Design and Performance of the ATLAS LAr Calorimeter

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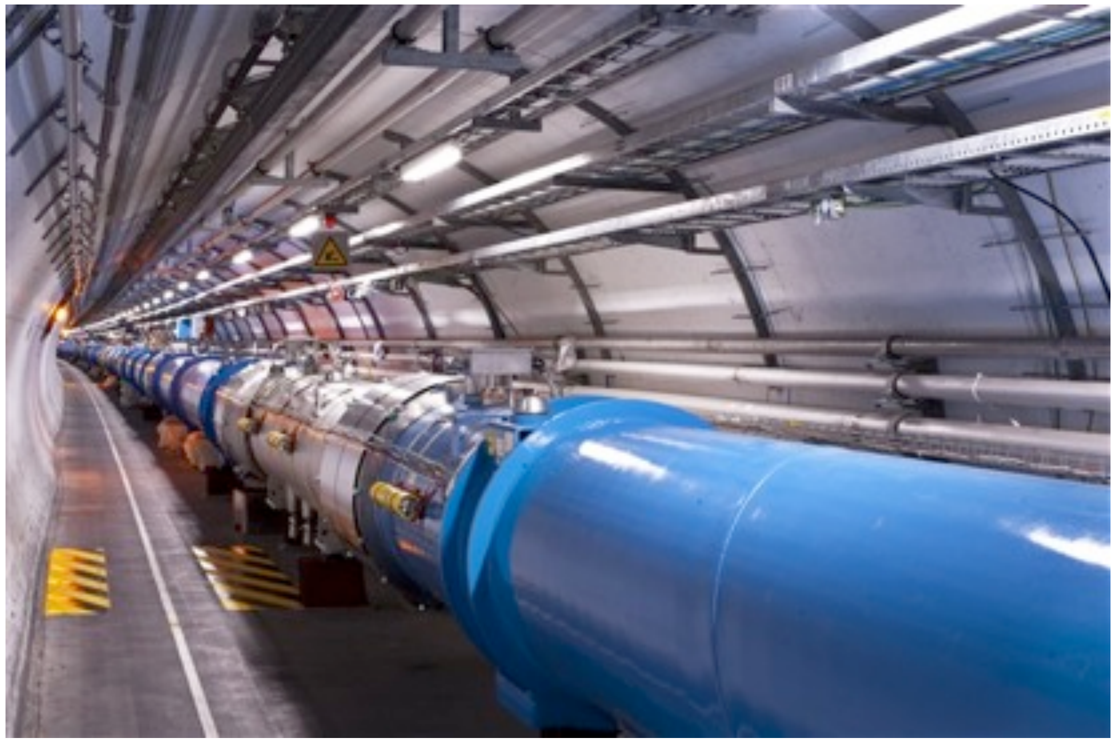
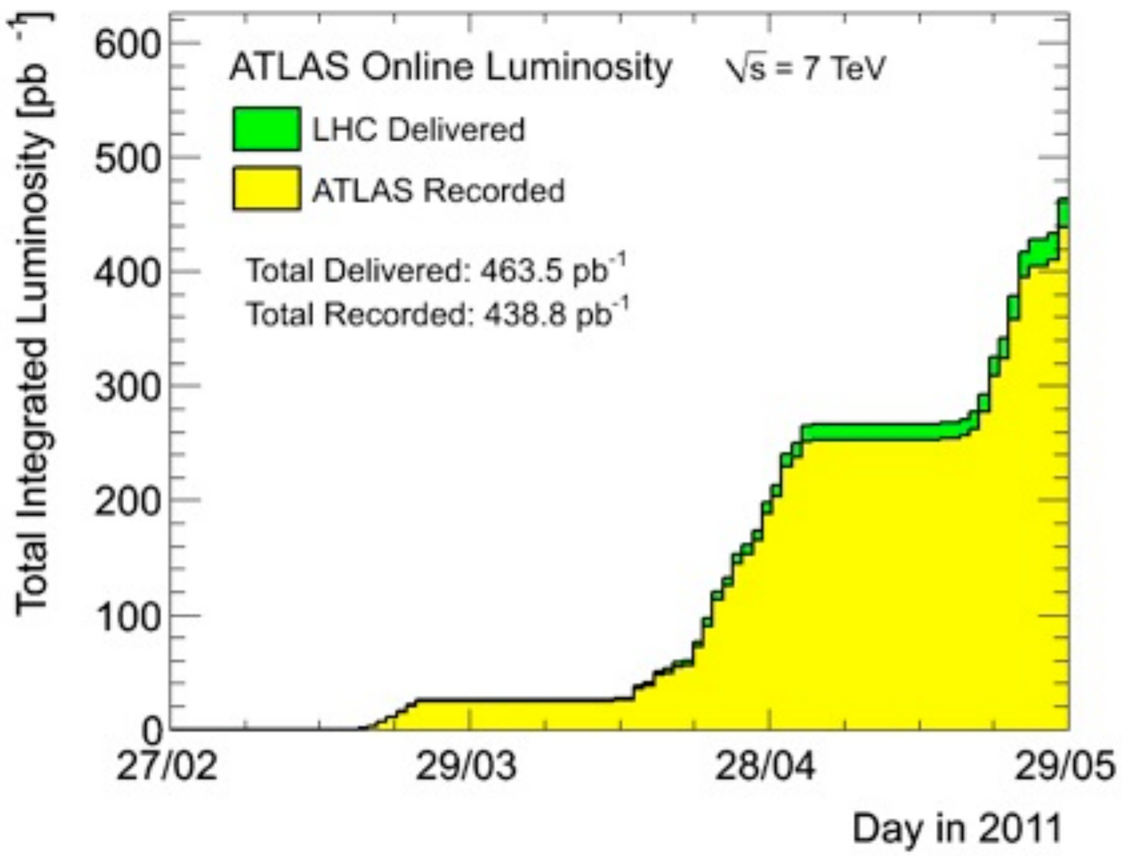
On behalf of the ATLAS LArg group

GLA2011 Workshop

LHC





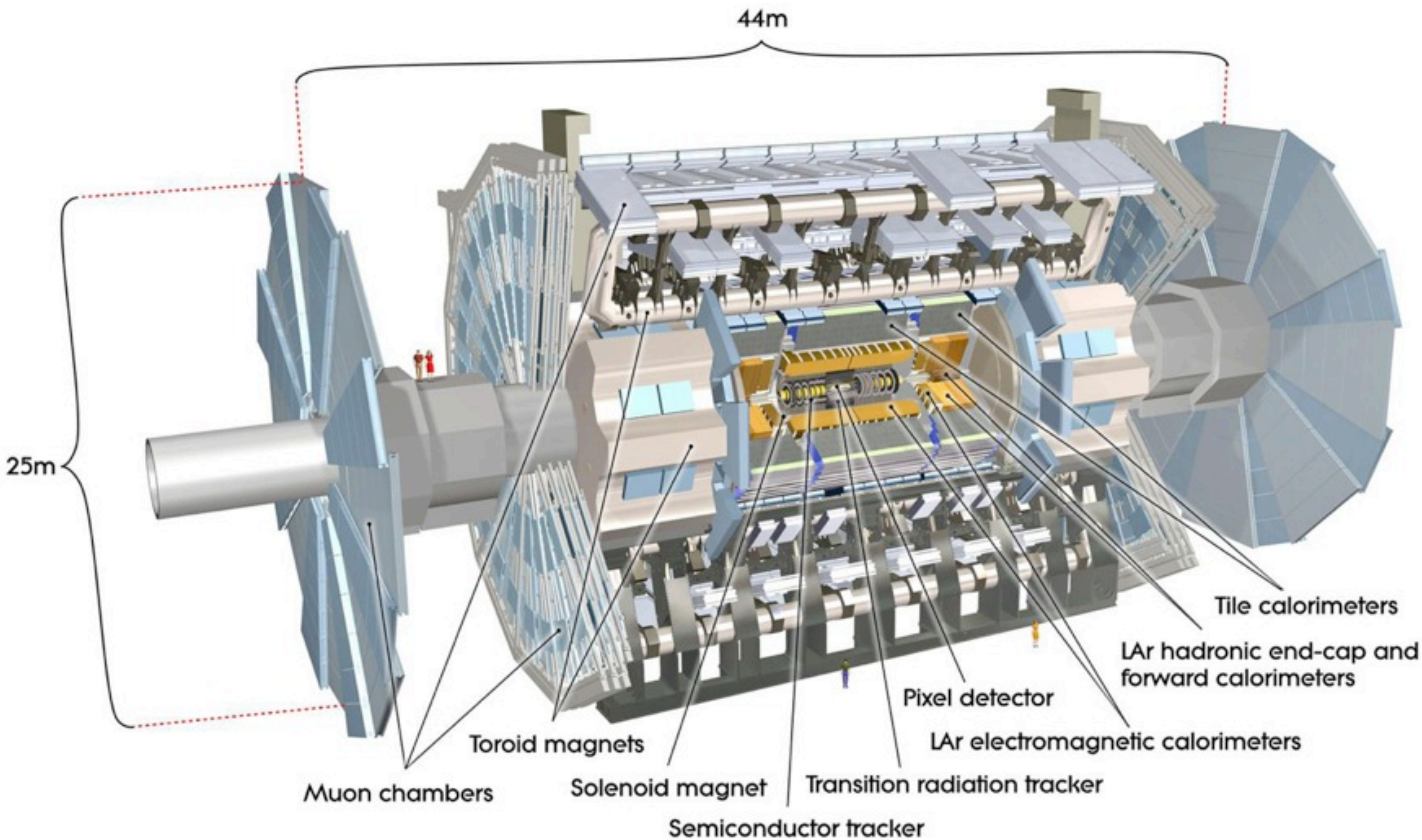
Nominal parameters:

- 27 km circumference, ~ 100 m beneath surface
- proton-proton collisions at 14 TeV
- 2808 bunches per beam
- 1.15 10^{11} protons per bunch
- ~ 25 interactions per bunch crossing at differential luminosity of $\sim 10^{34} cm^{-2} s^{-1}$
- Bunch crossing every 25 ns (40 MHz)

Present parameters:

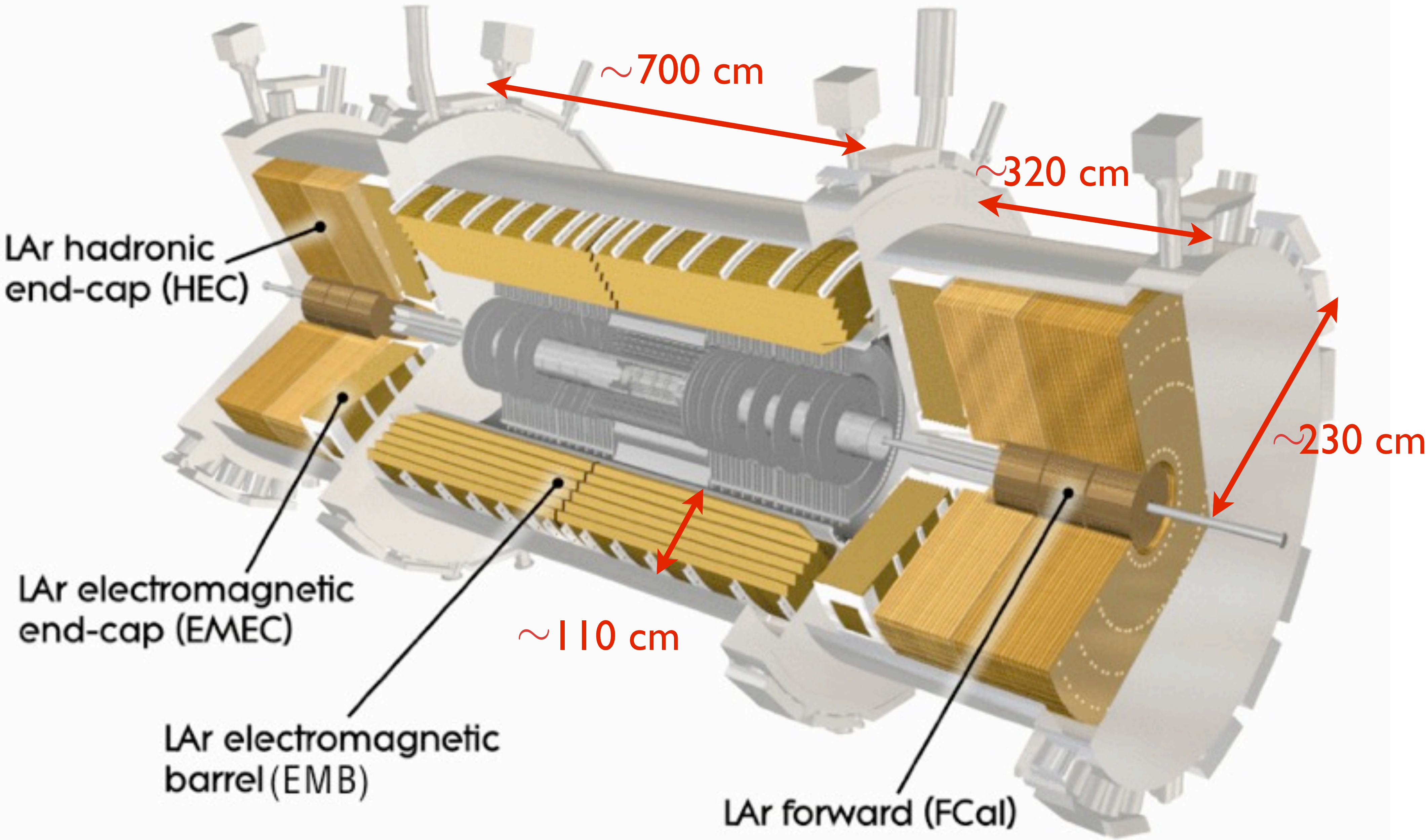
- proton-proton collisions at 7 TeV
- 1042 bunches/beam
- 1.15 10^{11} protons per bunch
- ~ 8 interactions per bunch crossing
- Max differential luminosity $\sim 1.1\ 10^{33}$

