Drift Time measurement in the ATLAS Liquid Argon electromagnetic calorimeter using cosmic muons

Carolina Gabaldon (CERN)

(on behalf of the ATLAS Liquid Argon Calorimeter Group)

Operating Calorimeters and Calibration Session

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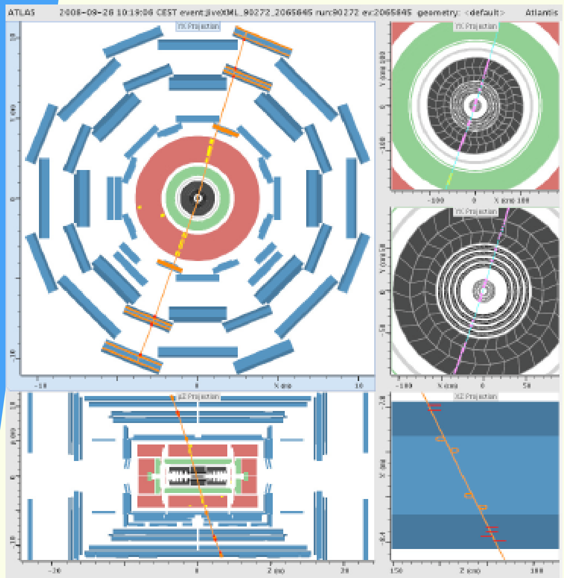
Motivation

- The calorimeter response needs to be known with a precision better than 1 %.
  - ✓ To reach this value a good uniformity is needed



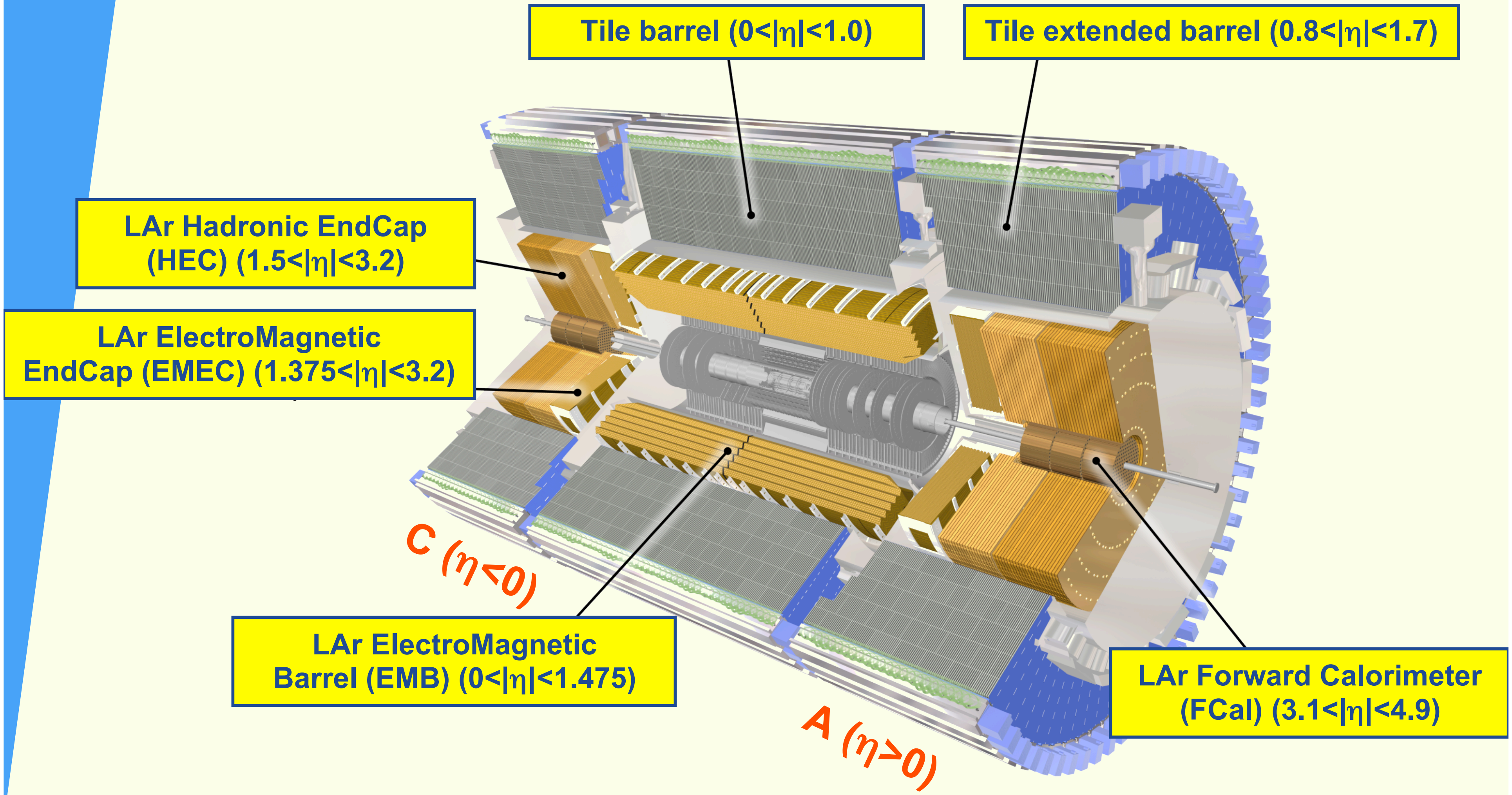
- The intrinsic non-uniformity ➔ constant term
  - ✓ from the lead thickness dispersion: measured during construction ➔ c ~ 0.18 %.
  - ✓ from the LAr gap size variations: obtained from drift time (T_{drift}) measurements.

- T_{drift} measured from the signal shape of any ionizing particle but requires to record the whole pulse shape (≥ 32 samples).

- After September 2008 LHC start-up 32 samples cosmic runs have been taken
  - ✓ Precise studies can be performed ➔Drift time measurements

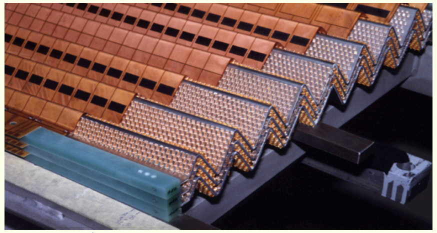
The ATLAS Calorimeters

- See Huaqiao Zhang's presentation



ATLAS Electromagnetic Calorimeter

- **A lead - liquid argon sampling calorimeter:**

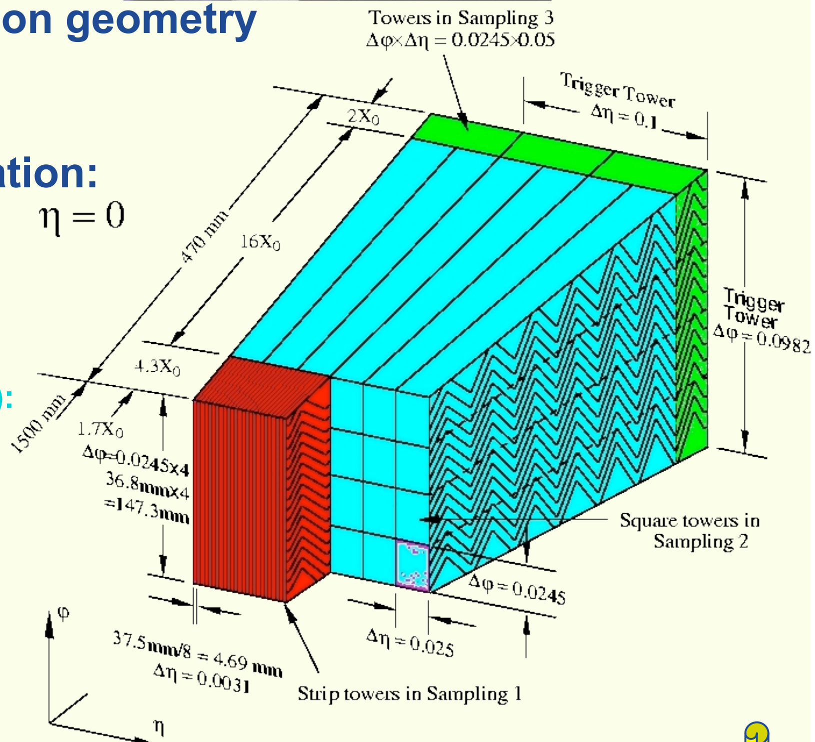


  - ✓ **Good pseudorapidity coverage ($|\eta|<3.2$)**
  - ✓ **Full azimuthal coverage due to accordion geometry**
  - ✓ **High granularity: 173,312 cells**
  - ✓ **Longitudinal and transversal segmentation:**
    - **Layer 1 (FRONT)** **($\Delta\eta,\Delta\varphi$) = (0.003, 0.025):**

      Position measurement, γ/π^0 separation
    - **Layer 2 (MIDDLE)** **($\Delta\eta,\Delta\varphi$) = (0.025, 0.025):**

      Main energy deposit
    - **Layer 3 (BACK)** **($\Delta\eta,\Delta\varphi$) = (0.05, 0.025):**

      High energy showers, had./em separation
    - **For $|\eta|<1.8$ a presampler**



➔ ***Calorimeter with a very high granularity and uniformity***

Signal formation in LAr

- The signal current in a LAr cell is given by:

$$I(t; I_0, T_{drift}) = I_0 \left(1 - \frac{t}{T_{drift}}\right) \quad \text{for} \quad 0 < t < T_{drift}$$

with $I_0 = \rho \cdot V_{drift}$ the current at t=0.

