Electron and photon energy reconstruction in the EM calorimeter of ATLAS

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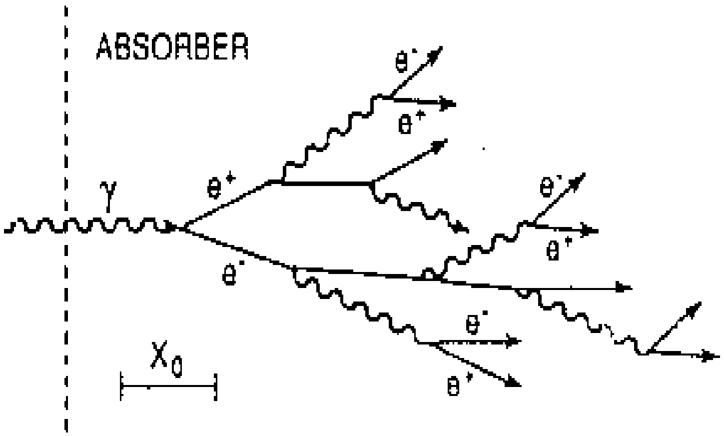
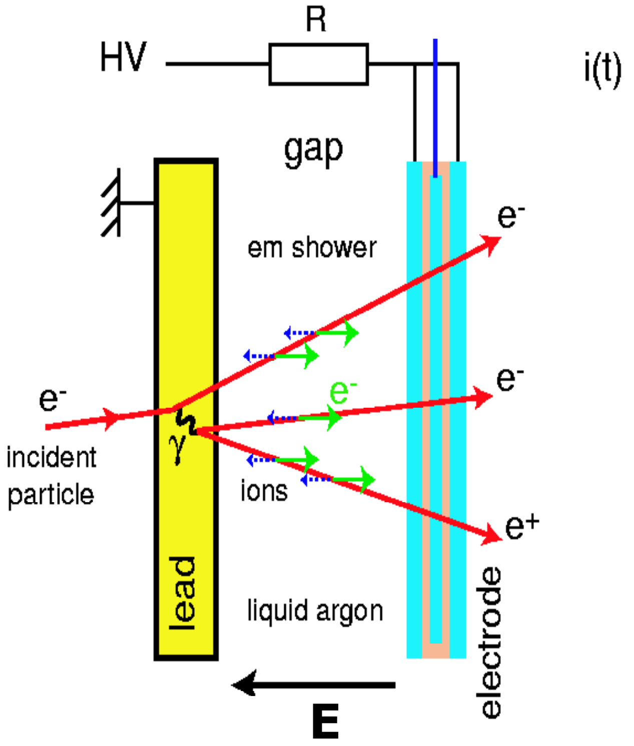
Introduction to EM calorimetry



The initial particle (e-gamma) via bremsstrahlung and/or pair production lead to a cascade of e+, e- and photons, and this process will continue until the energy of the secondary electrons falls below the critical energy Ec, when ionization losses equal those from bremsstrahlung.

Radiation lengt Xo is the length in which an electron reduces is energy by a factor 1/e

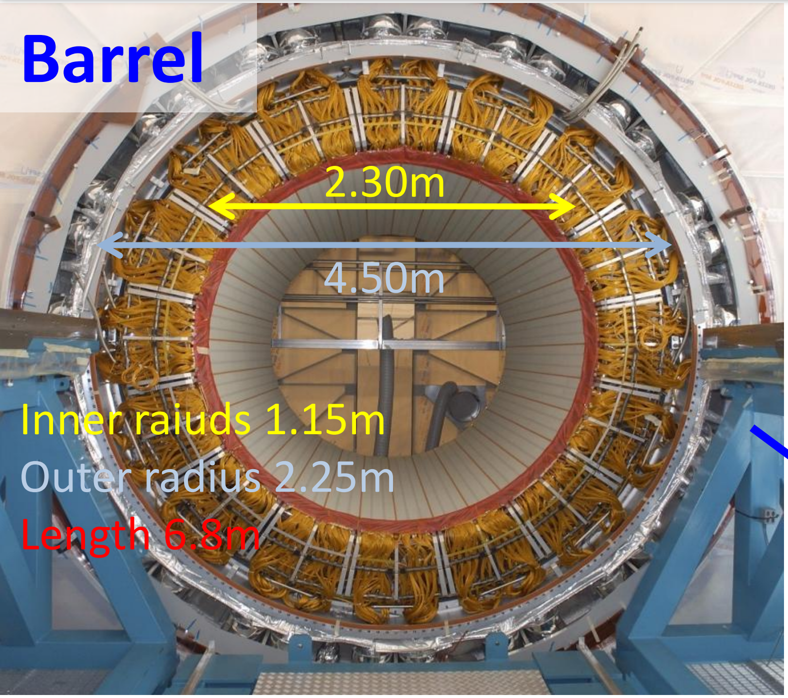


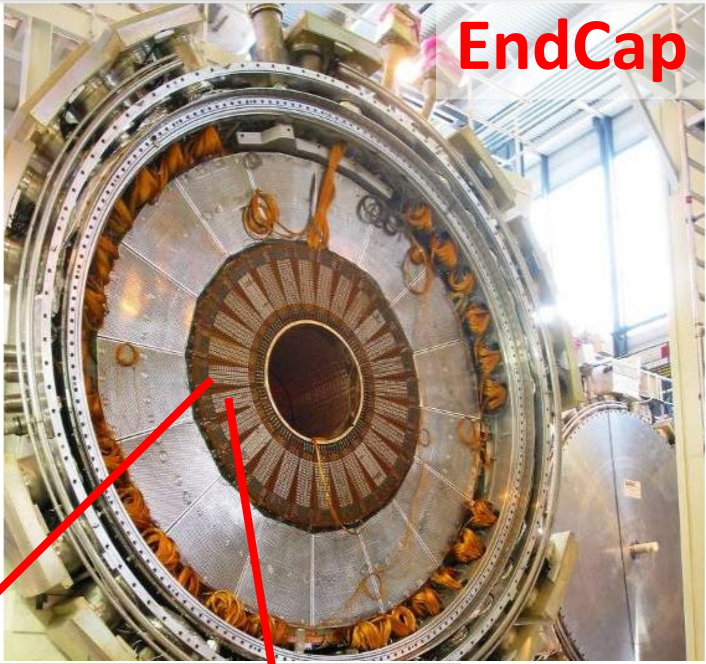
Schematically s Sampling Calorimeter is composed by:

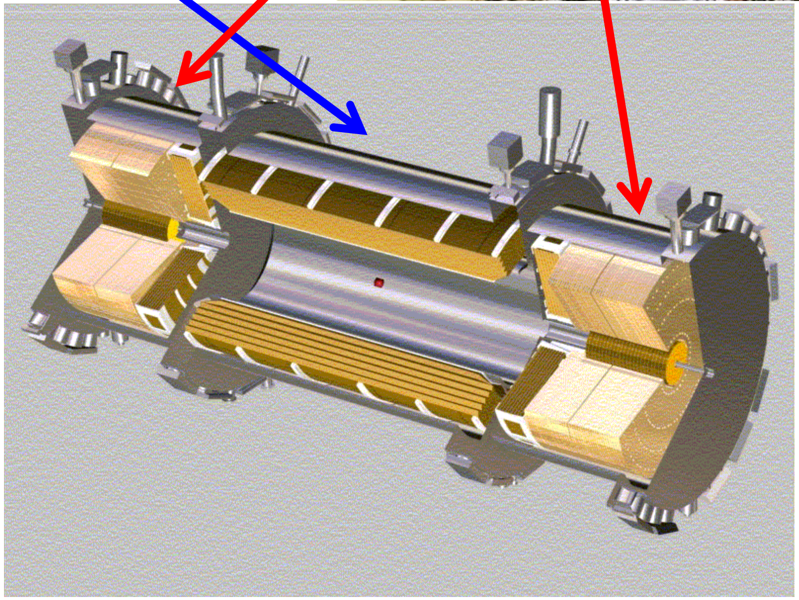
- layers of "active material" instrumented to measure the deposited energy (LAr, Xo=14 cm)
- layers of "inactive material" to enance the showering process (Pb, Xo=0.56cm)

Only a fraction of the energy deposited by the shower , the one in the active material, is measurable. This fraction is called **sampling fraction.**

EM Calorimeter





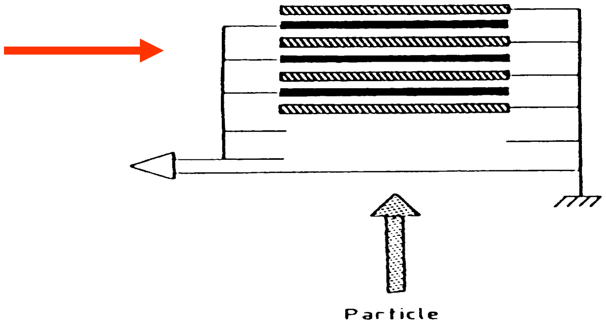


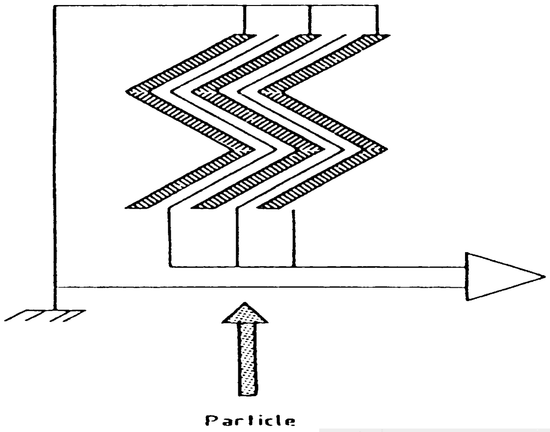
EM Calorimeter

- Sampling calorimeter Pb-Lar (87°K)
- Barrel + 2 EndCaps
- Depth 25-35X_0
- ~170k channel

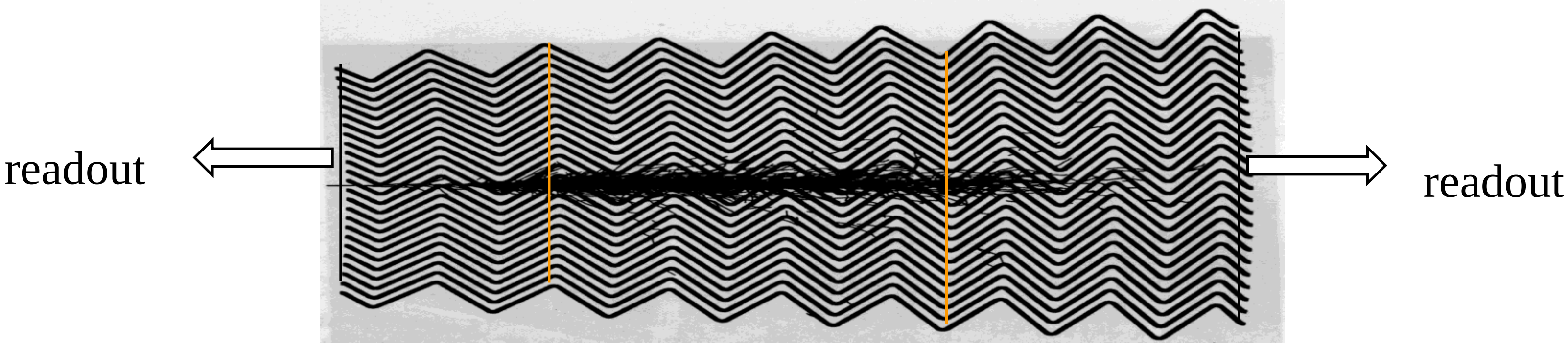
Accordion geometry

Traditional design:
Electrodes perpendicular to particles.
Long leads to gang together
successive layers introduce dead space.

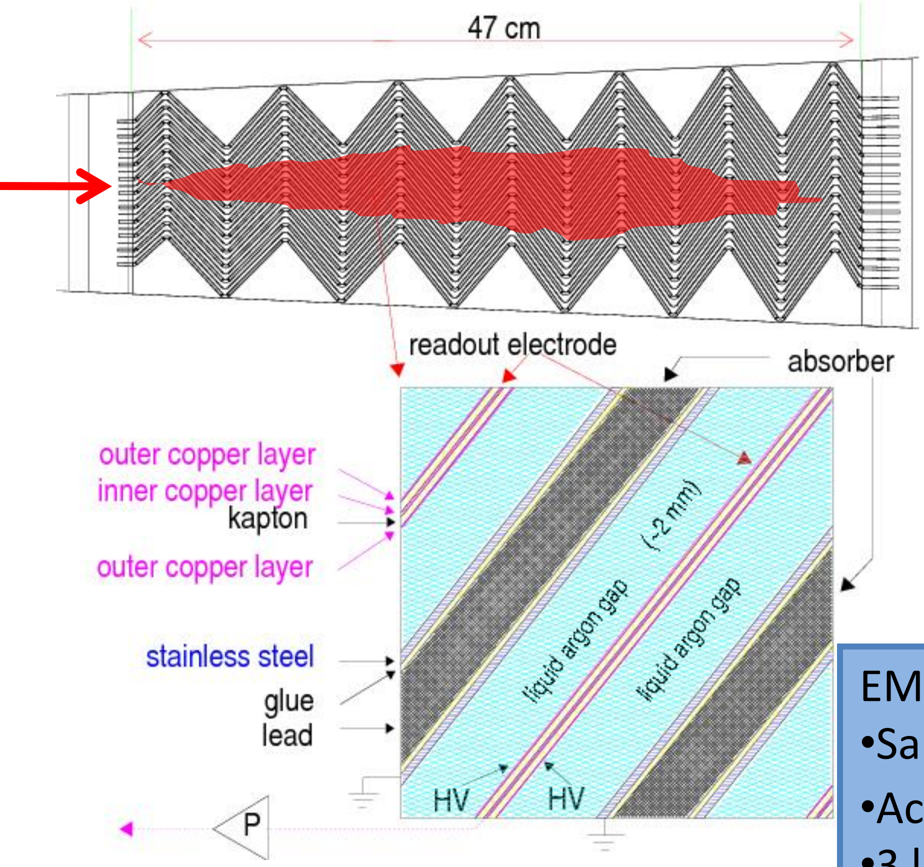


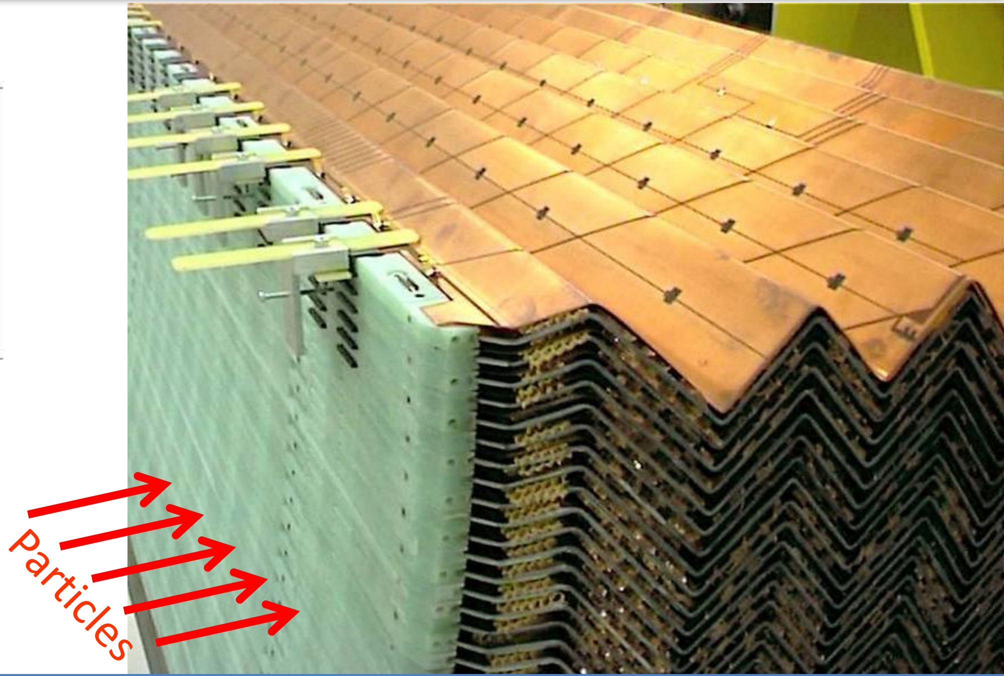


Accordion geometry : Electrodes parallel to the particles and folded in the same direction.
Signal read out at calo front/backfaces → no additional connections no dead space.
Lateral and longitudinal segmentation obtained by etching electrodes .