ATLAS Detector



Angular coordinates: $(\eta, \varphi), \quad \eta = -\ln(\tan\frac{\theta}{2})$

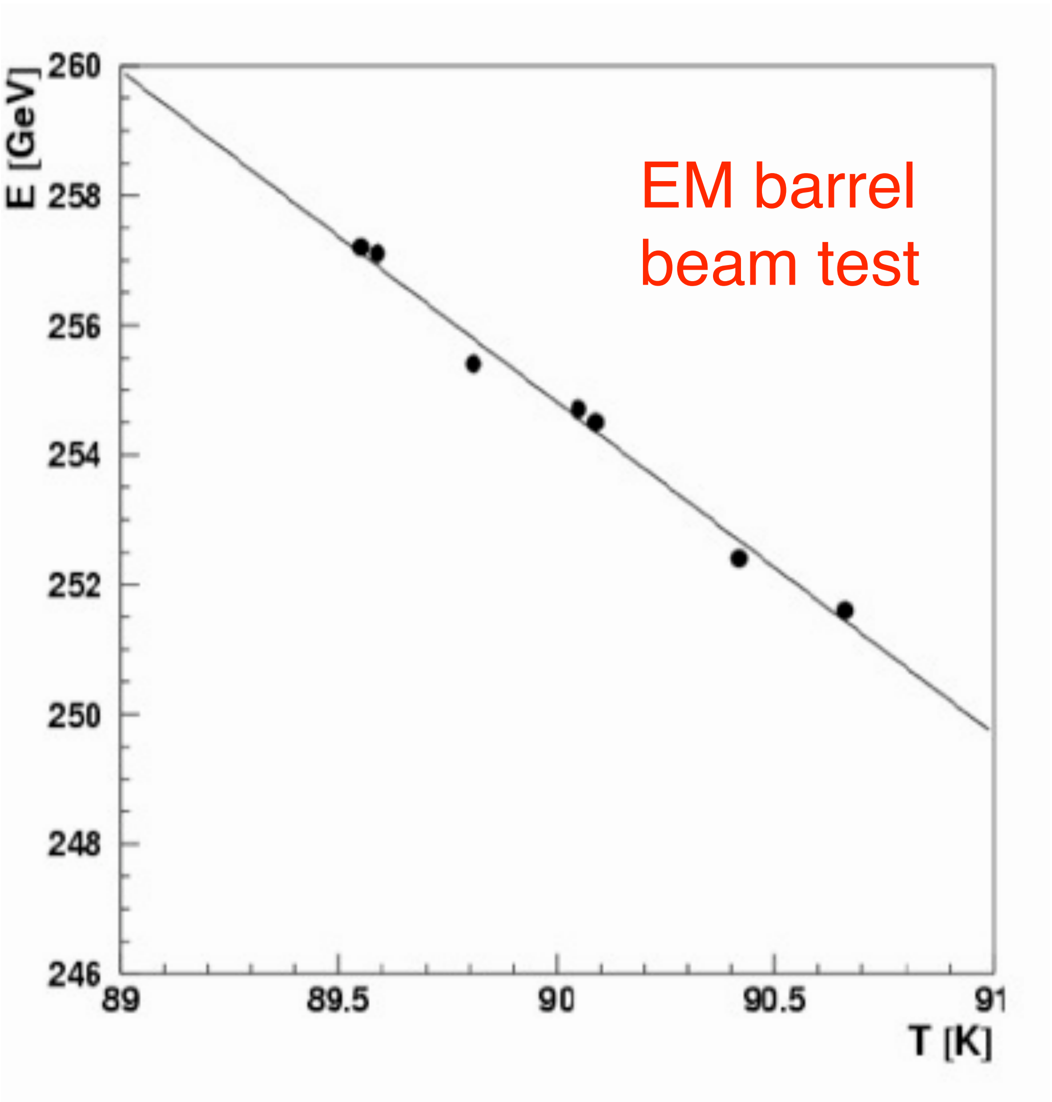
LAr Calorimeters



Liquid Argon 45 and 19 m^3 barrel and end-cap cryostat resp.

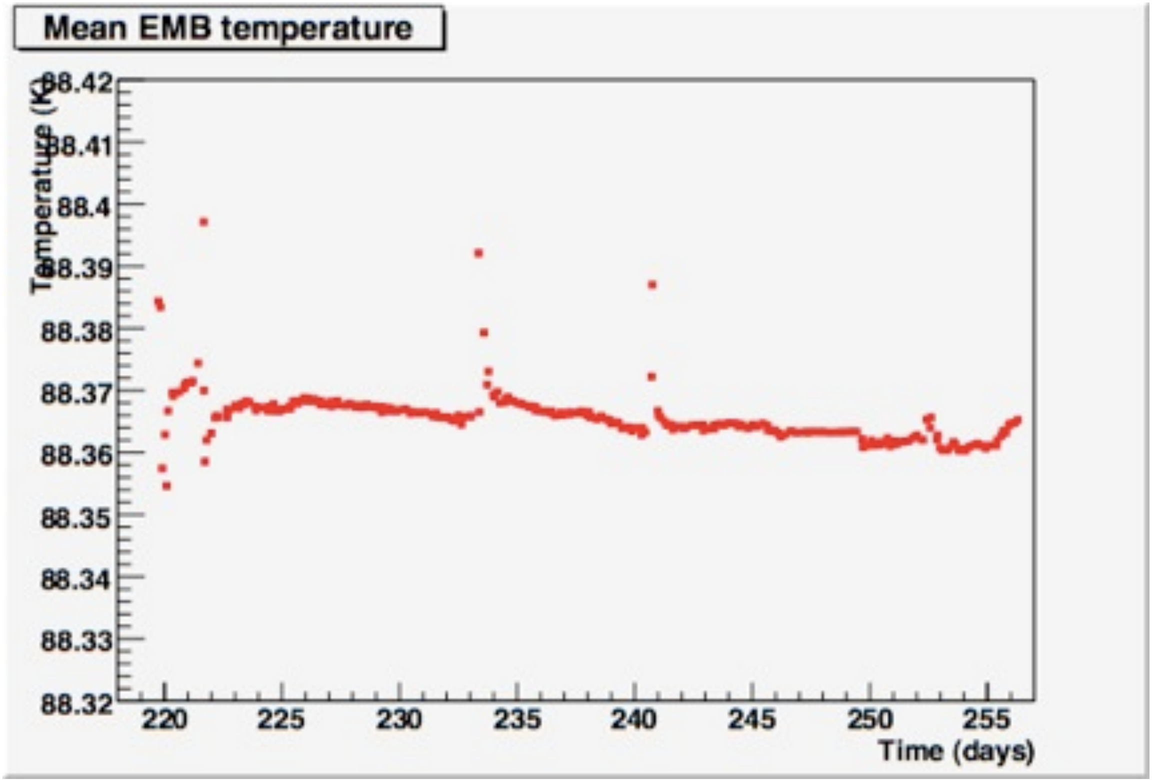
$\sim 80 m^3 LAr$ in detector or tanks

Energy dependence on LAr temperature

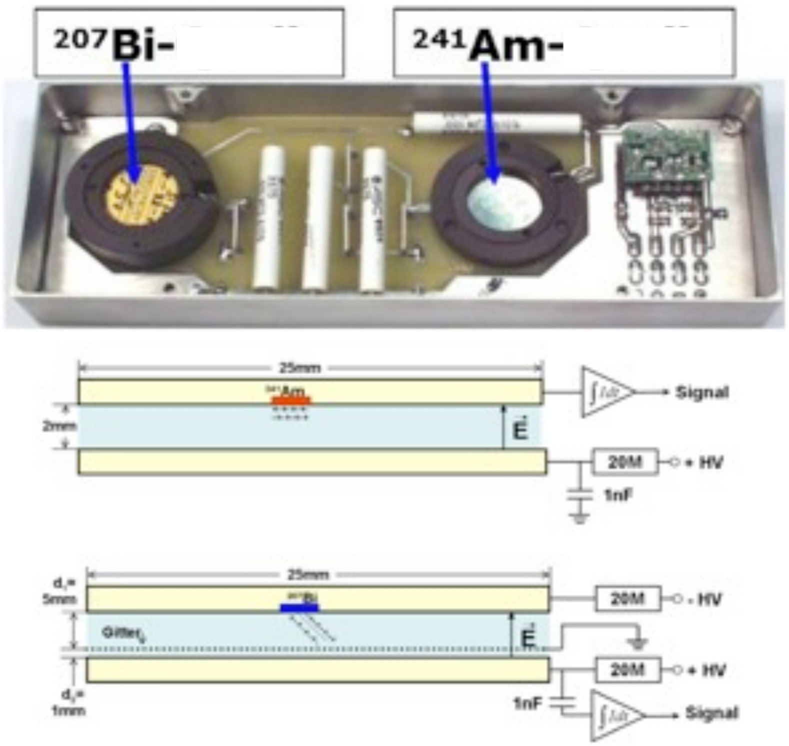


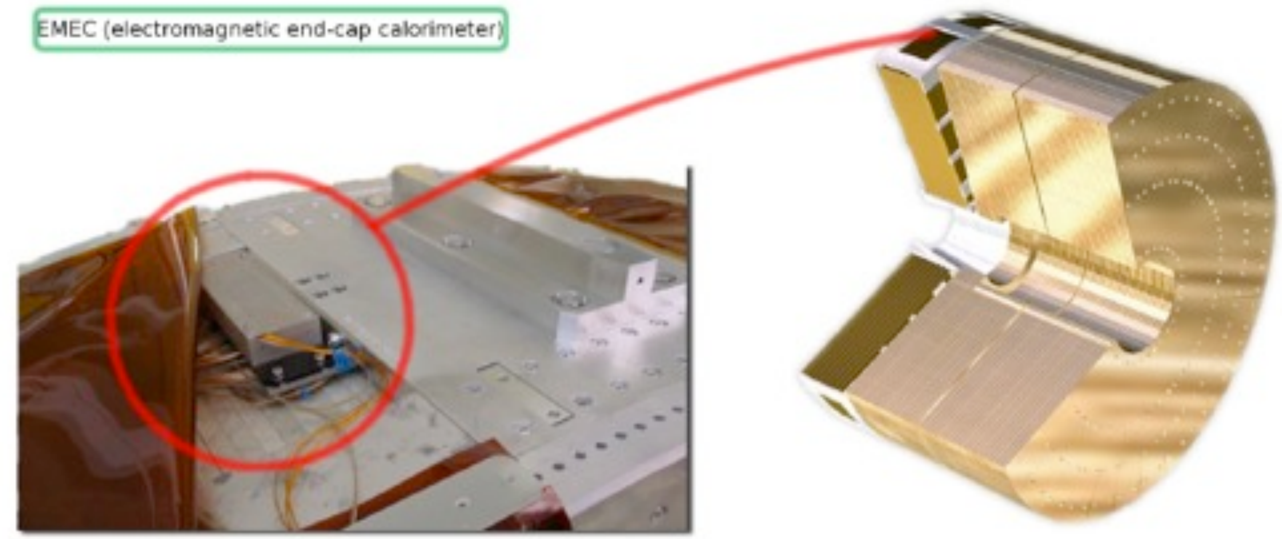
2% / K on the energy
(1.5% from drift velocity variation
+ 0.5% from density variation).

-Barrel 192 sensors, (ΔT=10mK)
-Endcaps 255 sensors.

