crystals each
  - 126 CsI(Tl) crystals, 3.6x3.6x3.6 cm^3

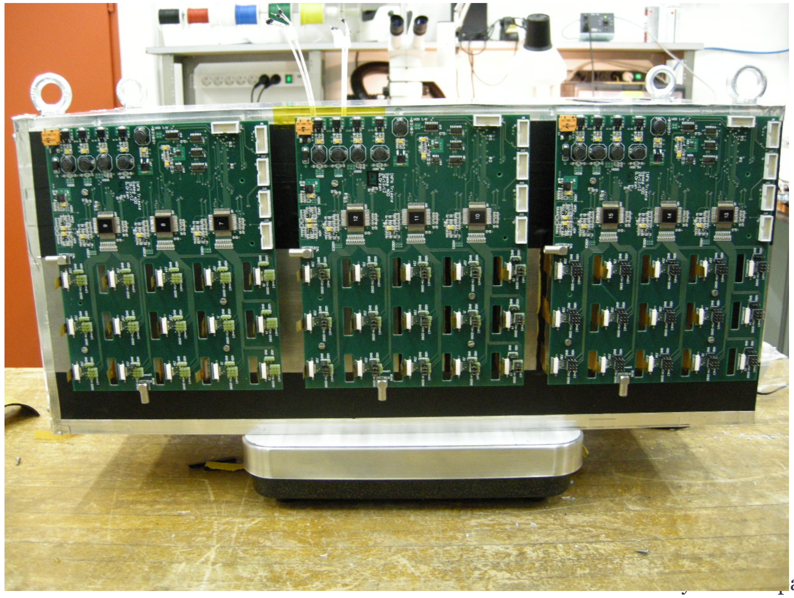
- Both devices have been tested at CERN SPS (pre-prototype in October 2012 and prototype in January-February 2013)

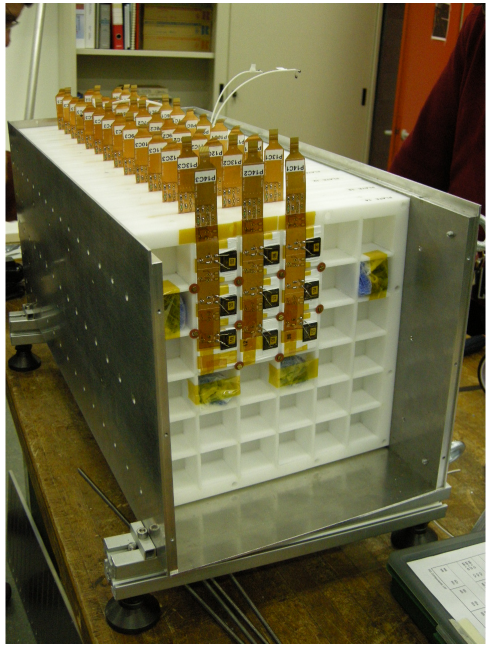
The prototype

14 Layers
9x9 crystals in each layer
126 Crystals in total
126 Photo Diodes
50.4 cm of CsI(Tl)
27 X_0
1.44 λ_I





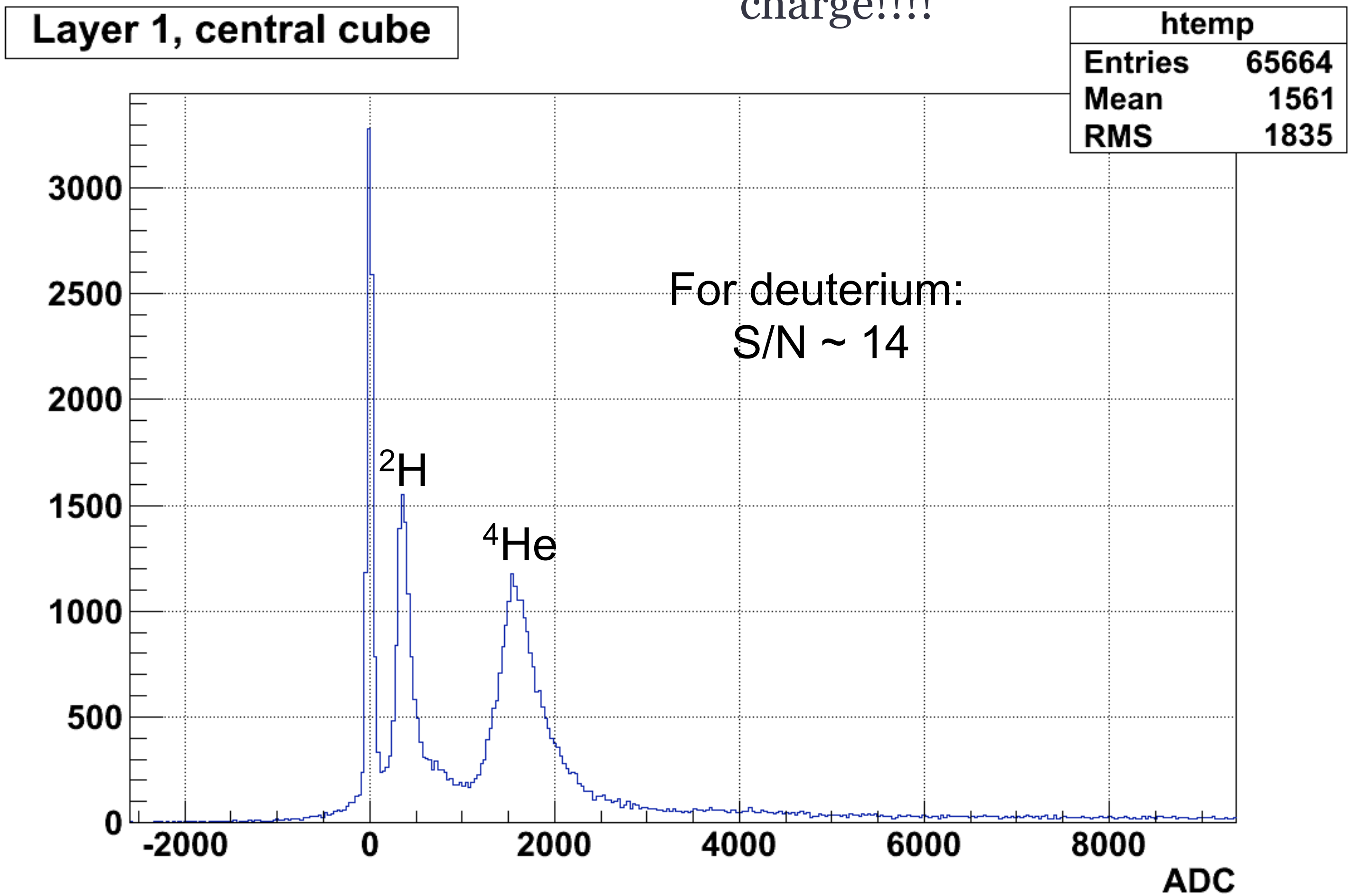




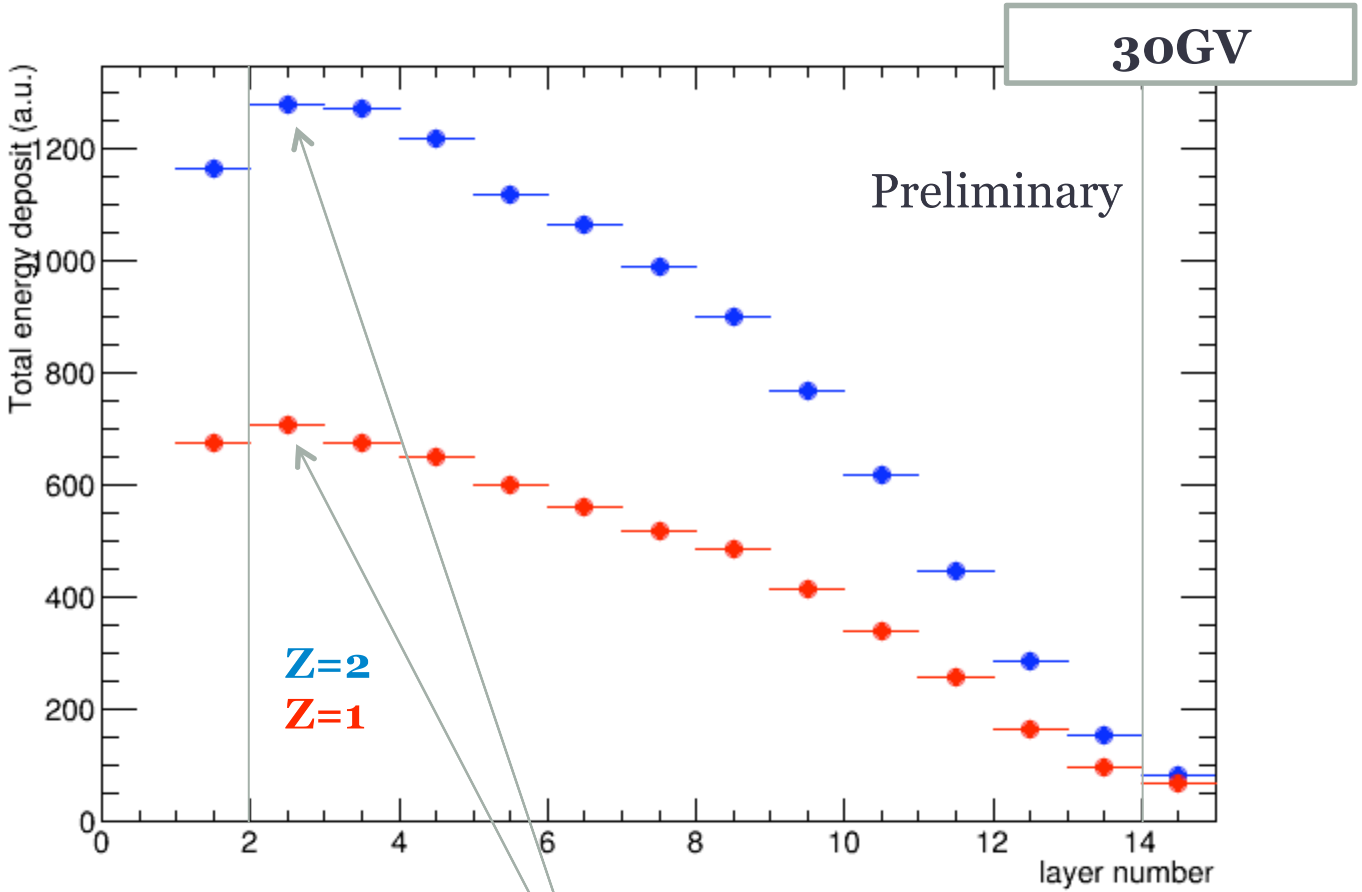
A glance at prototype's TB data

SPS H8 Ion Beam: Z/A = 1/2, 12.8 GV/c and 30 GV/c

Please note: we can use the data from a precise silicon Z measuring system located in front of the prototype to have an exact identification of the nucleus charge!!!!