- The signal height is proportional to the drift velocity (V_{drift}), hence to the inverse of the drift time:

$$T_{drift} = \frac{w_{gap}}{V_{drift}}$$

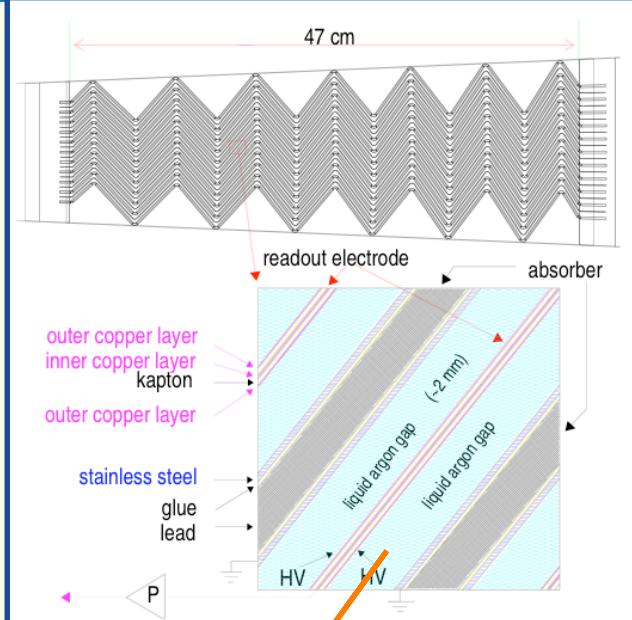
- The drift time (T_{drift}) is 4 times more sensitive to gap (w_{gap}) variations than E (the energy response):

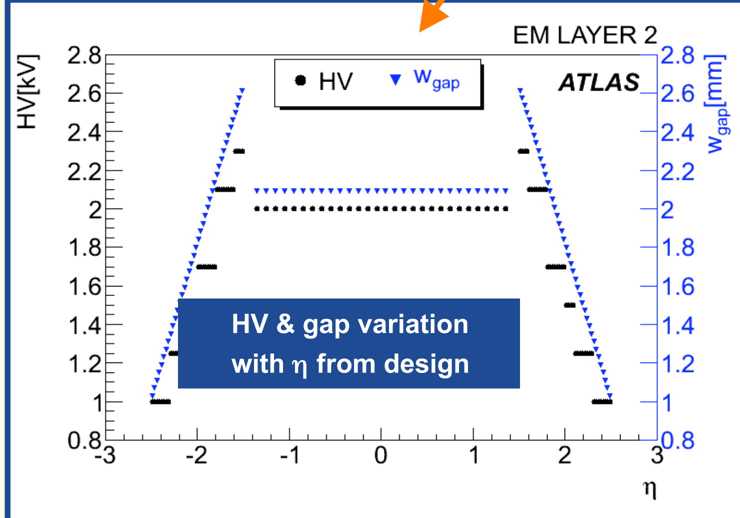
$$V_{drift} = V_{ref} \cdot \left[\frac{HV}{HV_0} \cdot \frac{w_{gap0}}{w_{gap}}\right]^{\alpha}$$

$$\alpha = 0.3$$

$$T_{drift} \sim w_{gap}^{1+\alpha} \simeq w_{gap}^{1.3}$$

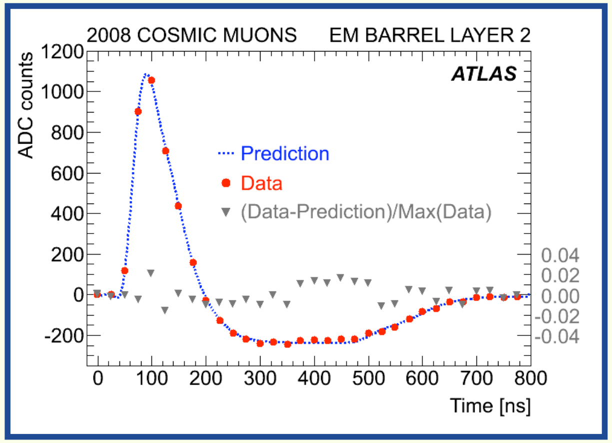
➔ **The drift time is sensitive to sources of non-uniformities inside the detector (gap variation, temperature, HV…)**

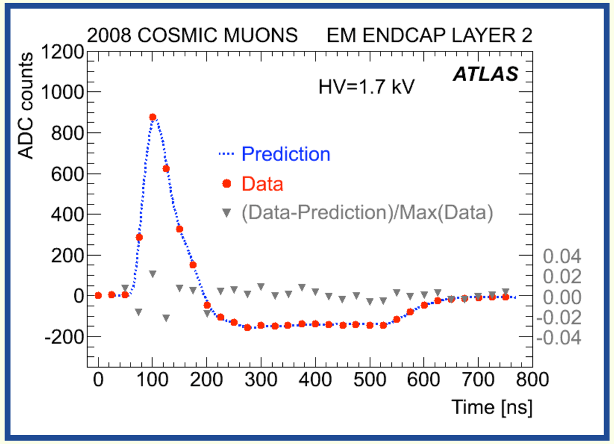




Ionization pulse shapes in the EM

- **Cosmic muon pulses with 32 samples are analyzed:**
  - ✓ **Period: September-November 2008**



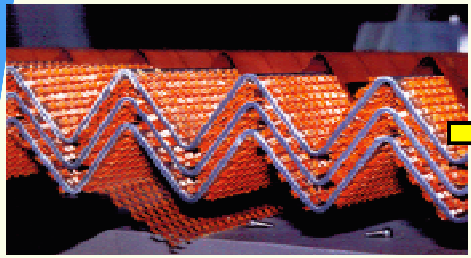


- **After selection cuts (~1-2 GeV):**

Layer	# pulses barrel	# pulses endcap
Presampler	20 K	
Layer 1	43k	13 k
Layer 2	331 k	45 k
Layer 3	79 k	18 k