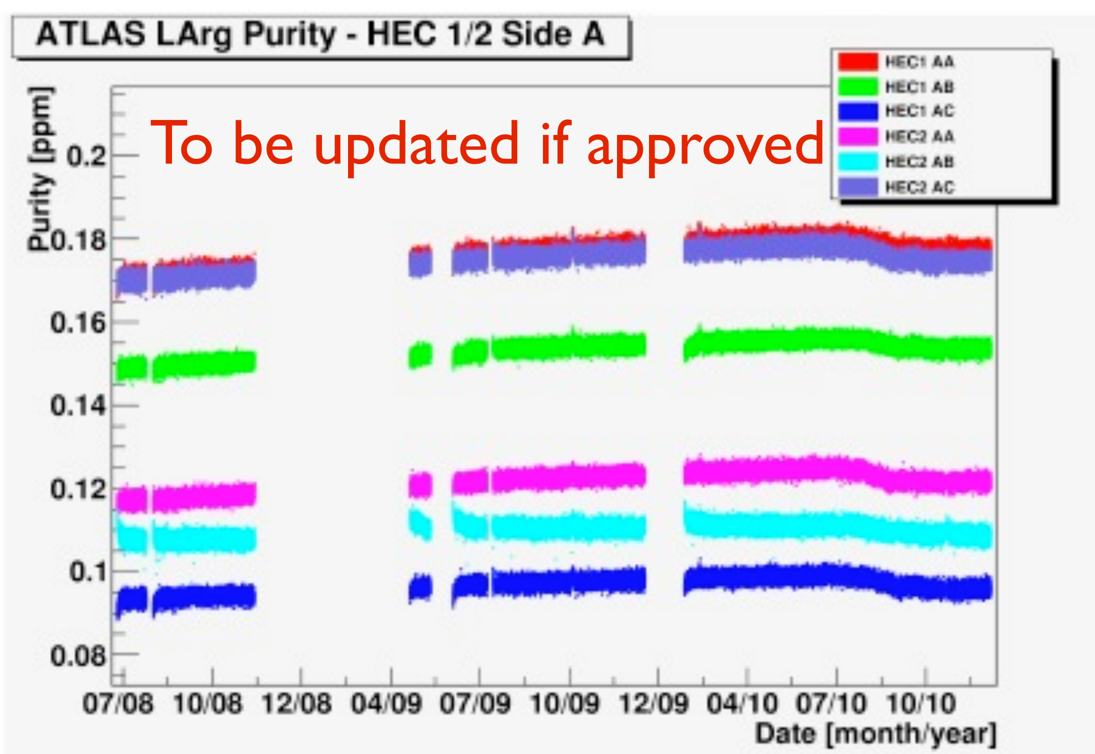


LAr purity





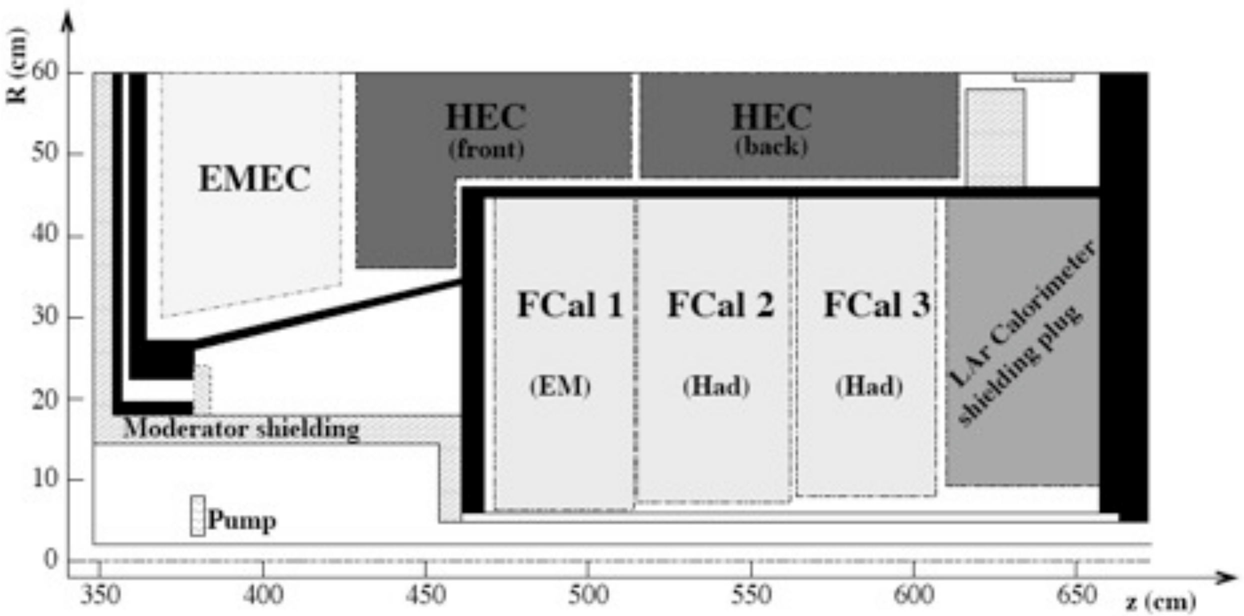
LAr purity:
- 10 monitors per cryostat.
- $Q_{Bi(1MeV\ e)}/Q_{Am(\alpha\ 5.5MeV)}$ gives O_2 content

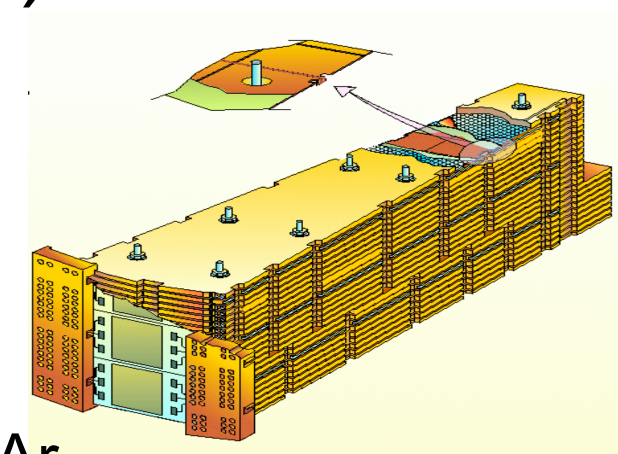


cryostat	O2 (ppb)
ECA	170
ECC	120
Barrel	240

requirement < 1000

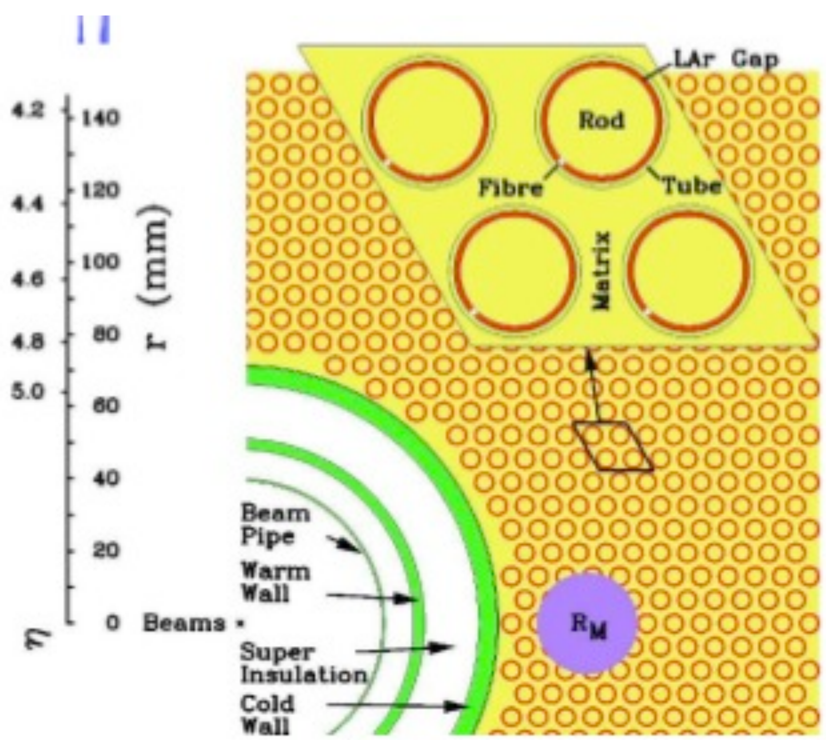
Hadronic (HEC) and forward (FCAL) calorimeters





HEC
- 2 parts Cu-LAr
- 5632 channels (two cryostats)
- Resolution for hadrons: $\frac{\sigma}{E} = \frac{70\%}{\sqrt{E}} \oplus 3\%$
  (50% for jets)
- Coverage:

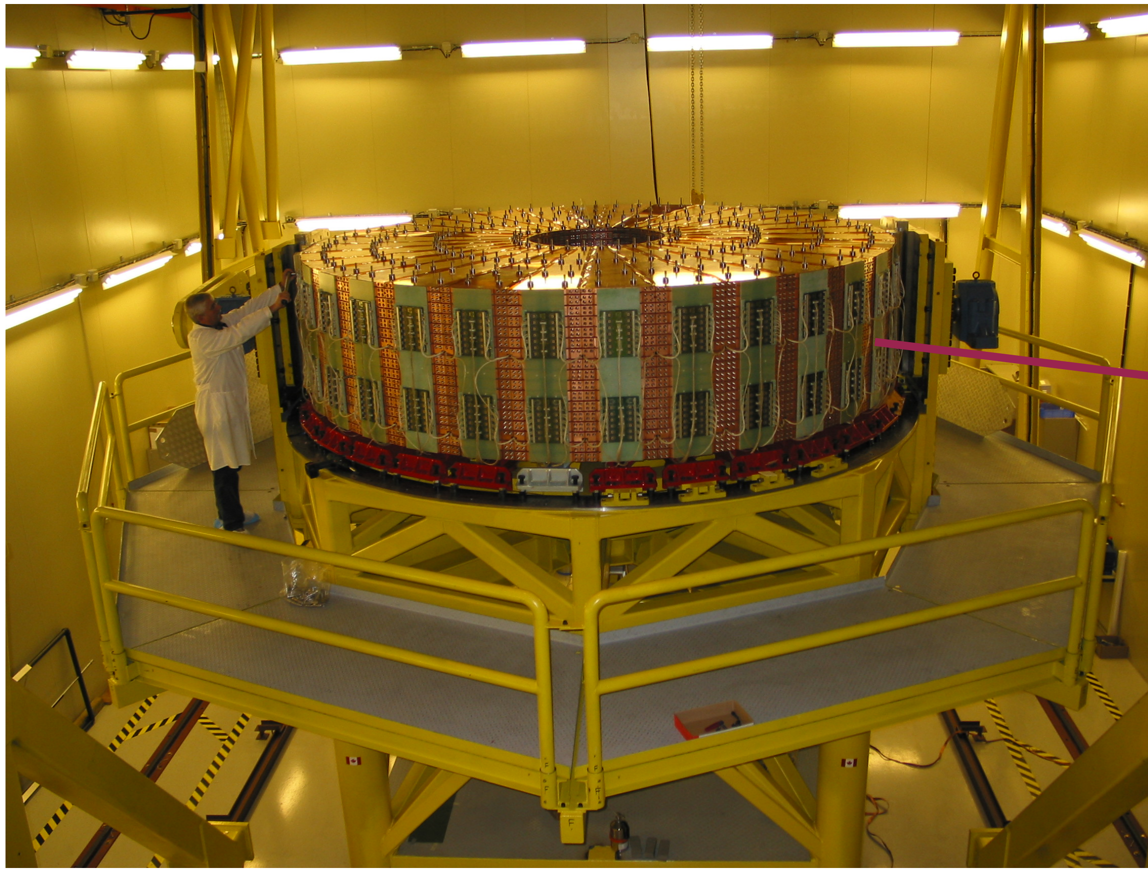
$$1.5 < |\eta| < 3.2 \quad ; \quad 0 < \varphi < 2\pi$$