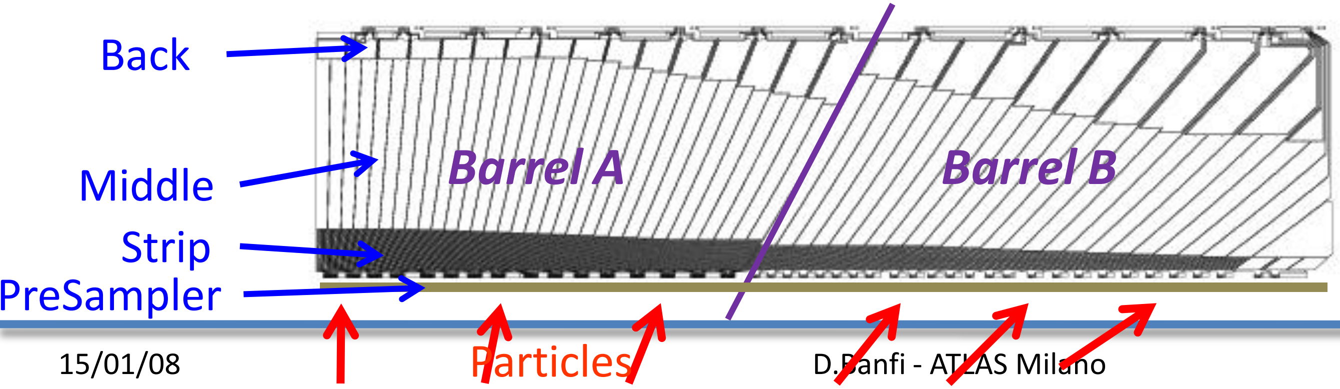
The Barrel EM Calorimeter



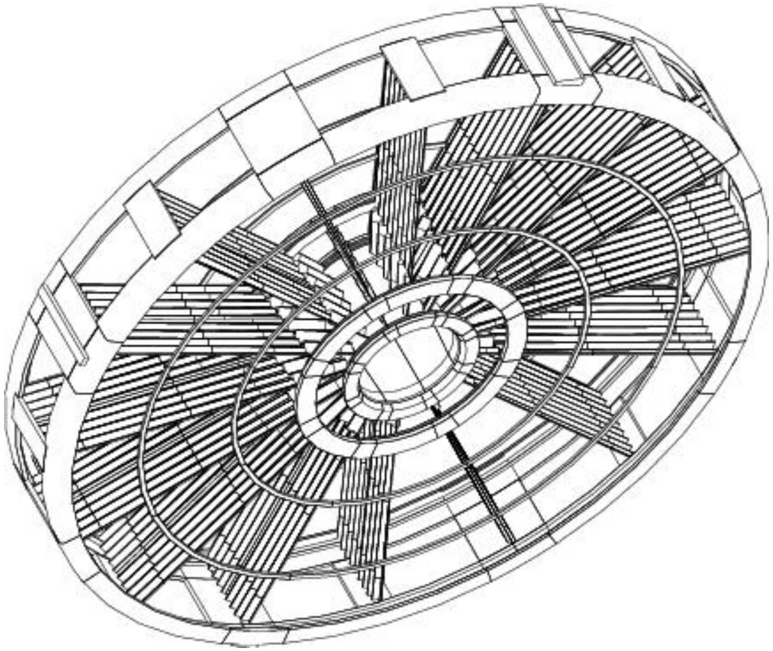


EM Calorimeter Barrel:

- Sampling Pb-Lar (Gap costant)
- Accordion geometry (coverage $|\eta|<1.475$, full in ϕ)
- 3 longitudinal compartments + PreSampler



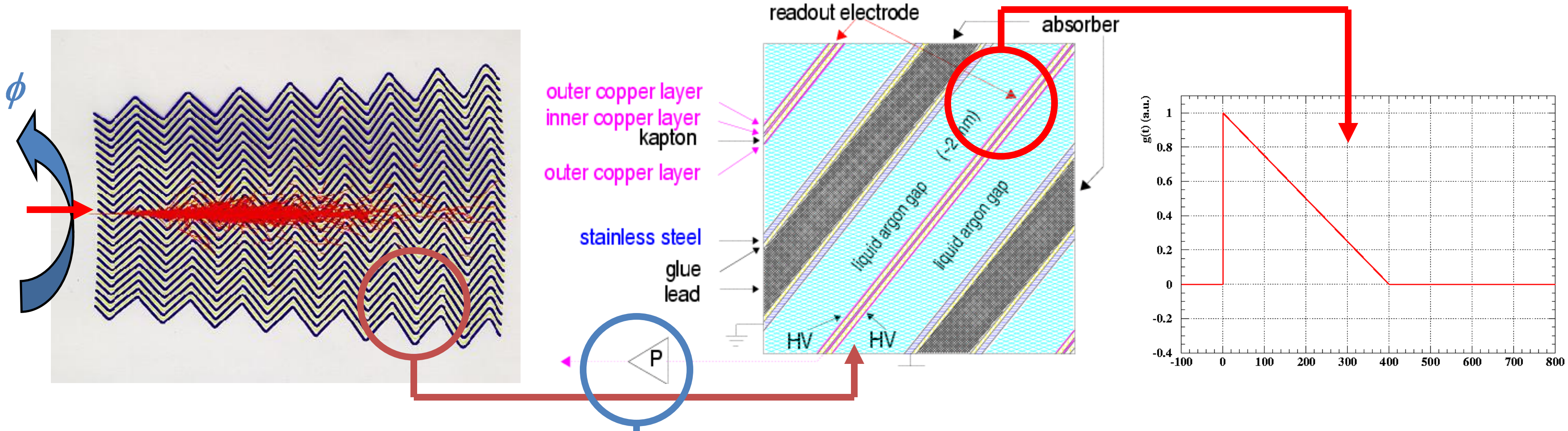
The Endcap EM calorimeter



Endcap EM calorimeter:

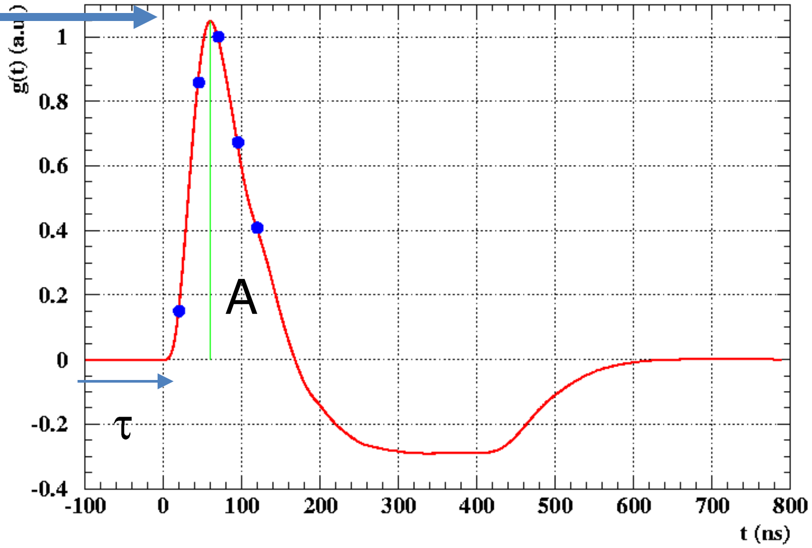
- Sampling Pb-Lar
- Accordion geometry
- 3 longitudinal compartments + PreSampler (only for $\eta<1.8$)
- LAr Gap variable with radius→ variation sampling fraction
- Conversion factor μA→GeV keept almost constant from the variation of the potential between electrodes and absorbers
- Coverture: $1.375<|\eta|<2.5$ (outer wheel), $2.5 <|\eta|< 3.2$(inner wheel), full in ϕ

LAr (EM) signal generation and readout



The LAr signal is generated by the ionisation electrons drifting in the LAr gap thanks to HV between electrodes and absorbers. The peak of the ionisation current is proportional to the energy released in LAr

The triangular current signal is pre-amplifed and shaped (bipolar filter CR-RC^2), then sampled at the LHC bunch crossing frequency (every 25 ns) and digitized



Optimal Filtering Procedure

Optimal Filtering Coefficients

Raw Samples

Energy

$$E = \underbrace{F}_{\frac{ADC}{DAC}\cdot\frac{DAC}{\mu A}\cdot\frac{\mu A}{MeV}} \sum_{i=1}^{5} a_i (ADC_i - P),$$

Pedestal Run

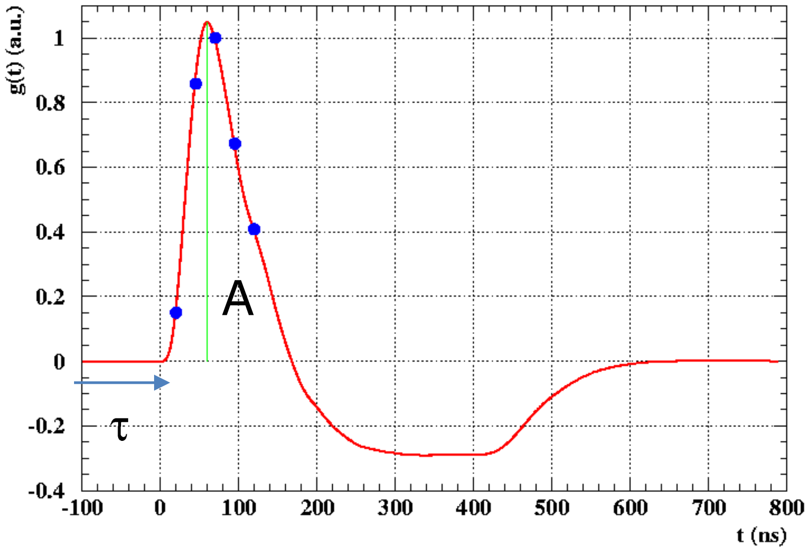
Ramp Run

From TB and MC

Time

$$E.\tau = F \sum_{i=1}^{5} b_i (ADC_i - P),$$

Optimal Filtering Coefficients

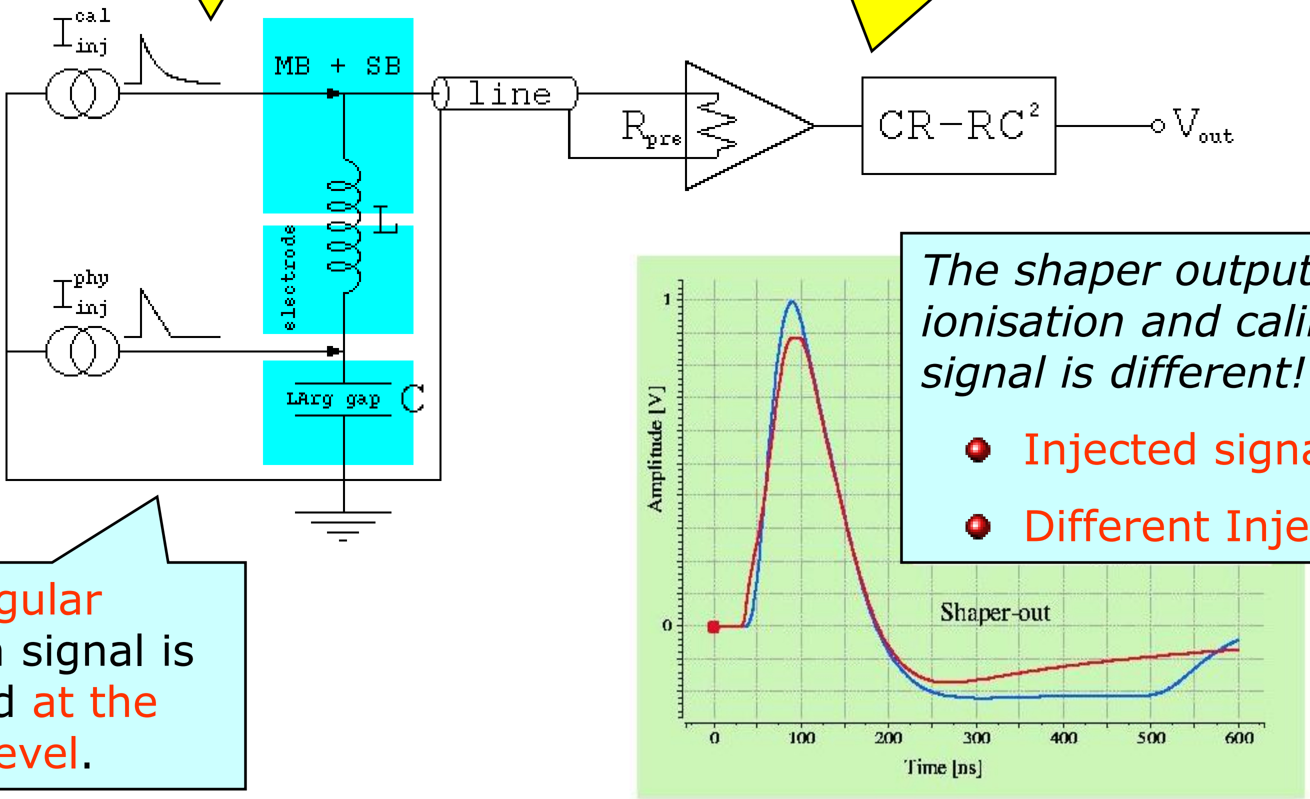


To compute OF Coefficients the shape of the physical signal and the noise autocorrelation matrix are needed.

Calibration of the electronic response

A known exponential current pulse is injected at the MB level…

… and reconstructed through the full readout chain. The actual gain of each readout channel is computed.



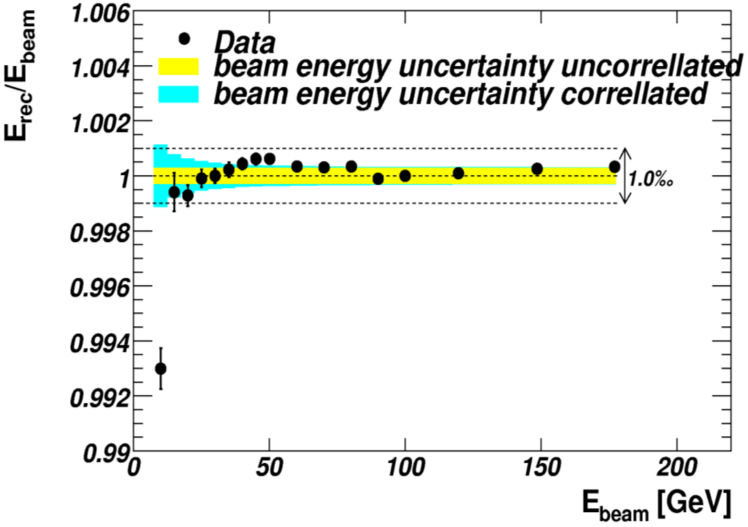
The shaper output of the ionisation and calibration signal is different!

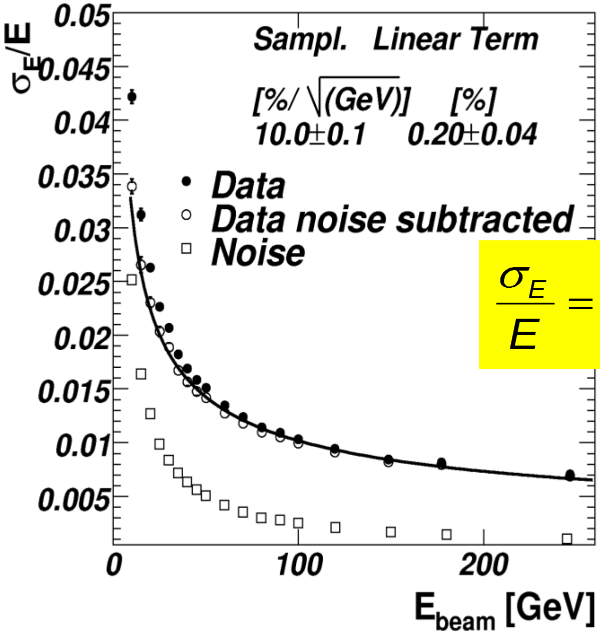
- Injected signal shape
- Different Injection point

The triangular ionisation signal is generated at the LAr gap level.

Physical requirements and TB results

- Resolution and Linearity: exellent performance in the range O(100 GeV) to small E_t to study benchmarks channels H→ γγ, H → eeee
- Dynamic Range: electron and photon reconstruction capability from few GeV (b-physics) up to few TeV (Z'→ ee) is required (three gain levels)
- Calo TDR goals for $|\eta| < 2.5$:
  - Constant term < 0.7% (ATLAS)
  - Linearity better than 0.5%





$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

Linearity (barrel):

- ± **0.1%** (excluded 10 GeV point)
- Better than ± **0.1%** between 20 – 180 GeV

Resolution:

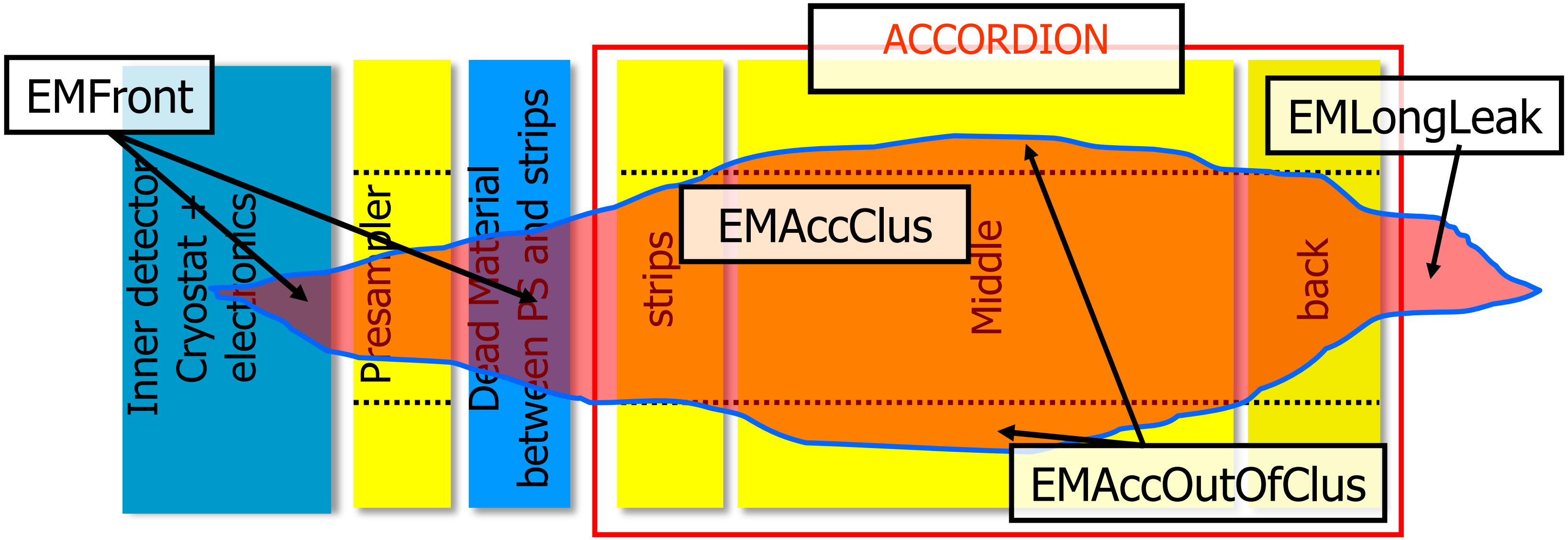
- Sampling term(a): Barrel **~10%** Endcap **<12.5%**
- Noise elettronico(b): **~250 MeV** (cluster 3x3)
- Local constat term(c): **~0.2 %**

e-gamma energy reconstruction methods

- Two available methods for electrons and photons calibration: now both available into Athena
  - Calibration weights from minimization (default until release 13)
  - Calibration coefficients from calibhits based simulations (default from release14)
- Both method based on MC simulation
- The new method is based on Calibration Hits simulation that allows to know all the energy depositions into the detector, not only the ones in the active layers
- The proposed method starts from the knowledge of the energy deposited from electrons and photons into the various compartments already calibrated to EM scale

CalibHits based e-gamma calibration

- Compute corrections for each effect (from montecarlo) correlating each energy depositions to a measurable quantity
- Different parameterizations of the different corrections have been used
- Parameters extracted for each cell adding the statistics of five adjacent cells



CalibHits based e-gamma calibration (2)