➔ **The length of the undershoot being equal to the drift time.**

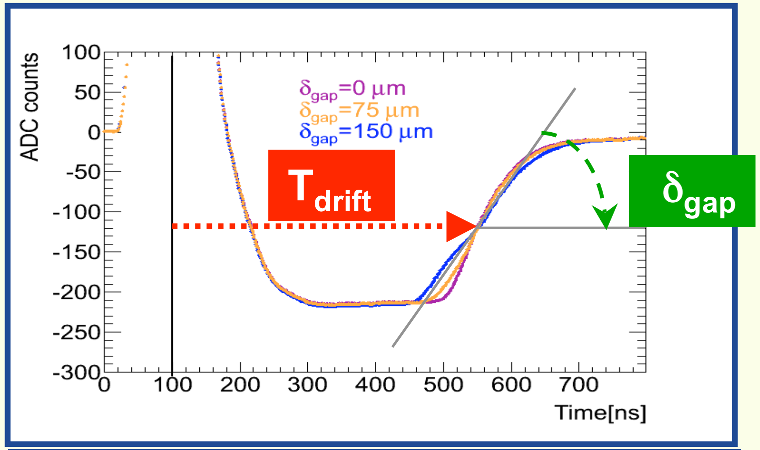
Accordion geometry: Flat sections



flat sections

Displacement of the readout electrode in between the absorbers

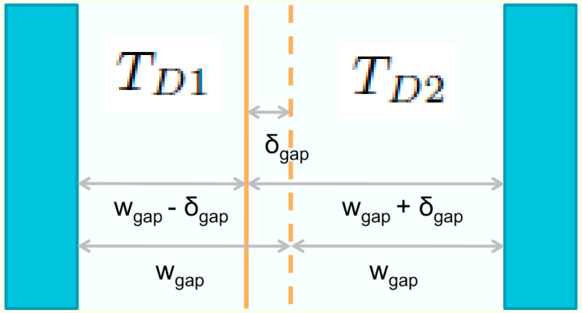
$$\delta_{gap} = x \cdot w_{gap}$$

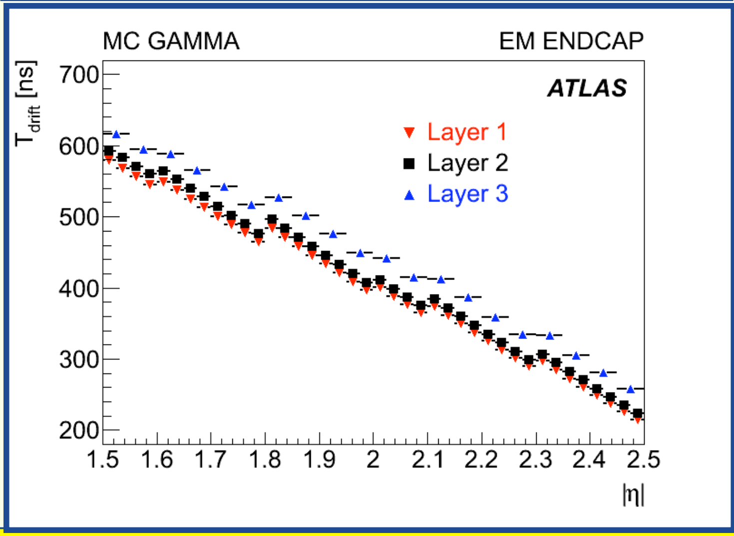


$$T_{D1} = T_{drift}\,(1 - x)^{1+\alpha}\,(HV_1/HV_{nom})^{-\alpha}$$

$$T_{D2} = T_{drift}\,(1 + x)^{1+\alpha}\,(HV_2/HV_{nom})^{-\alpha}$$

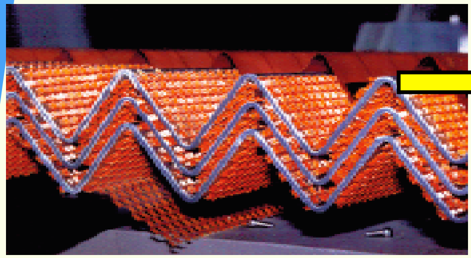
$\alpha = 0.3$





→ **T_{drift} is constant (~458 ns) in barrel and depending on η in endcap**

Accordion geometry: Bent sections



bent sections

In the bends of the accordion the drift time is bigger: $T_{bend} > T_{drift}$

$$T_{D3} = T_{bend}\,(HV_1/HV_{nom})^{-\alpha}$$

$$T_{D4} = T_{bend}\,(HV_2/HV_{nom})^{-\alpha}$$

$$f_{nom} + f_{bend} = 1$$

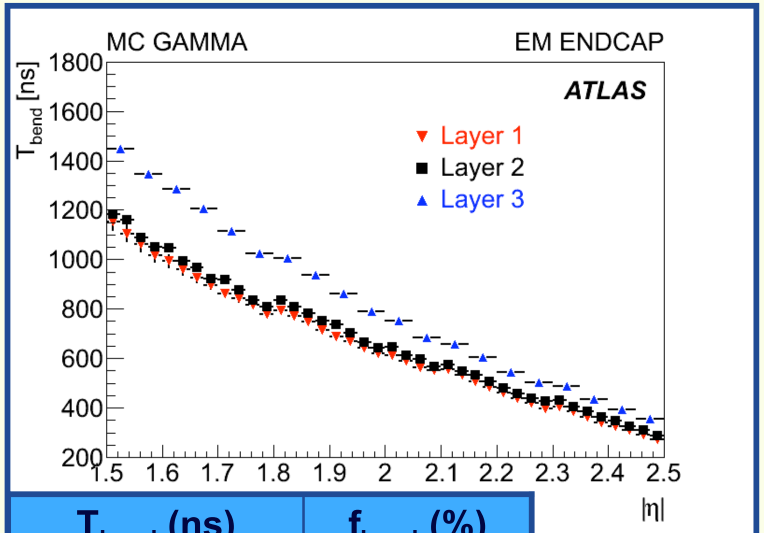
$$I_0 = I_{nom} + I_{bend}$$

"nom" represents the flat section

- **Barrel: Fixed value extracted from GEANT 4 simulation:**

Layer	T_{bend} (ns)	f_{bend} (%)
Layer 1	820.	4.9
Layer 2	898.	7.1
Layer 3	941.	8.5

- **Endcap: η-dependent value extracted from MC EM shower:**



T_{bend} (ns)	f_{bend} (%)
300. to 1500.	5 to 20

How do we measure the drift time?

- The ionization pulse at the end of the readout chain:

$$g_{fit}(t; A_{max}, t_0, T_{drift}, x) = A_{max} \cdot g_{phys}(t; f_{nom}, T_{drift}, x, f_{bend}, T_{bend}) \quad \text{for} \quad t > t_0$$

- Least squares method, minimization of:

$$Q_0^2 = \frac{1}{n - N_p} \sum_{i=1}^{n} \frac{(S_i - g_{fit}(t_i; A_{max}, t_0, T_{drift}, x))^2}{\sigma_{noise}^2}$$

✓ with 4 free parameters:

T_{drift}, x, A_{max} and t_0

- Two methods to predict the pulse shape g_{phys}: (see spares)
  - ✓ RTM: standard ATLAS method, extracted from calibration signals.
  - ✓ FPM: analytical description of signal propagation through the electronic chain (only barrel).

T_{drift} measurements: Layer 2 (EM barrel)

- **Prediction from absorber thickness measurement:**

$$\text{Absorber}\,(2.2\ mm) + w_{gap}\,(2.09\ mm) \;+\; \text{Electrode}\,(0.280\ mm) + w_{gap}\,(2.09\ mm) = \\ = 6.66\ mm = (2\pi/1024)\cdot R_i \cos\theta_i$$

Fixed by geometry

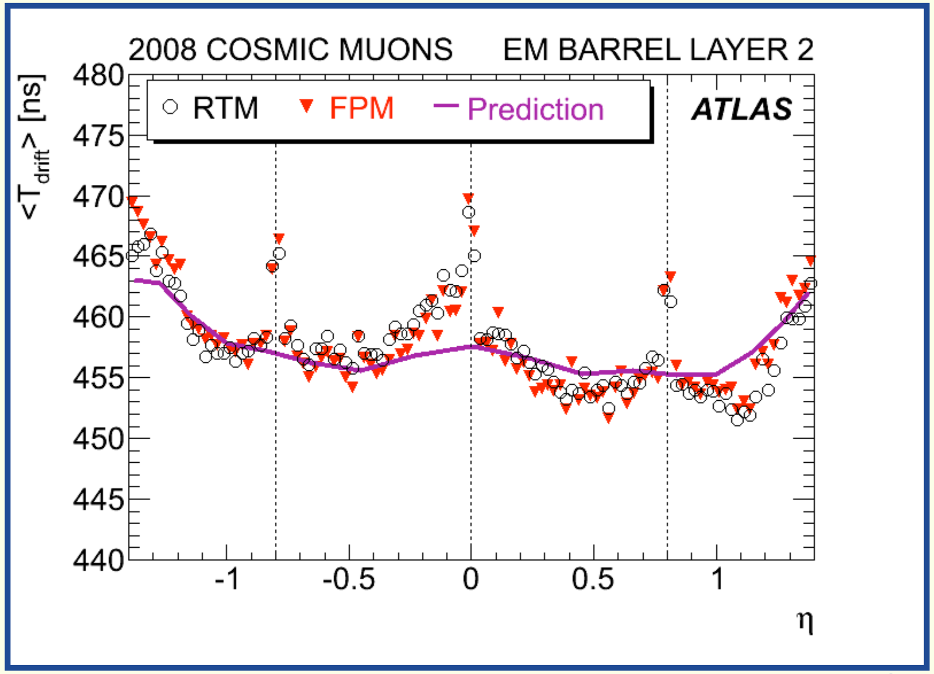
✓ **Gap variation:**

$$T_{drift} = T_{D0}(w_{gap}/w_{gap0})^{1+\alpha}$$

where:

$$w_{gap0} = 2.09\ \text{mm}$$

$$T_{D0} = \langle T_{drift}\rangle = 457.9\ \text{ns}$$



➔ **Sensitivity to transition regions where electric field is lower**

➔ **Good agreement between RTM and FPM methods ➔ 0.2 ns average difference, 1.3 ns RMS**

➔ **Agreement prediction and data at the level of 2.9 ns RMS excluding transition regions.**

T_{drift} measurements: Presampler (EM barrel)