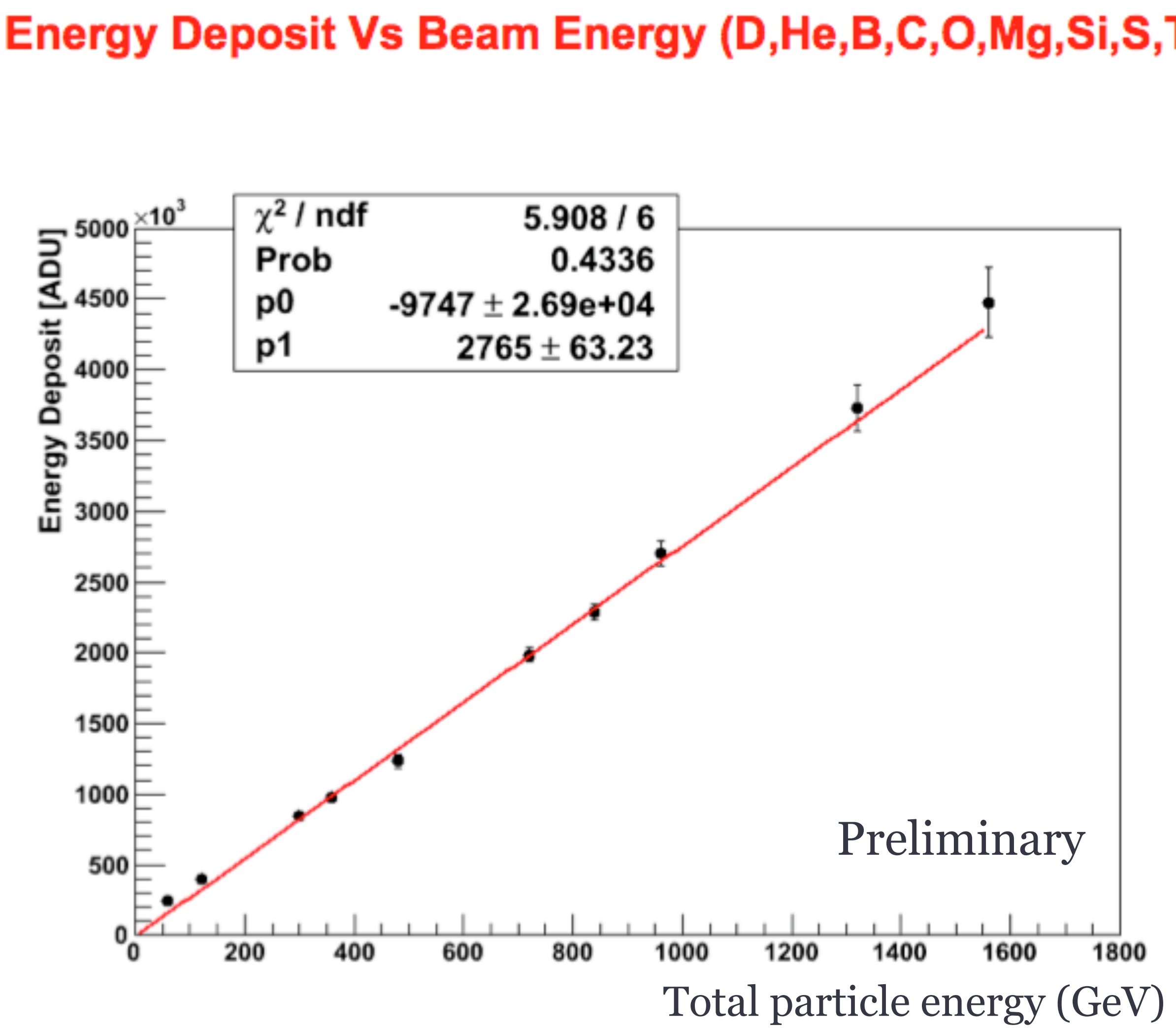


Total energy deposit VS shower-starting layer



Maximal containment when starting-layer == 2

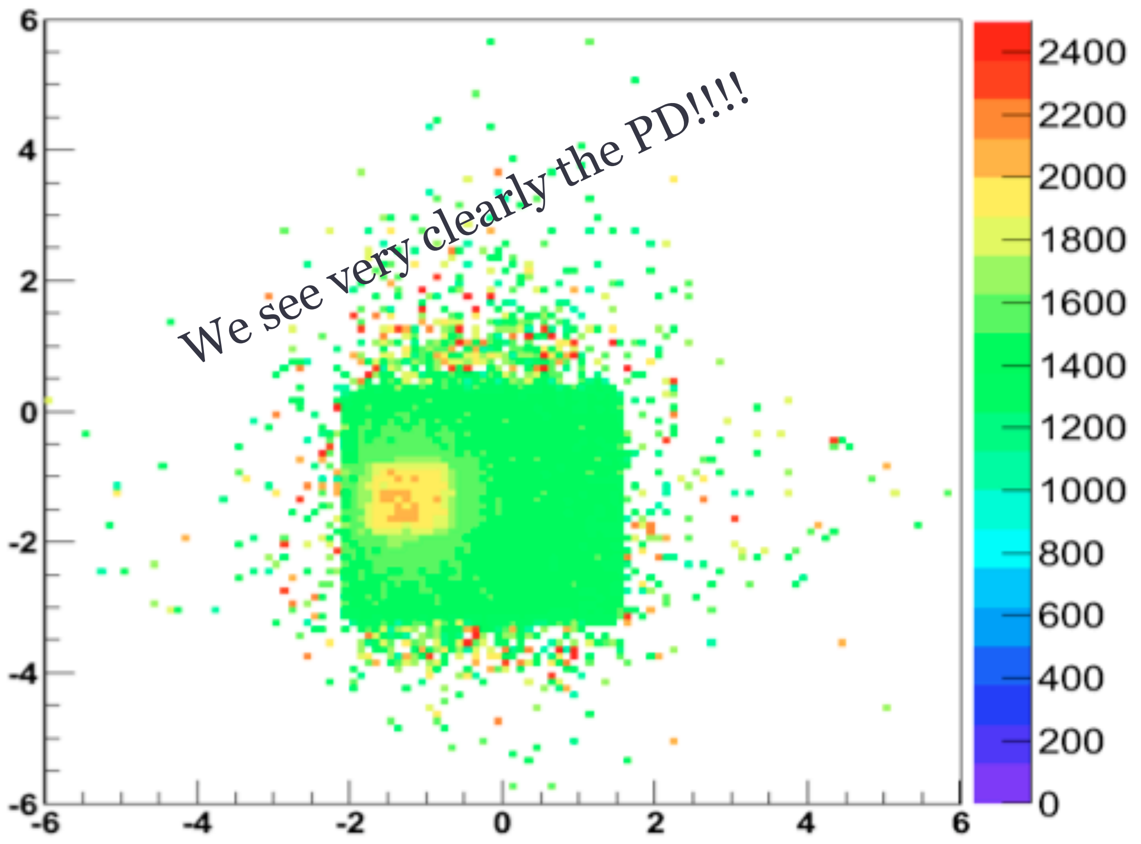
Energy deposit for various nuclei



Charge is selected with the placed-in-front tracking system

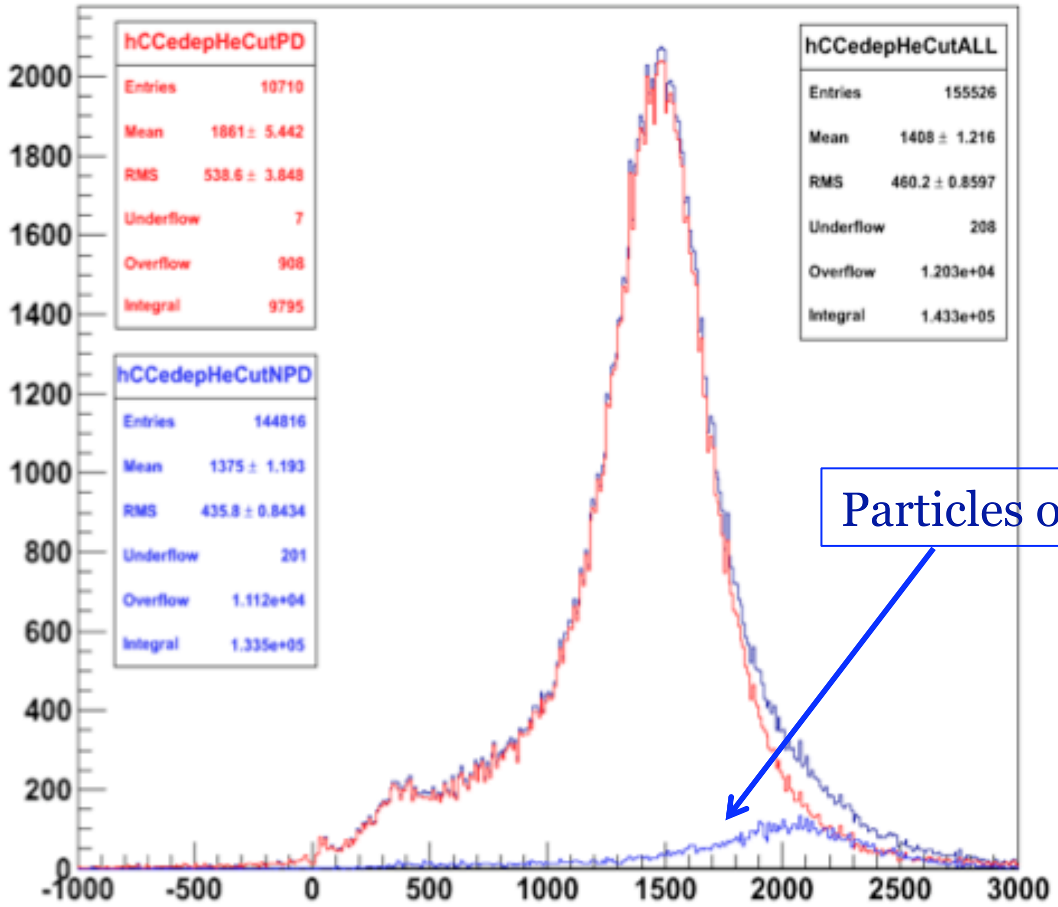
Good Linearity even with the large area PD!

Response as function of impact point



Mean PH in central cube vs particle (He) entry point coordinates (using Si strips tracking)

Signals for different impact points



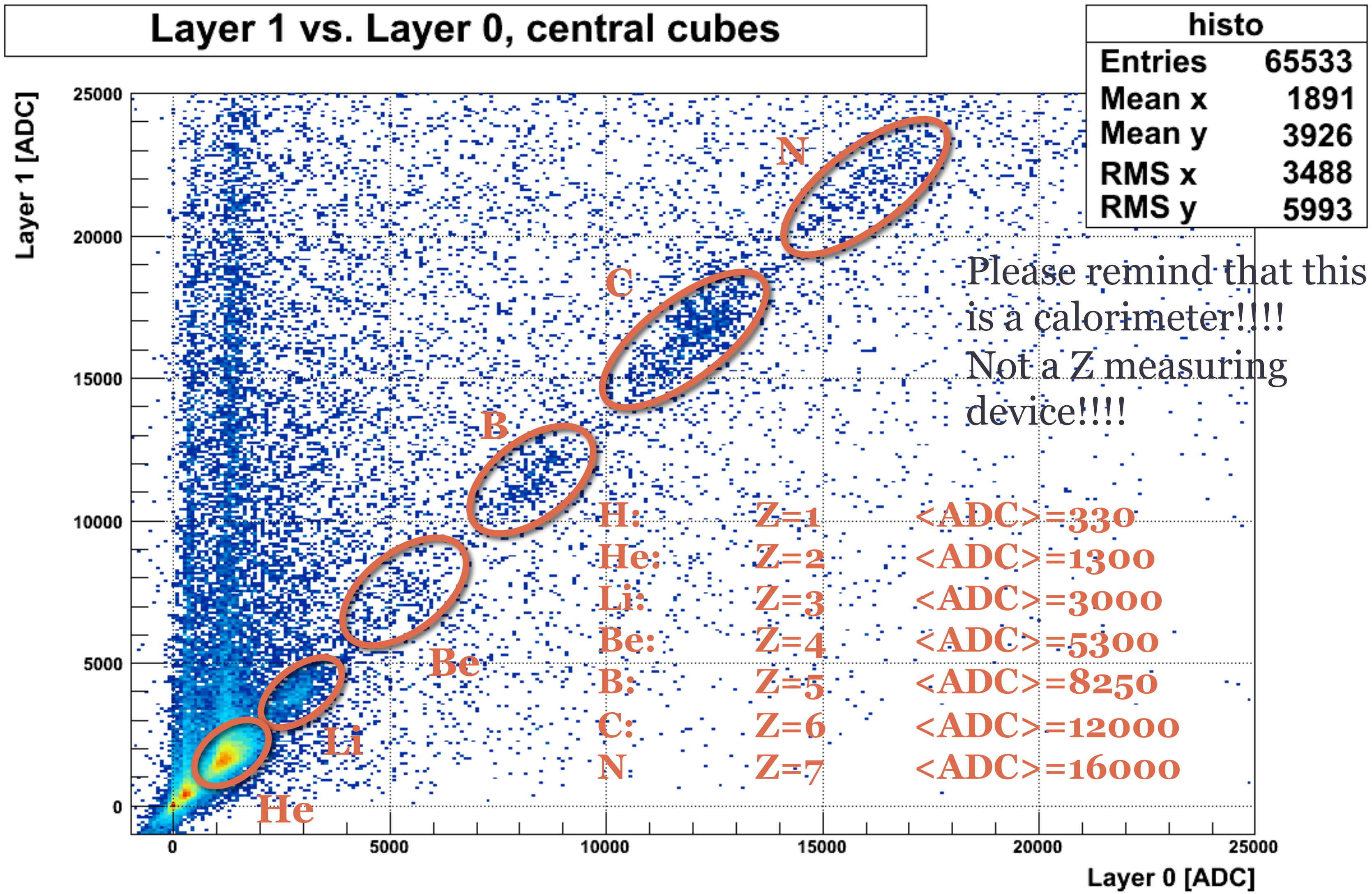
PD Signal

PD contribution is compatible with the expectations!

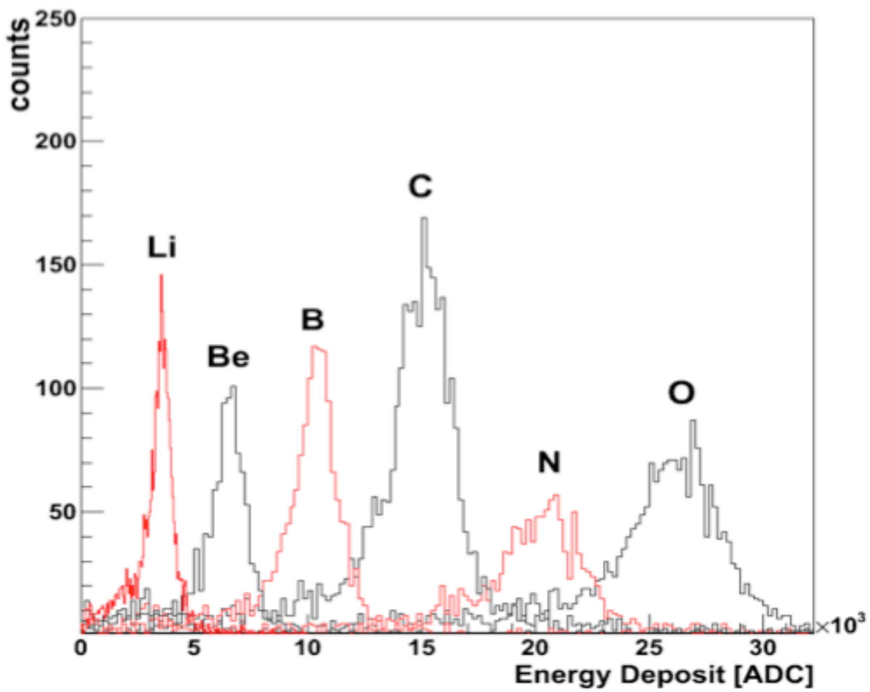
PH cube energy distributions:

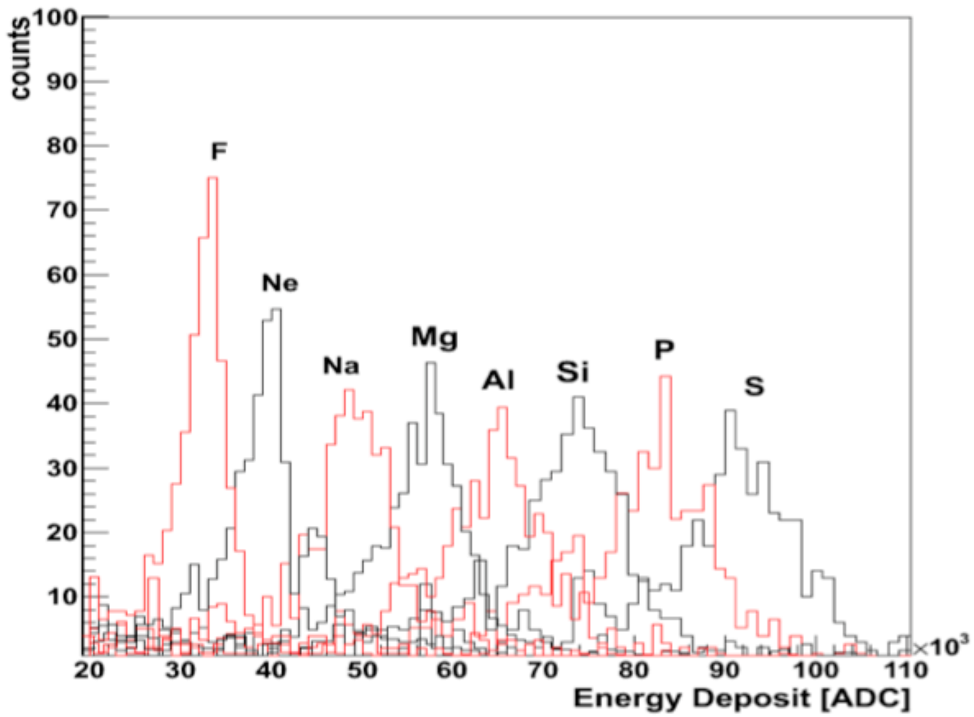
- Black line: all signals
- Red line: tracks not crossing the phodiode
- Blue line: tracks crossing the photodiode