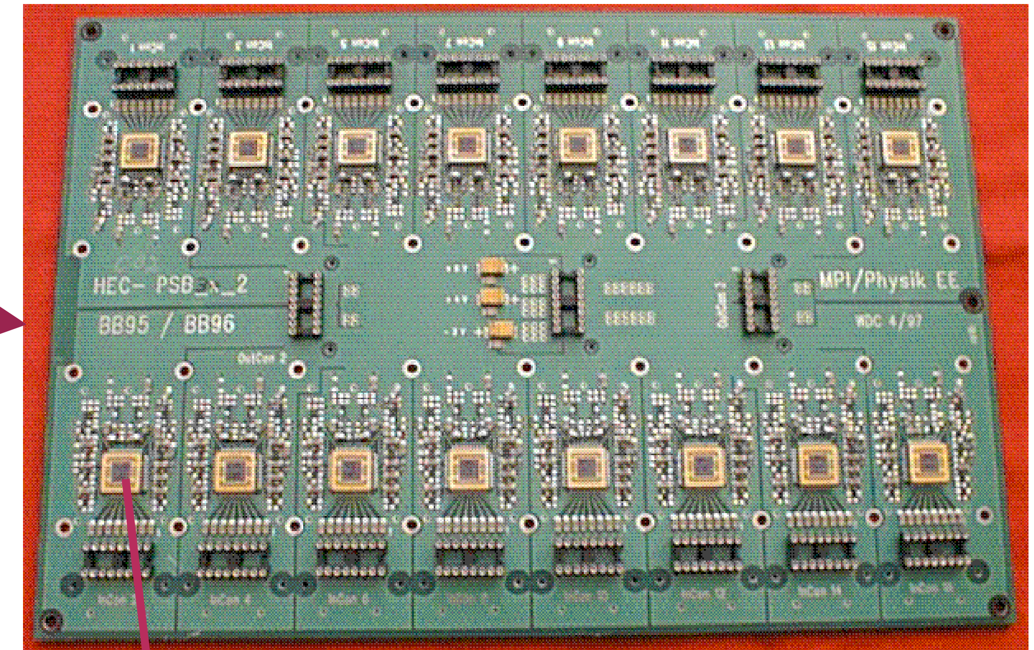


FCAL.
- 3 parts: one Cu-LAr and two W-LAR
  - 3524 channels (two cryostats)
- Resolution for hadrons: $\frac{\sigma}{E} = \frac{100\%}{\sqrt{E}} \oplus 10\%$
- Resolution for electrons: $\frac{\sigma}{E} = \frac{25\%}{\sqrt{E}} \oplus 3.8\%$
  - Coverage:

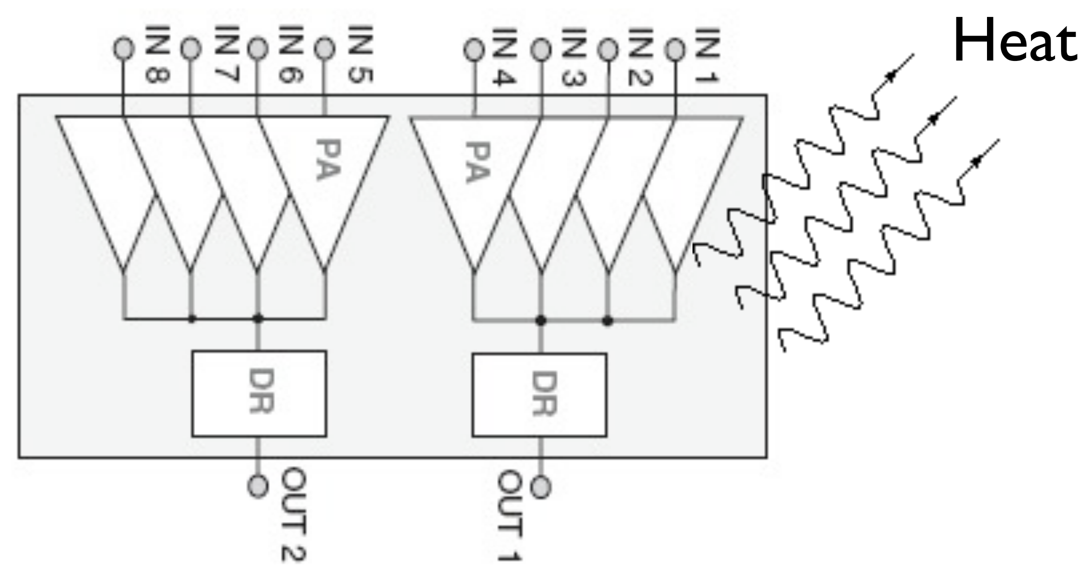
$$3.2 < |\eta| < 4.9 \quad ; \quad 0 < \varphi < 2\pi$$

HEC Cold Electronics





- GaAs TriQuint QED-A $1\mu m$
  - Stable operation at cryogenic temperatures



35840 preamps , 8960 summing amp,
5632 read-out channels
In 2005 first commission in cold: 5 dead channels (< 0.1 %). None due to preamps.
Two due to sum amp (already at warm).
In 2011 still 5 dead channels:
stable after 6 six years of operation.
High reliability of this cold electronics

Electromagnetic Calorimeter

Summary of characteristics

- Pb-LAr. Accordion geometry.
- Pb thickness:
  Barrel 1.5mm ($\eta < 0.8$) ; 1.1mm ($0.8 < \eta < 1.475$)
  Endcaps 1.7mm ($1.375 < \eta < 2.5$) ;
  2.2mm ($2.5 < \eta < 3.2$)
- LAr gap:
  Barrel 2.09mm at HV = 2000 Volts
  Endcaps $2.8 - 0.9mm$ at HV = 2500 - 1000 Volts
  ($1.375 < \eta < 2.5$)
  Endcaps $2.7 - 1.8mm$ at HV = 2300 - 1800 Volts
  ($2.5 < \eta < 3.2$)
- $\frac{\sigma}{E} \sim \frac{10\%}{\sqrt{E(GeV)}} \oplus 0.7\%$
- Energy range: $50MeV$ to $3TeV$
- Fast shaping to optimise signal/noise ratio
- Radiation hardness
- Linearity $< 0.5\%$
- Time resolution $\sim 100ps$
- Coverage: $0 < |\eta| < 3.2$; $0 < \varphi < 2\pi$

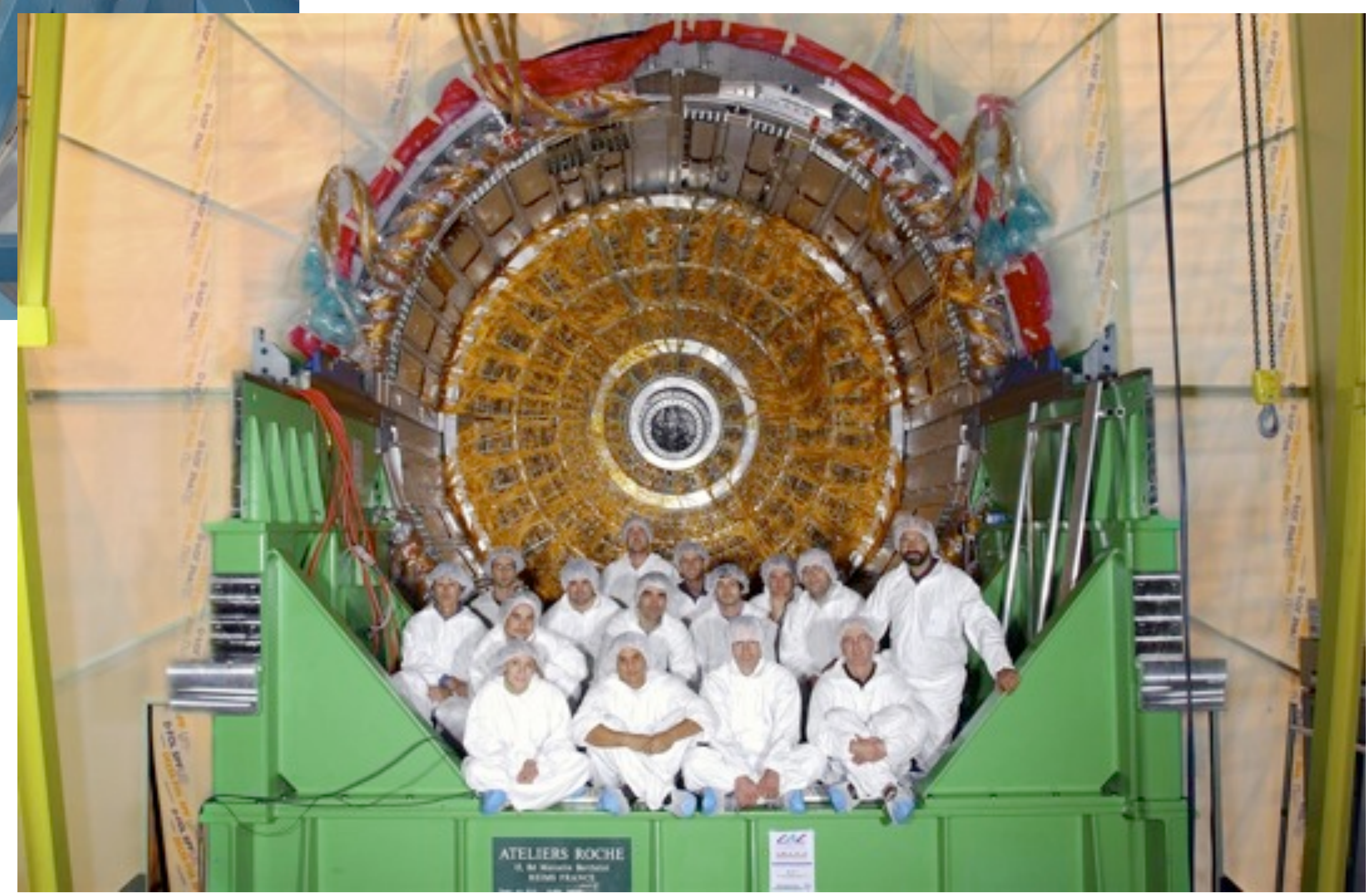
- Minimum impact of noise
- Excelent γ/jet and $electron/jet$ separation
- Photon angular resolution $\sim \frac{50\mu rad}{\sqrt{E(GeV)}}$
- Presampler (layer 0) to correct for energy losses in front $|\eta| < 1.8$.

- High granularity.

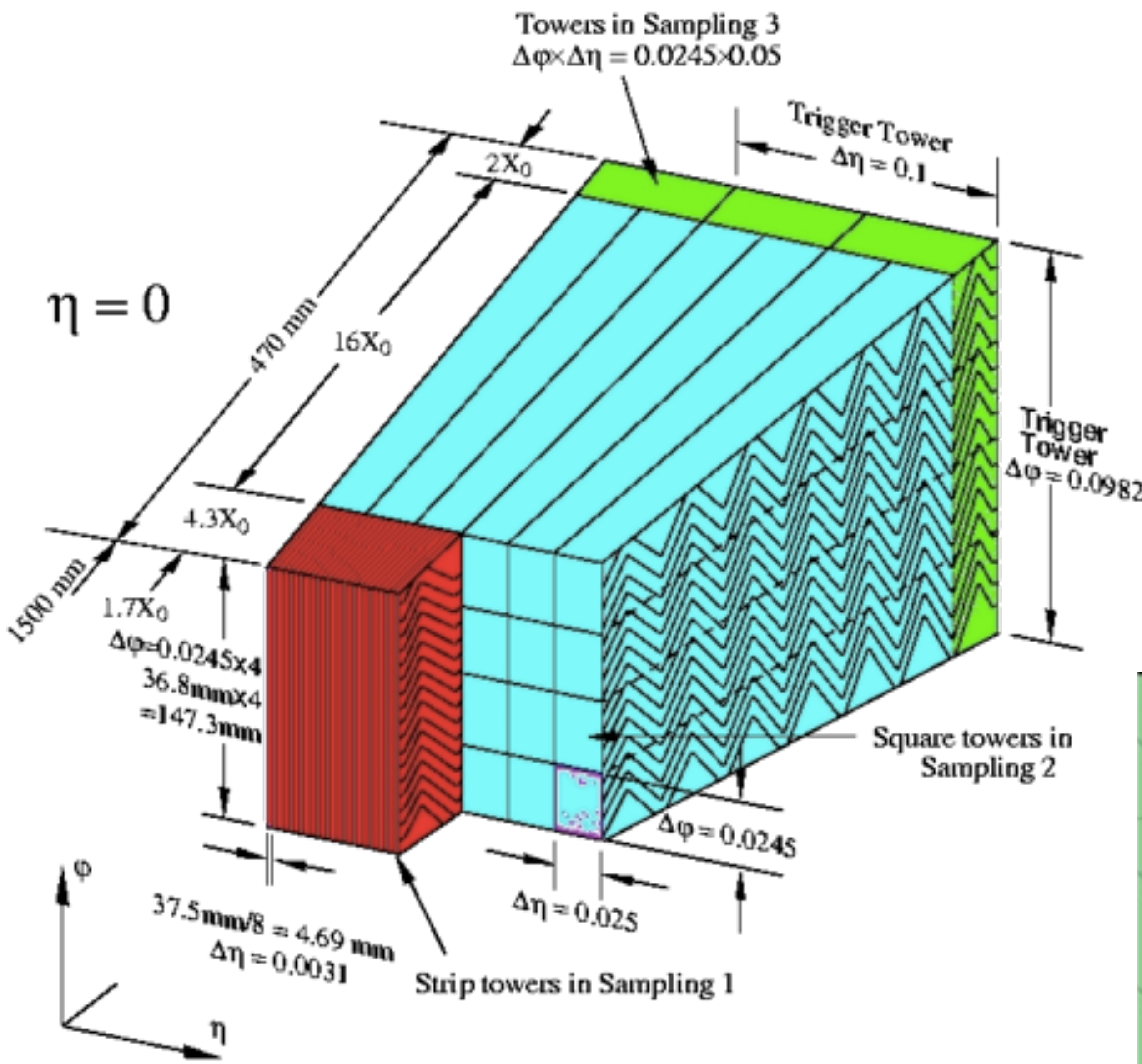
		Layer 1	Layer 2	Layer 3
Barrel	$\|\eta\| \leq 1.35$	$0.025/8 \times 0.1$	0.025×0.025	0.050×0.025
	$1.35 \leq \|\eta\| \leq 1.4$	$0.025/8 \times 0.1$	0.025×0.025	–
	$1.4 \leq \|\eta\| \leq 1.475$	0.025×0.025	0.075×0.025	–
Endcaps	$1.375 \leq \|\eta\| \leq 1.425$	0.050×0.1	0.050×0.025	–
	$1.425 \leq \|\eta\| \leq 1.5$	0.025×0.1	0.025×0.025	–
	$1.5 \leq \|\eta\| \leq 1.8$	$0.025/8 \times 0.1$	0.025×0.025	0.050×0.025
	$1.8 \leq \|\eta\| \leq 2.0$	$0.025/6 \times 0.1$	0.025×0.025	0.050×0.025
	$2.0 \leq \|\eta\| \leq 2.4$	$0.025/4 \times 0.1$	0.025×0.025	0.050×0.025
	$2.4 \leq \|\eta\| \leq 2.5$	0.025×0.1	0.025×0.025	0.050×0.025
	$2.5 \leq \|\eta\| \leq 3.2$	0.1×0.1	0.1×0.1	–