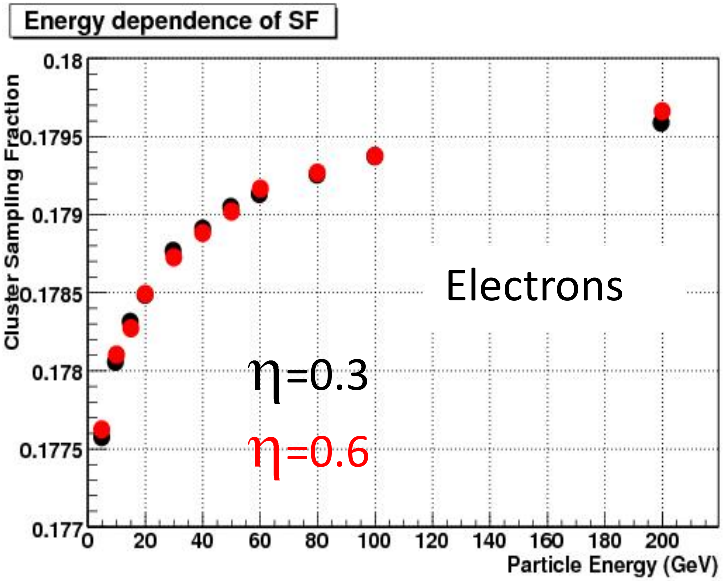
- The presented results are based on one implementation of the calibhits method (ATL-LARG-2007-007) and currently implemented into Athena:
  - EMAccClus :
    - energy deposited in the accordion in the cluster (fz. of longitudinal barycenter)
    - cluster dependent, common e/γ
  - EMAccOutOfClus:
    - energy deposited in the accordion outside the cluster (fz. of longitudinal barycenter)
    - cluster dependent, different for e/γ
  - EMLongLeak:
    - energy longitudinally escaped from the em calo (fz. of longitudinal barycenter)
    - cluster independent, different for e/γ
  - EMFront :
    - energy lost in the material in front of the accordion (fz. of energy in the accordion)
    - cluster independent, different for e/γ

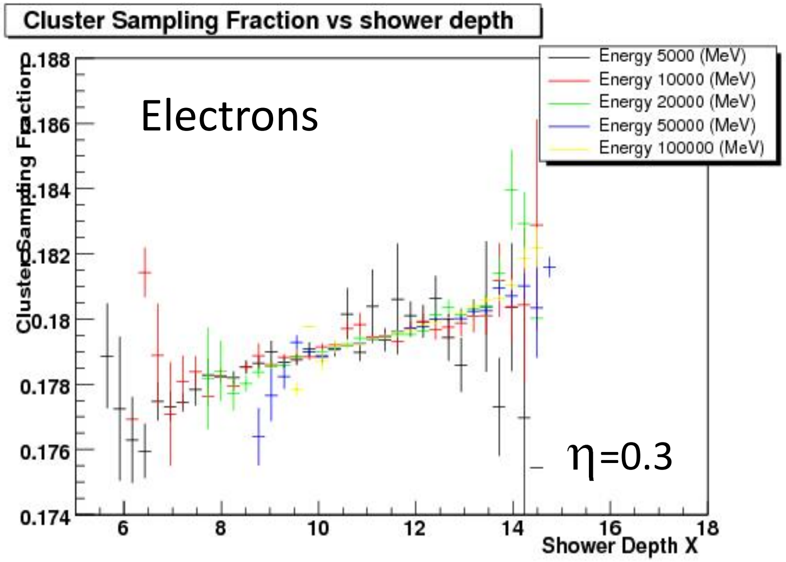
$$E^{reco} = F(E^{reco}_{acc},\eta)\cdot E^{cl\,lAr}_{ps} + S_{acc}(X,\eta)\cdot\Big(\sum_{i=1,3} E^{cl\,lAr}_{i}\Big)\cdot(1+C_{out}(X,\eta))\cdot(1+f_{leak}(X,\eta))$$

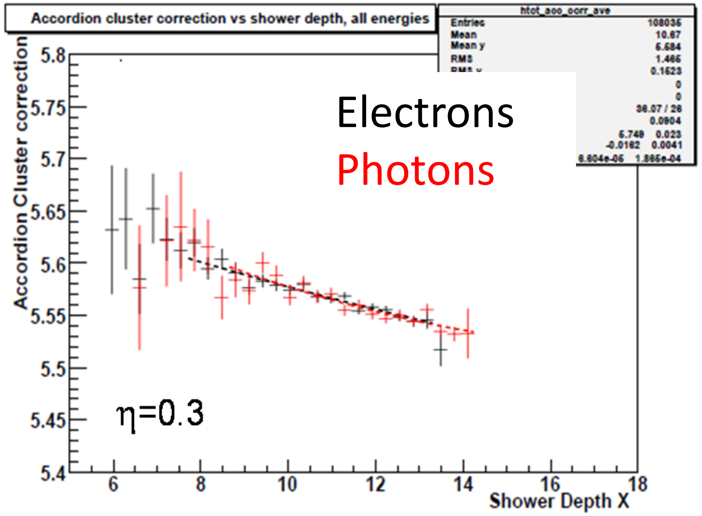
Longitudinal Barycenter
(Shower depth)

$$X = \frac{\sum_{i=1}^{4} E_i^{LAr} X_i}{\sum_{i=1}^{4} E_i^{LAr}}$$

Energy reconstruction in the accordion Cluster



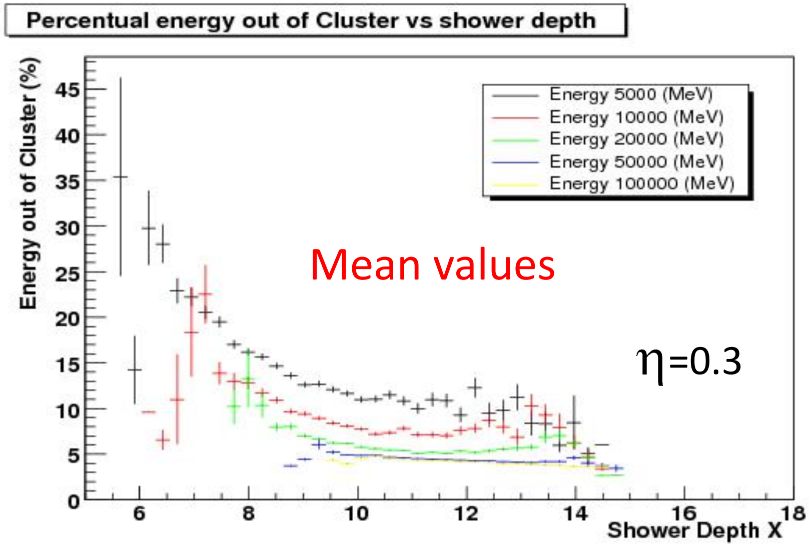




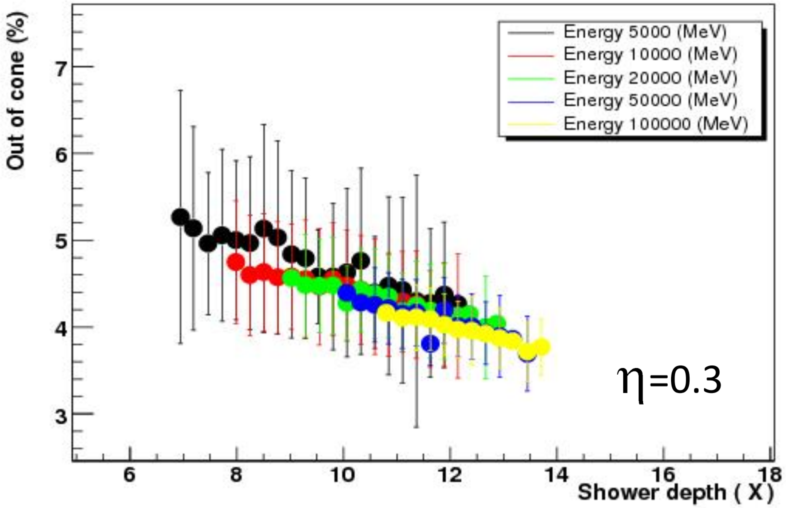
- Sampling fraction is energy dependent (ATL-LARG-2004-001, Linearity paper..)
- From ATLAS simulation parametrize as a function of the longitudinal barycenter makes the sf pretty energy independent.

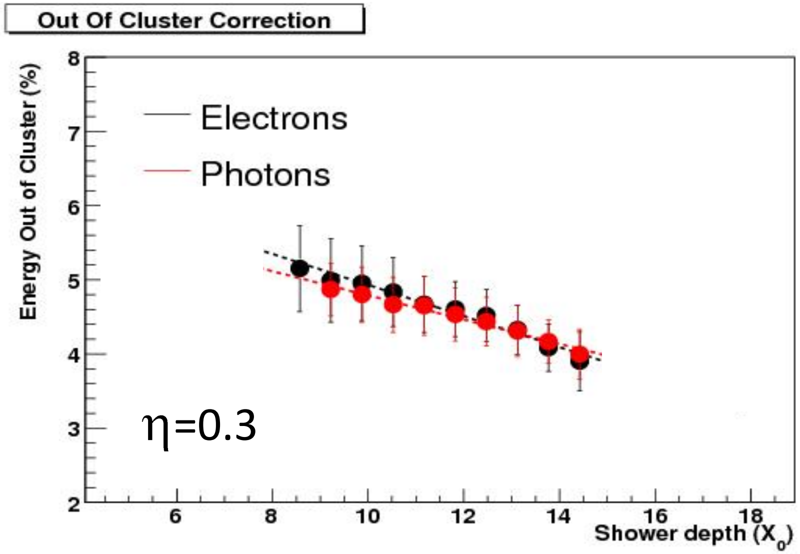
$$S_f = \frac{E_{Acc}^{cl\_LAr}}{E_{Acc}^{cl\_LAr} + E_{Acc}^{cl\_Abs}}$$

Energy reconstruction in the accordion: out of cone correction



The distribution inside each X bin are not Gaussian→ the mean does not represent the average behavior of the sample

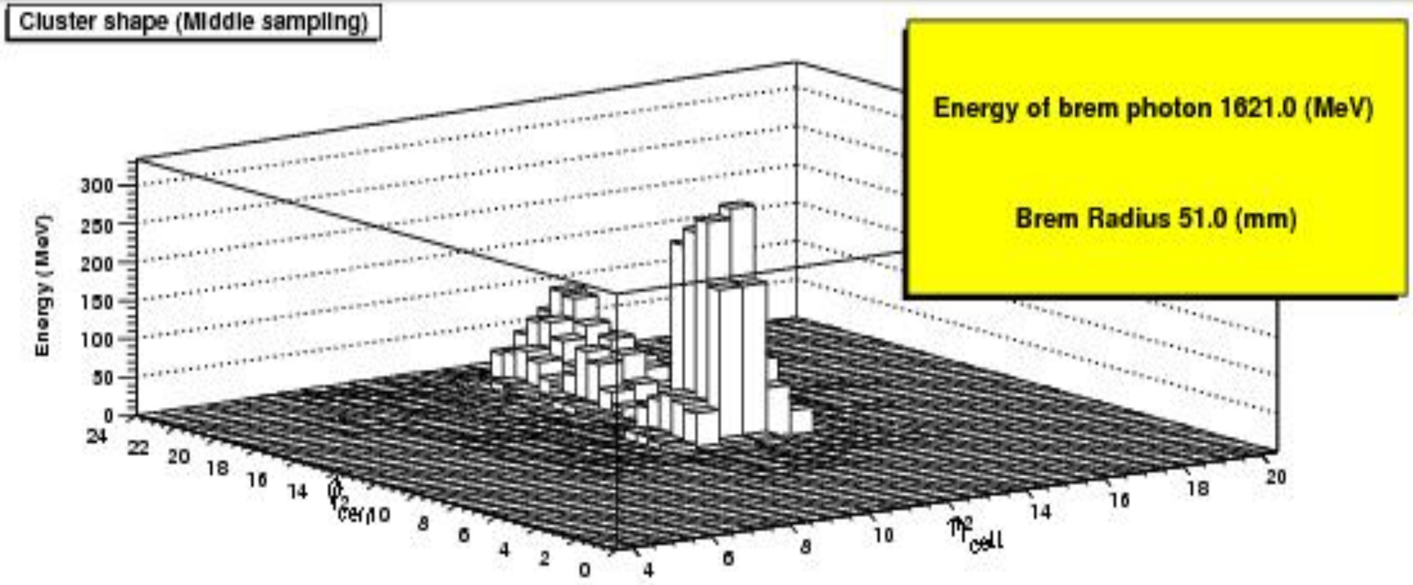




- In ATL-LARG-PUB-2007-012 we separate the correction for accordion and out of cone : this turned out to be relevant when the B field is on in order to make the correction energy independent

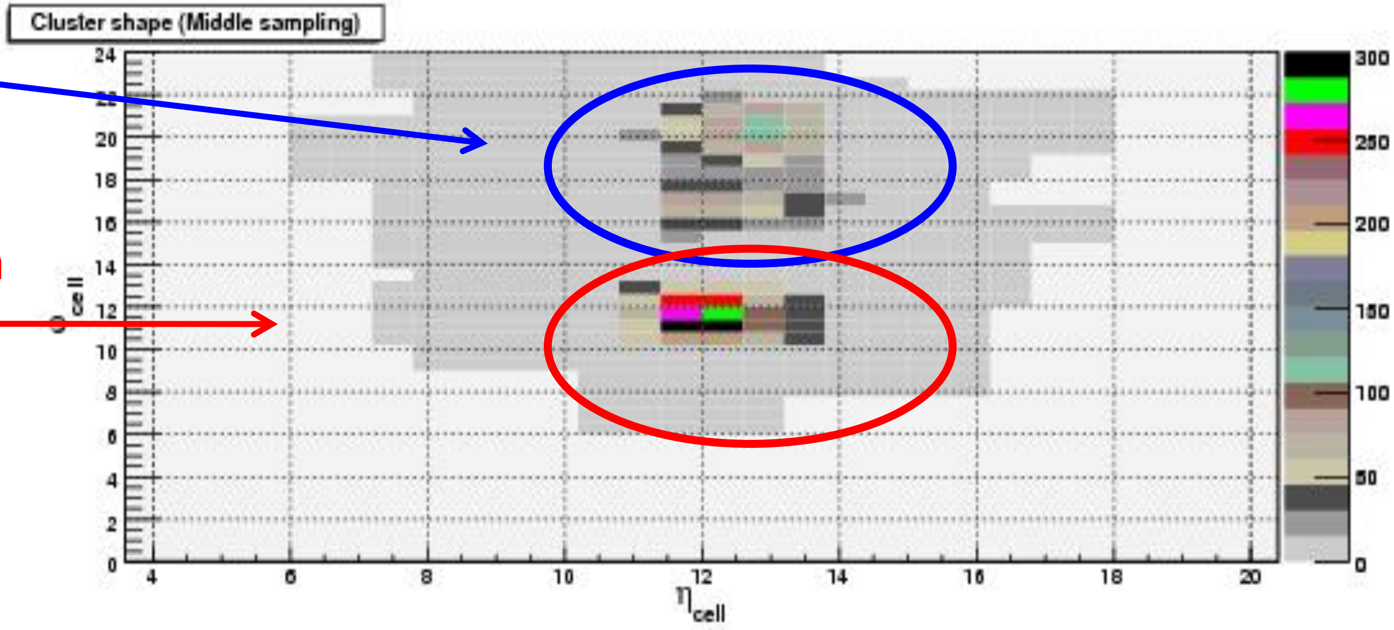
Effect of the B Field: very low energy example

5 GeV electrons simulated at η=0.3

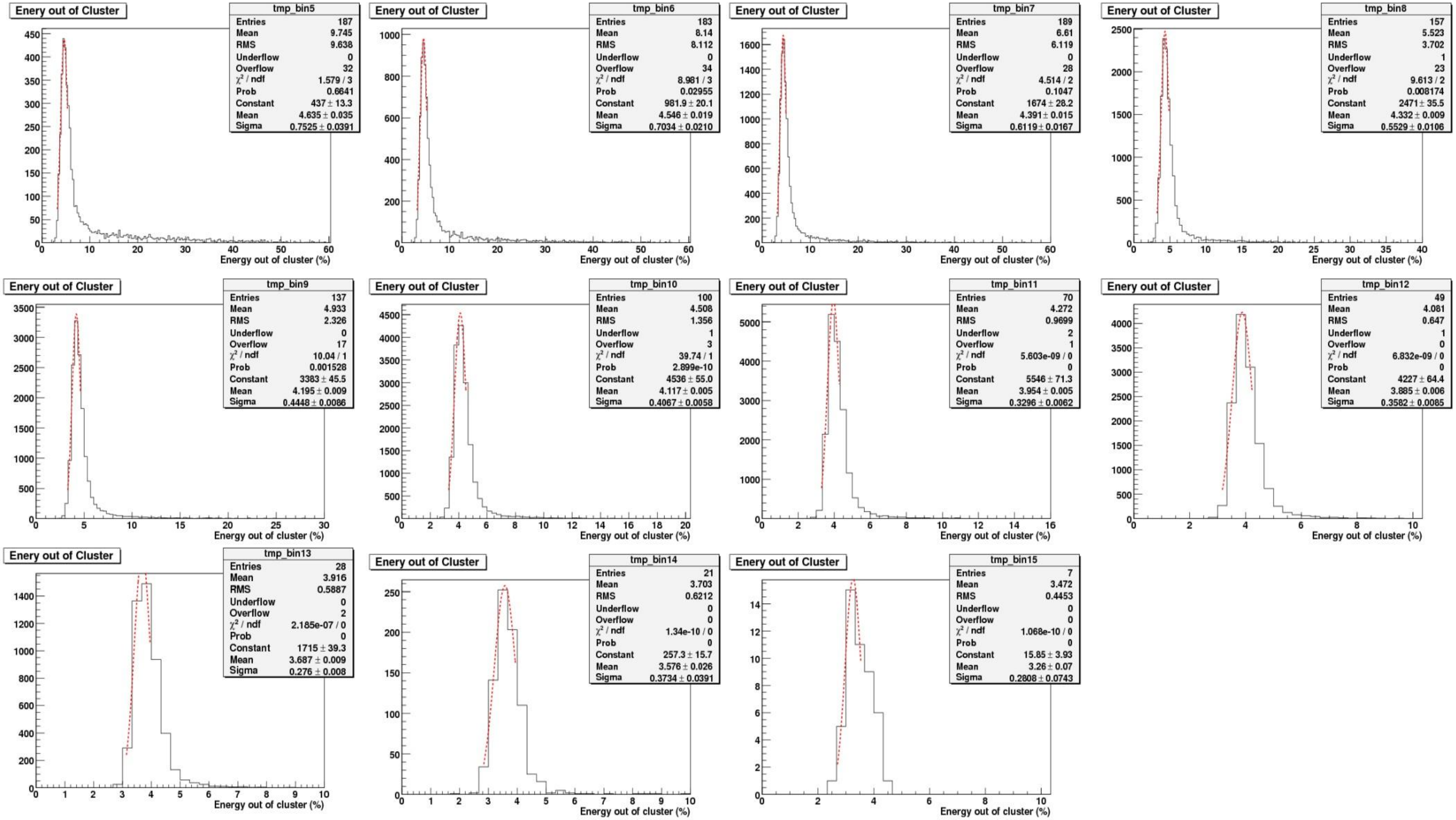


Second cluster a η=0.5 (cell 20)