Non interacting ions

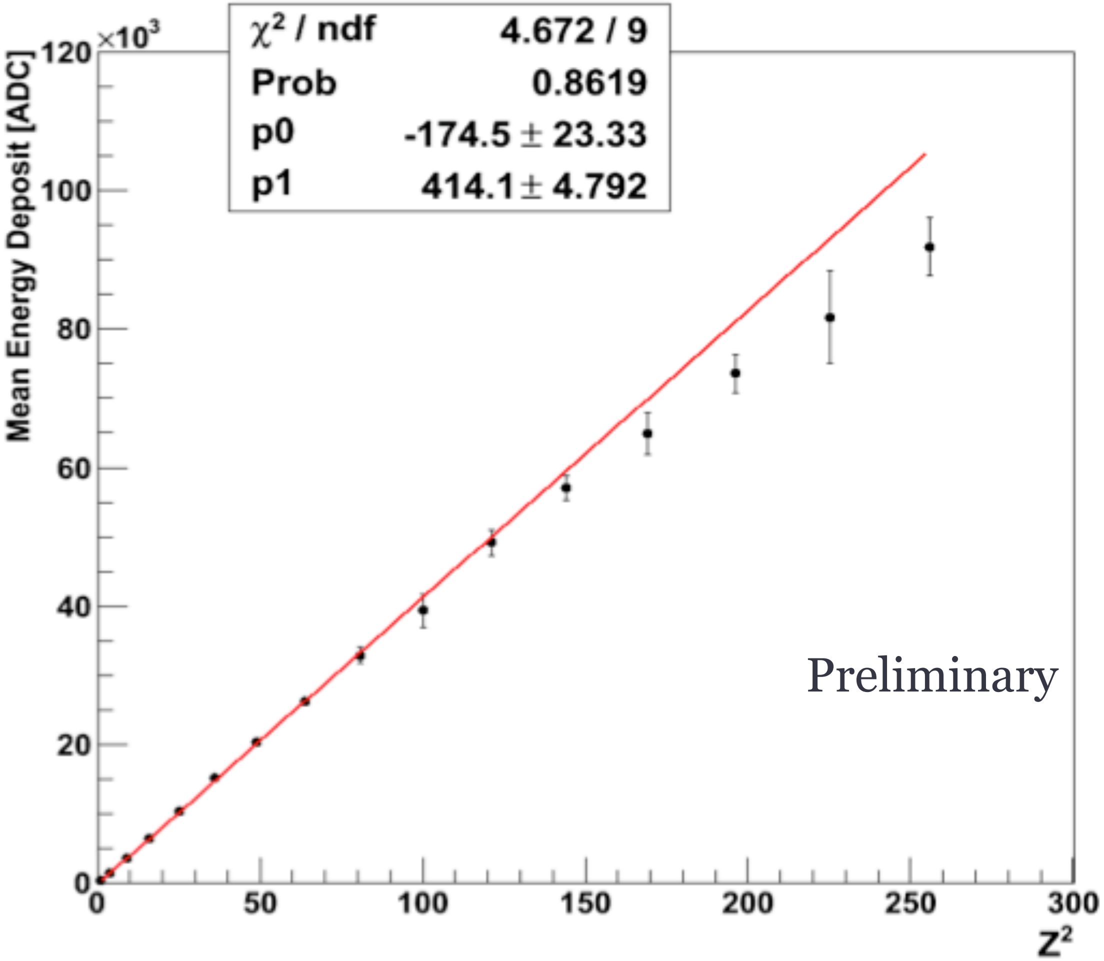


Charge selected with the Pisa-Siena tracker located in front (non interacting ions)





Charge linearity on the single crystal (non interacting ions)



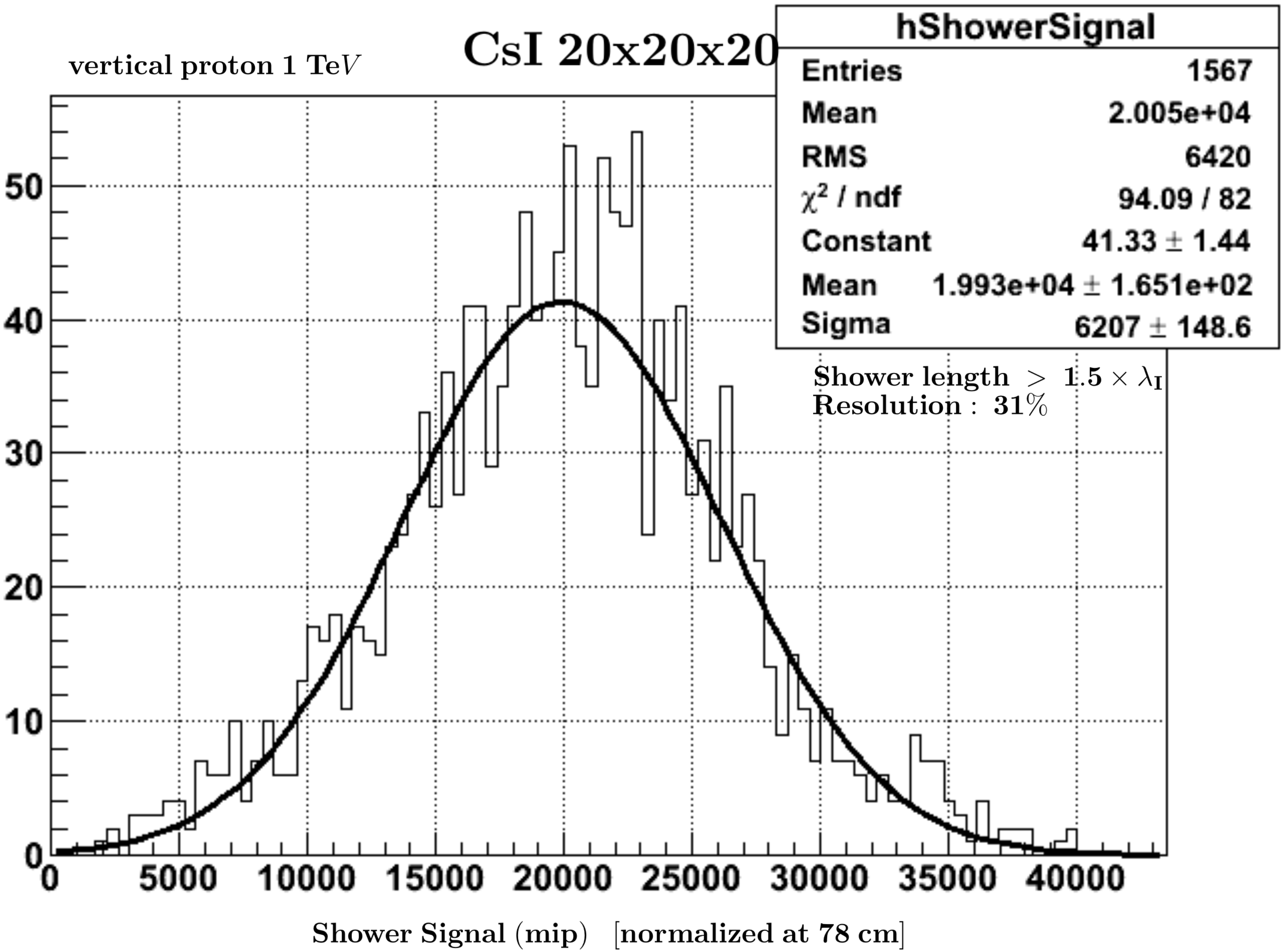
Please note: fit function calculated using data from Helium up to Magnesium

HOW TO IMPROVE THE CALOCUBE PERFORMANCES?

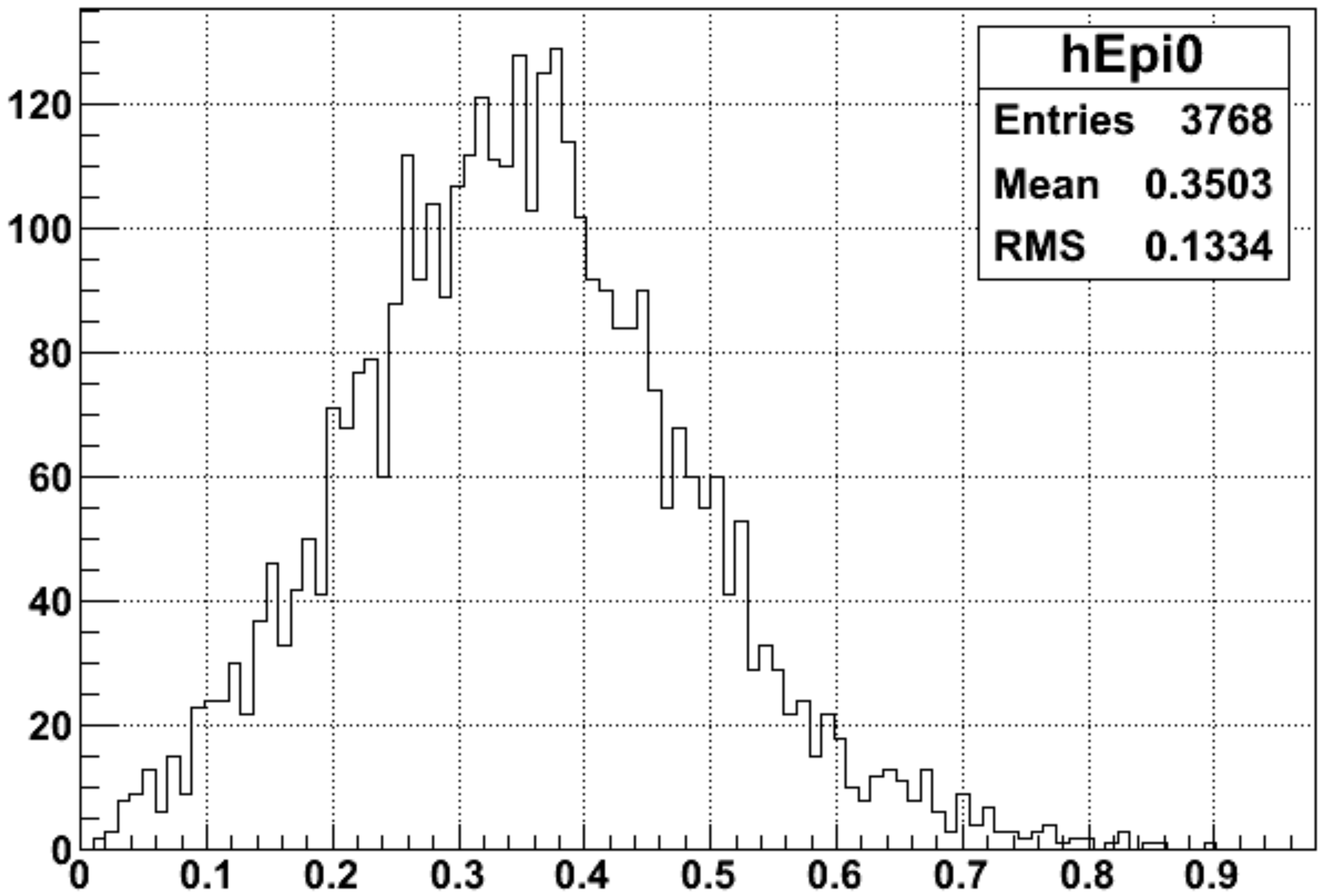
Basic ideas

Optimization of the overall calorimetric performances

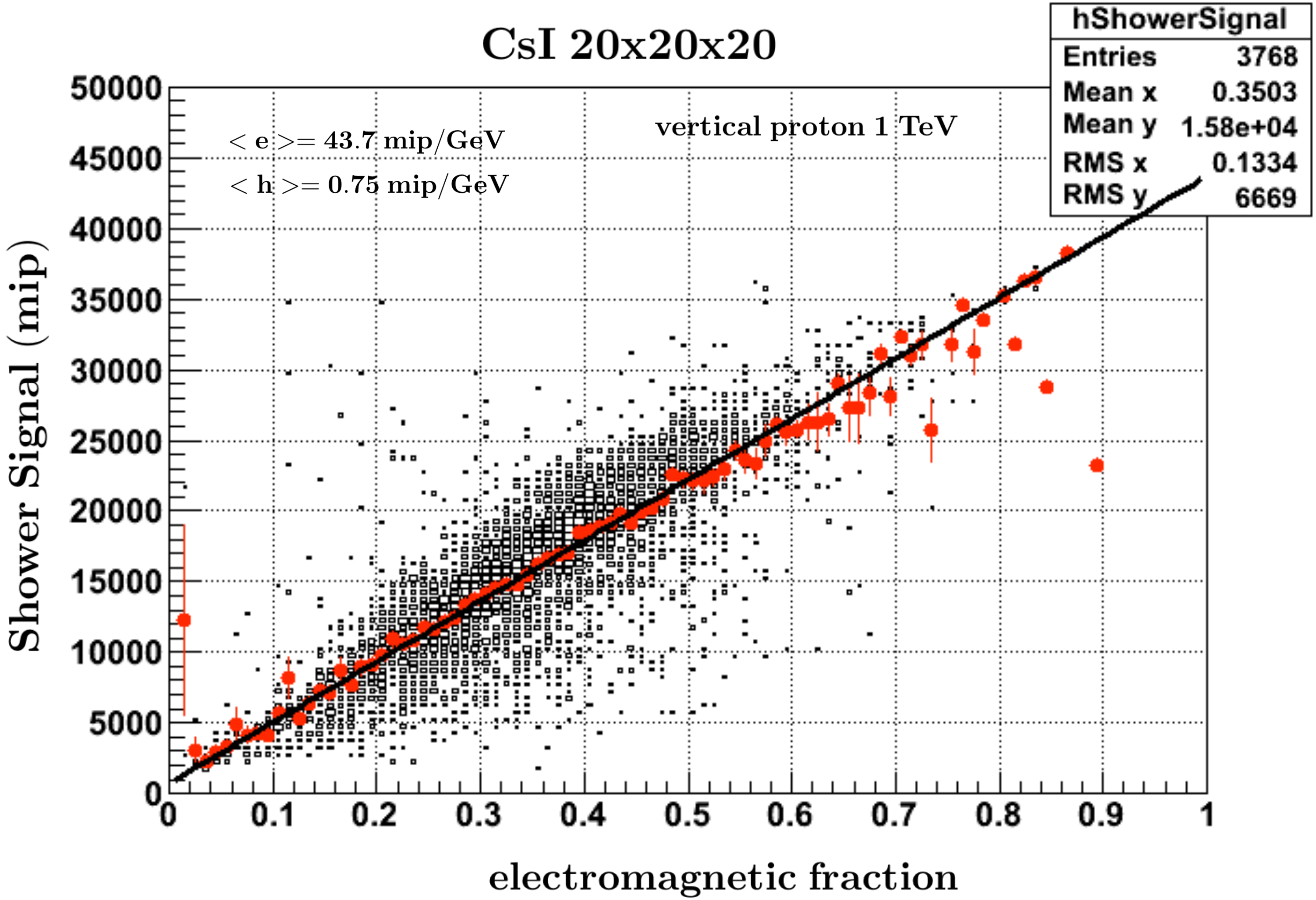
- Optimize the hadronic energy resolution by means of the dual - or multiple - readout techniques (Compensation techniques)
  - Scintillation light, Cherenkov light, neutron related signals
- Innovative analysis techniques (software compensation)
  - Possible, due to the very fine granularity
- Development of innovative light collection and detection systems
  - Optical surface treatments directly on crystals, to collect/convert the UV Cherenkov light
    - Dichroic filters
    - WLS thin layers
  - UV sensitive SiPM and small/large area – twin - Photo Diodes
- New development of front end and readout electronics
  - Huge required dynamic range (>10^7)
  - Fast, medium and slow (delayed) signals together
  - New CASIS chip ASIC with integrated ADC