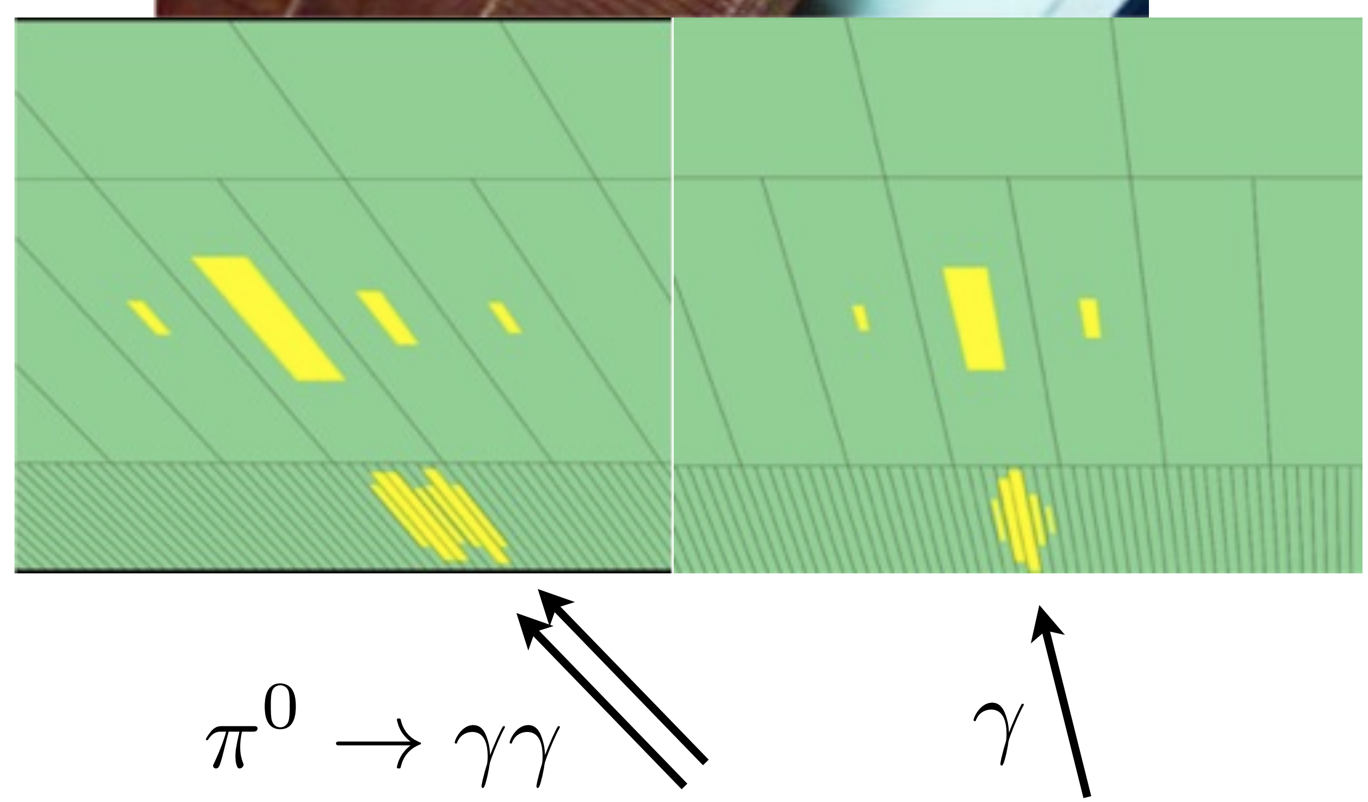
- 173312 readout channels ← > 170,000 channels