First Cluster a η=0.3 (cell 12)

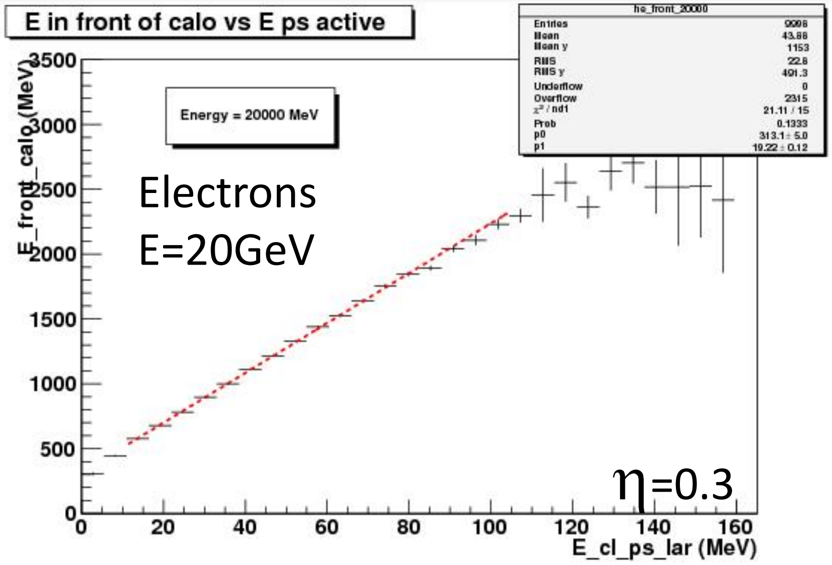


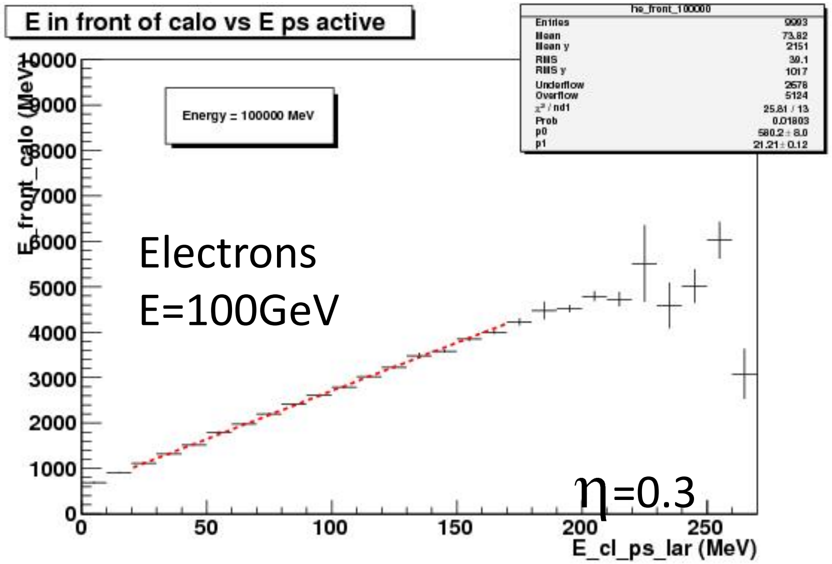
Out of cluster: fit on X bins



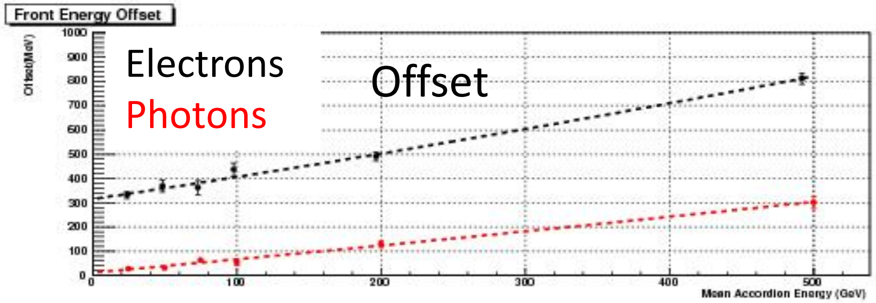
Energy lost outside the cluster for each X bins ($7X_0<X<14X_0$).
Asimmetric Gaussian Fit → mean-sigma

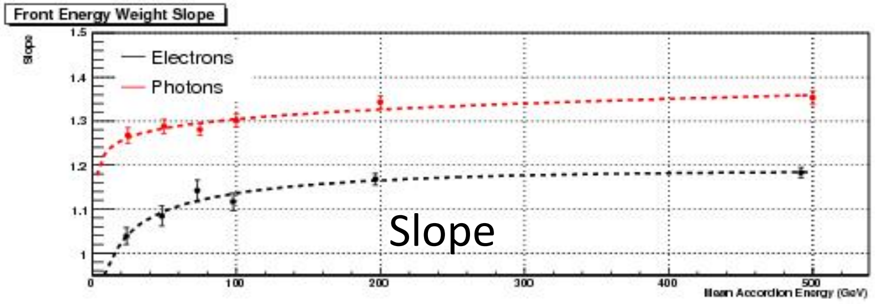
Energy deposited in front of calo





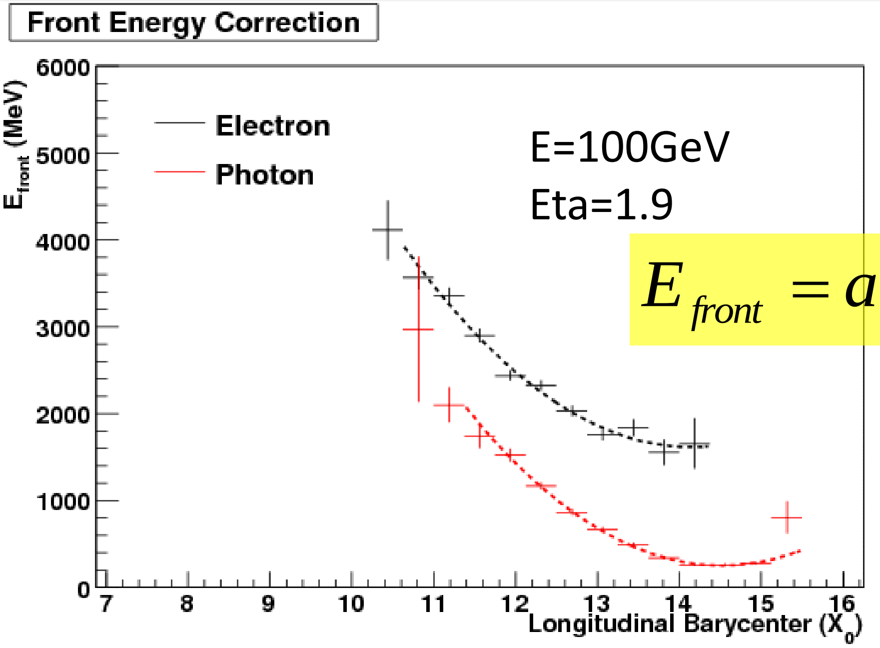
Total Energy into Accordion and PS
→ Energy lost in front of Accordion





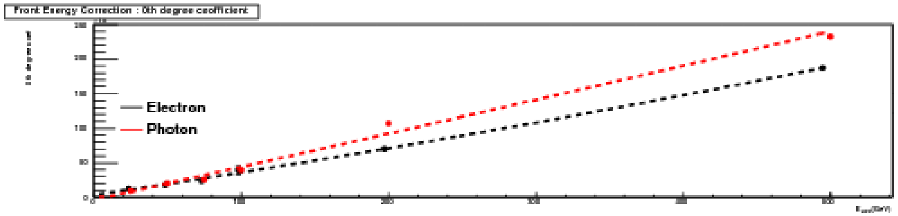
From 2 to 6 X_0 of material present in front of calorimeter (Inner Detector, cryostat, etc.)

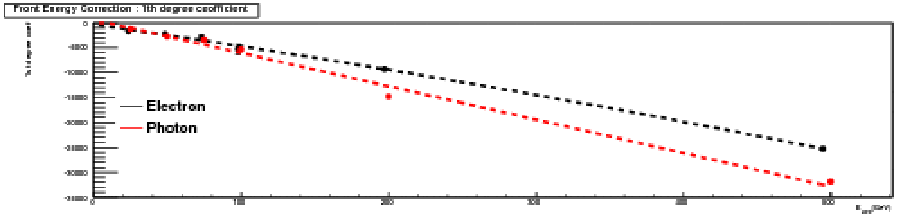
Energy deposited in front: no PS region

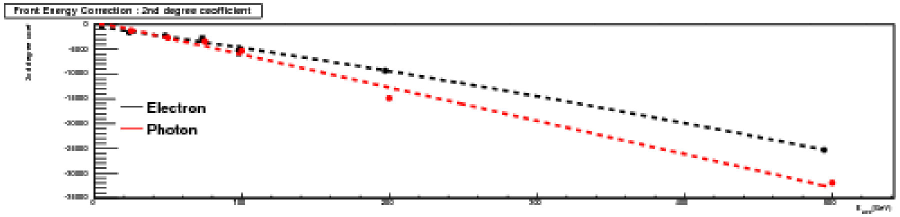


$$E_{front} = a(E_{acc},\eta) + b(E_{acc},\eta)\cdot X + c(E_{acc},\eta)\cdot X^2$$

In the region of the endcap without the PS a parametrization of the energy deposited in front of calorimeter as a function of the longitudinal baricenter is adopted



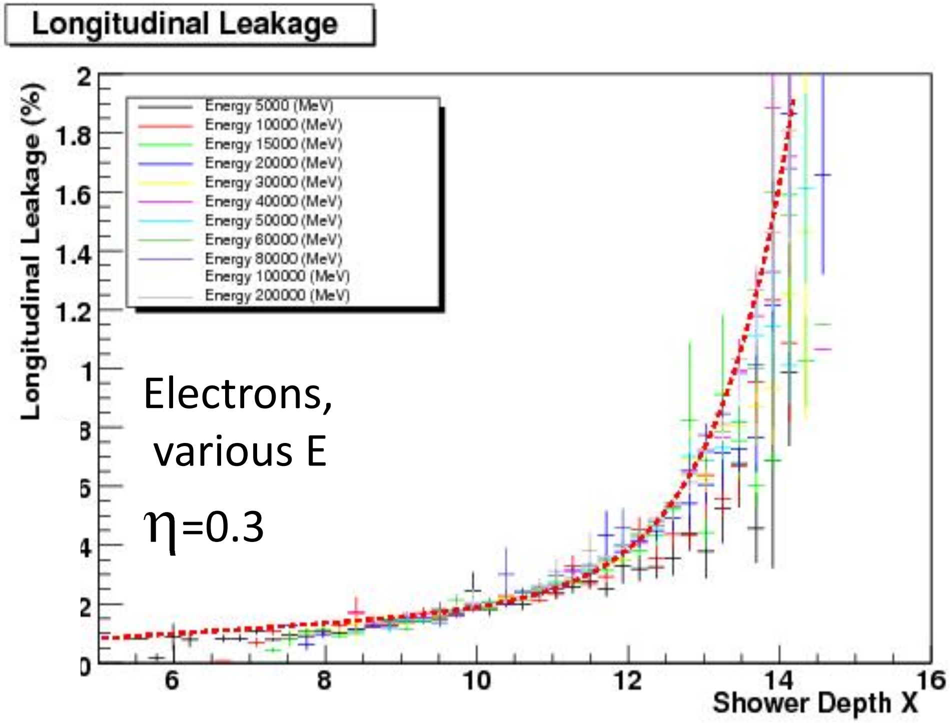




Longitudinal leakage reconstruction

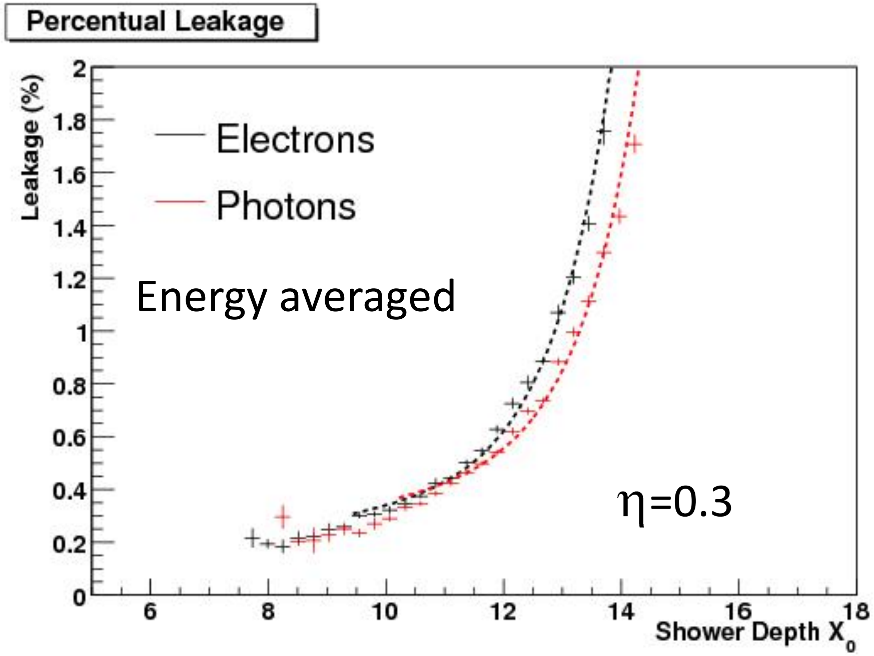
- Parameterize the longitudinal leakage as a function of the longitudinal barycenter (fairly energy independent)