CsI 20x20x20
vertical proton 1 TeV
hShowerSignal
Entries 1567
Mean 2.005e+04
RMS 6420
χ2 / ndf 94.09 / 82
Constant 41.33 ± 1.44
Mean 1.993e+04 ± 1.651e+02
Sigma 6207 ± 148.6
Shower length > 1.5 × λI
Resolution : 31%
0
10
20
30
40
50
0
5000
10000
15000
20000
25000
30000
35000
40000
Shower Signal (mip) [normalized at 78 cm]

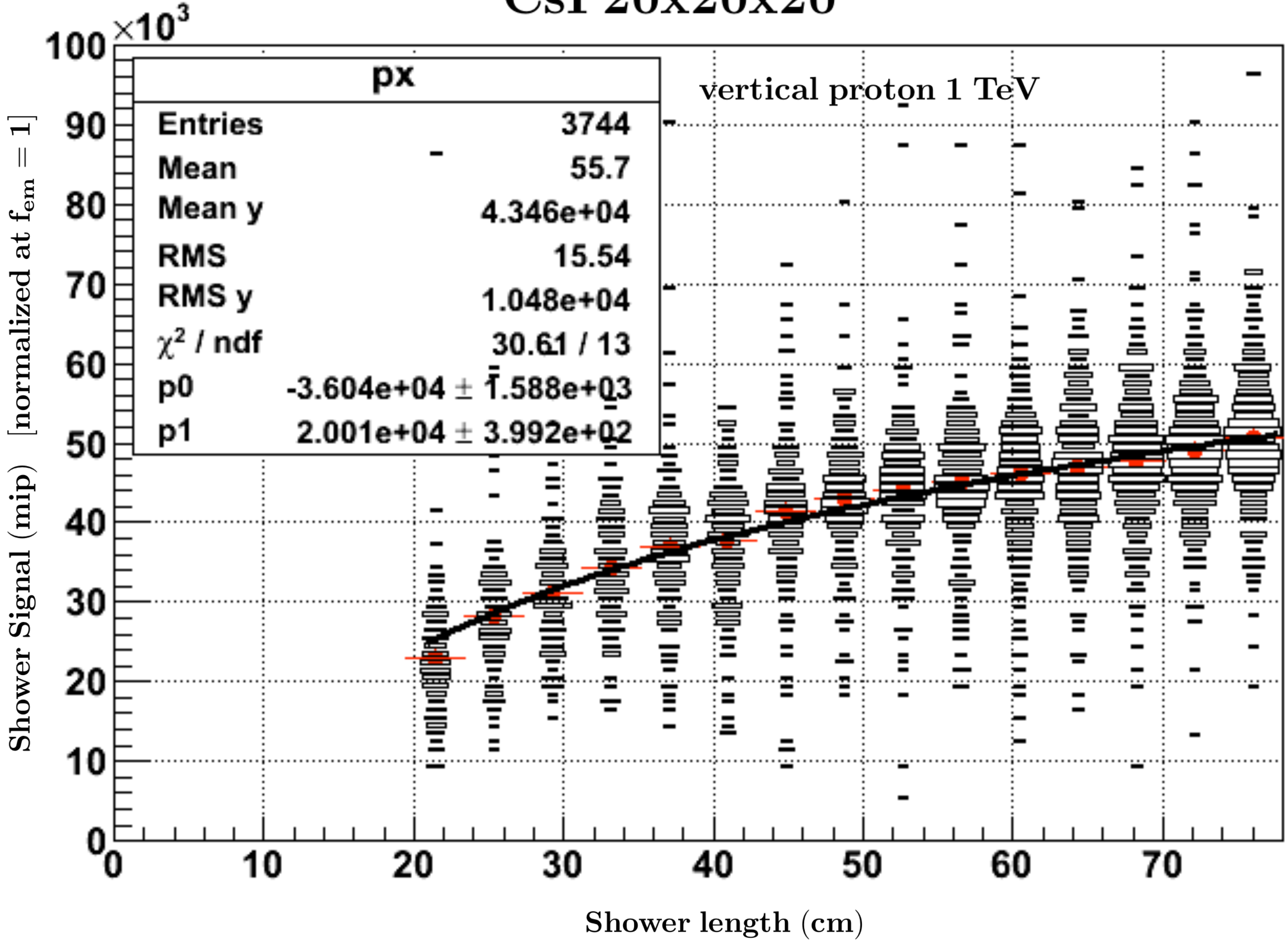
CsI 20x20x20

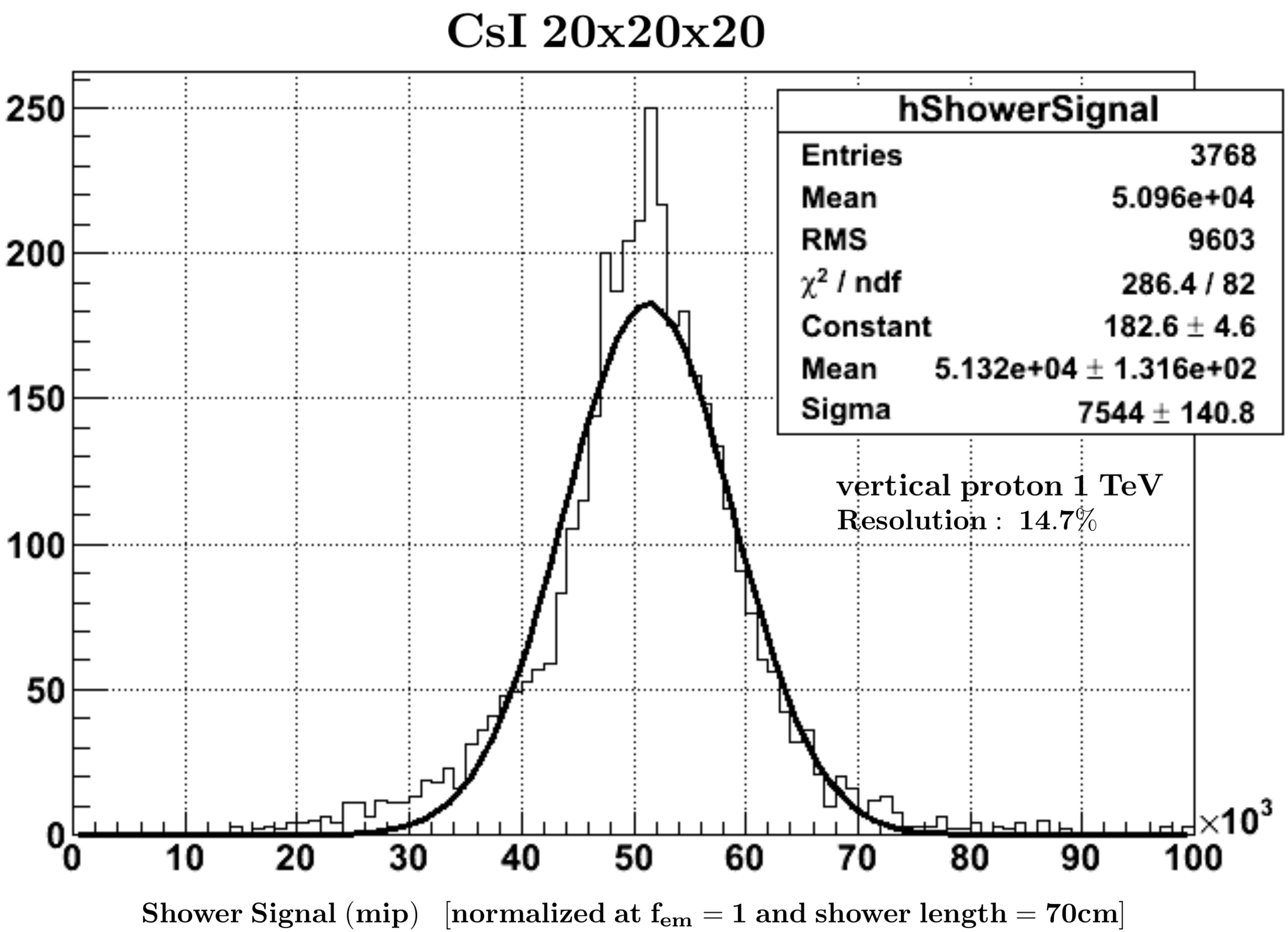


electromagnetic fraction


CsI 20x20x20
hShowerSignal
Entries 3768
Mean x 0.3503
Mean y 1.58e+04
RMS x 0.1334
RMS y 6669
< e >= 43.7 mip/GeV
< h >= 0.75 mip/GeV
vertical proton 1 TeV
Shower Signal (mip)
electromagnetic fraction
0
5000
10000
15000
20000
25000
30000
35000
40000
45000
50000
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

CsI 20x20x20




CsI 20x20x20
hShowerSignal
Entries 3768
Mean 5.096e+04
RMS 9603
χ2 / ndf 286.4 / 82
Constant 182.6 ± 4.6
Mean 5.132e+04 ± 1.316e+02
Sigma 7544 ± 140.8
vertical proton 1 TeV
Resolution : 14.7%
0
50
100
150
200
250
0 10 20 30 40 50 60 70 80 90 100
×10³
Shower Signal (mip) [normalized at f_em = 1 and shower length = 70cm]

The challenge: how to measure f_{em}?

Dual readout –> BGO: scintillation + Cherenkov

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

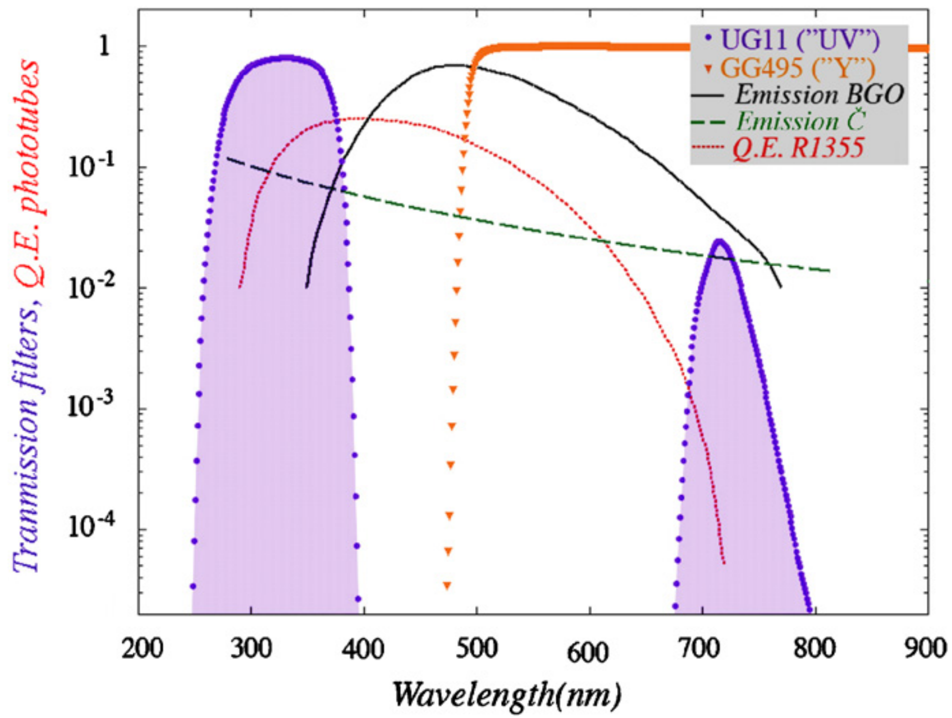
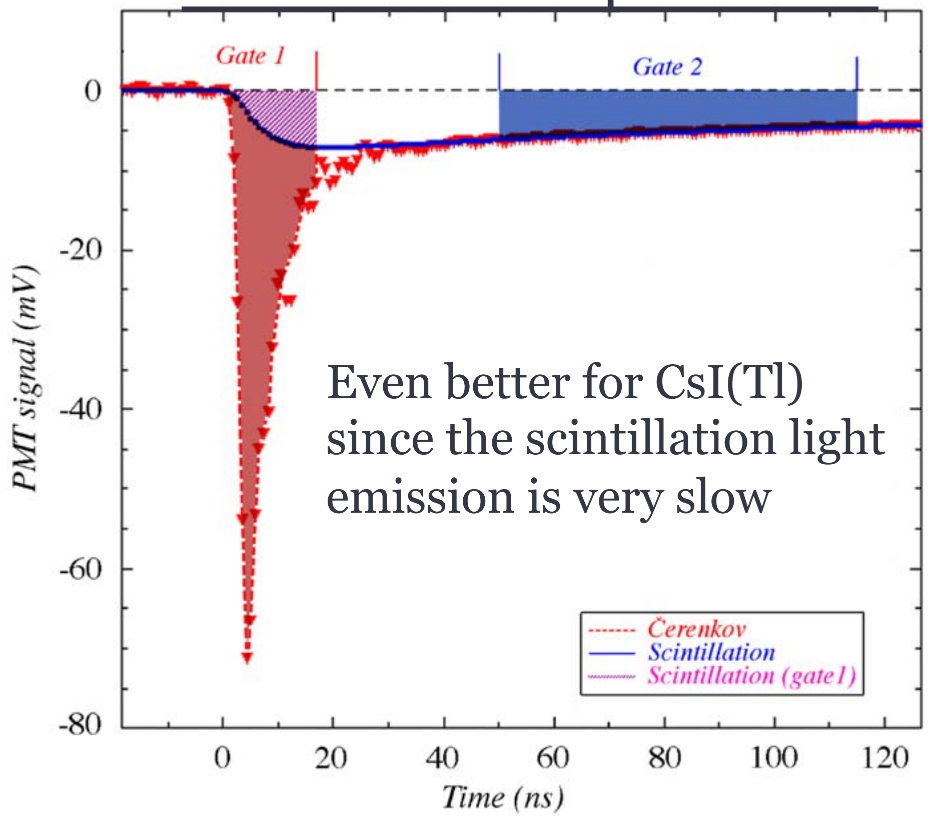