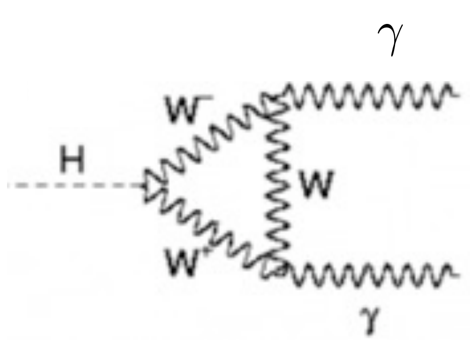
EM Calorimeter inside cryostat

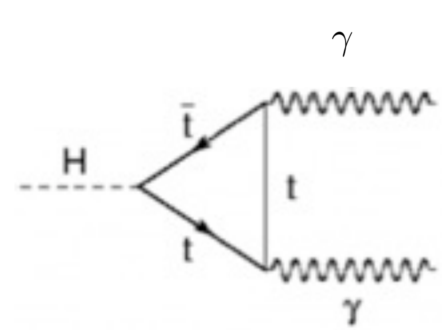


Segmentation

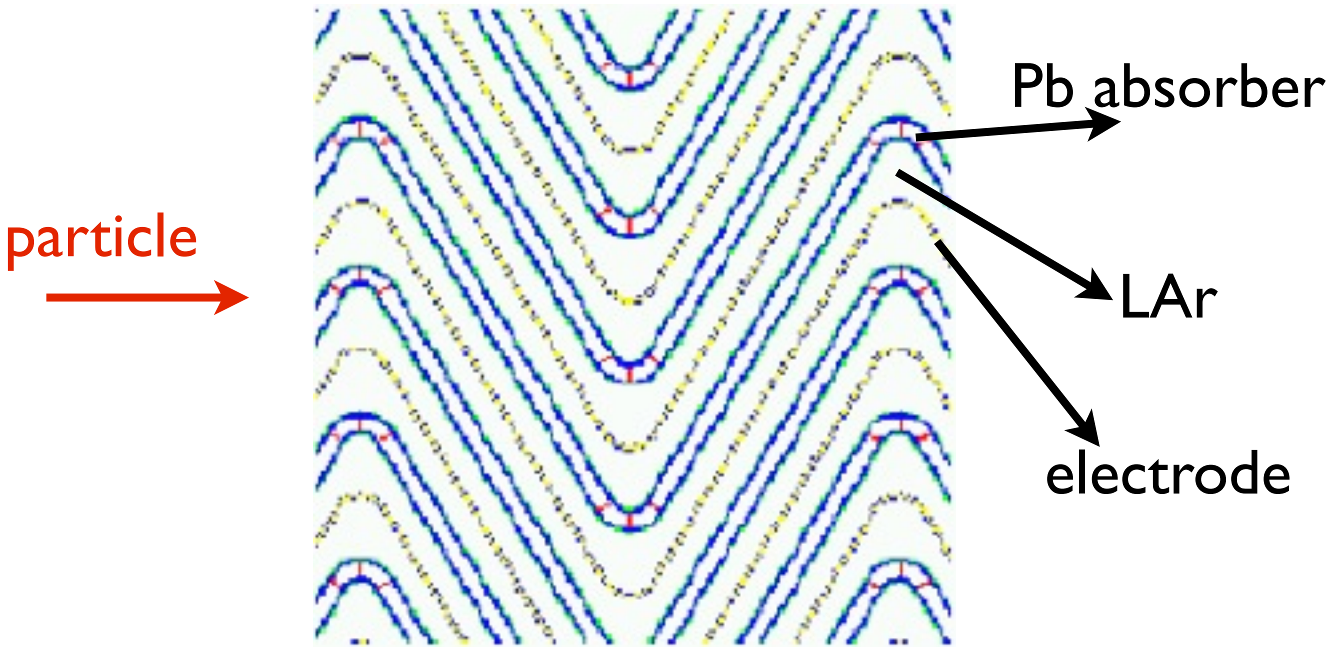


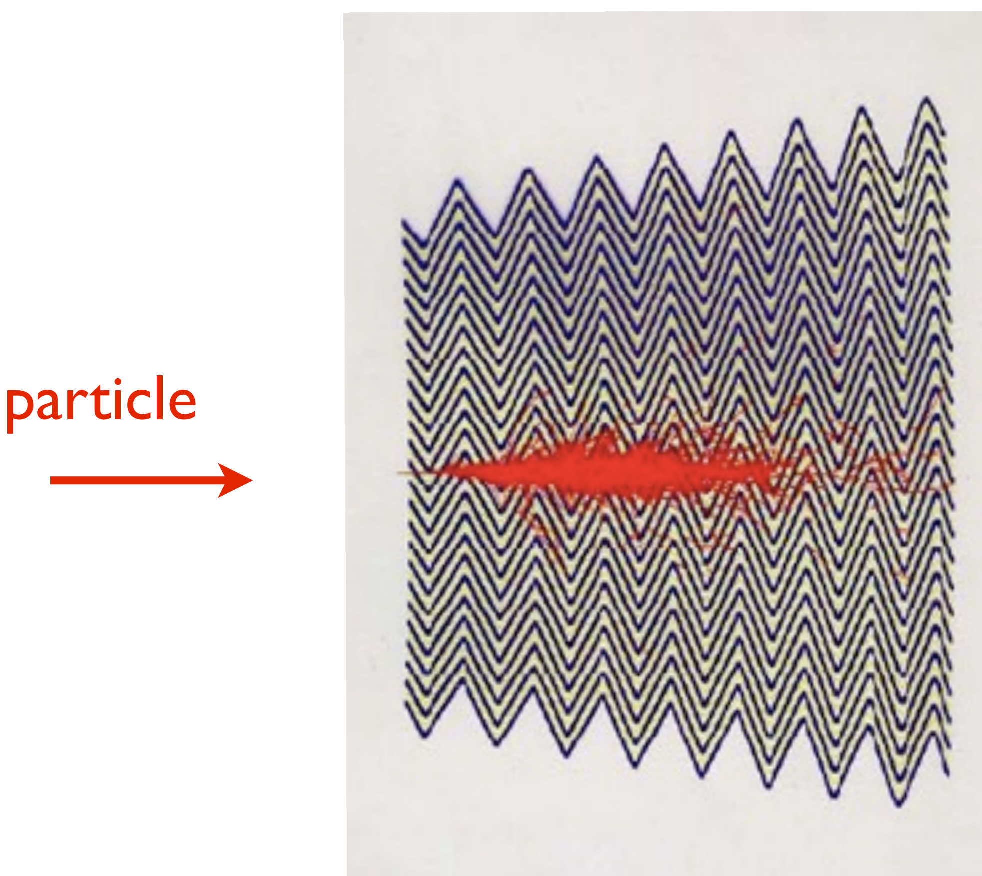


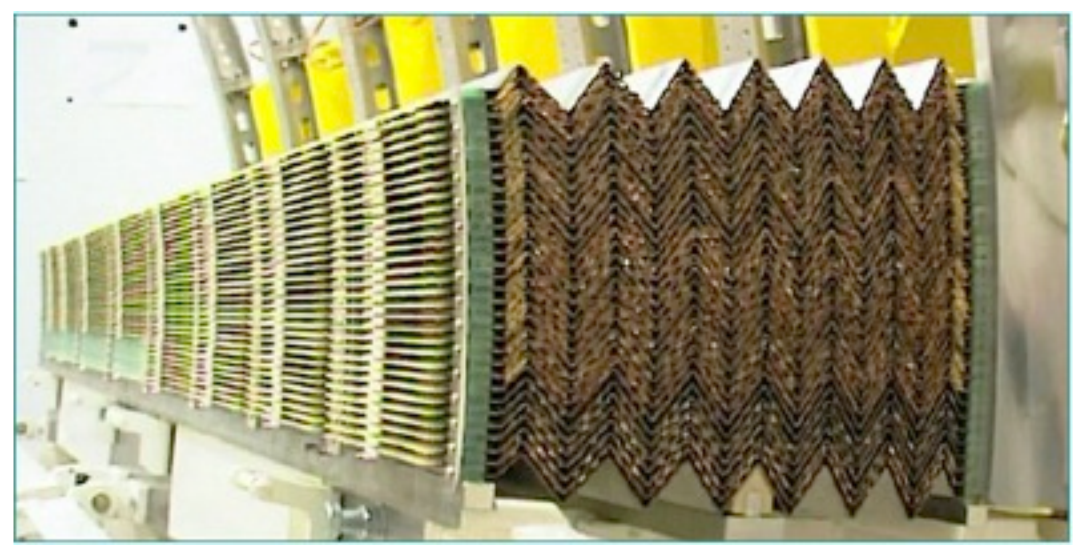




EMcalo: the accordion shape

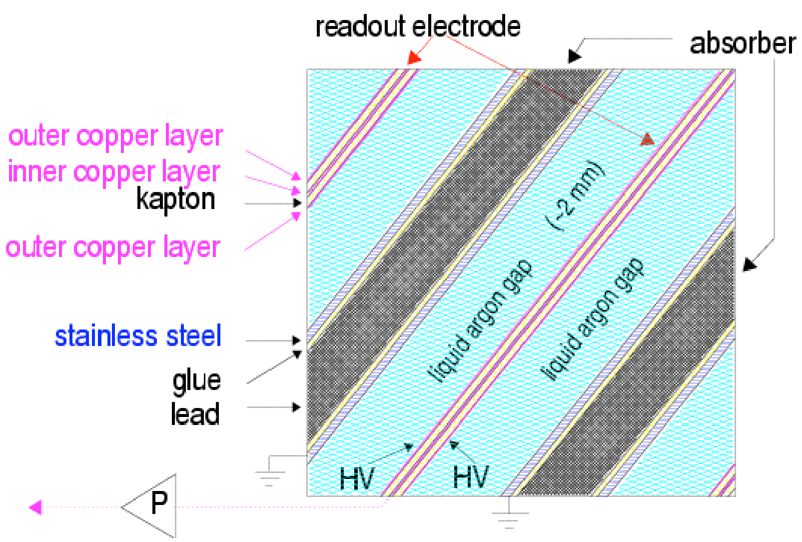


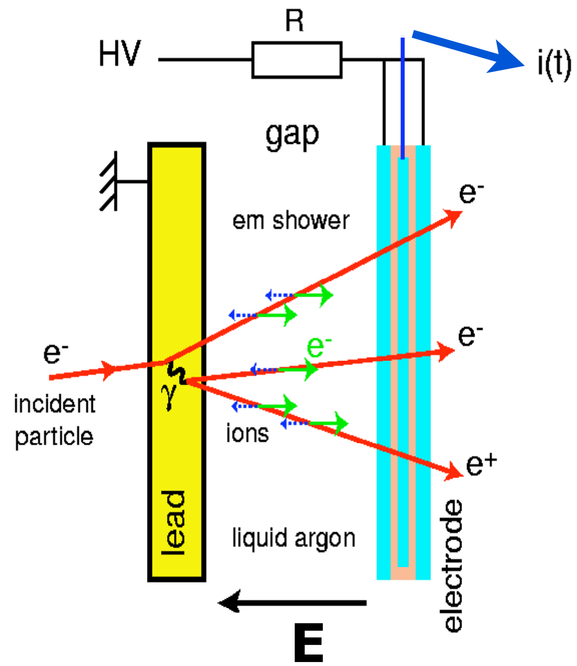


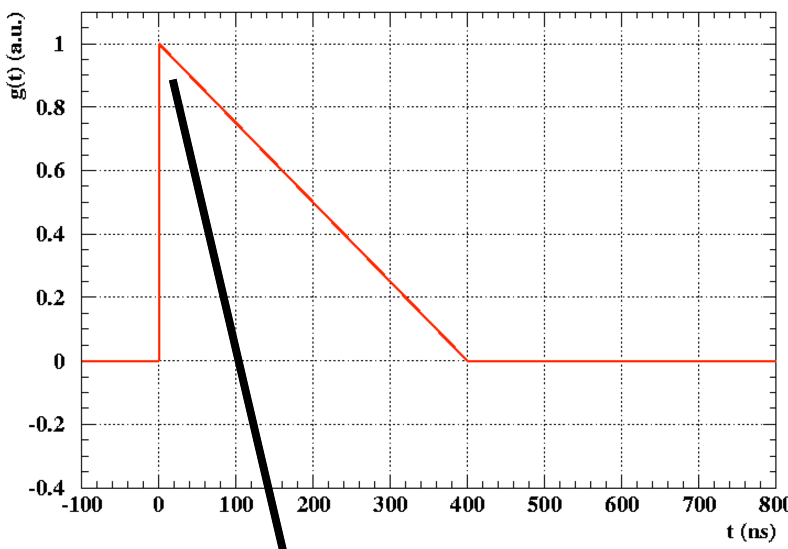


Avoids cracks for readout: better uniformity

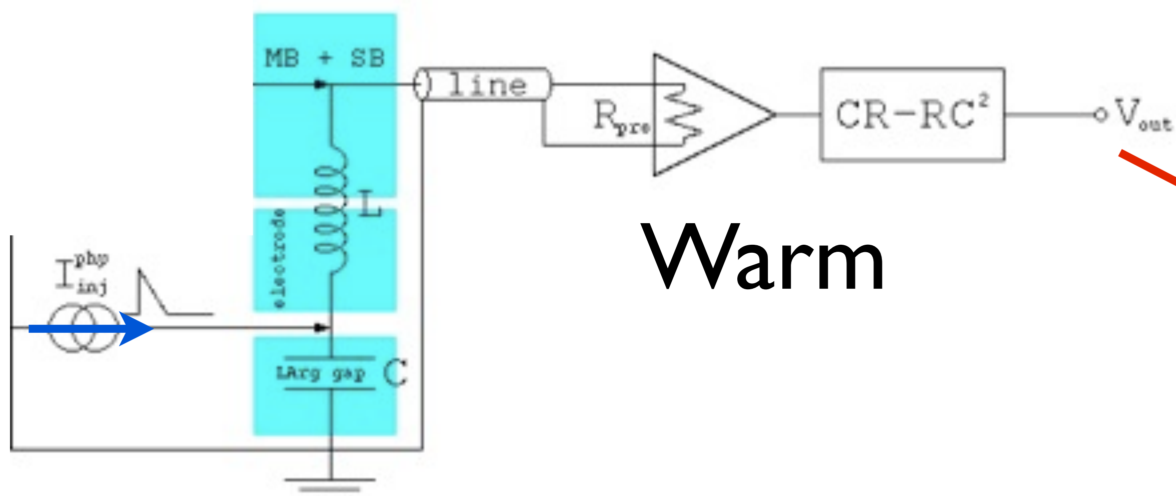
Signal readout



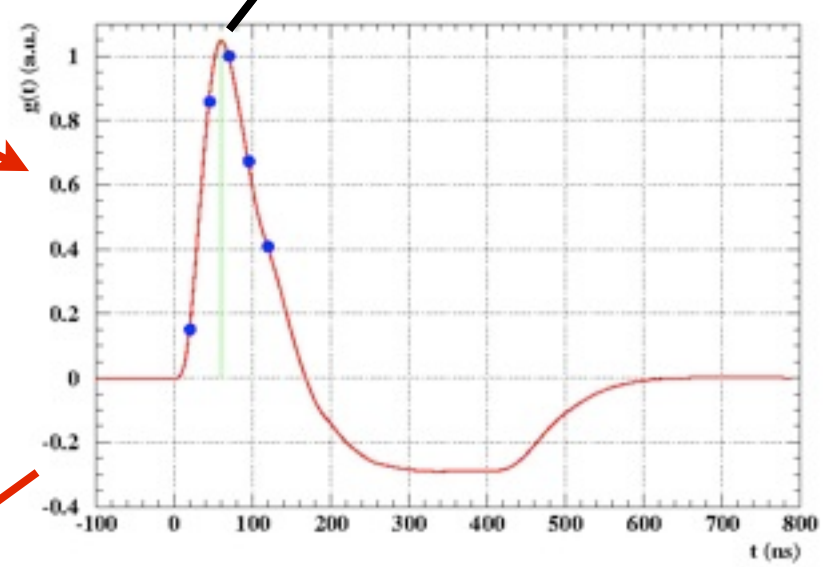




Proportional to particle Eloss



Warm



Cold

sca

ADC

optical link

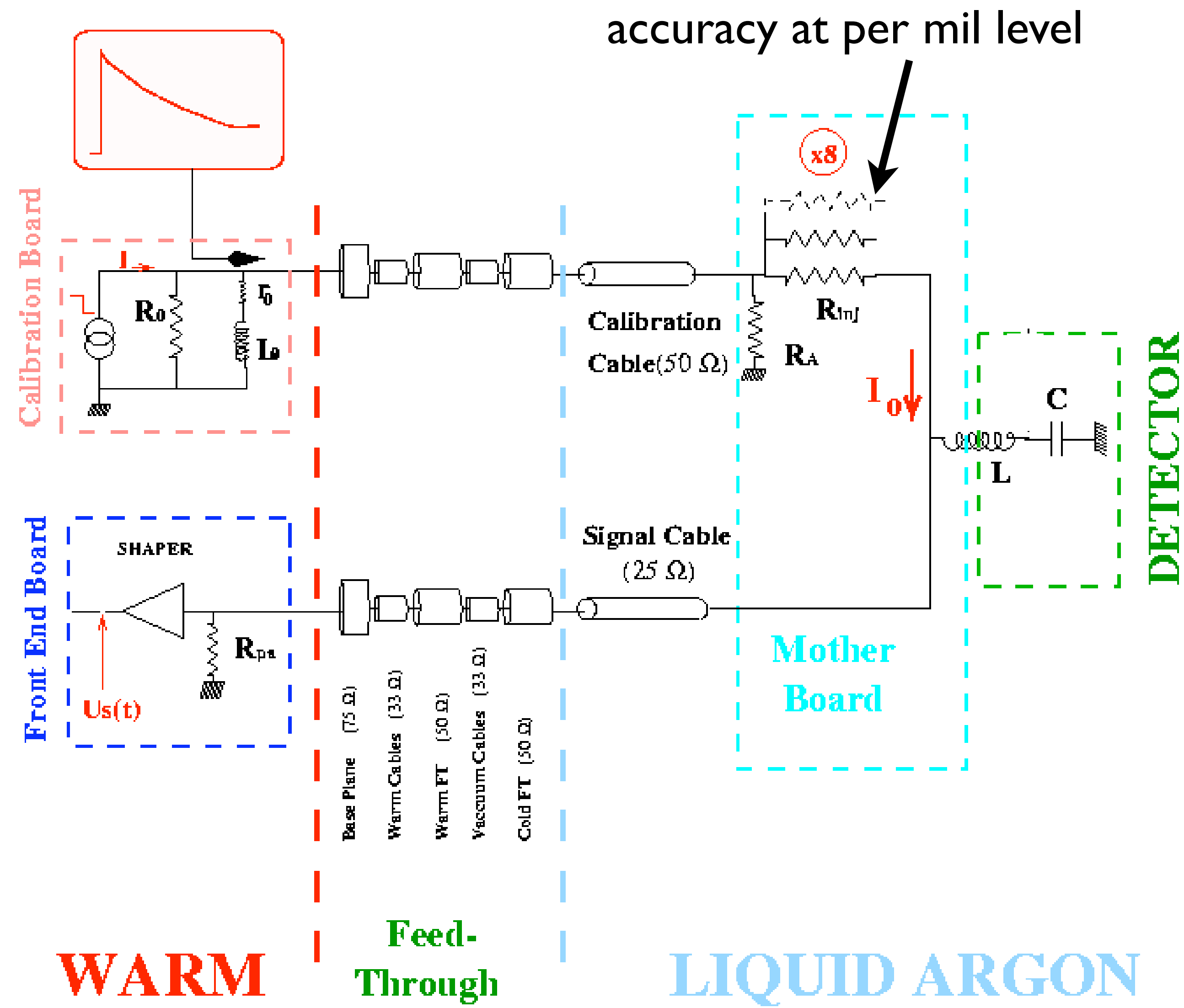
To computer room

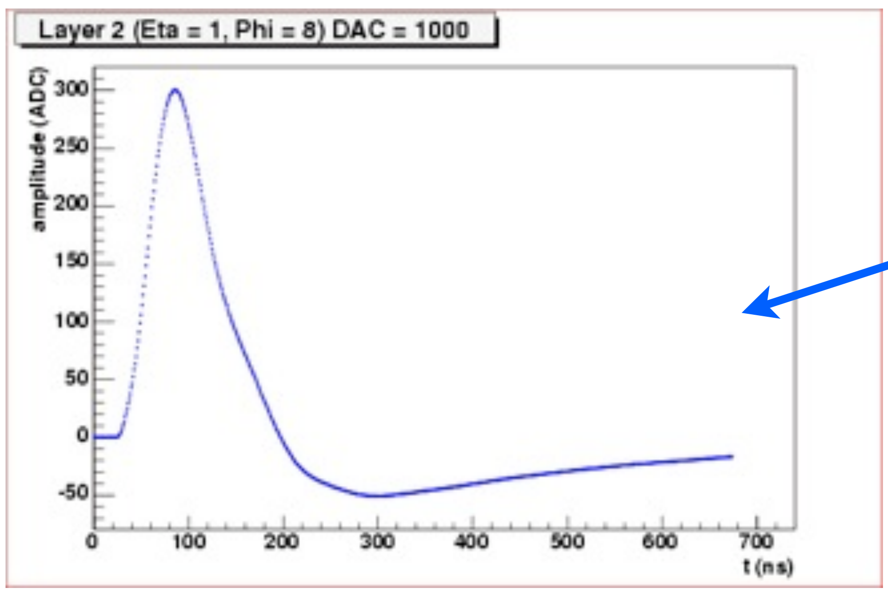
n samples

$$A_{max} = \sum_{i=1}^{n} a_i (S_i - p)$$

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

Calibration system





Typical Calibration data set:
- Pedestal (random triggers)
- Ramp (16 diff. amplitudes)
- Delay (24 diff. phases)