$$f_{leak}(X) = d_0 \cdot X + d_1 \cdot e^{X/X_0}$$



Electrons,
various E

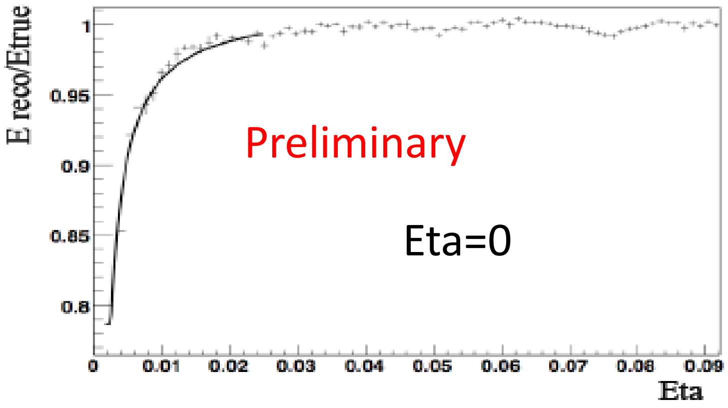
η=0.3

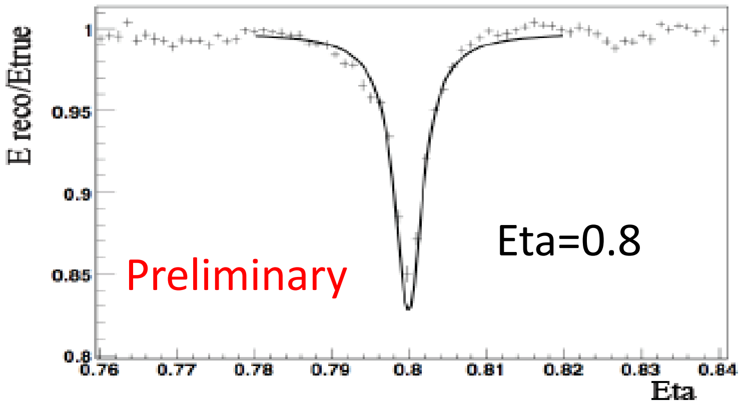


Energy averaged

η=0.3

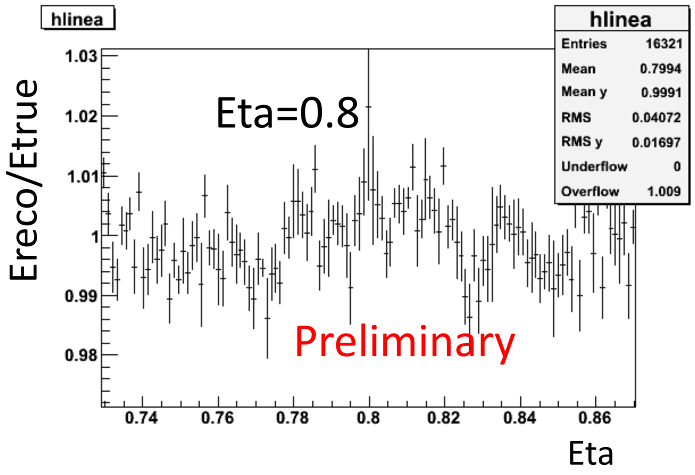
Crack and transition correction





Doulbe Fermi-Dirac fit fuction, like in the Test Beam analysis

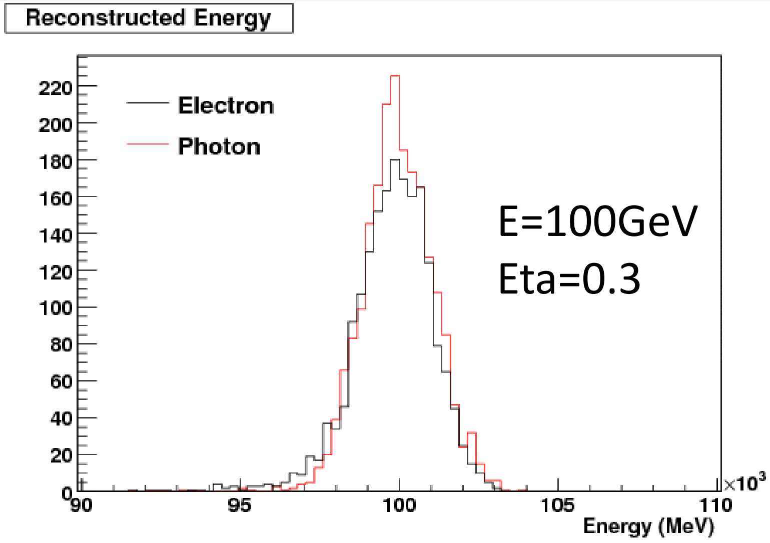
After Correction

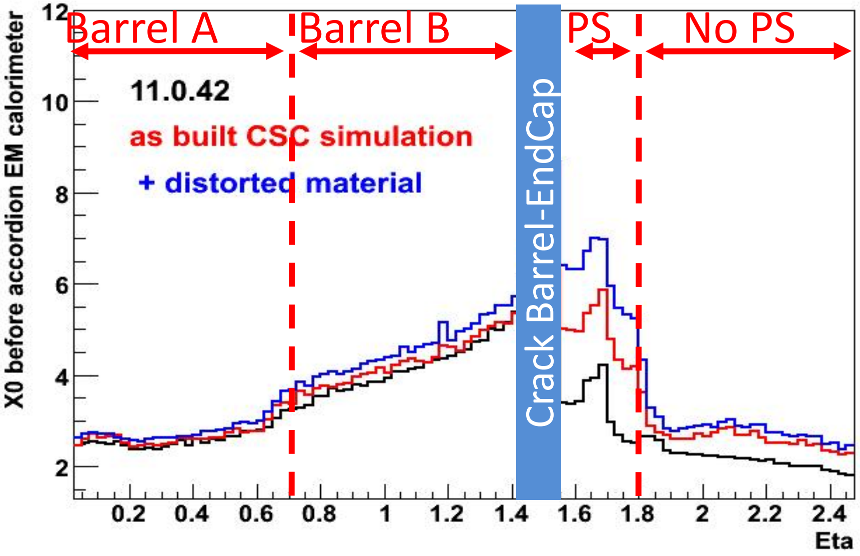


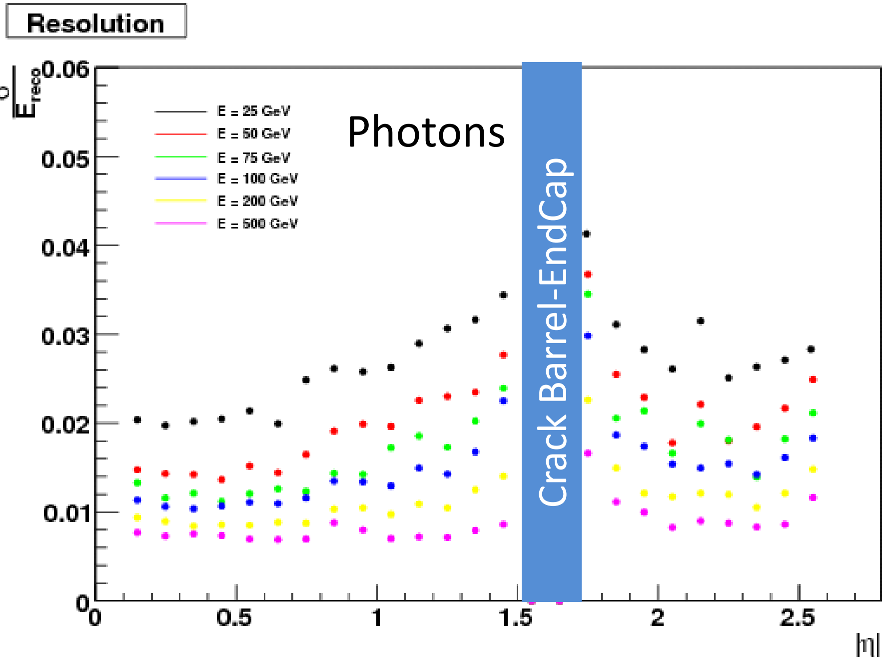
Correction for the energy lost in the crack at eta=0 and at eta=0.8 (transition between electrode A and B).
This correction must be applied on top of the other correction, it is not a part of the calibration hit method.

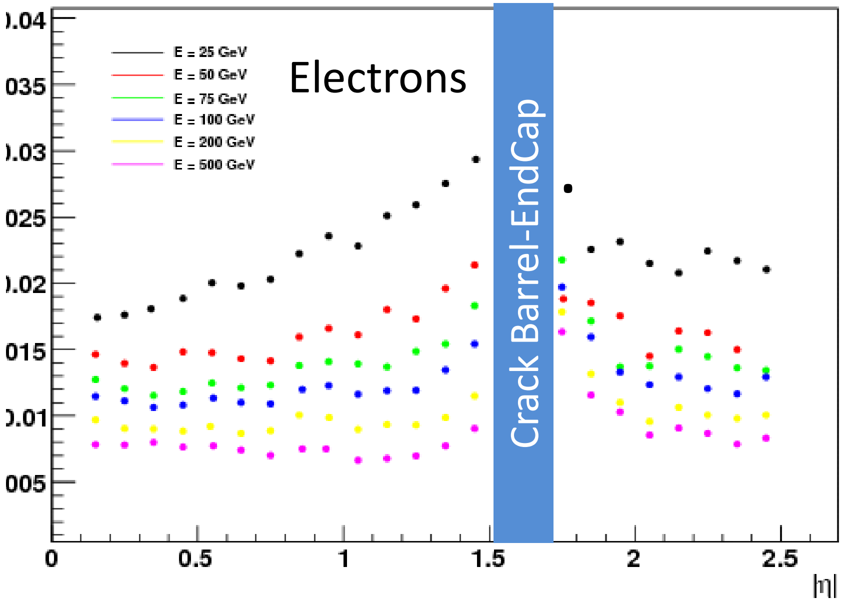
No cell modulation are applied at this level

Resolution σ/E

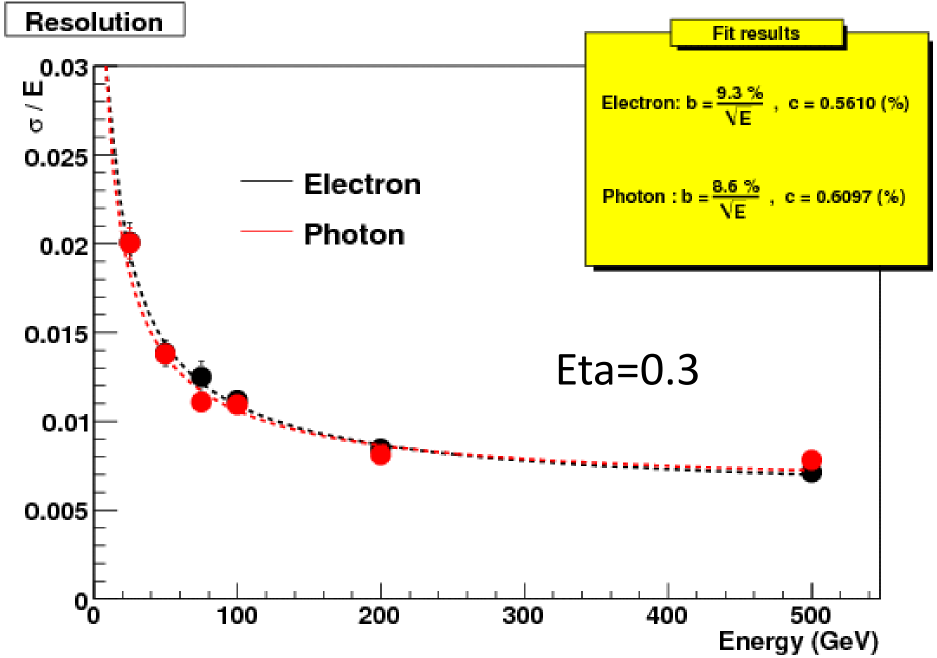


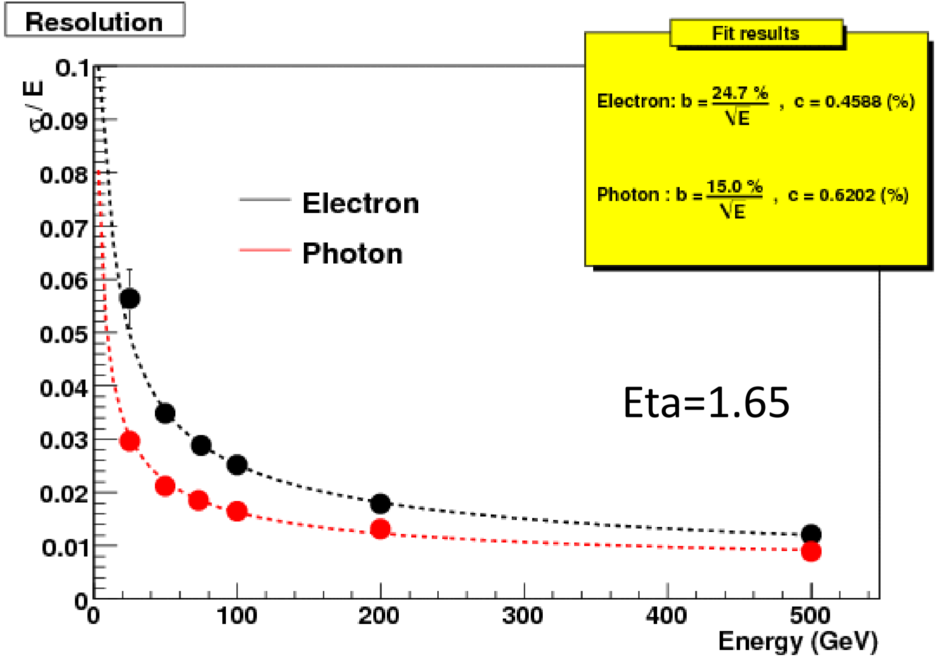




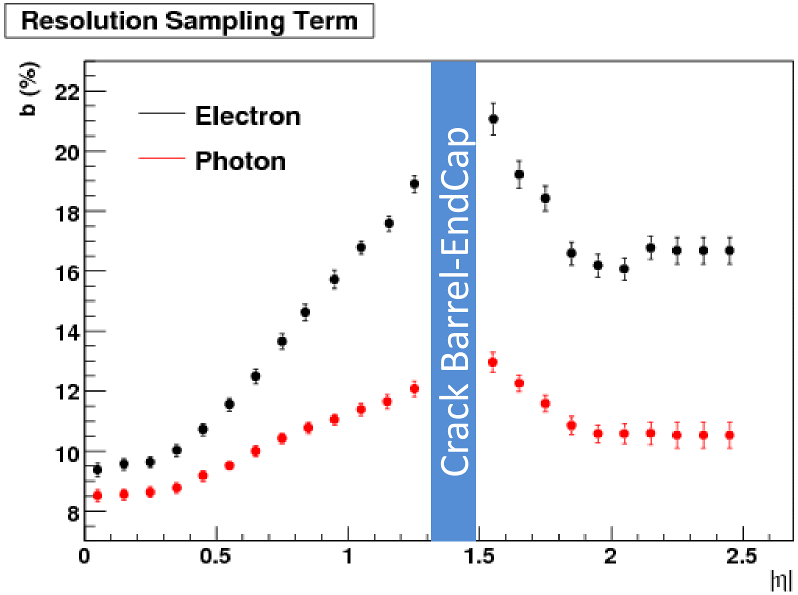


Resolution vs E



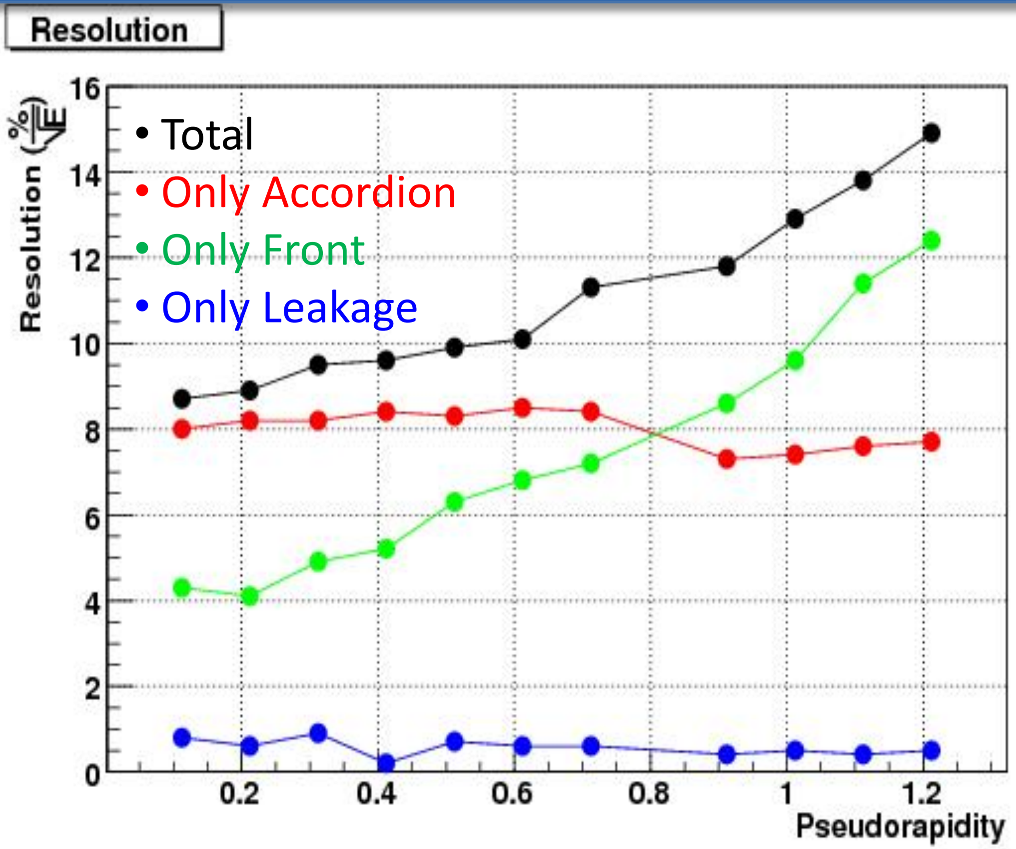


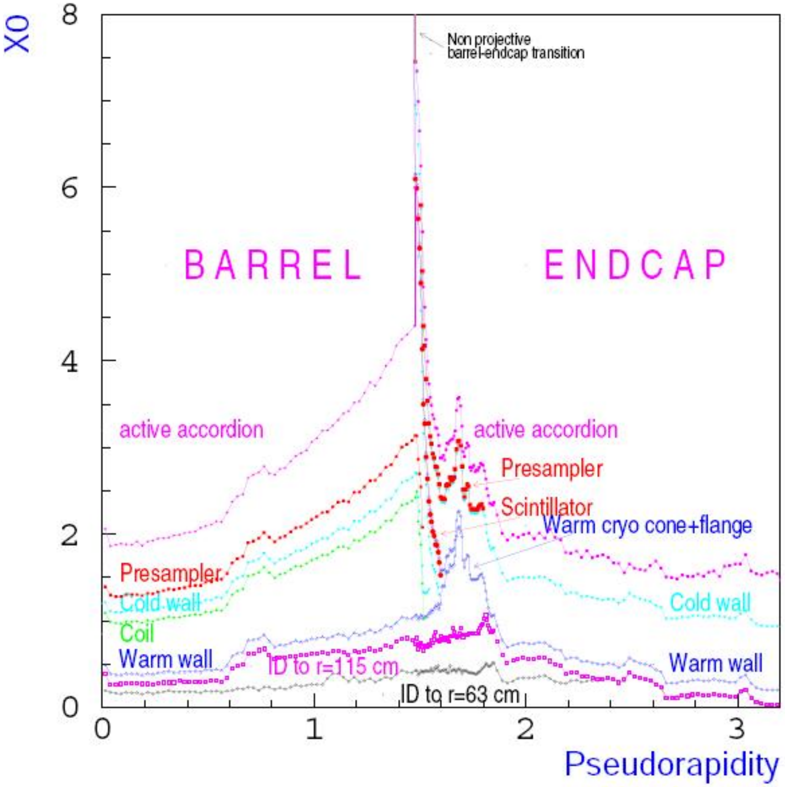
$$\frac{\sigma}{E} = \frac{b(\%)}{\sqrt{E}} + c(\%)$$



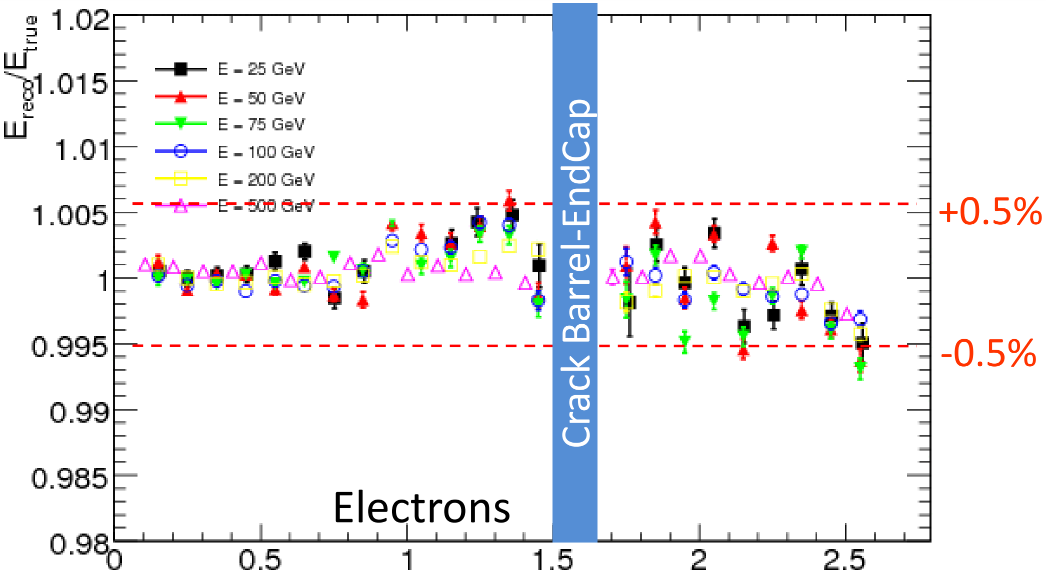
Constant term c < 0.6%

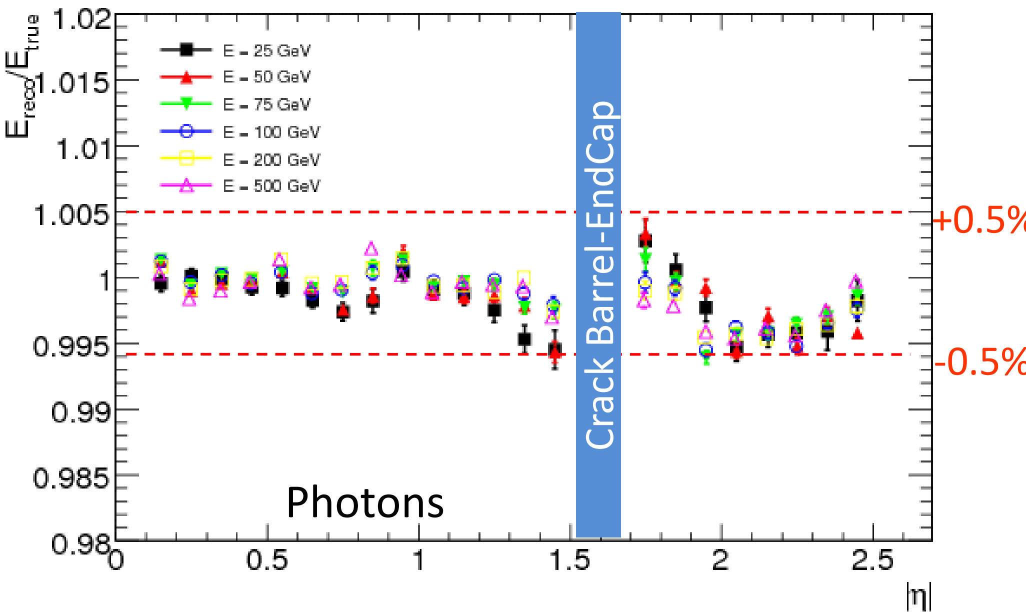
Contributions to total resolution





Linearity





Maximum deviation from linearity within 0.5% for electrons and photons over all the eta range