Fig. 14. Light transmission as a function of wavelength for the two filters used to read out the BGO crystal. The light emission spectrum of the crystal, the spectrum of the Cherenkov light generated in it and the quantum efficiency of the PMTs used to detect this light are shown as well. The vertical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

Hardware compensation

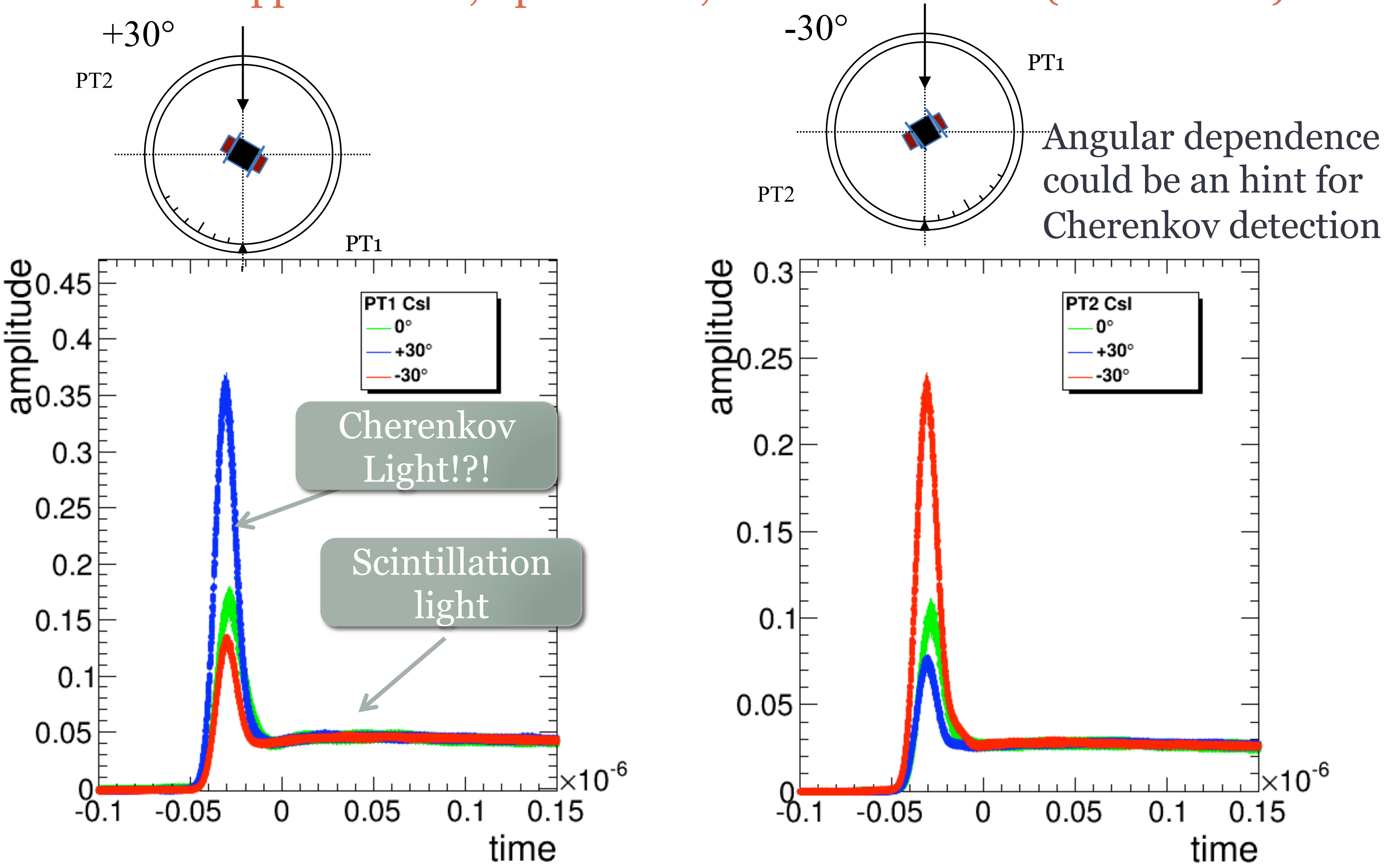


Even better for CsI(Tl) since the scintillation light emission is very slow

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).

Test beam with 500 MeV electrons:

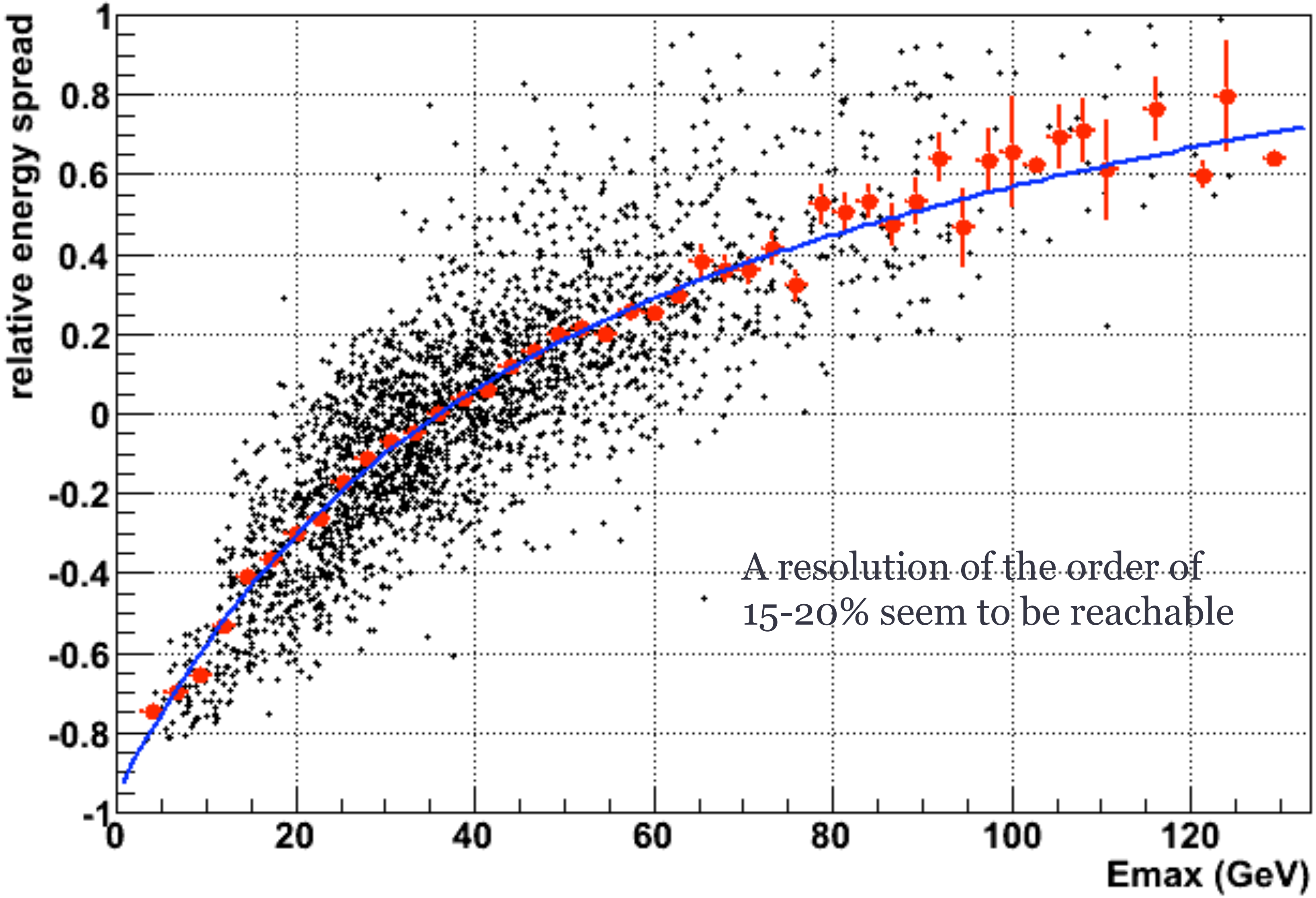
CsI cube wrapped in black, 2 phototubes, both with UV filters (DREAM-like)



Angular dependence could be an hint for Cherenkov detection

Possibility to compensate with homogeneous calorimeter?!?!?!!?

Software compensation



BACKUP

Basic ideas – B and C

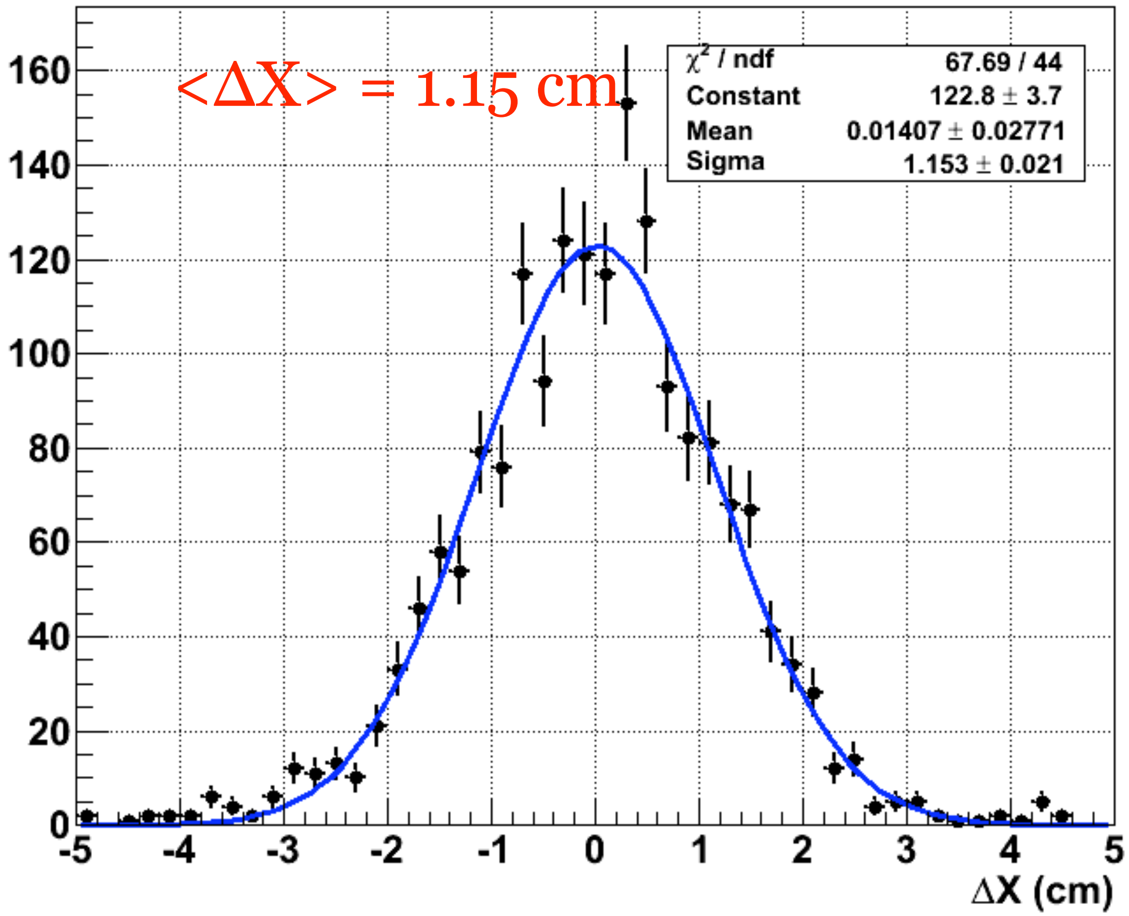
Optimization of the charge identifier system - CIS

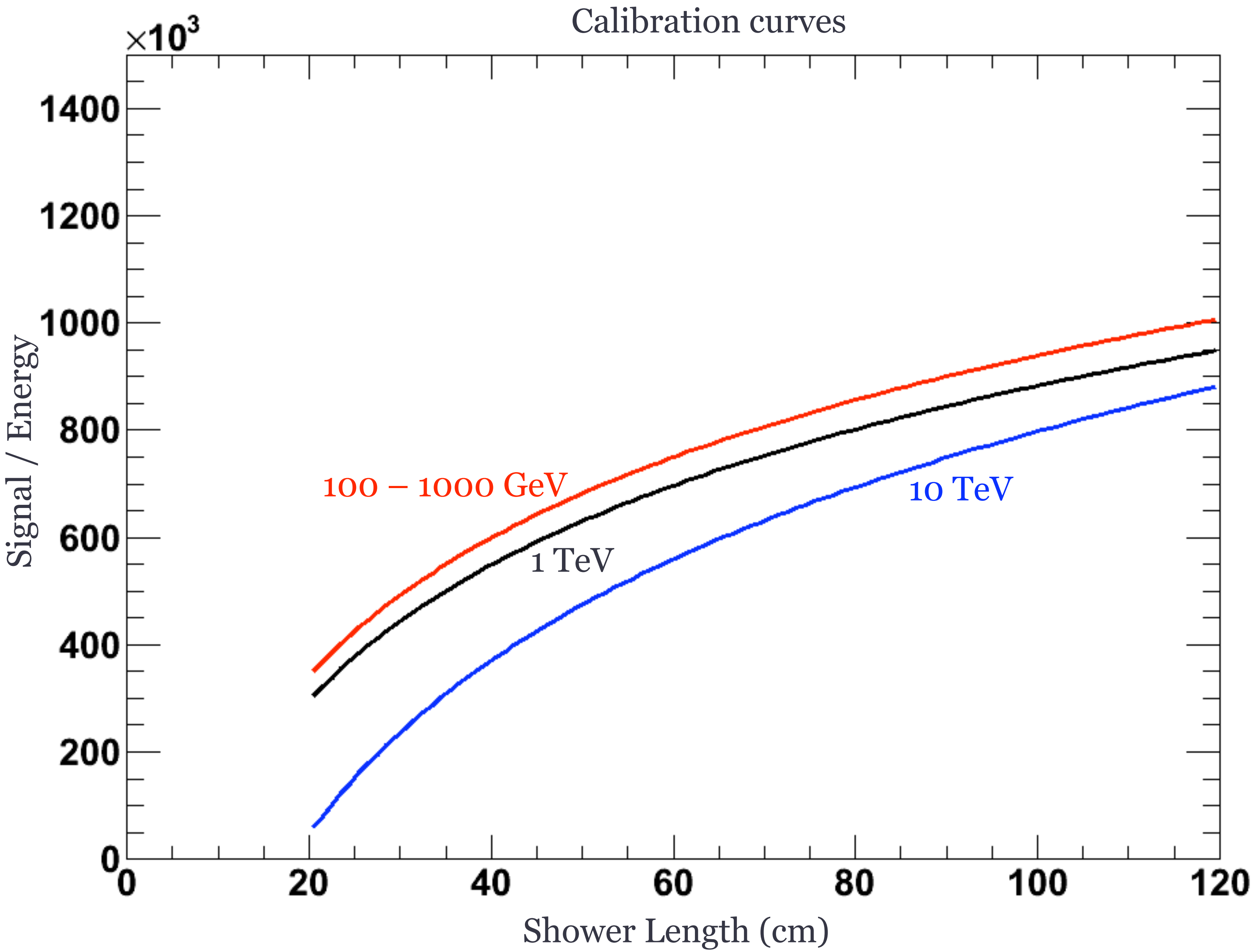
- The integration of the charge identifier system inside the calorimeter is a real break through for a space experiment
  - Huge reduction of mass, power and cost, simplification of the structure
- Thinner size scintillators crystals/Cherenkov radiators
- Pixel structure
- Multiple readouts in the ion track
- Back scattering problem to be carefully studied