- **Prediction from geometry:**
  - ✓ **Gap variation:**

$$T_{drift} = T_{D0}(w_{gap}/w_{gap0})^{1+\alpha}$$

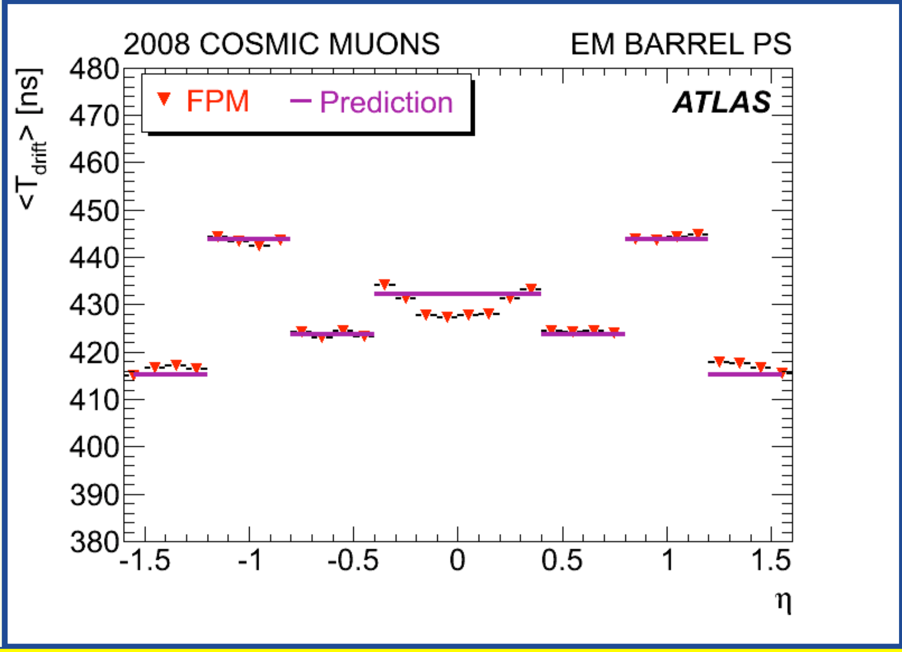
where:

$$w_{gap0} = 2.006 \text{ mm}$$ **($0.8 \leq |\eta| < 1.2$)**

$$T_{D0} = 445 \text{ ns}$$

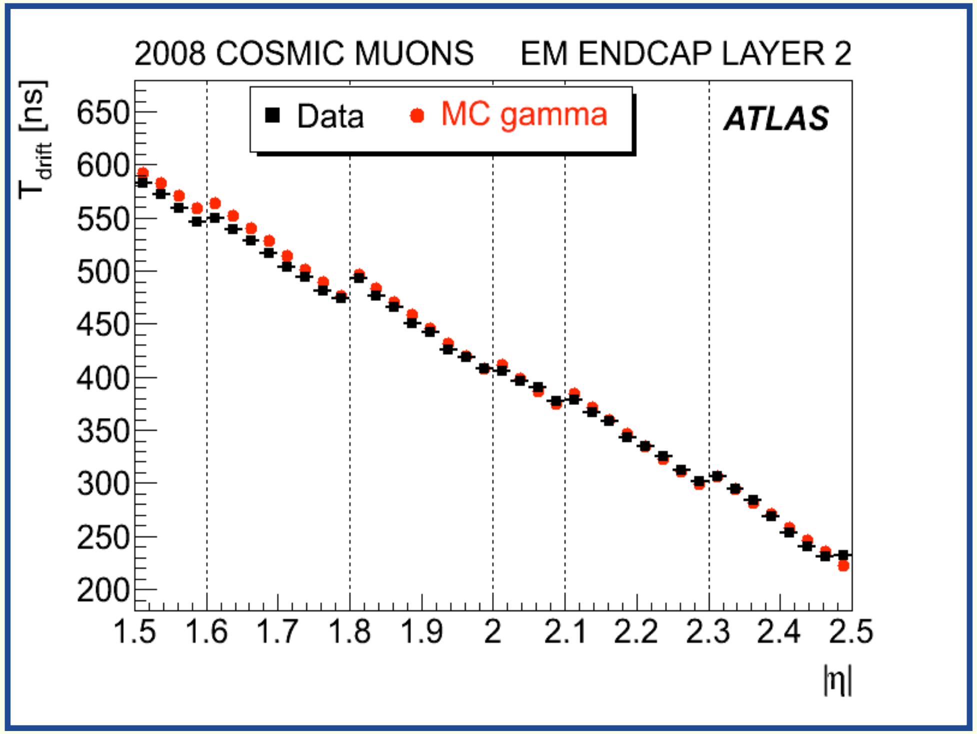
Different gap regions
➡ different T_{drift}

η region	w_{gap} (mm)
$|\eta| < 0.4$	1.966
$0.4 \leq |\eta| < 0.8$	1.936
$0.8 \leq |\eta| < 1.2$	2.006
$1.2 \leq |\eta|$	1.906



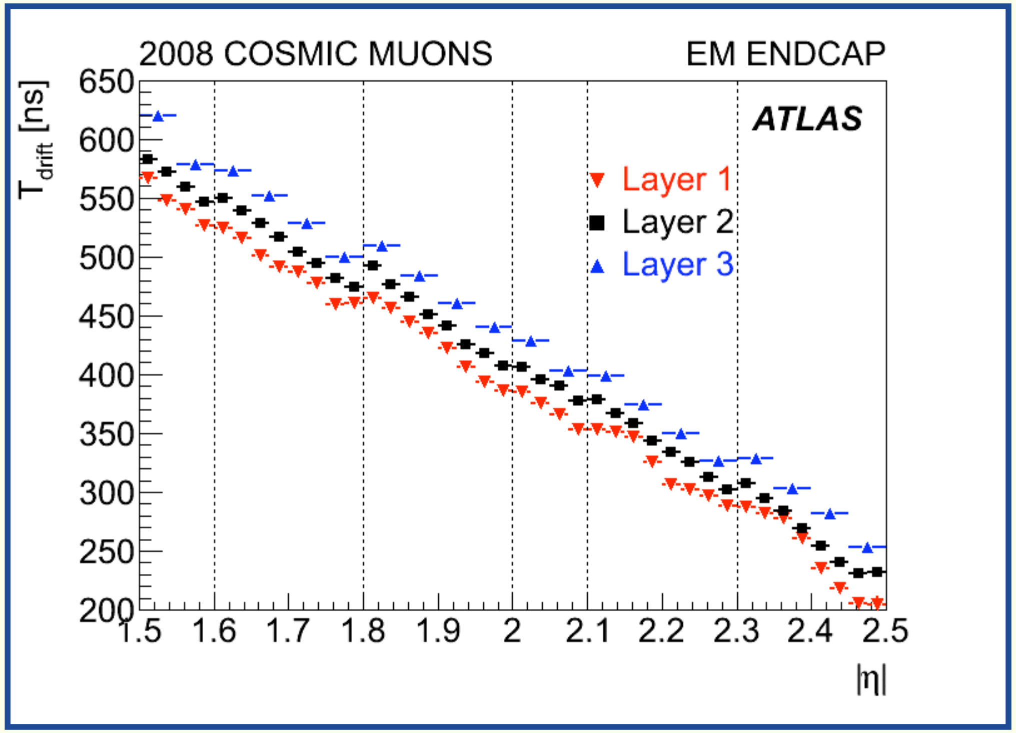
➔ Very good agreement between the measured and predicted T_{drift}.

T_{drift} measurements along η (2)

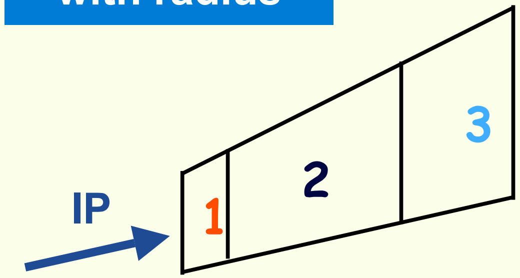


- ➔ **Tdrift decreases with W_{gap} hence with η.**
- ➔ **Visible steps at the transition between HV regions.**
- ➔ **Reasonable agreement with MC (at the level of 1% in layer 2)**