Minimization weights based egamma calibration

- Energies in the samplings are reconstructed with approximate sampling fraction at the cell level

- Weights are extracted by a chi^2 fit on a sample of single electrons in the [-2σ;+3σ] around the MPV (most prob. value) of the reconstructed energy distribution:

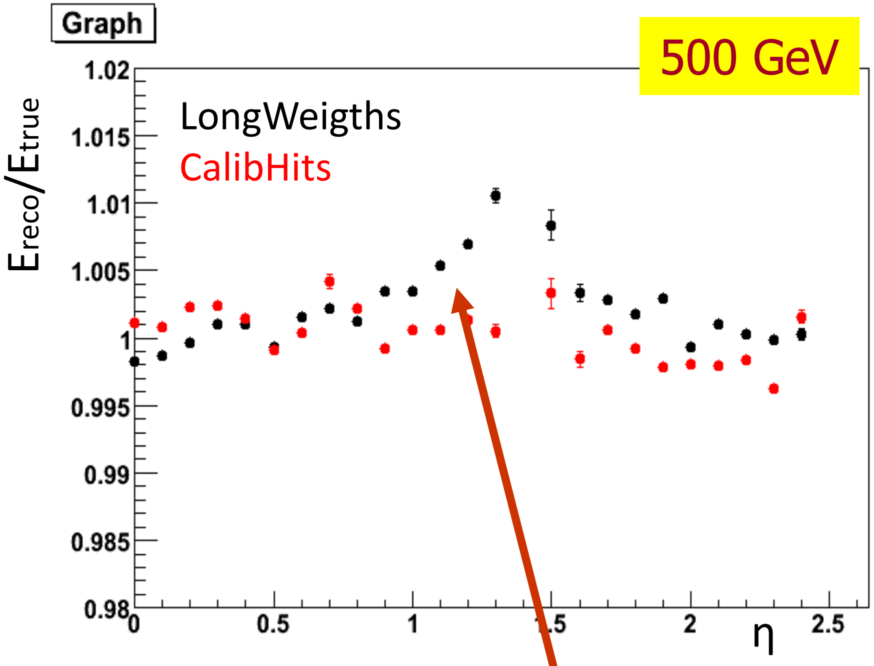
$$E_{rec} = \lambda(off + w_0 E_0 + E_1 + E_2 + w_3 E_3)$$

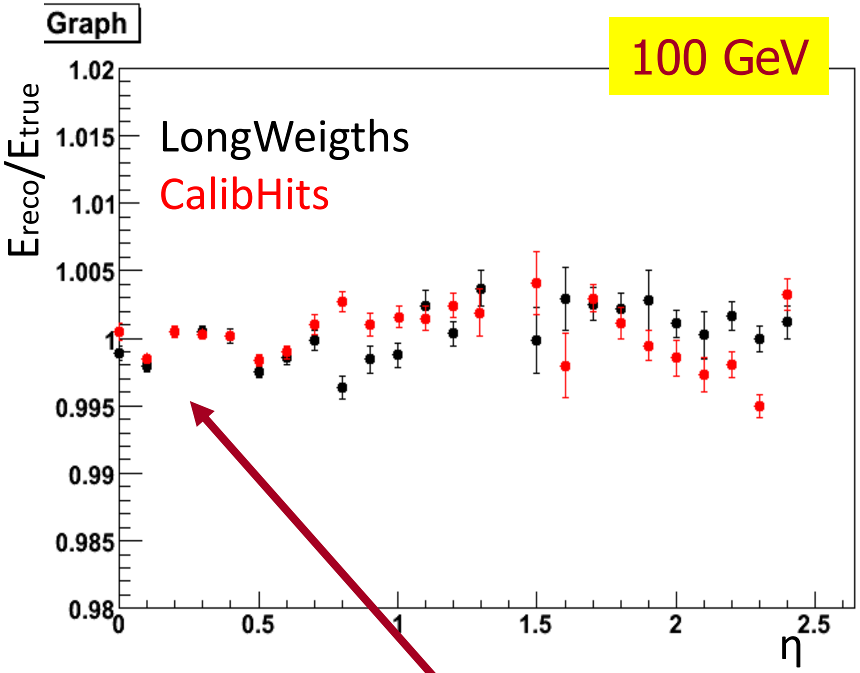
$$\chi^2 = \sum_i^N \frac{(E_{rec}^i - E_{true}^i)^2}{\sigma_E^2}$$

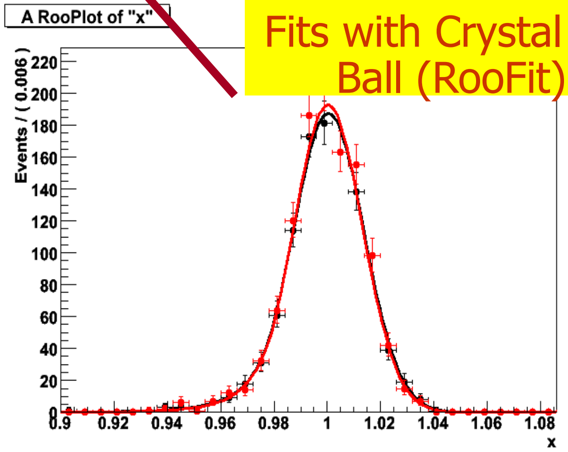
- It's a more refined version of the TDR/DC1 calibration: the introduction of the offset cures most of the low energy linearity problems (TB2002)

- 4 energy-independent parameters per cell – per cluster size – per particle type (electron/photon)

Performance on ideal0 samples: electrons



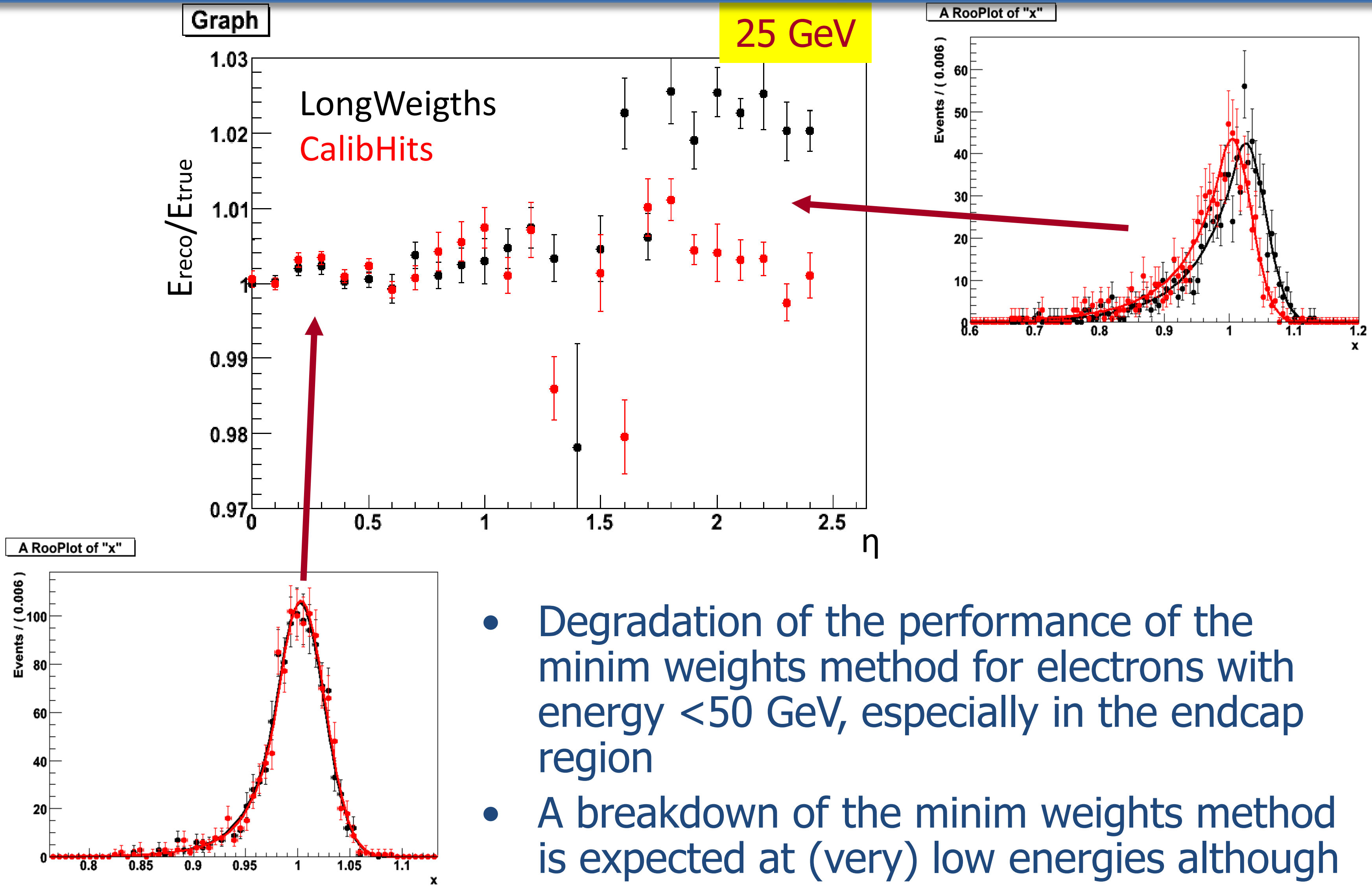




Fits with Crystal Ball (RooFit)

- Electrons with E >50 GeV the two methods are basically equivalent: linearity < 0.5%
- Small overshoot in the minim weights method for very high energy (500 GeV)

Performance on ideal0 samples: electrons



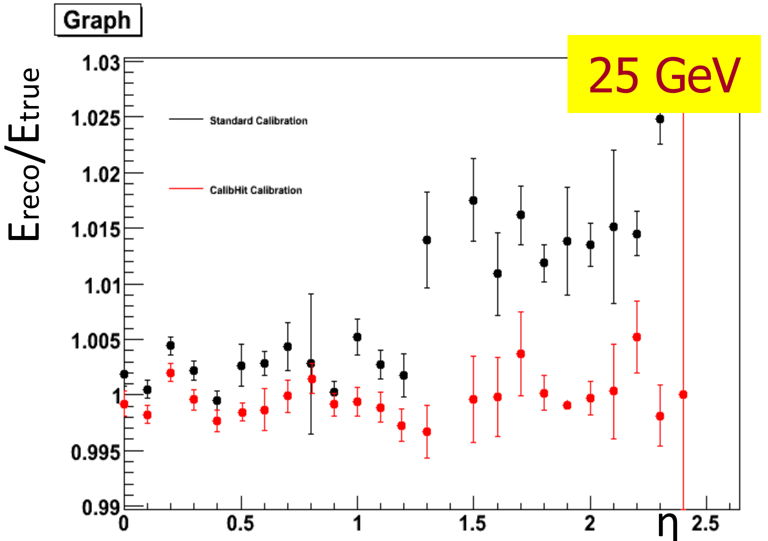
- Degradation of the performance of the minim weights method for electrons with energy <50 GeV, especially in the endcap region
- A breakdown of the minim weights method is expected at (very) low energies although some improvement is still expected with more statistic

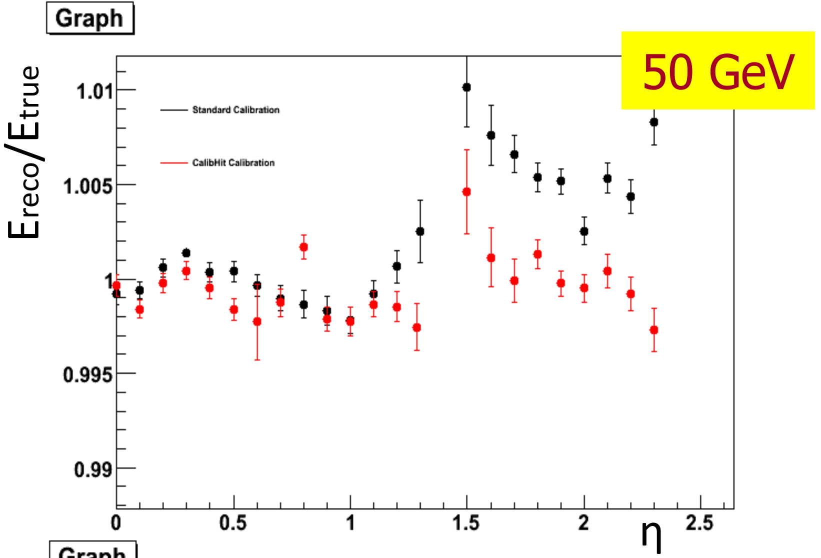
Performance on ideal0 samples: photons

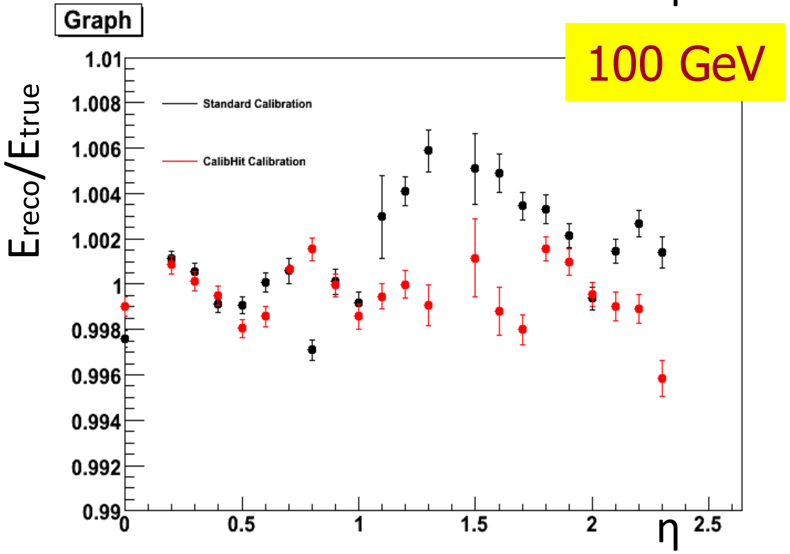
- Similar trends as for electrons

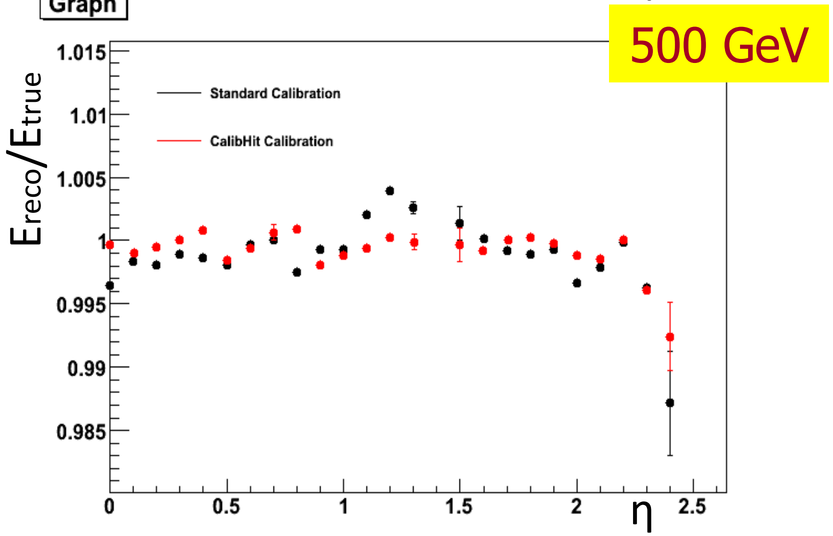
LongWeigths

CalibHits









Systematics effect on performance

Effect of systematics on the energy reconstruction:

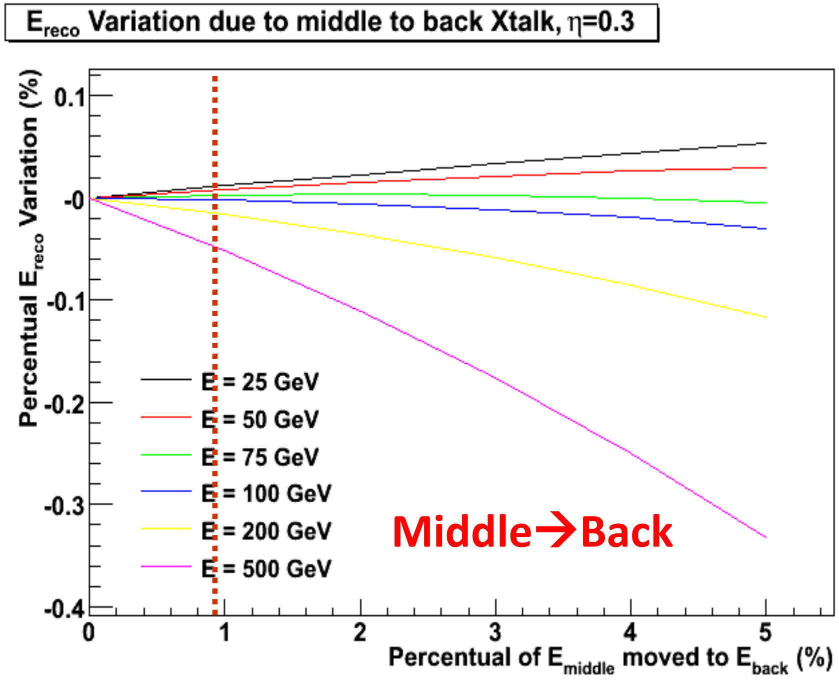
- Effect of the material in front of the calorimeter
  - Comparison of the performance of the two methods on calib1 geometry
  - Additional studies on calibhits based method