Space qualification

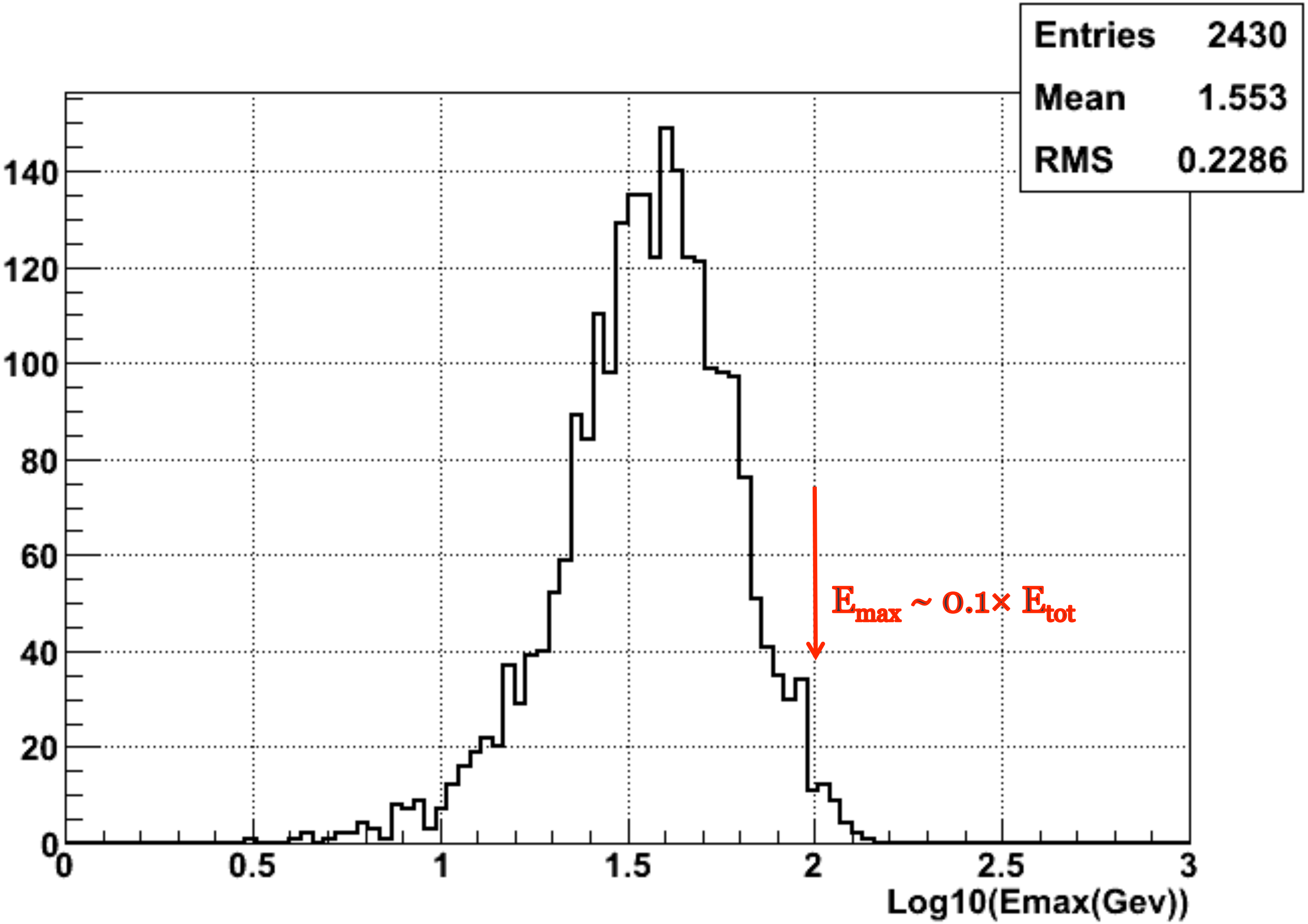
- Demonstrate that such a complex device can be built with space qualified technologies
  - Necessary step for a real proposal for space
  - Production of a space qualified medium size prototype (~700 crystals)
  - Composite materials mechanics
  - Thermal aspects
    - Microcooling technologies to cool down sensors and/or electronics
  - Radiation damage issues

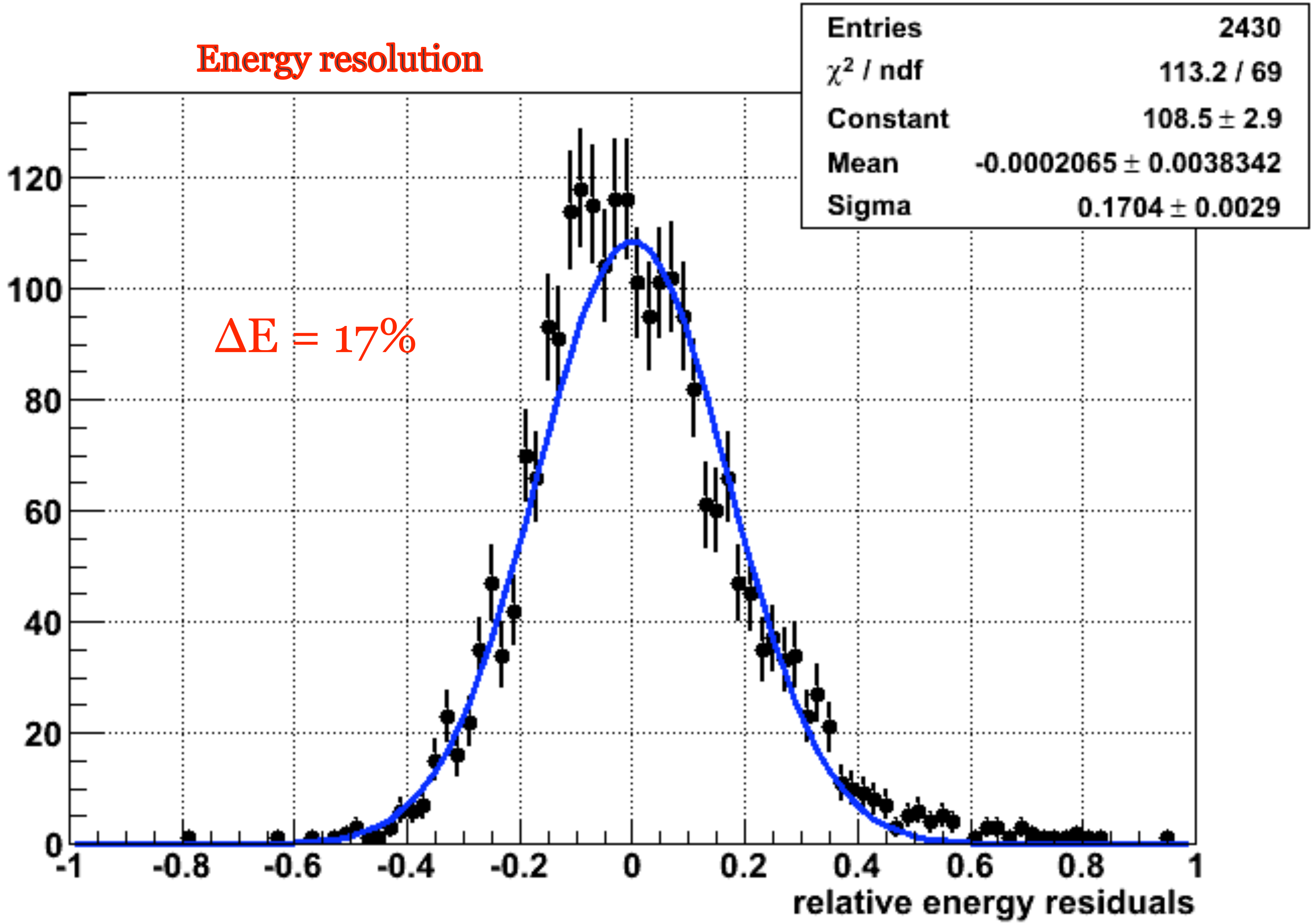
Shower starting point resolution



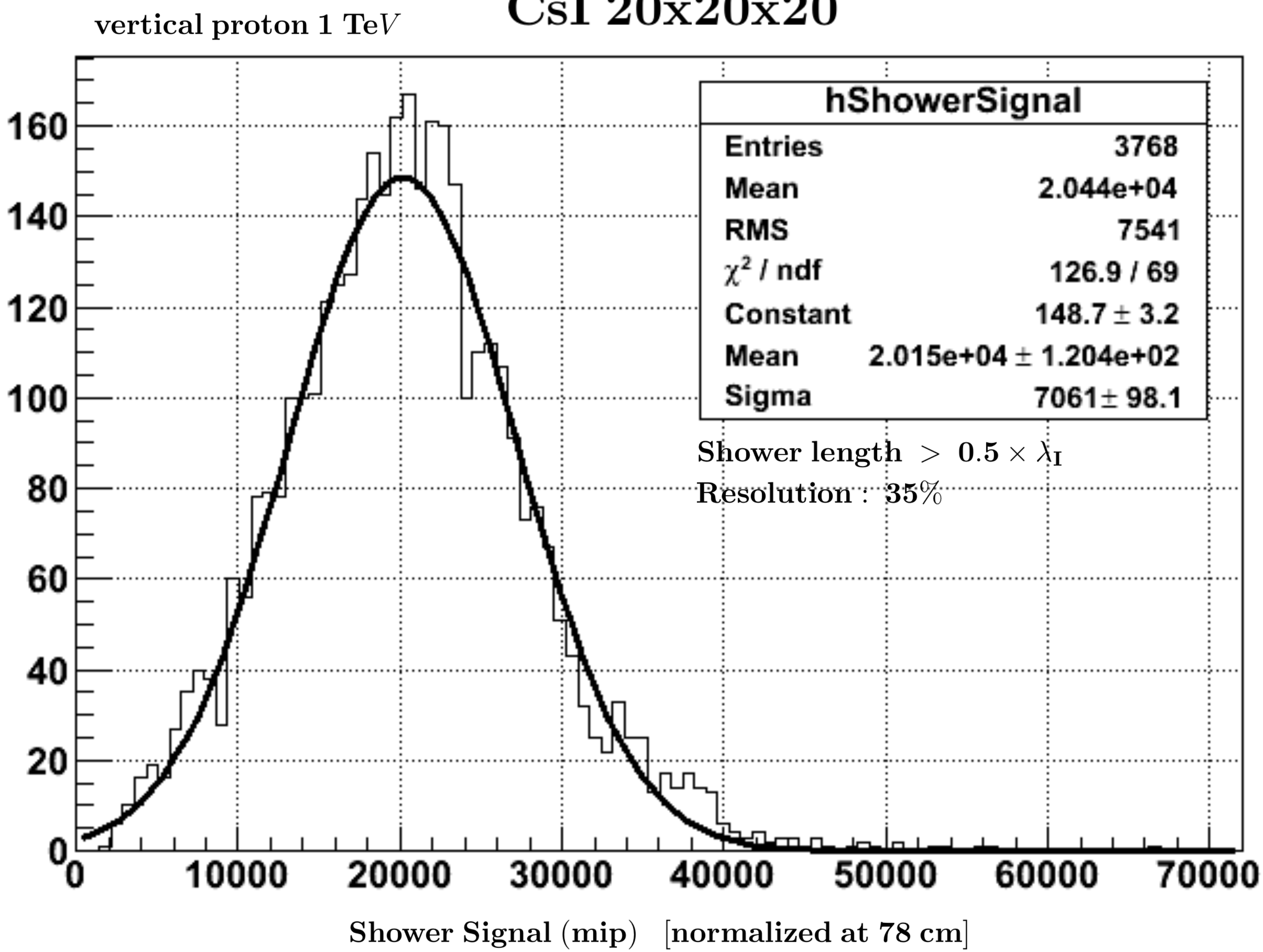


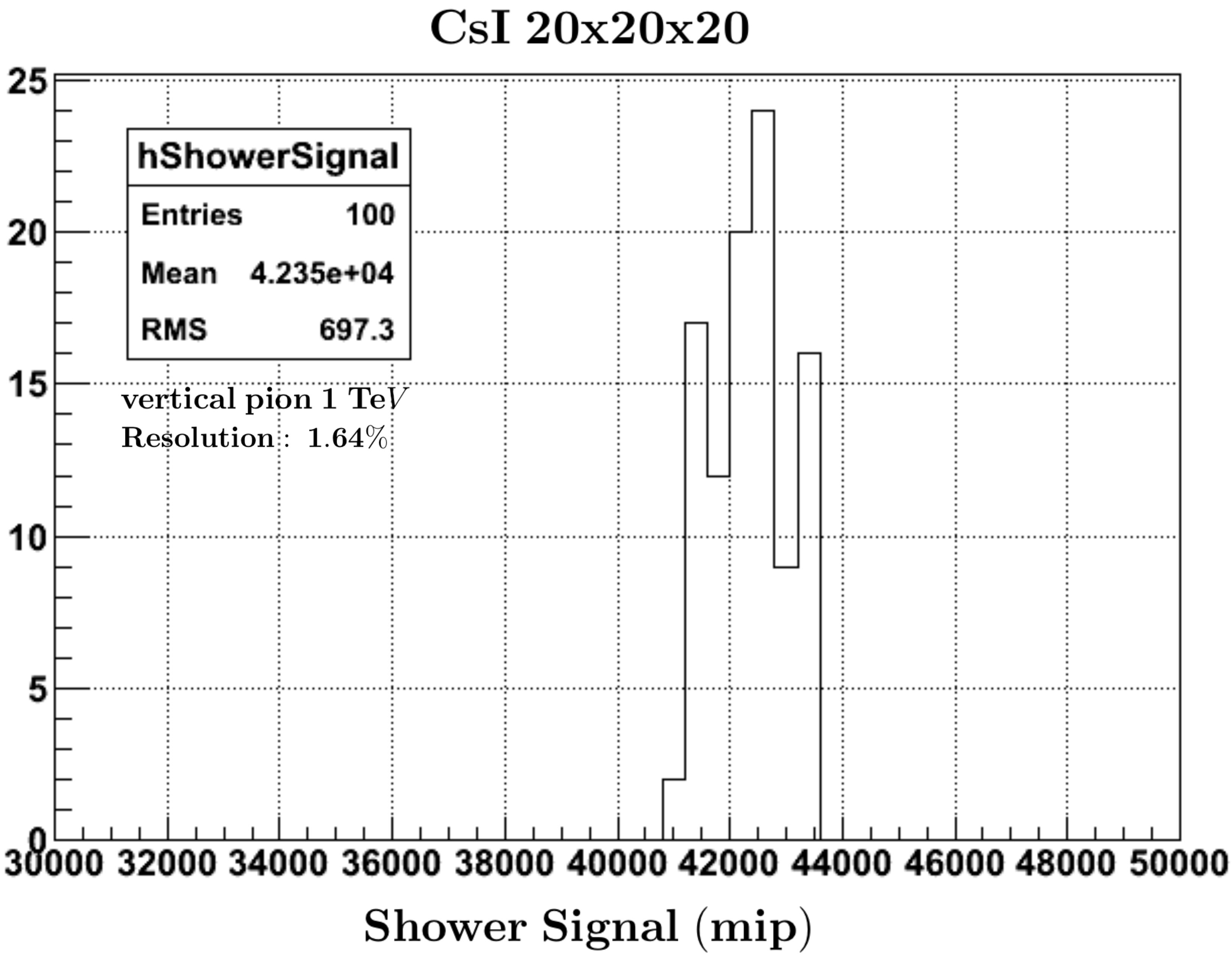
Calibration curves
×10³
1400
1200
1000
800
600
400
200
0
0
20
40
60
80
100
120
Signal / Energy
Shower Length (cm)
100 – 1000 GeV
1 TeV
10 TeV