T_{drift} measurements: Sensitivity to gap variation along depth (EM endcap)



gap increases with radius

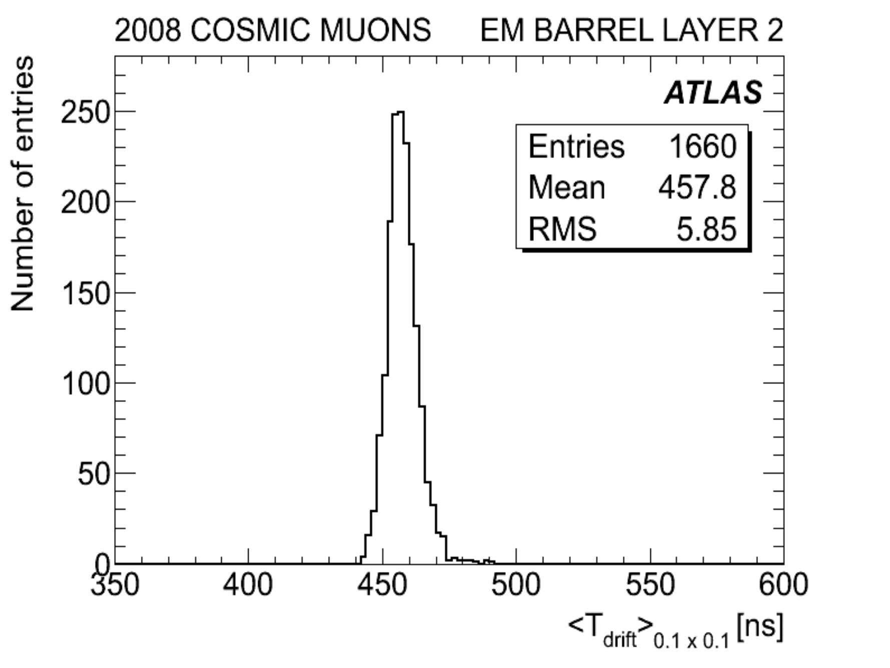


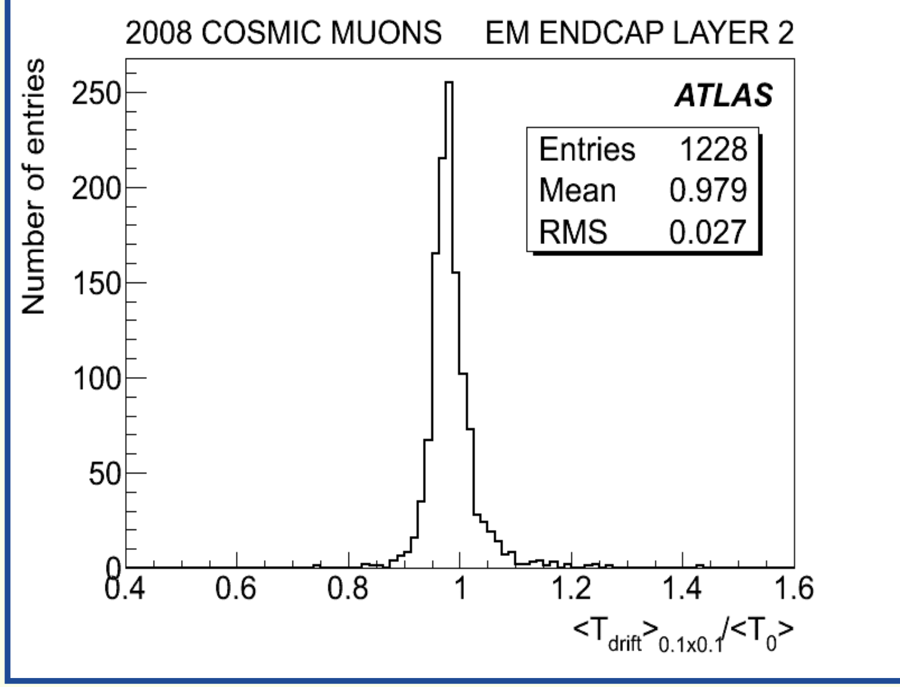
→ **The gap size for a given η increases with depth: $T_{drift1} < T_{drift2} < T_{drift3}$**

Response uniformity from T_{drift} measurements

➢ **Drift time uniformity within groups of 4 x 4 cells ($\Delta\eta \times \Delta\phi$ = 0.1 x 0.1):**

✓ **$\langle T_0 \rangle$ is the normalization to cancel the variation with η due to the gap size variation**

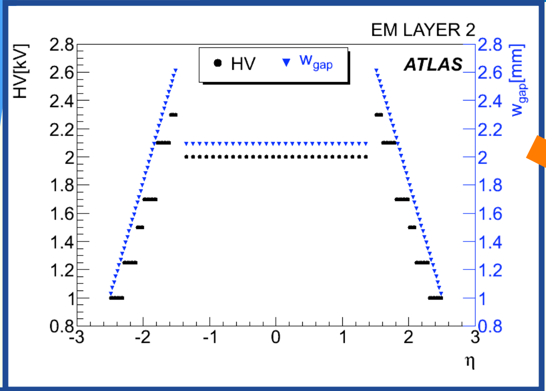


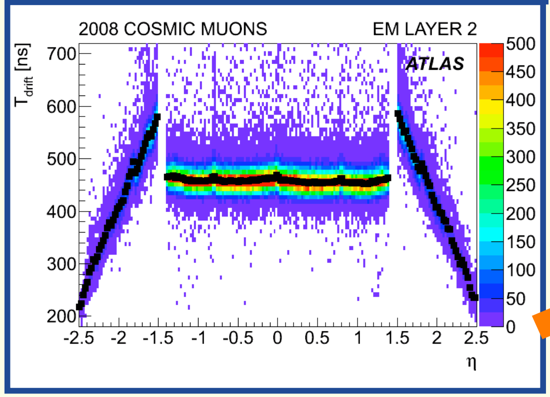


➔ **The drift time uniformity leads to a dispersion of the response due to the gap variations of:**

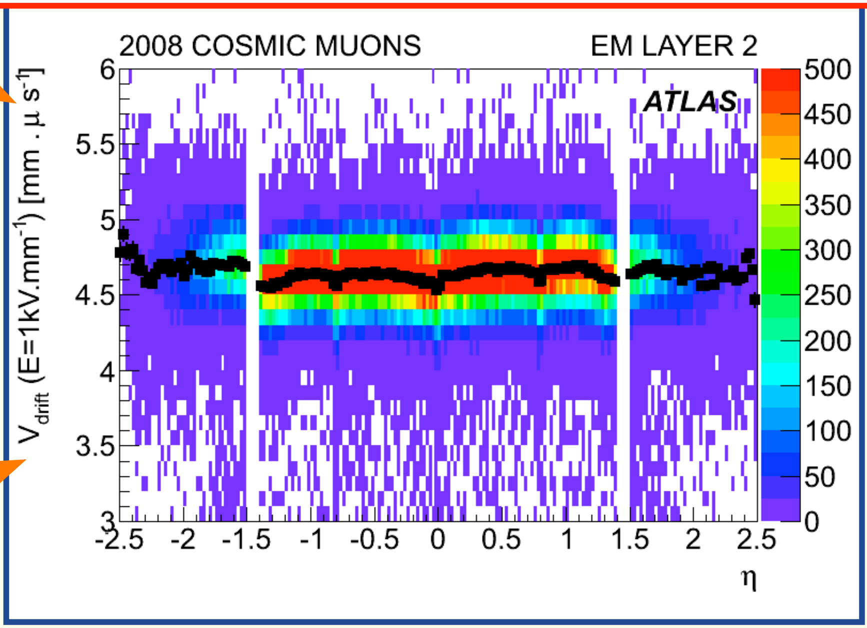
➔ **EM barrel: $(0.29\,^{+0.05}_{-0.04})$ % ; EM endcap: $(0.53\,^{+0.06}_{-0.04})$ %**

Drift velocity at 1 kV/mm (1)





$$V_{drift}(1\,\mathrm{kV/\,mm}) = \frac{w_{gap}}{T_{drift}}\left(\frac{2000\,\mathrm{V}\cdot w_{gap}}{HV_{nom}\cdot 2\,\mathrm{mm}}\right)^{\alpha}$$



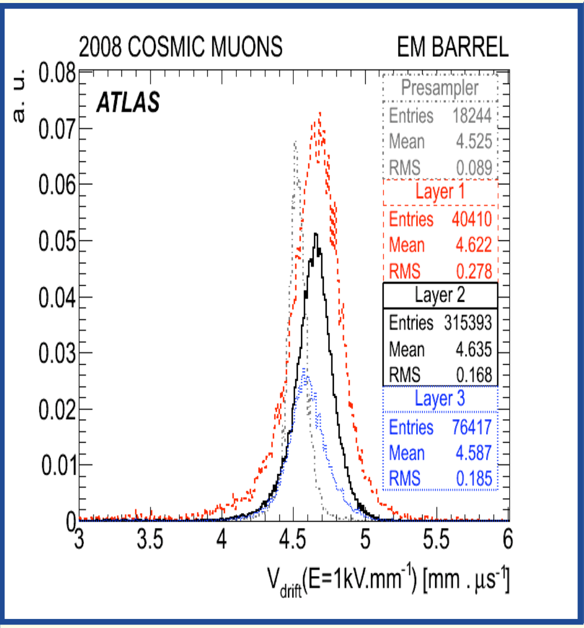
- Flat behavior is observed in the whole EM calorimeter
- LAr temperature 0.3 K higher for endcap A than C
    - ➔ Drift velocity measured in endcap C larger than in A (0.6 %)