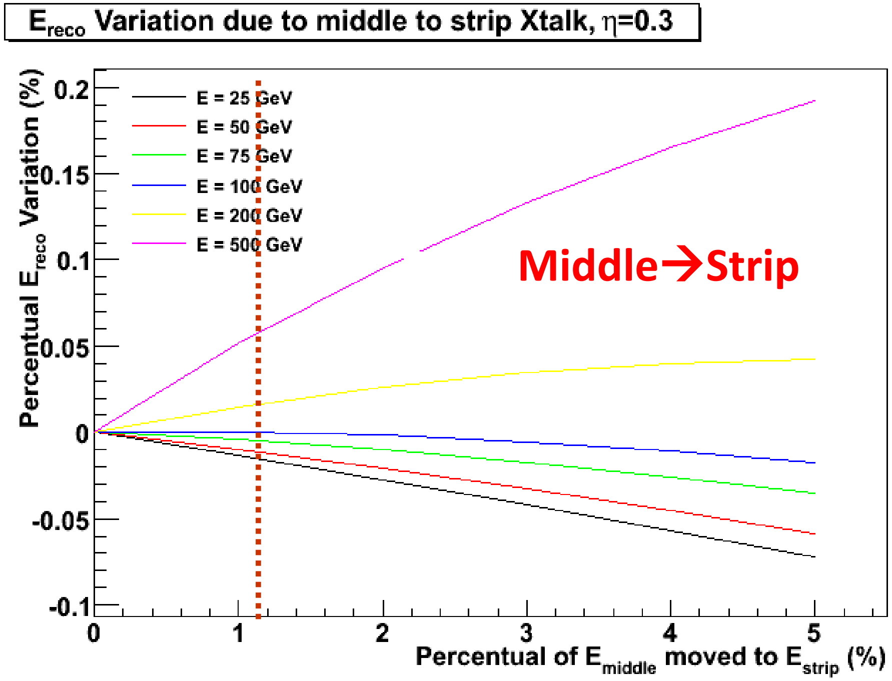
- Effect of middle-back cross-talk , effect of middle-strips cross-talk (for calibhits based method only)

- Effect of calorimeter cells miscalibration

Cross talk effect on recontructed energy

Cross Talk affect the Calib Hits method because most of the parametrisation are fz of the longitudinal barycenter.

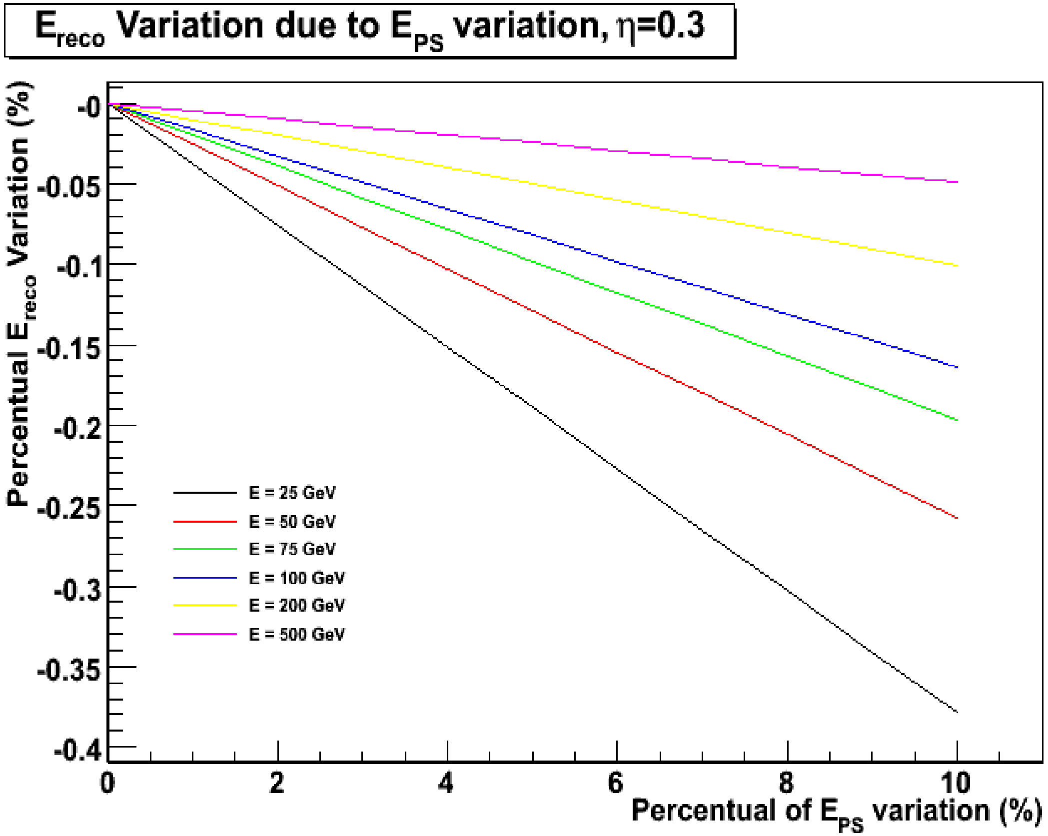




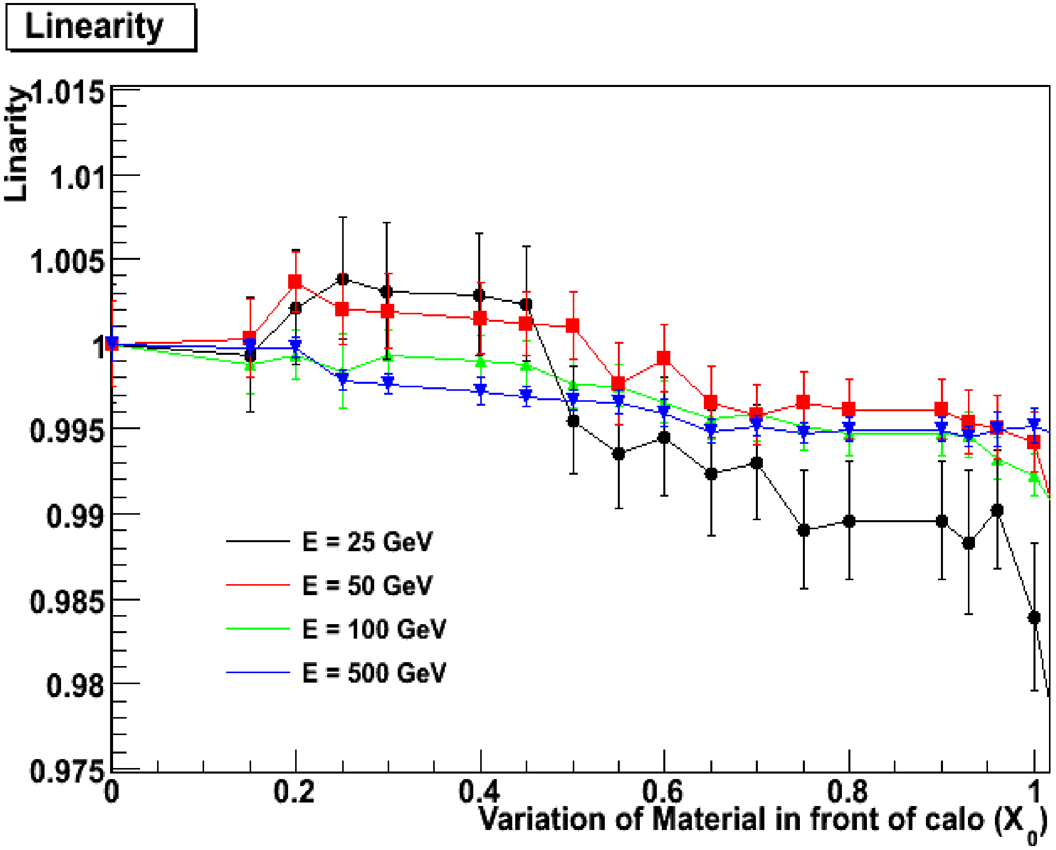
- The expected cross talk, even before correction, has a impact on the calibration which is less than 0.1%

Effect of presampler cells miscalibration

- Introduce artificially an overestimation of the energy in the presampler: low energy electrons are more affected (as expected). Not dramatic up to 10 % more energy in the presampler



Effect of the material in front of calorimeter



+1Xo of material in front →
~1% in the linearity

- Trick: select electrons around eta = 1.2. Right coefficients for accordion and leakage while coeffs from other eta positions (so different material in front) for the front.

Understanding the material with early data

Contributes to quantify the amount of material in the ID with early data

ID based methods

Number and radius of γ-conversions

ID & calo

E/p of high Pt electrons

EM calo based methods

Thanks to its high lateral and longitudinal granularity

Energy flow of minimum bias (MB) events

(ATL-LARG-PUB-2007-007)

&

electron shower shape

Understanding the material: conversion

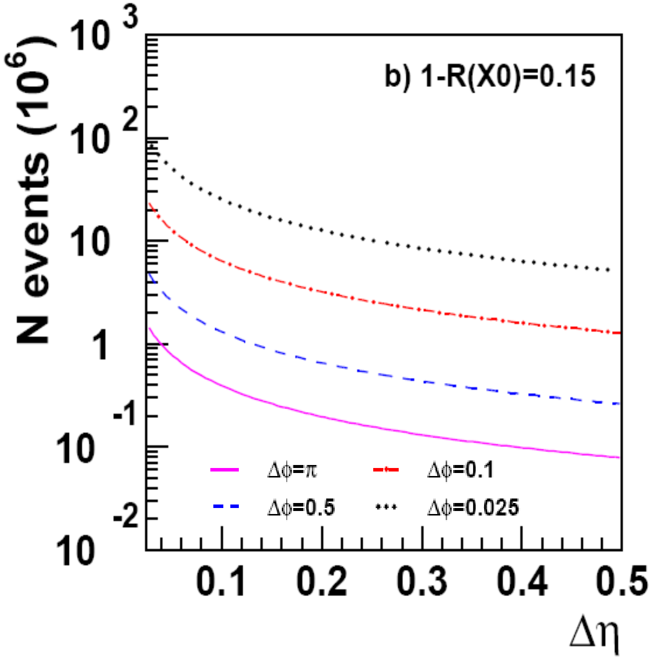
Some educated guesses:

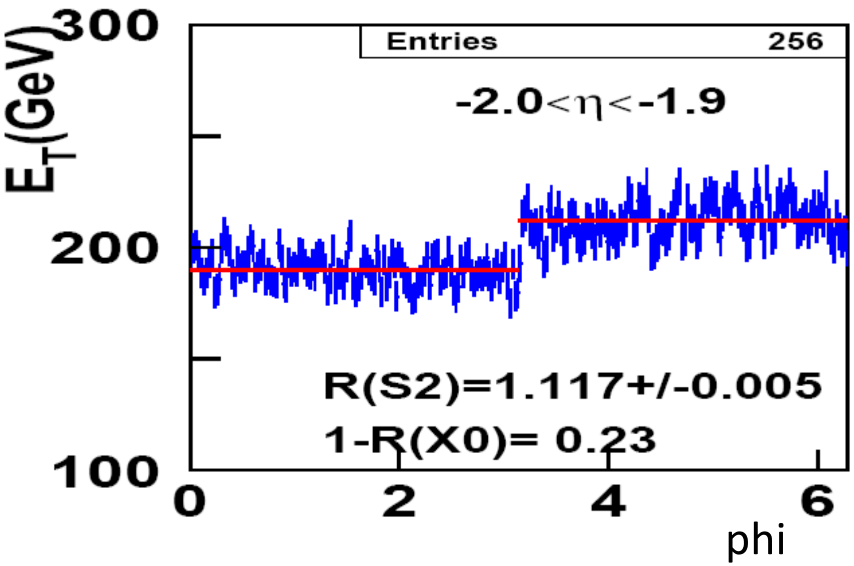
- From minbias expect to have ~1 conversion/ev with P_T(e+, e-) > 500 MeV
- Assuming a minbias trigger rate of 100 Hz we have ~100 photons / sec
- From the analysis of the minimum bias with today's state of the art tracking and vertexing we have a reconstruction efficiency of about 60%
- 60 reconstructed photon conversion / second
- ~10^7 photons estimated for the material map in eta (0.1 bins) at 1% so ~ 2 days of minbias
- With 10 bins in radius we have ~ 20 days of data taking

Understanding the material: 'energy flow' in MB

- Exercise done on misal1 geometry: (remind excess of material in the inner detector for $\pi<\phi<2\pi$)

E_T^{S2} ($\pi<\phi<2\pi$) / E_T^{S2} ($0<\phi<\pi$)



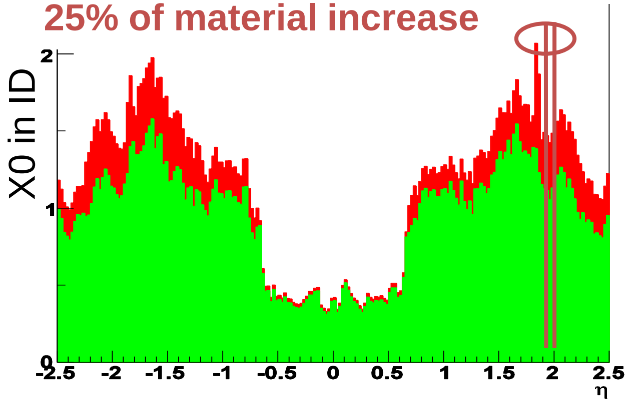


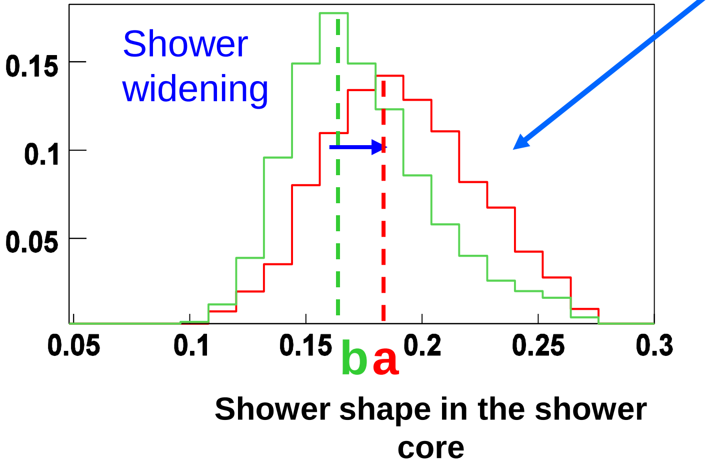
As an example, with 3 millions of events (~1 day), it is possible to identify a region $\Delta\eta x \Delta\phi = 0.2x0.1$ with a 15% X_0 ID matter excess.

Understanding the material: high Pt electrons shower shape

<u>Leading idea :</u> the more matter in the ID, the earlier the shower starts
- wider electromagnetic shower, especially in S1
- bigger ratio of the energy in S1 over the energy in S2

Example for 1.8<η<1.9 :
25% of material increase



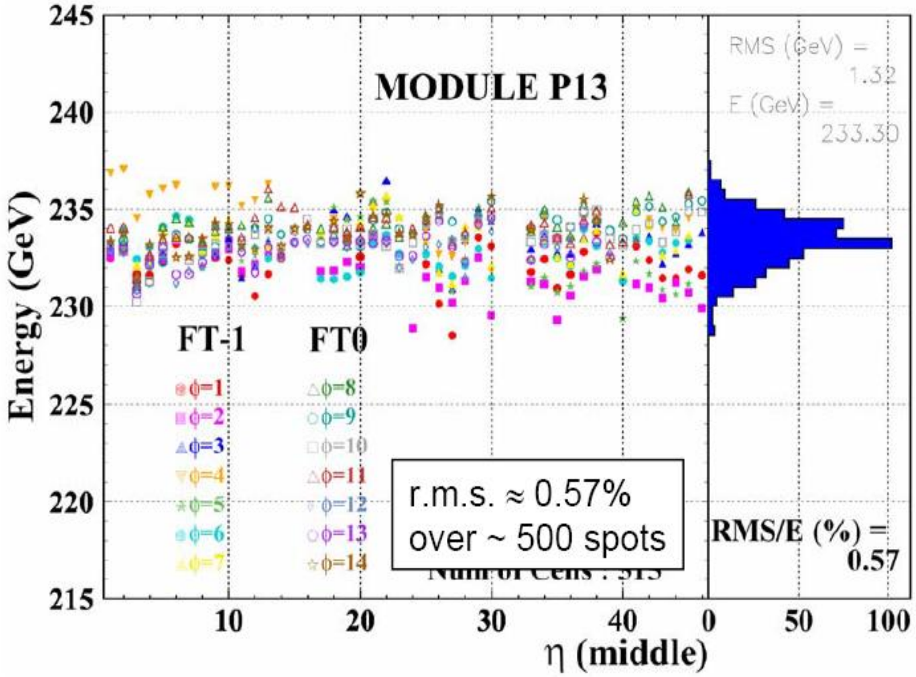


- High Pt electrons are sensitive to extra material
  - Shower width
  - Shower longitudinal development
  - Track quality
  - E/p
- the shower width in S1 is the most sensitive variable (shower shape in the shower core)
  - 5σ effect : 20% of ID material excess in $\Delta\eta x \Delta\varphi \sim 0.11x0.11$ with ~ 100 pb^{-1}
- High energy depos its ➔ lower systematic errors: complementary to MB energy flow.
- The shower's longitudinal development is also sensitive to the material <u>directly in front of the calo</u>

Detector equalization using Z→ee events

Final setting of constant term through use of Z → ee and Z mass constraint to correct for long-range uniformities: local constant term ~0.5% proved on testbeam