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))
$E_{max} \sim 0.1\times E_{tot}$

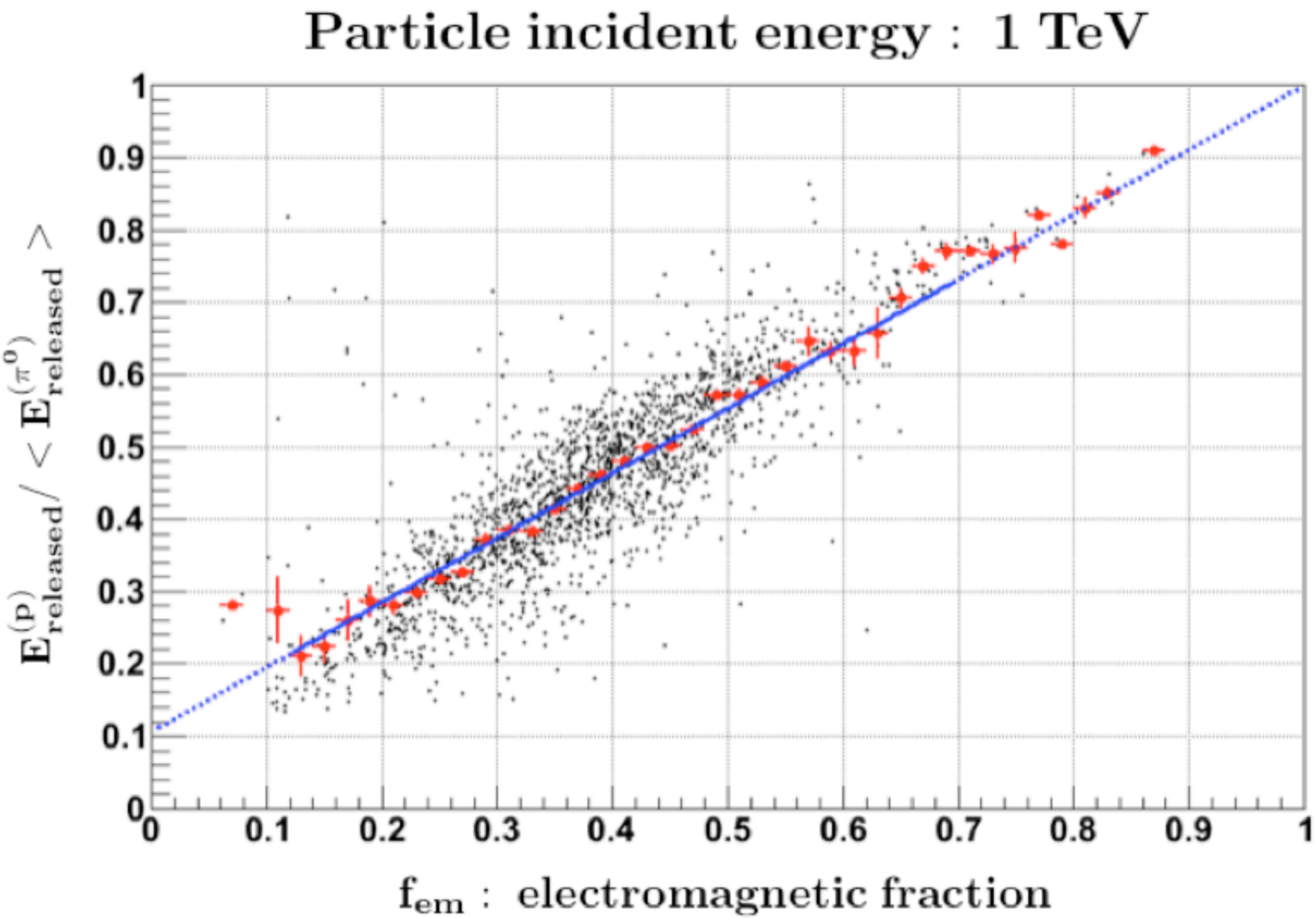

Energy resolution
Entries 2430
χ^2 / ndf 113.2 / 69
Constant 108.5 ± 2.9
Mean -0.0002065 ± 0.0038342
Sigma 0.1704 ± 0.0029
$\Delta E = 17\%$
0
20
40
60
80
100
120
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
relative energy residuals

CsI 20x20x20




CsI 20x20x20
hShowerSignal
Entries 100
Mean 4.235e+04
RMS 697.3
vertical pion 1 TeV
Resolution : 1.64%
0
5
10
15
20
25
30000 32000 34000 36000 38000 40000 42000 44000 46000 48000 50000
Shower Signal (mip)

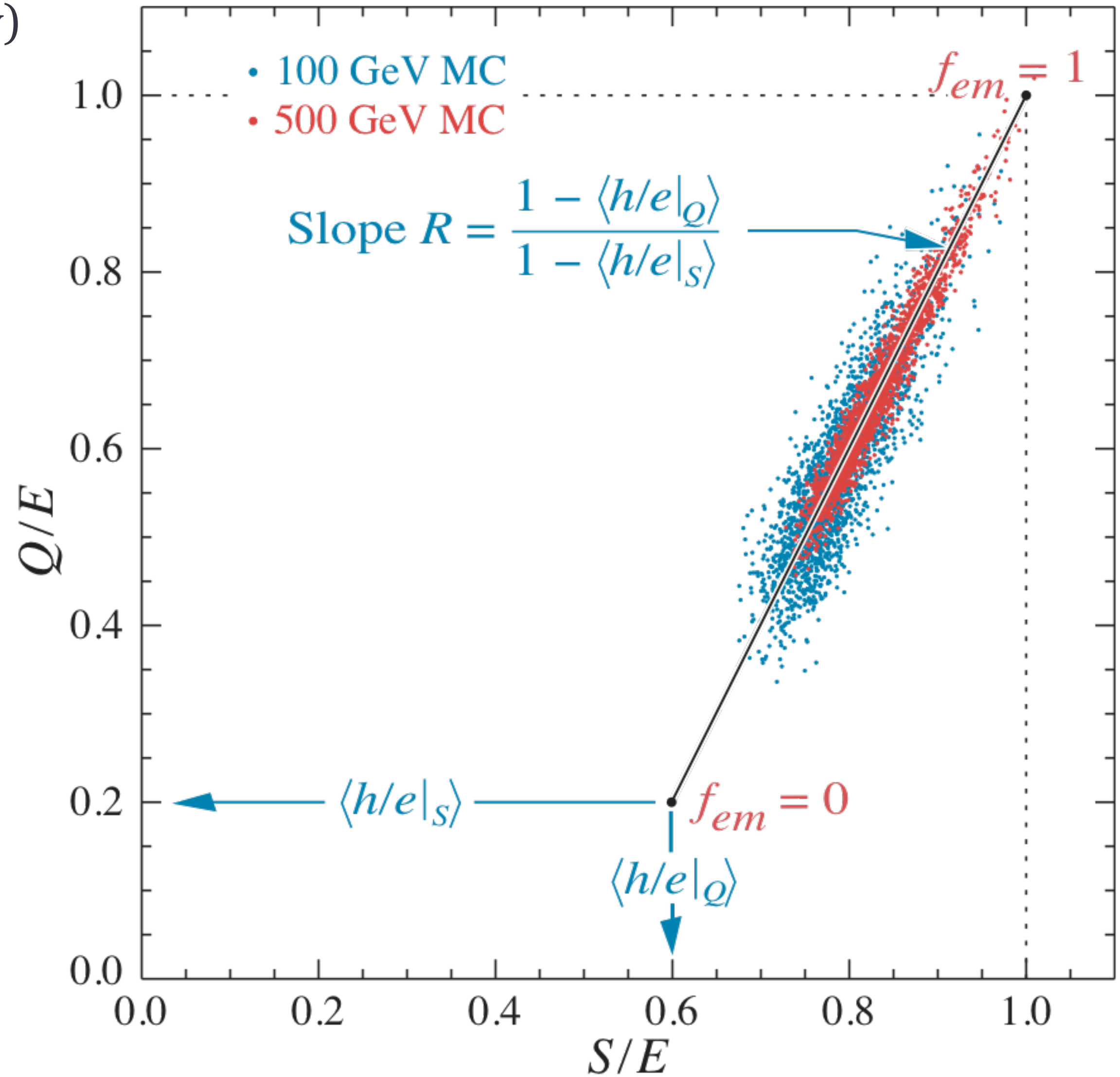
Principle of compensation



Cerenkov detection

$$S = E[f_{em} + (1 - f_{em})\eta_S], \qquad \eta_S = (h/e)_S$$
$$C = E[f_{em} + (1 - f_{em})\eta_C], \qquad \eta_C = (h/e)_C$$
$$E = \frac{RS - C}{R - 1}$$

Q=Quartz (Cherenkov)
S=Scintillator



Sampling fluctuations

Fluctuations in the number of shower particle traversals of the sampling elements

Total track length ($\Delta E_{abs} >> \Delta E_{act}$):

$$T_r = f_s T_0 = f_s N_{tot} X_0^{abs} \approx f_s \frac{E}{E_C^{abs}} X_0^{abs}$$

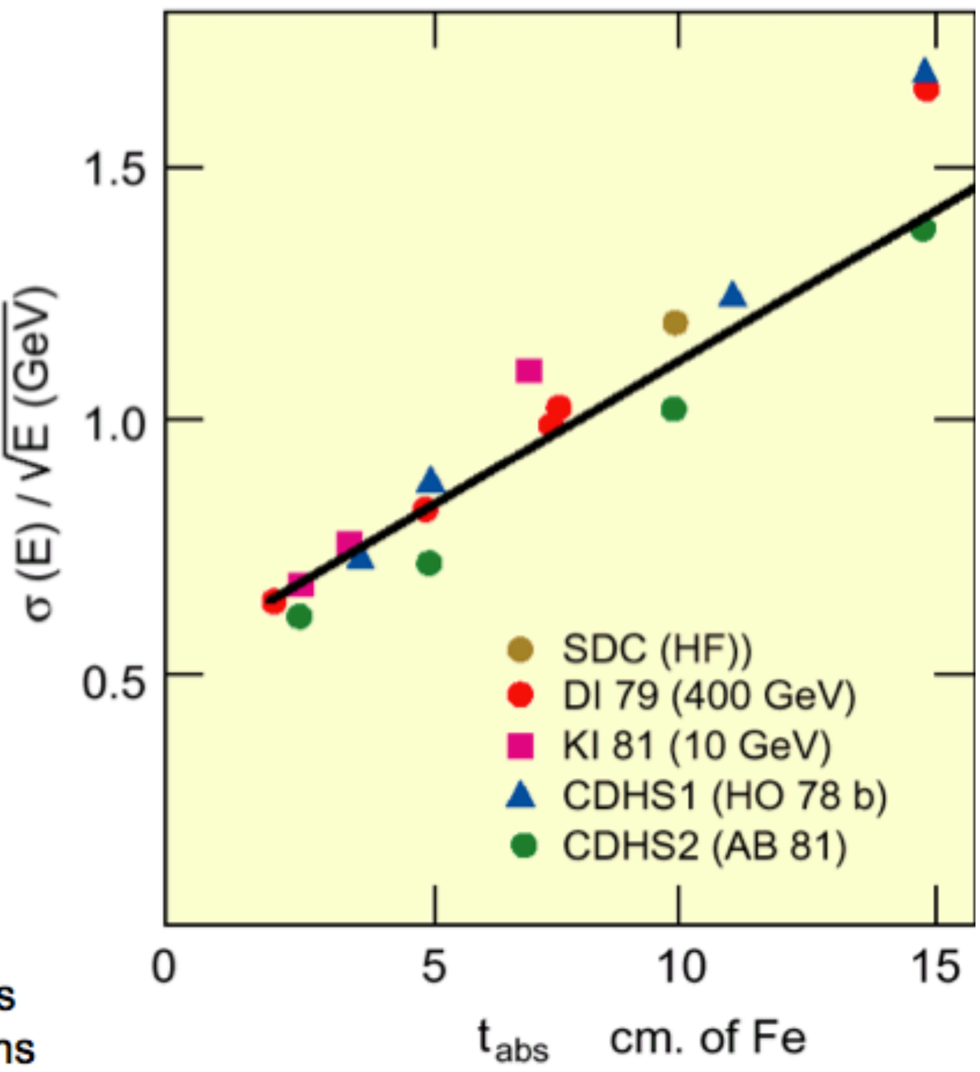
Number of crossings of active layers at distance **d** $\quad d \geq X_0^{abs}$

$$N_r = \frac{T_r}{d} = f_s \frac{E}{E_C^{abs}} \frac{X_0^{abs}}{d}$$

Resolution scales with absorber thickness ($t_{abs} = d/X_o$)