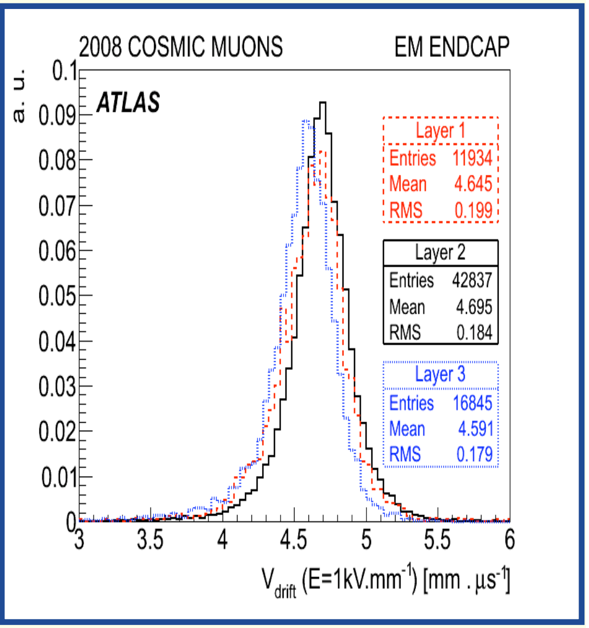
Drift velocity at 1 kV/mm (2)

- All studied systematics are between 1 and 6 ns
- Translate to V_{drift}:

$$V_{drift}(1\,\mathrm{kV/mm}) = \frac{w_{gap}}{T_{drift}}\left[\frac{1000\,\mathrm{V}}{1\,\mathrm{mm}}\,\frac{w_{gap}}{HV}\right]^{\alpha}$$

Layer	Layer	V_{drift} (mm/µs at 1 kV/mm)
Barrel	PS	4.52 ± 0.001 (stat) $^{+0.11}_{-0.07}$ (syst)
	L1	4.62 ± 0.003 (stat) $^{+0.06}_{-0.14}$ (syst)
	L2	4.63 ± 0.002 (stat) $^{+0.06}_{-0.14}$ (syst)
	L3	4.59 ± 0.002 (stat) $^{+0.06}_{-0.14}$ (syst)
Endcap	L1	4.65 ± 0.002 (stat) $^{+0.10}_{-0.14}$ (syst)
	L2	4.69 ± 0.001 (stat) $^{+0.10}_{-0.14}$ (syst)
	L3	4.59 ± 0.002 (stat) $^{+0.10}_{-0.14}$ (syst)





→ Barrel and endcap layers: compatible within errors

→ Average over all significance layers: V_{drift} = (4.61 ± 0.07) mm/µs

➔ compatible with previous published measurements at 88.5 K

Direct determination of local w_{gap} and V_{drift}

$$T_{drift} = \frac{w_{gap}}{V_{drift}}$$

$$V_{drift} = V_{ref}\left[\frac{HV}{HV_0}\cdot\frac{w_{gap0}}{w_{gap}}\right]^{\alpha}$$

$$w_{gap} = [A \cdot T_{drift}]^{1/(1+\alpha)}$$

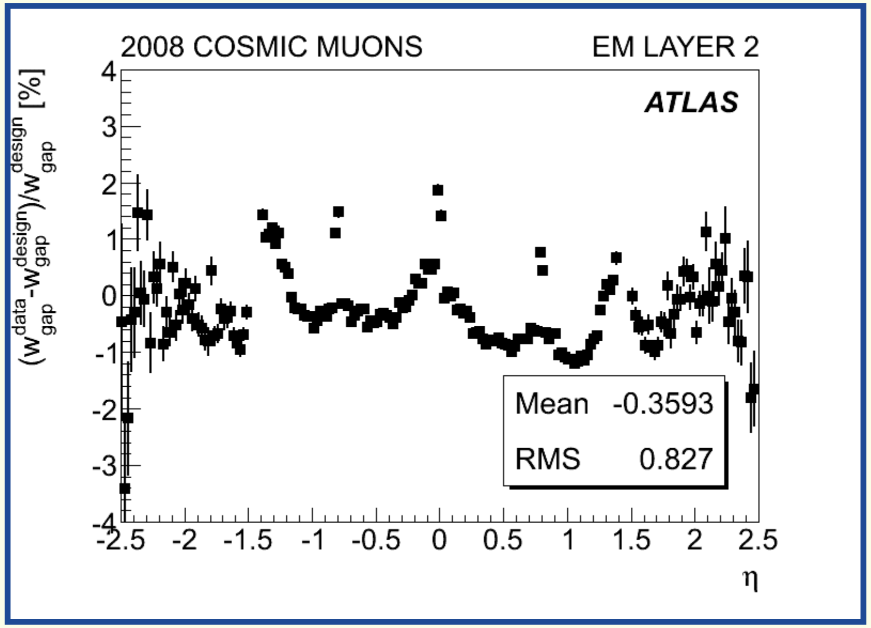
$$V_{drift} = \frac{A^{1/(1+\alpha)}}{T_{drift}^{\alpha/(1+\alpha)}}$$

where

$$A = V_{ref}\left[\frac{HV}{HV_0}\right]^{\alpha} w_{gap0}^{\alpha}$$

$$V_{ref} = 4.61\ \mathrm{mm}/\mu s$$

temperature correction endcap C/A



➔ **Good agreement, at the level of 1%, between the measured w_{gap} and the design values, except on transition regions.**

Conclusions

- Sufficient amount of ionization data pulses of E>1 GeV can be used for precision measurement of average drift time in each cell.

- Measured T_{drift} → estimate of calorimeter non-uniformity of response due to gap variations:
  - ✓ c_{gap}= 0.29 % (barrel) , c_{gap}=0.53 % (endcap)

- Average drift velocity measurement: V_{drift} = (4.61 ± 0.07) mm/μs
  - ✓ compatible with previous measurements at 88.5 K.

- Gap thickness direct from T_{drift} measurement:
  - ✓ Ratio (measured/design) uniform to better than 1 % over the full η range.

- Presented results are published in ATLAS-LARG-2009-02-004 and submitted to EPJ.

SPARES

ATLAS Electromagnetic Calorimeter

➤ **EMC performance requirements to reach discovery potential (Higgs, W', Z'…):**

✓ **Energy resolution:** $$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

Sampling term

$$\frac{a}{\sqrt{E}} < \frac{10\ \%}{\sqrt{E[\mathrm{GeV}]}}$$

Noise term

$$b < 50\ \mathrm{MeV/cell}$$

constant term

$$c < 0.7\ \%$$

✓ **Angular resolution:** $$\frac{50\ \mathrm{mrad}}{\sqrt{E[\mathrm{GeV}]}}$$ **(γγ invariant mass reconstruction)**

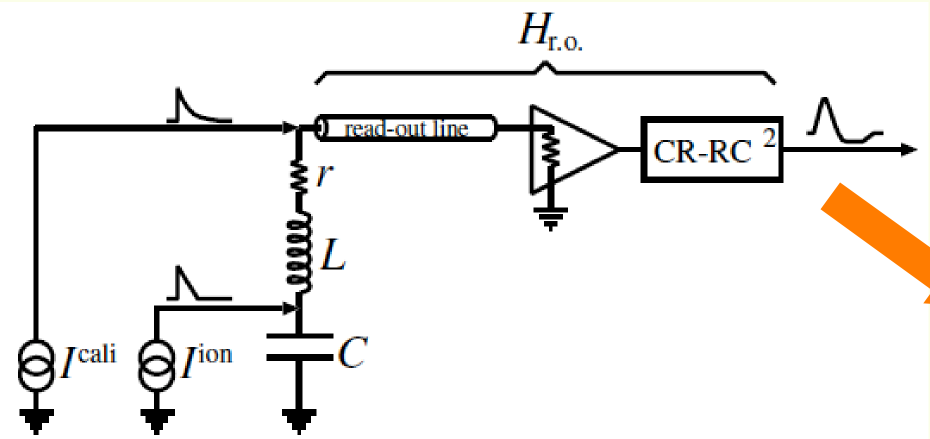
✓ **Time resolution:** $0.1\ \mathrm{ns}$ **(background rejection)**

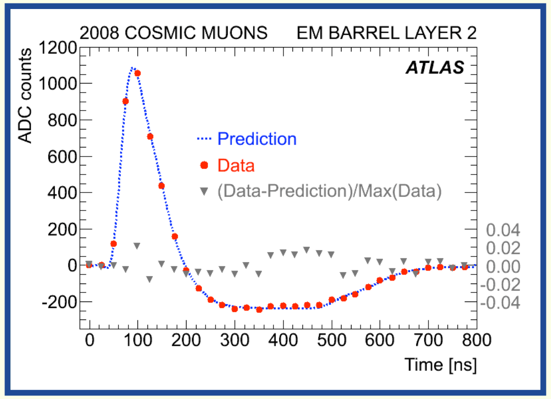
✓ **Particle identification/rejection (e.g. γ/π^0, e, …)**