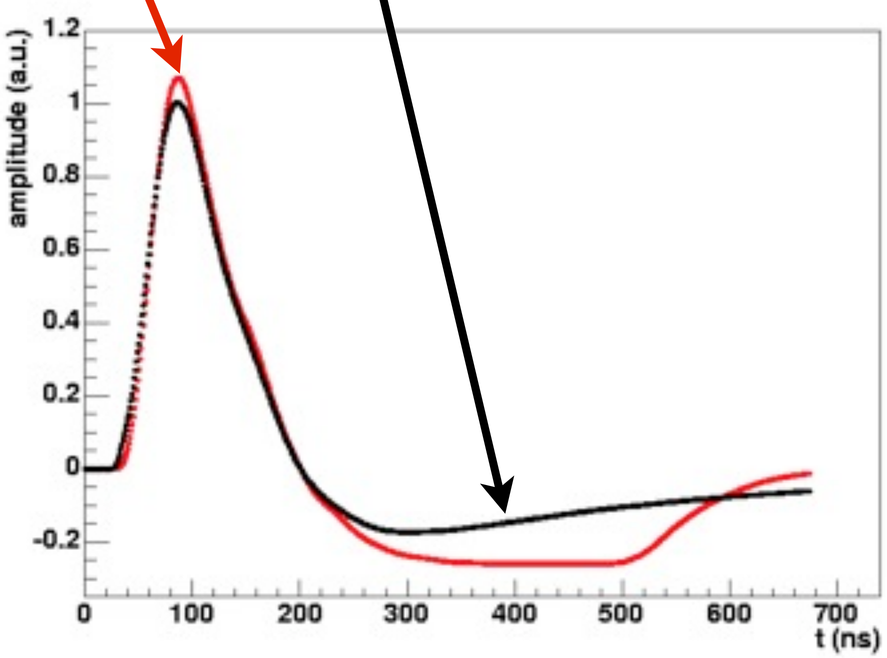
x 3 gains.

Provides:
Baseline, noise, auto-correlation.
Electronics gain.
Pulse shape -> physics pulse prediction, Cross-talk corrections.
Optimal filtering coefficients.
Used to calculate Energy online

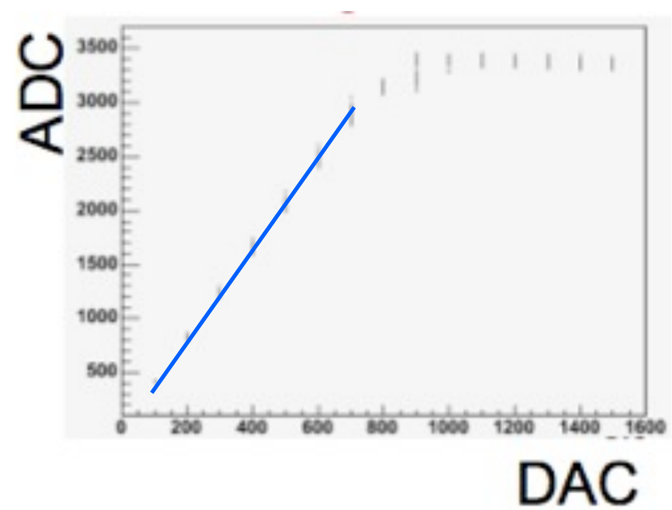
Energy reconstruction

physics pulse prediction

$$g_e^{\mathrm{phys}}(t) = g^{\mathrm{cali}}(t) * \mathcal{L}^{-1}\left\{\frac{(1+s\tau_{\mathrm{cali}})(sT_D - 1 + e^{-sT_D})}{sT_D(f_{\mathrm{step}} + s\tau_{\mathrm{cali}})}\right\} * \mathcal{L}^{-1}\left\{\frac{1}{1+s^2LC+srC}\right\}$$



$$\left.\begin{array}{ll} g_e^{phys}(t) & \dfrac{dg_e^{phys}(t)}{dt} \\ & \\ \text{noise covariance matrix} & \end{array}\right\} \rightarrow \text{optimal filtering coef. } a_j$$



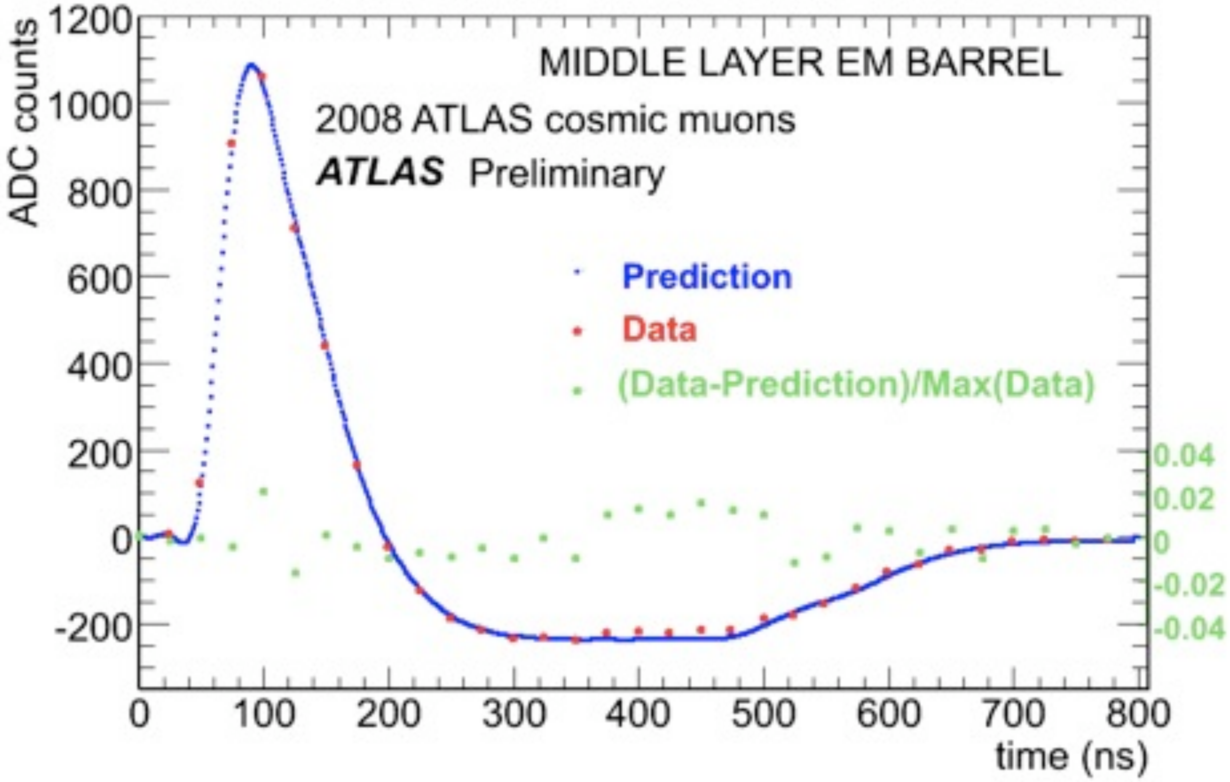
$\longrightarrow G_{ADC\rightarrow DAC}$

$$E_{cell} = F_{\mu A\rightarrow GeV} F_{DAC\rightarrow\mu A} \frac{M_{cali}}{M_{phys}} G_{ADC\rightarrow DAC} \sum_{j=1}^{n} a_j\,(S_j - P)$$

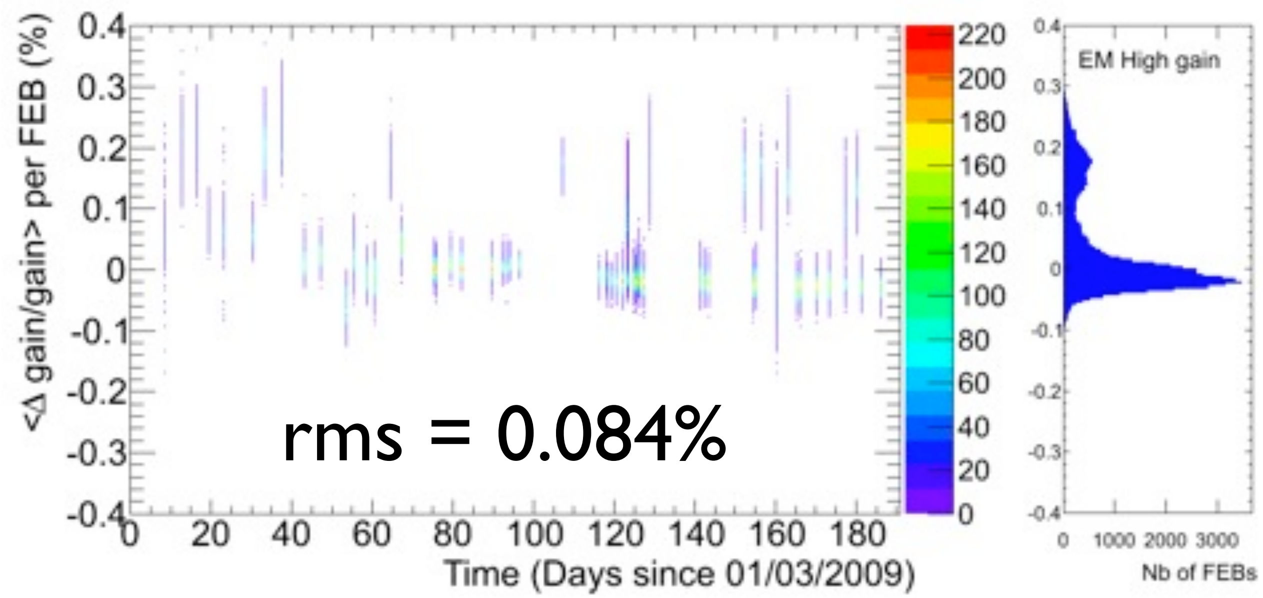
$\longrightarrow$ Ecluster corrections: Eloss in front (uses presampler signal), lateral+longitudinal leakage, ...