- Worst case scenario: no corrections
  - c_{local} = 1.3% ”on-line” non uniformity of individual modules
  - $C_{long\text{-}range}$ = 1.5% no Z→ee correction, poor knowledge of upstream material
  - Worst-case total constant term 2%.
- 10 pb^{-1} (10^5 s at $10^{32} cm^{-2}s^{-1}$): 5 × 10^3 Z : Achieve 1-1.5% intercalibration
- 100 pb^{-1}: 5 × 10^4 Z : achieve 0.5% intercalibration (need 250 $e^{\pm}$ per unit)



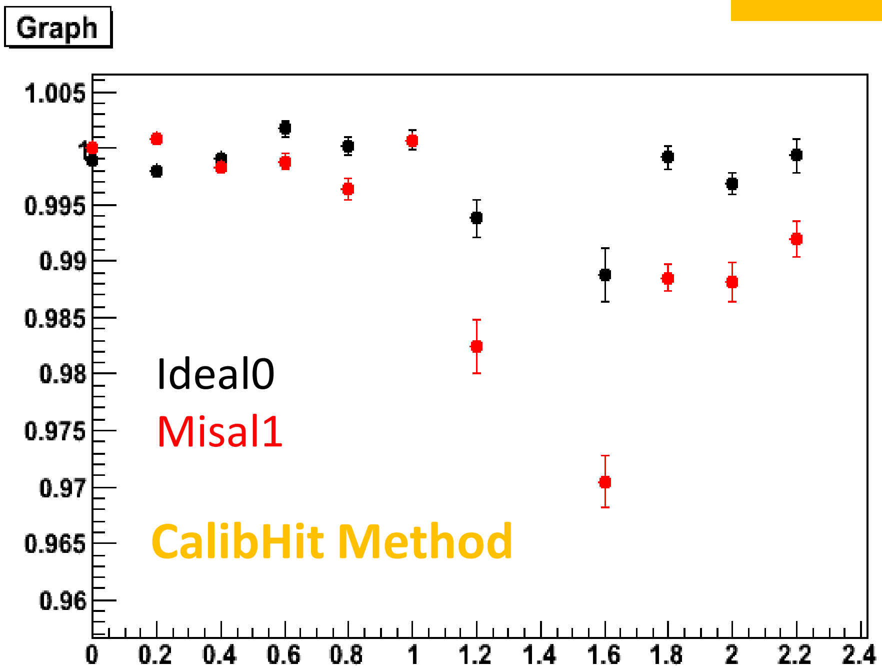
Scan of a barrel module with 245 GeV e^-

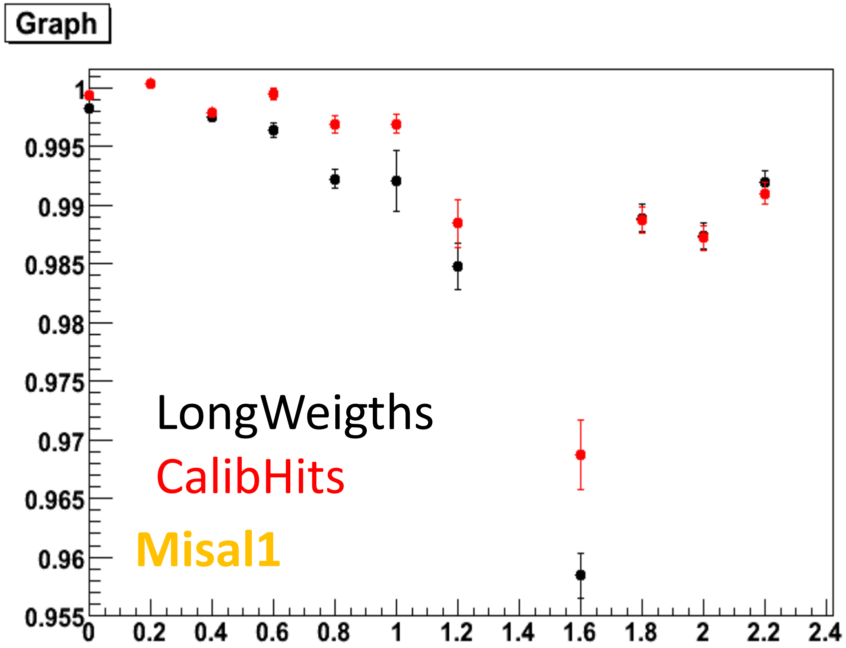
r.m.s. ≈ 0.57%
over ~ 500 spots

BackUp Slides

Effect of material in front of calo: Misal1 geometry

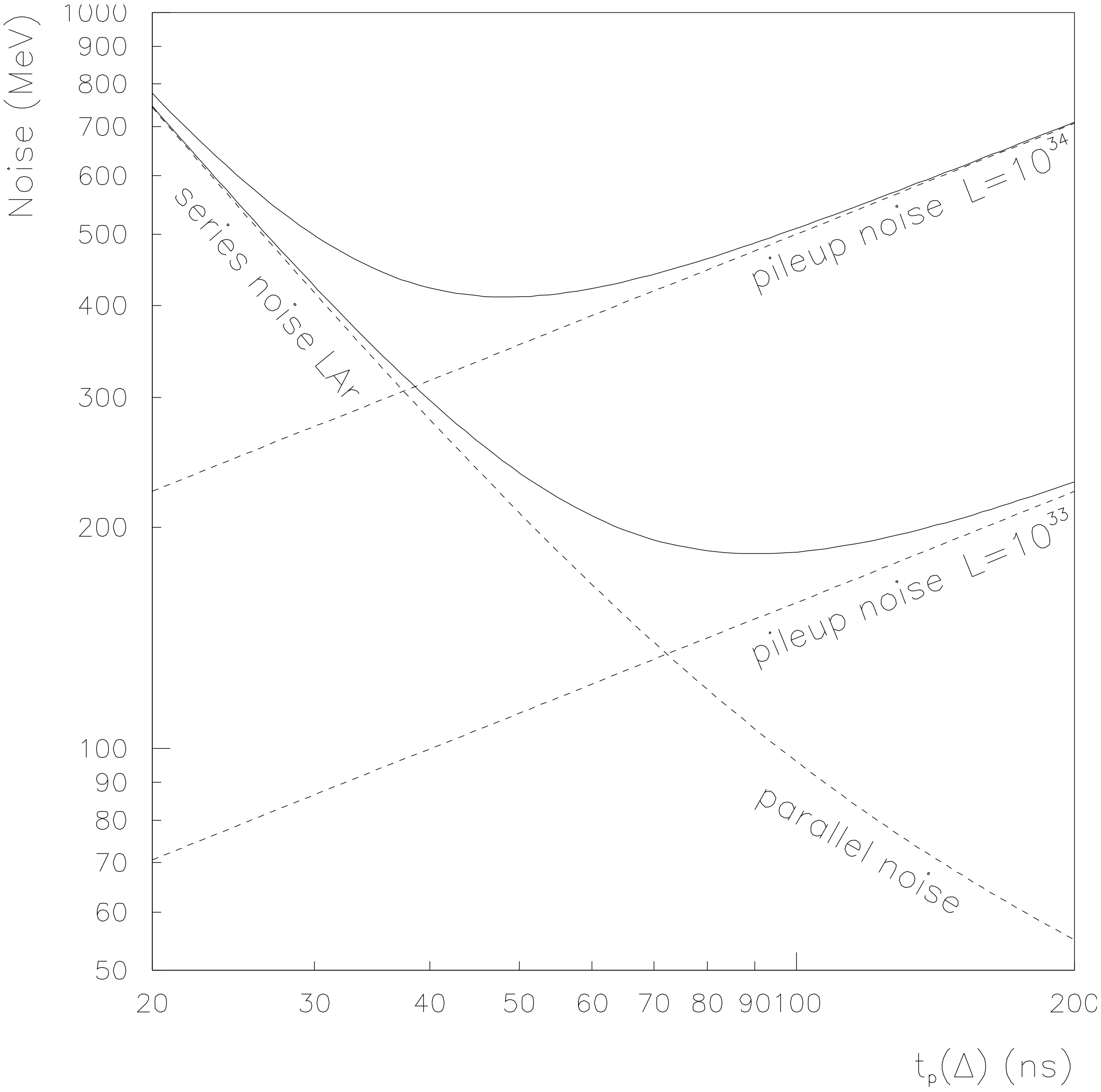
Electrons 100GeV



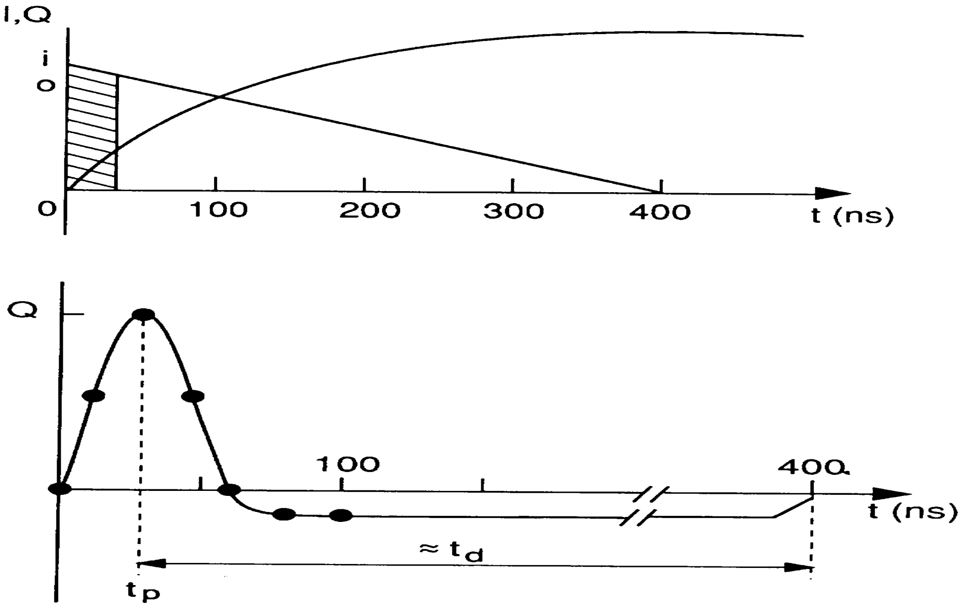


Misal1 geometry have from 0.1 to 0.7 Xo added in front of the calorimeter. The shown results are averaged over all the material condition.

The CalibHits method shows to be less sensitive to the material in front of calorimeter.


Noise (MeV)
1000
900
800
700
600
500
400
300
200
100
90
80
70
60
50
20
30
40
50
60
70
80
90
100
200
$t_p(\Delta)$ (ns)
series noise LAr
pileup noise $L=10^{34}$
pileup noise $L=10^{33}$
parallel noise

How to make a liquid calorimeter fast?

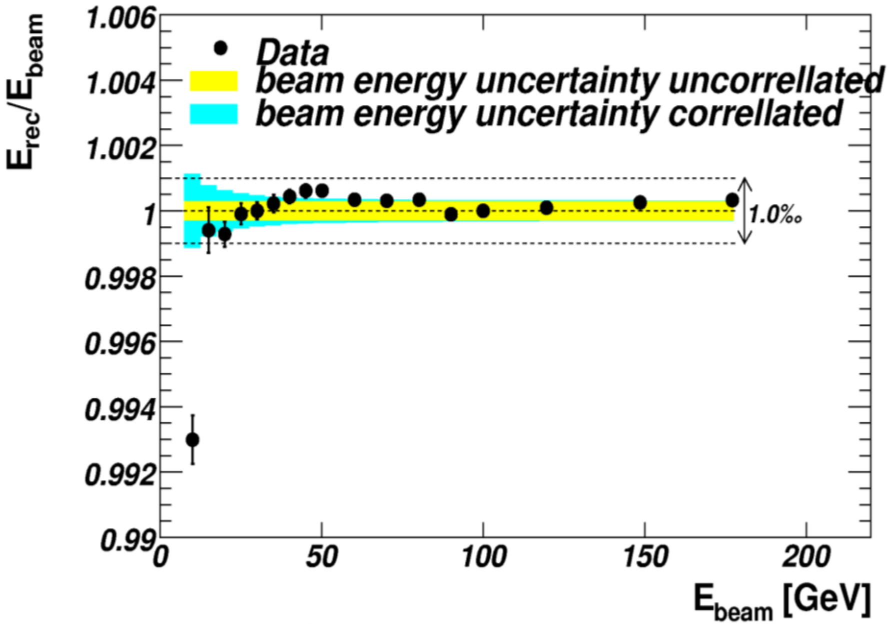


Integrate the current over time t_p << t_D (t_p ~ 40 ns)
with
a bipolar shaper response
to the triangular signal.

The signal has zero area and consequently pile up introduces an error but not a baseline shift

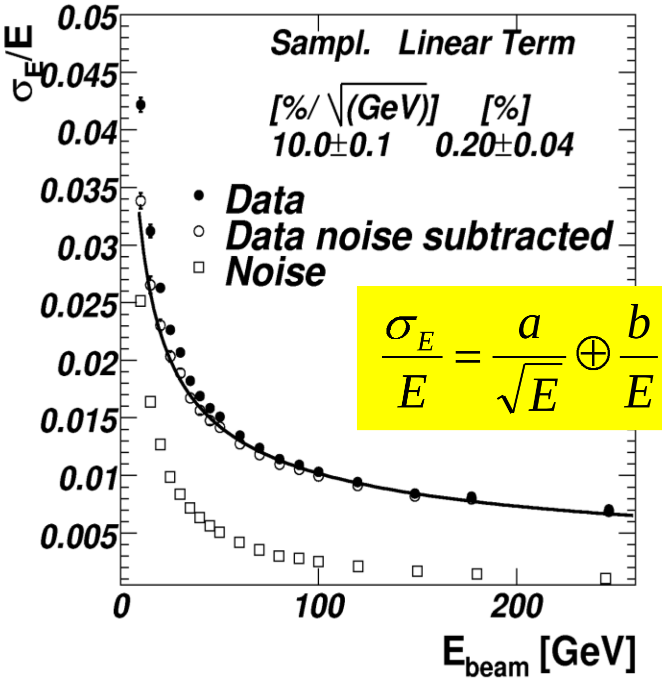
Performance at TestBeam

Dati di testbeam 2002 a η = 0.7 ⇒ ~ 2 anni di lavoro!!!



Linearita' del calorimetro (barrel):

- ± **0.1%** (escluso il punto a 10 GeV)
- Meglio dello ± **0.1%** tra 20 – 180 GeV
- Entro le specifiche richieste dalla fisica



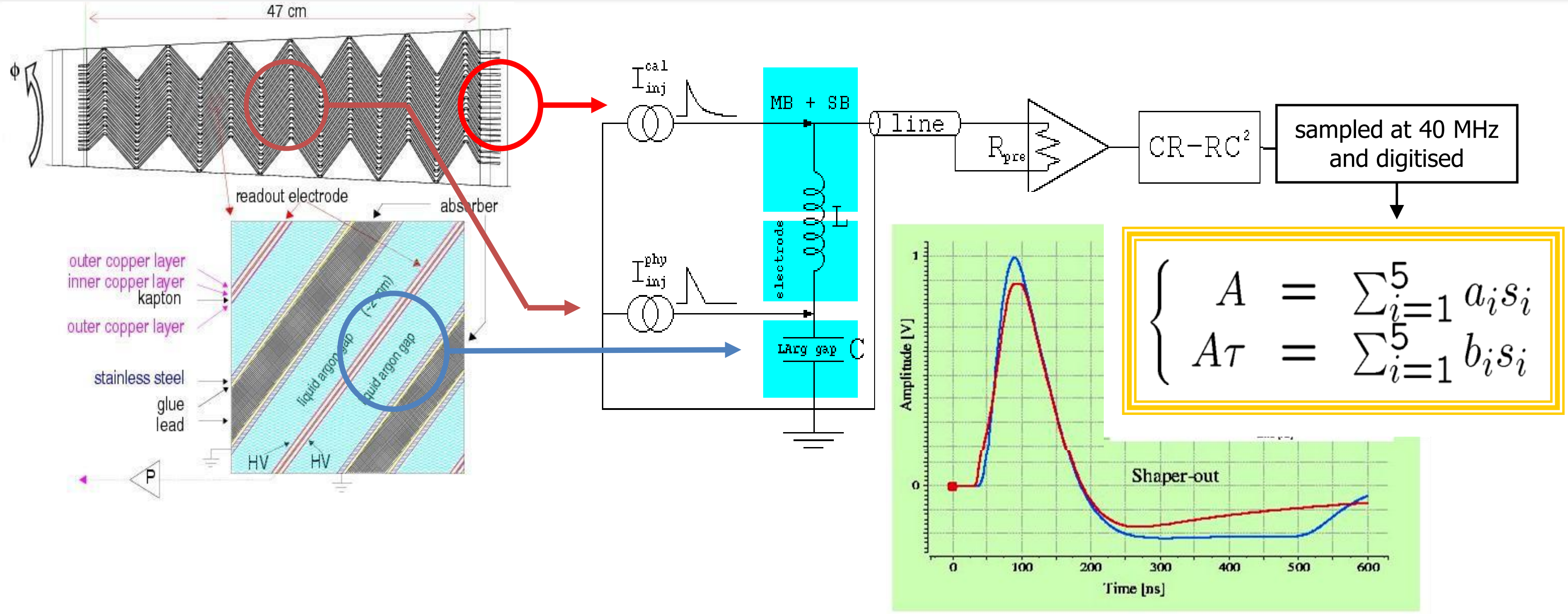
$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

Risoluzione del calorimetro:

- Sampling term(a): Barrel **~10%** Endcap **<12.5%**
- Noise elettronico(b): **~250 MeV** (cluster 3x3)
- Local constat term(c): **~0.2 %**

Entro le specifiche richieste dalla fisica

Signal generation and electronic calibration



$$\begin{cases} A = \sum_{i=1}^{5} a_i s_i \\ A\tau = \sum_{i=1}^{5} b_i s_i \end{cases}$$

- Il segnale di fisica : triangolare lughezza ~ 400 ns. Il segnale dopo la formatura ha un tempo di picco ~50 ns. Il valore del picco e' ricostruito usando 5 campioni del segnale (Δt = 25 ns) mediante una tecnica di *Optimal filtering* che minimizza l'effetto del noise elettronico + pileup. Il segnale di fisica e' sensibile principalmente a:
  - Spessore di assorbitori e gap di LAr , Alta tensione, Temperatura , LAr purity
- Un segnale di calibrazione viene usato per calibrare il guadagno del sistema di read-out (~0.2% accuracy) : segnale di fisica e calibrazione differiscono in forma e ampiezza: la forma di fisica puo' essere predetta dalla calibrazione e usata per calcolare i coefficienti di OF
- Grosso lavoro a **CTB 2004** per rendere il software pronto per ATLAS (nel framework Athena)