➔ **The physics imposes a challenge in the construction and calibration of the calorimeter**

Physics signal for the EM Calorimeter

- **In every EMC cell, the signal is generated by the drift of the ionization electrons inside the LAr gap:**





Triangular signal is amplified and shaped by bipolar filter CR-RC (shaper) and then sampled every 25 ns (S_i) by SCA

- **The Optimal Filtering (OF): signal maximum amplitude (A_{max}), temporal position (Δt)**

$$A_{max} = \sum_{i=1}^{n} a_i S_i$$

$$\Delta t = \frac{\sum_{i=1}^{n} b_i S_i}{A_{max}}$$

OF coefficients (OFC), a_i and b_i, are calculated from the signal shape with the condition to minimize the noise (including pile-up)

Default value for n in physics mode is 5 samples

→ **OF requires the knowledge of signal shape (g^{phys}) and autocorrelation matrix between samples for every cell**

LAr electronics calibration

- During normal LHC operation a calibration system is used to monitor the ~173k cells regularly:

Pedestal (P)
noise and autocorrelation matrix for OFC computation

Ramp (g)
compute electronic gain/cell

Delay
Cell response to a calibration signal shape

- Energy per cell is calculated as:

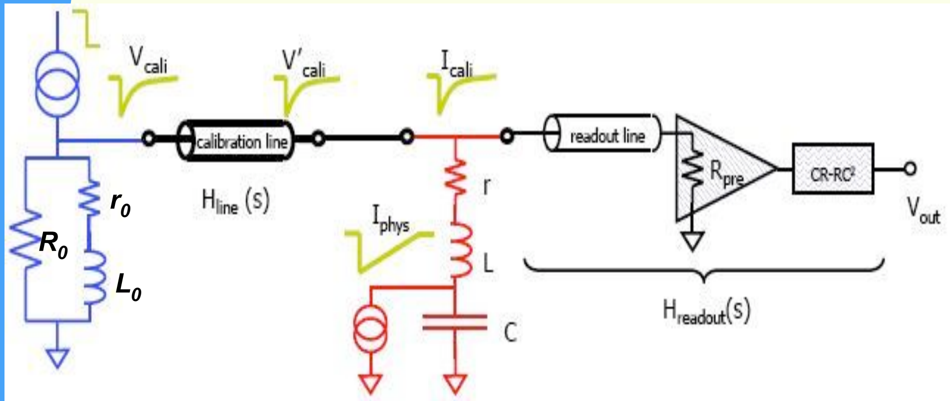
$$E(GeV) = f_{DAC\rightarrow\mu A} \times f_{\mu A\rightarrow GeV} \times \frac{M_{cali}}{M_{phys}} \times g_{ADC\rightarrow DAC} \times \sum_{i=1}^{n} a_i (S_i - P)$$

Signal reconstruction in EM Calorimeter

RTM Method

"Factorization of the readout response"

The readout response of each cell is probed by the calibration pulses, and directly transferred to the physics pulse prediction

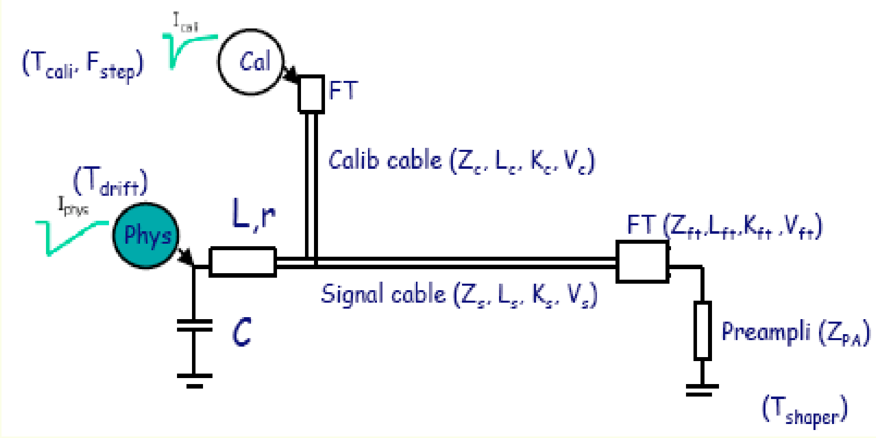


- The cell and pulse parameters (f_{step}, T_{cali}, rC, LC) are completely obtained from the calibration pulses
- The only additional parameter required it T_{drift} (now from calculation, can be refined when enough data is collected)

➔ **This method was successfully used in 2004 test beam and is the standard ATLAS pulse shape prediction.**

FPM Method

"Analytical model of the readout response"



- Uses measured parameters where possible
- A few parameters (T_{shaper}, Z_s) are left free to vary in order to match the measured calibration pulse response thus absorbing residual effects absent in the model

➔ **Currently, available only in the barrel**

T_{drift} measurements: Layer 2 (EM barrel)

- **Prediction from absorber thickness measurement:**
  - ✓ **Gap variation:**

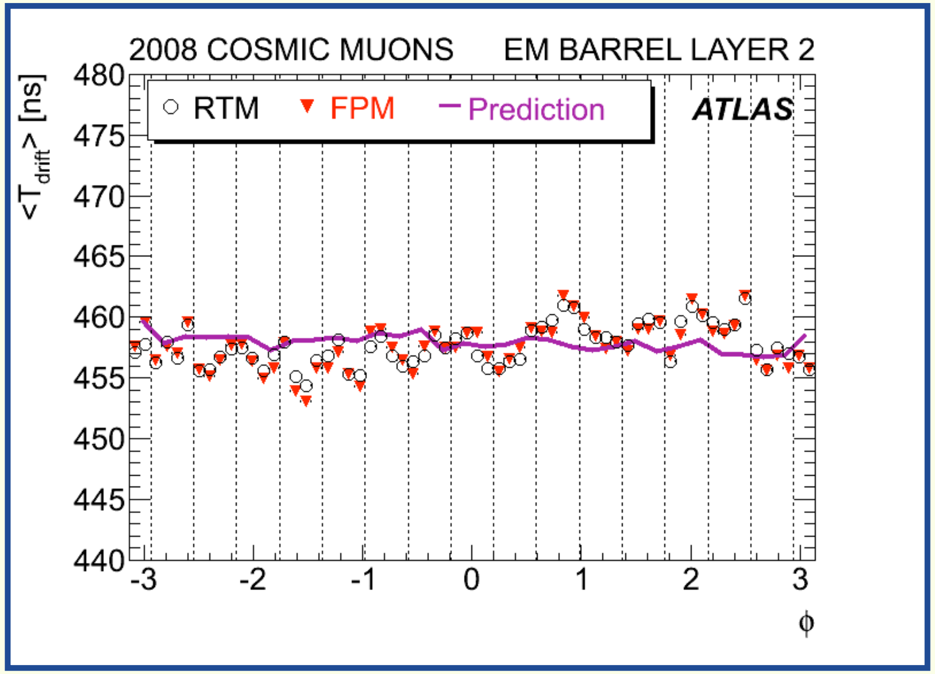
$$T_{drift} = T_{D0}(w_{gap}/w_{gap0})^{1+\alpha}$$

where:

$$w_{gap0} = 2.09 \text{ mm}$$

$$T_{D0} = \langle T_{drift} \rangle = 457.9 \text{ ns}$$

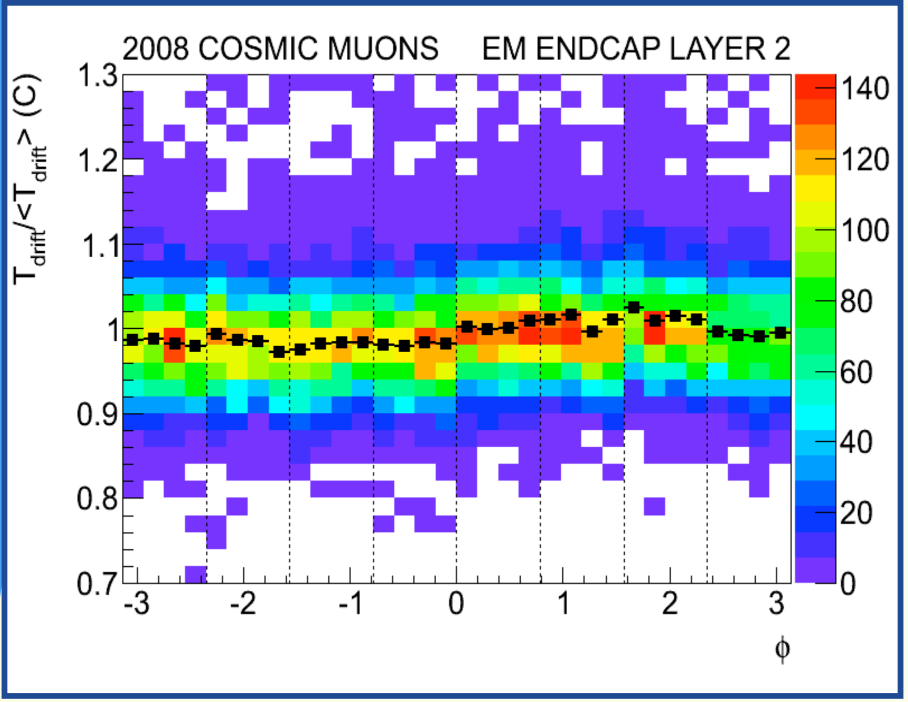
➔ **No significant variations are expected from absorber thickness measurements.**