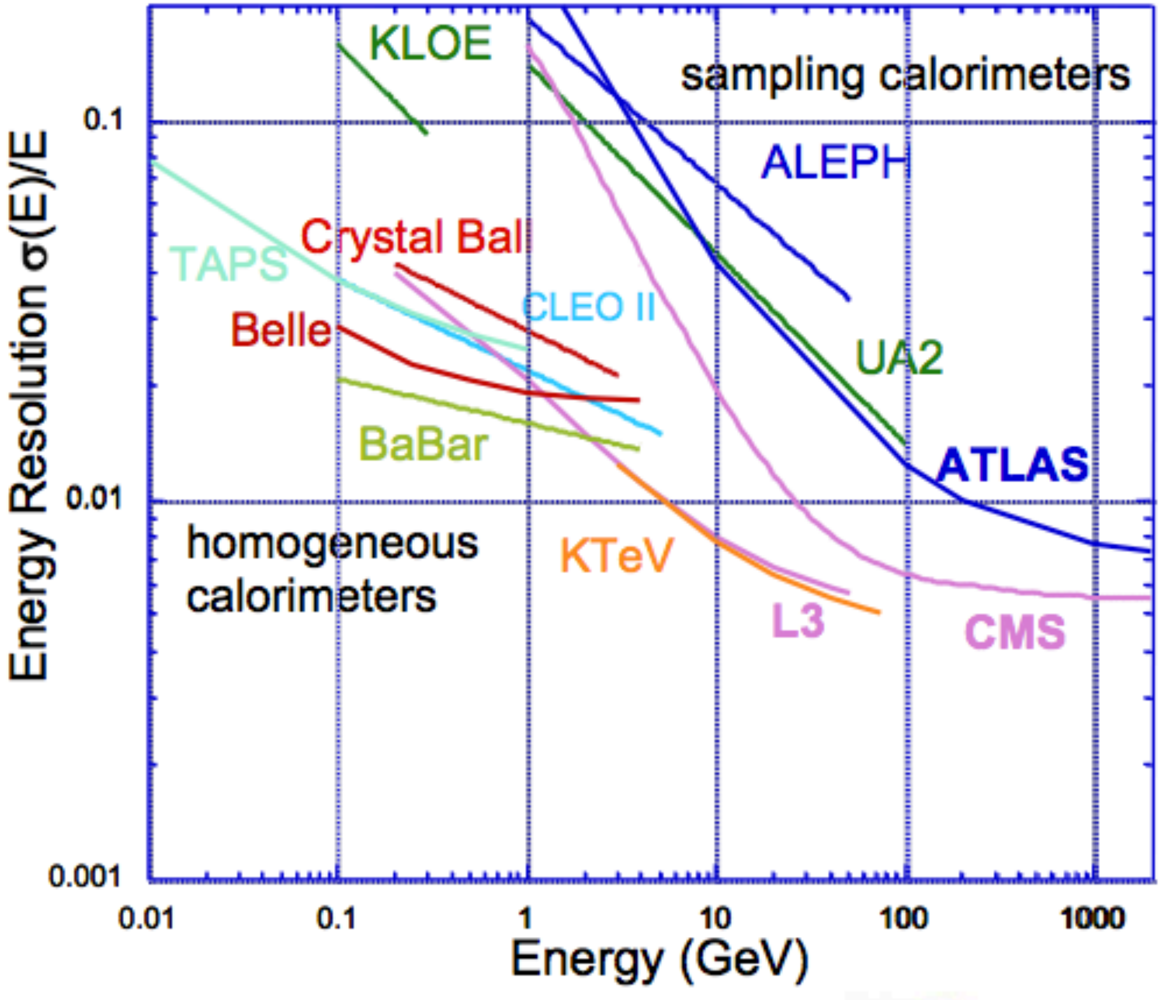
$$\frac{\sigma(E)}{E} \propto \frac{1}{\sqrt{N_r}} \propto \frac{1}{\sqrt{f_s}} \sqrt{\frac{E_C t_{abs}}{E}}$$

NB. Crude approx. valid for solid active materials like plastic scintillators, no path length fluctuations



Calorimeters: a comparison

EACH SYSTEM OPTIMIZED FOR THE ENERGY RANGE OF INTEREST FOR THE EXP



The constant term

c = (leakage)$\oplus$(intercalibration)$\oplus$(system instability)$\oplus$(nonuniformity)

To have c ~ 0.5 % all contributions must stay below 0.3 %

- Leakage
  - front: negligible at high energies
  - rear: dangerous

    increases with $\ln(E)$

    fluctuations are due to interactions in the first X_0 $\not\propto 1/\sqrt{E}$

    but simple to remove $\Rightarrow$ increase number of X_0

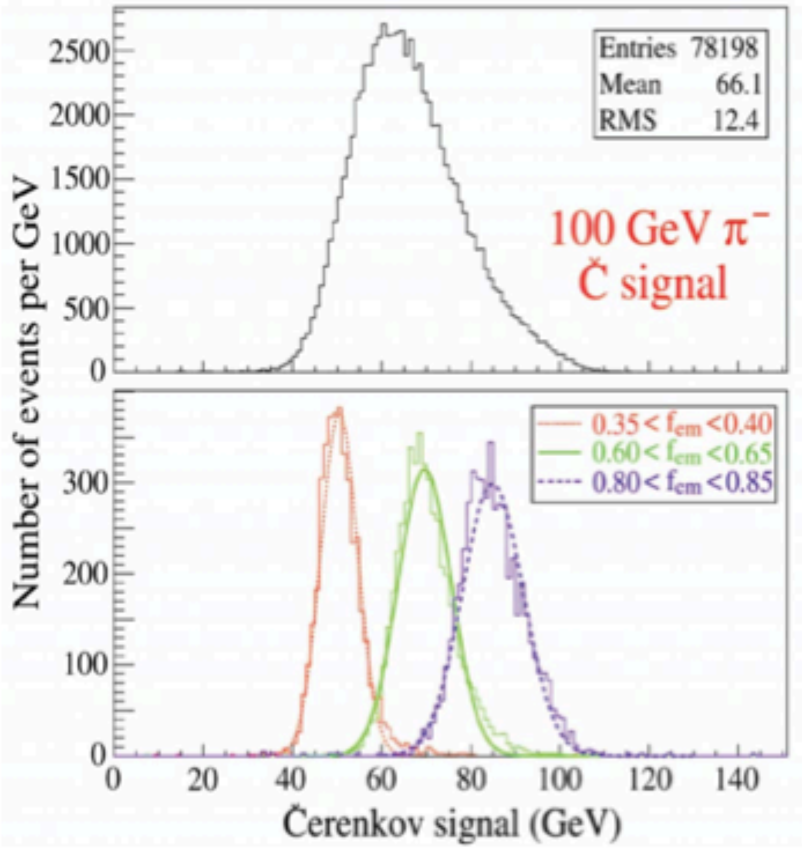
    an empirical parametrization (fraction of energy lost $f<0.1$)

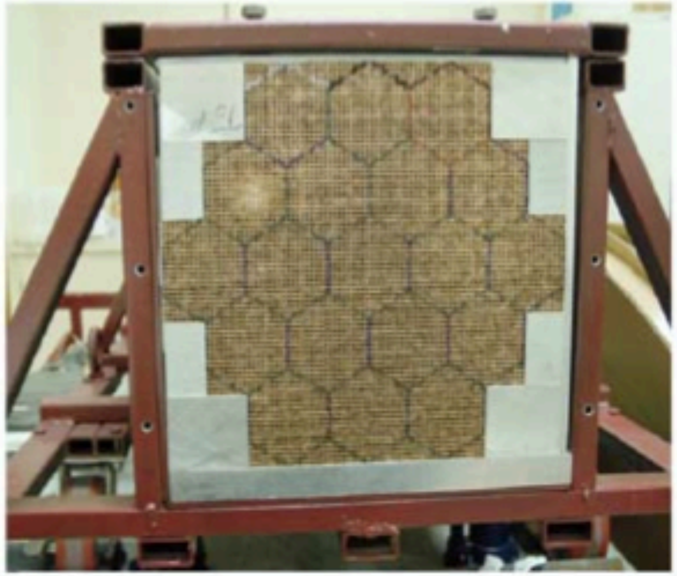
$$\frac{\sigma}{E} \approx \left[\frac{\sigma}{E}\right]_{L=\infty} \cdot (1+4f+50f^2)$$

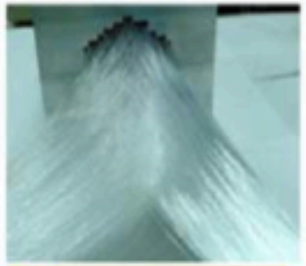
- Blind material: walls, gaps etc.

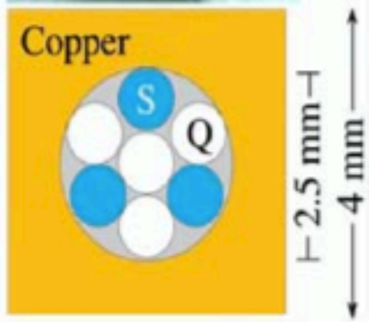
  (CMS full shower simulation: total contribution < 0.2%)

Dual readout: DREAM



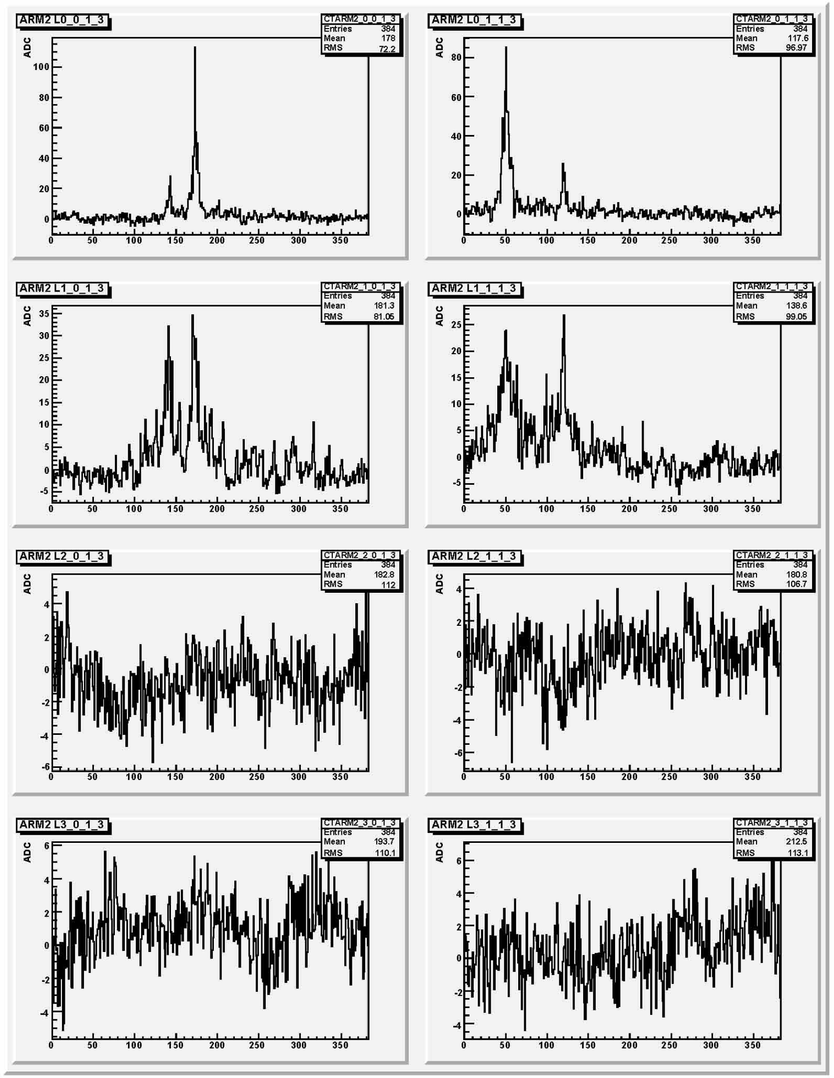




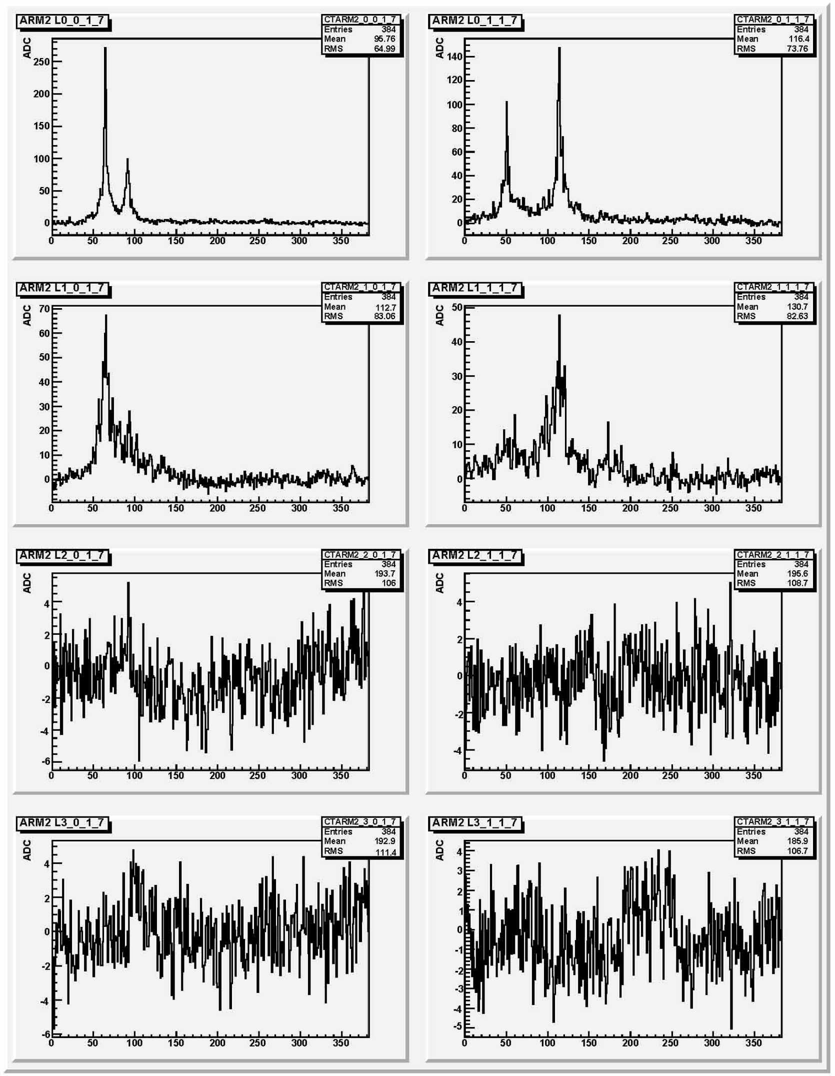


- *Some characteristics of the DREAM detector*
  - Depth 200 cm (10.0 λ_{int})
  - Effective radius 16.2 cm (0.81 λ_{int}, 8.0 ρ_M)
  - Mass instrumented volume 1030 kg
  - Number of fibers 35910, diameter 0.8 mm, total length ≈ 90 km
  - Hexagonal towers (19), each read out by 2 PMTs

100 GeV e-



200 GeV e-



Electron #1

Longitudinal profile