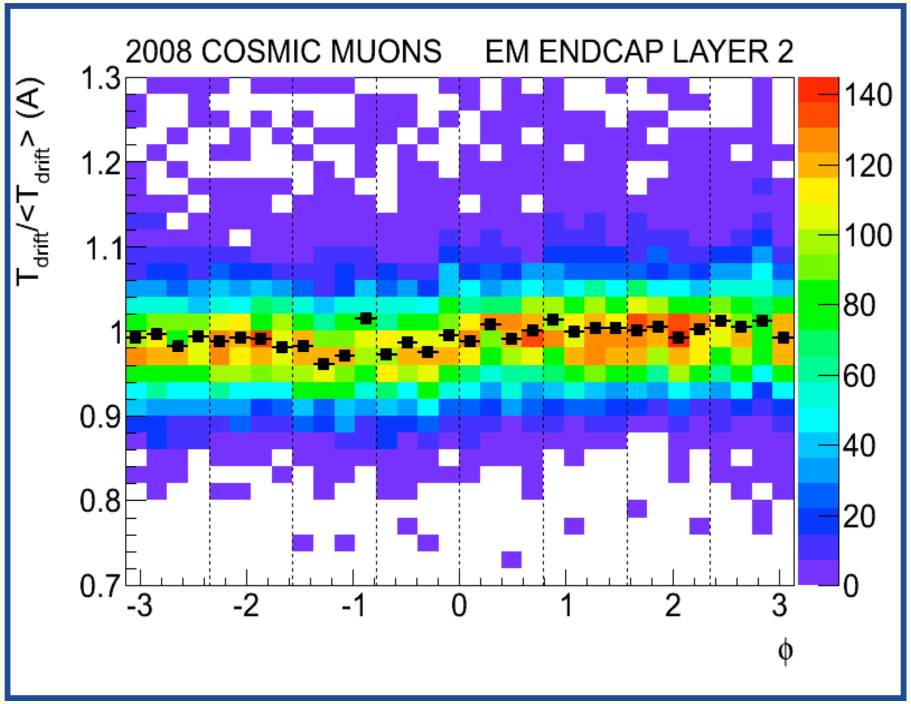


➔ **Asymmetry between ϕ>0 and ϕ<0 ➔ (0.3 ± 0.1) %**
➔ gravity can compress the lower part leading to slightly smaller gaps

T_{drift} measurements: Layer 2 (EM endcap)

✓ $<T_{drift}>$ is the normalization to cancel out the variation with η





➔ **Asymmetry between ϕ>0 and ϕ<0 ➔ (1.6 ± 0.2) %**

➔ **gravity can compress the lower part leading to slightly smaller gaps**

Response uniformity from T_{drift} measurements

- **The drift time uniformity gives:**

  EM barrel: (1.28 ± 0.03) % ; EM endcap: (2.3 ± 0.1) %

  ✓ **The contribution from the pure statistical fluctuations must be subtracted. For the barrel is negligible but for the endcap is (1.4 ± 0.1) %**

- **The drift time uniformity leads to a dispersion of the response due to the gap variations of**

  ✓ **EM barrel: (1.28 ± 0.03) % · (α/(1+α)) = (0.29 ± 0.01) %**

  ✓ **EM endcap: (2.3± 0.1) % · (α/(1+α)) = (0.53 ± 0.02) %**

- **Included systematic uncertainties:**

  ✓ **Changing the weighting, fit strategy or pulse reconstruction method**

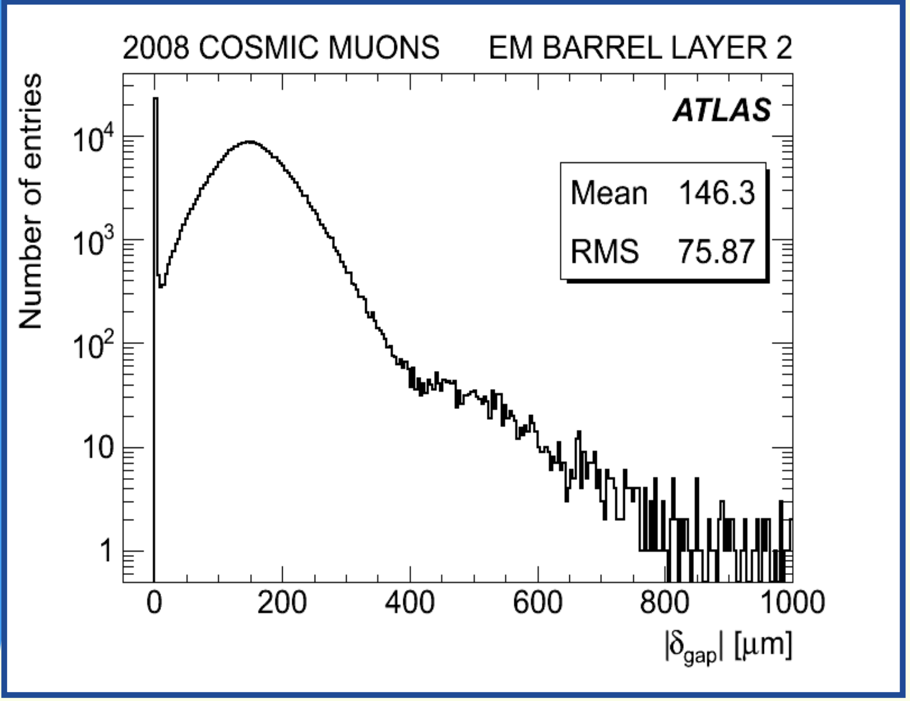
  ✓ **The uncertainty on α contributes with: $^{+0.04}_{-0.02}$**

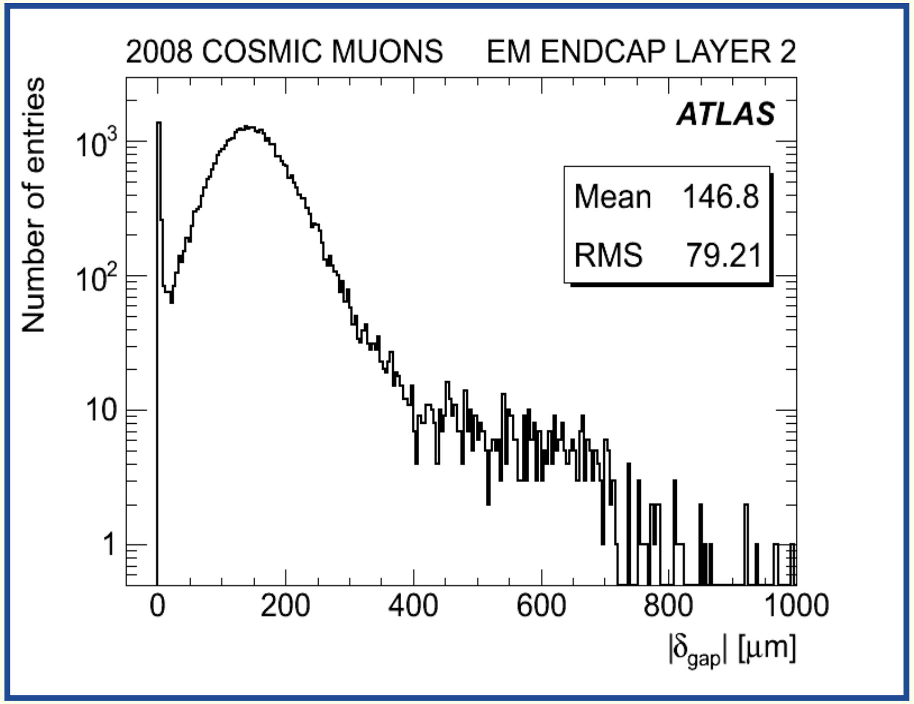
- **Final results:**

  ✓ **EM barrel:** $(0.29^{+0.05}_{-0.04})\ \%$

  ✓ **EM endcap:** $(0.53^{+0.06}_{-0.04})\ \%$

Electrode-Shift measurements





- ➔ On average 146 μm deviation around exact middle of the gap (the ionization pulse shape is only sensitive to the absolute value of the off-centering).
- ➔ Only 67 μm in the presampler.