Channel response: performance

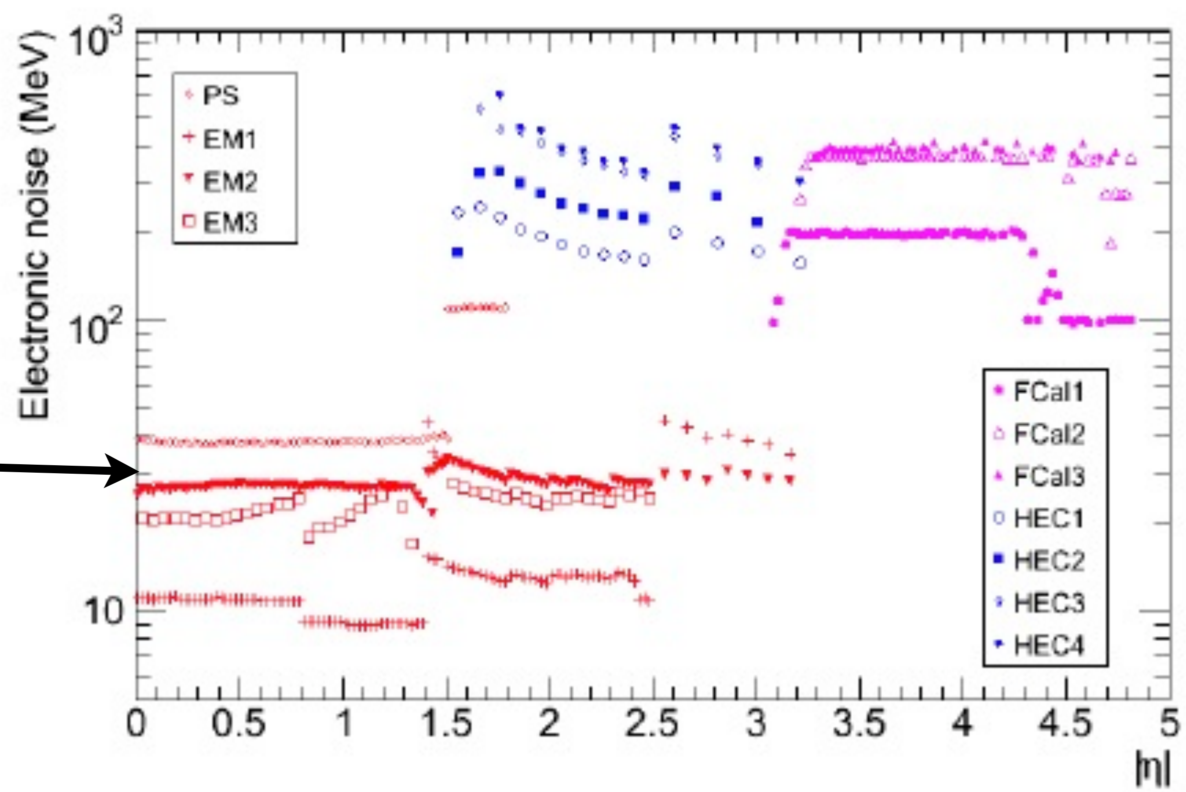
$g_e^{phys}(t)$



$G_{ADC \rightarrow DAC}$



rms = 0.084%



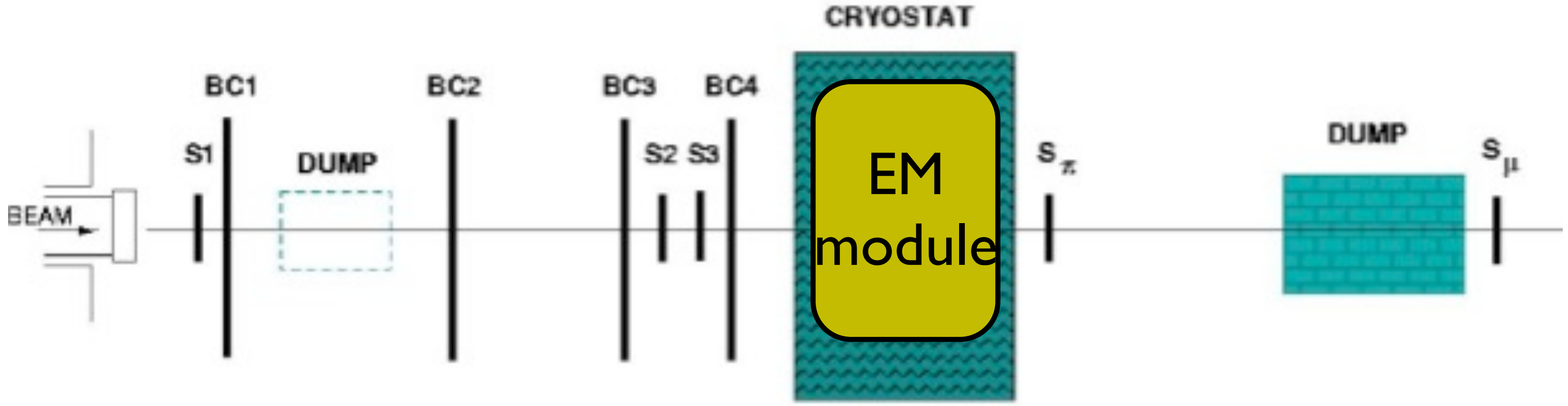
30 MeV

Problematic channels

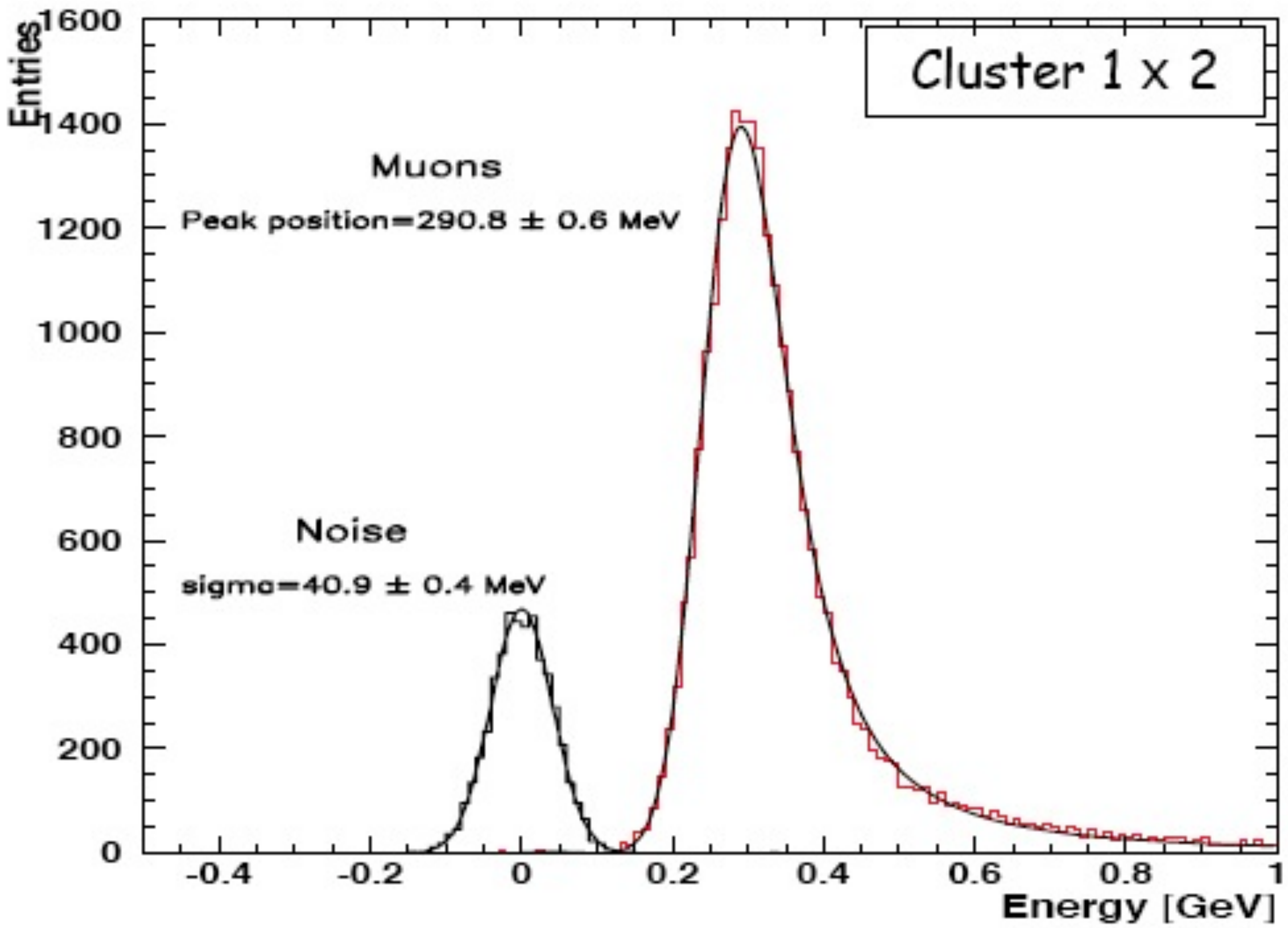
EM	0.5%
HEC	0.37%
FCAL	0.23%

No missing channels could be attributed to thermal expansion/contraction of the several thousand circuit boards immersed in LAr

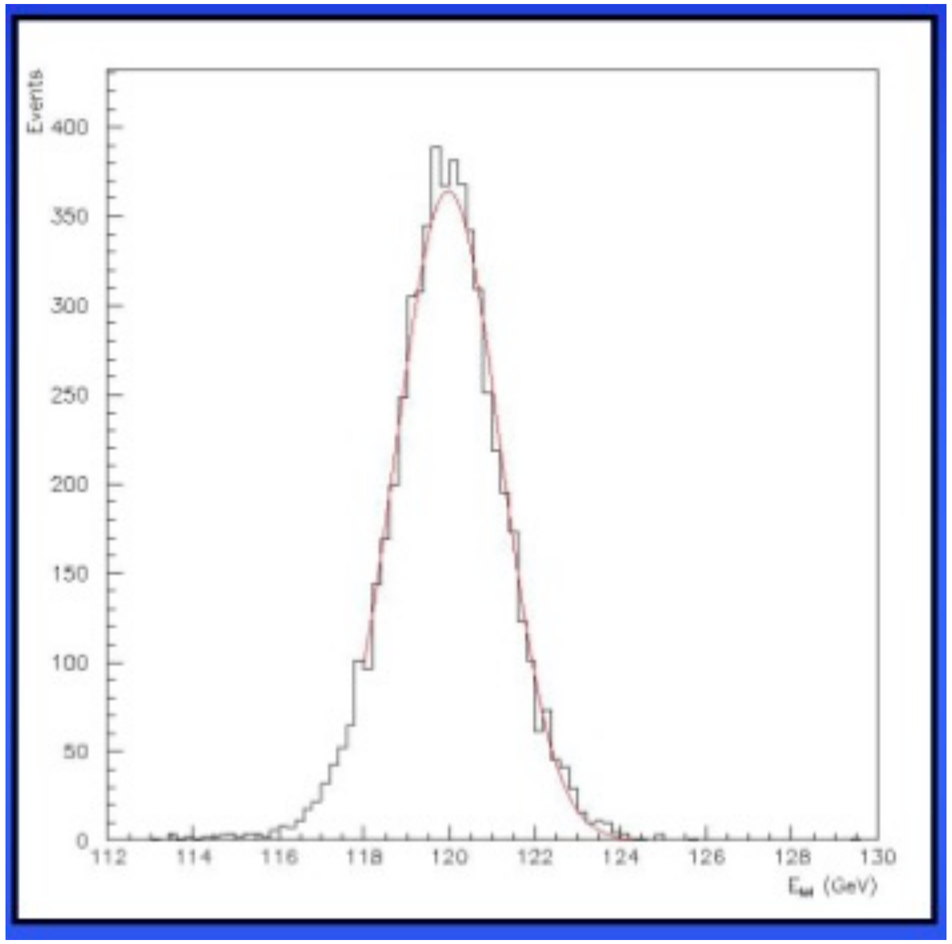
Beam test: particle distributions

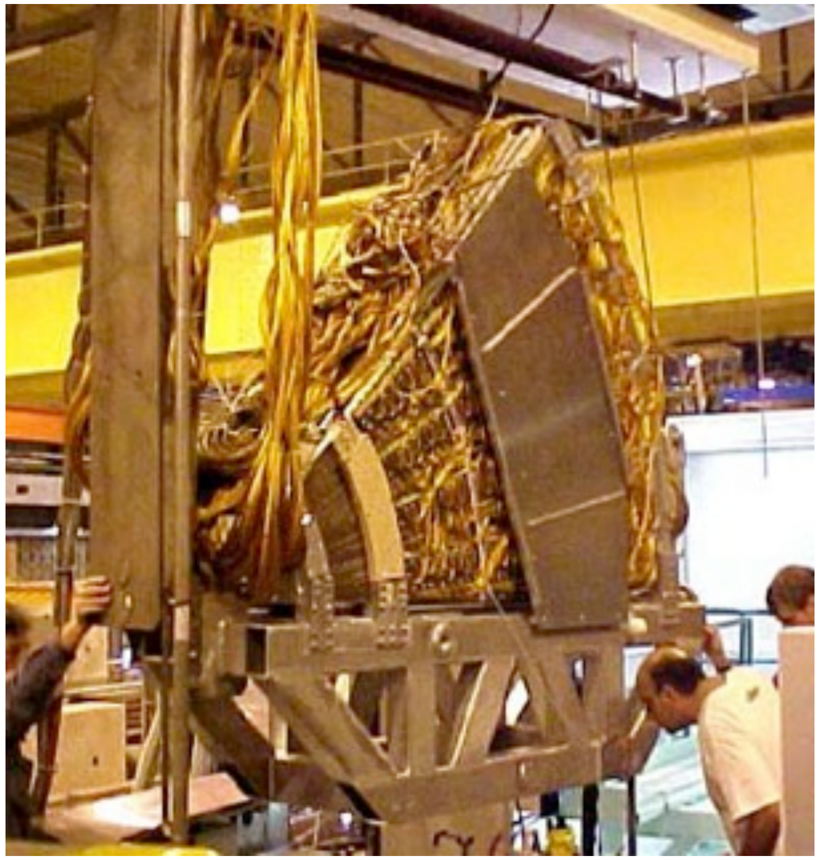


muons as mip



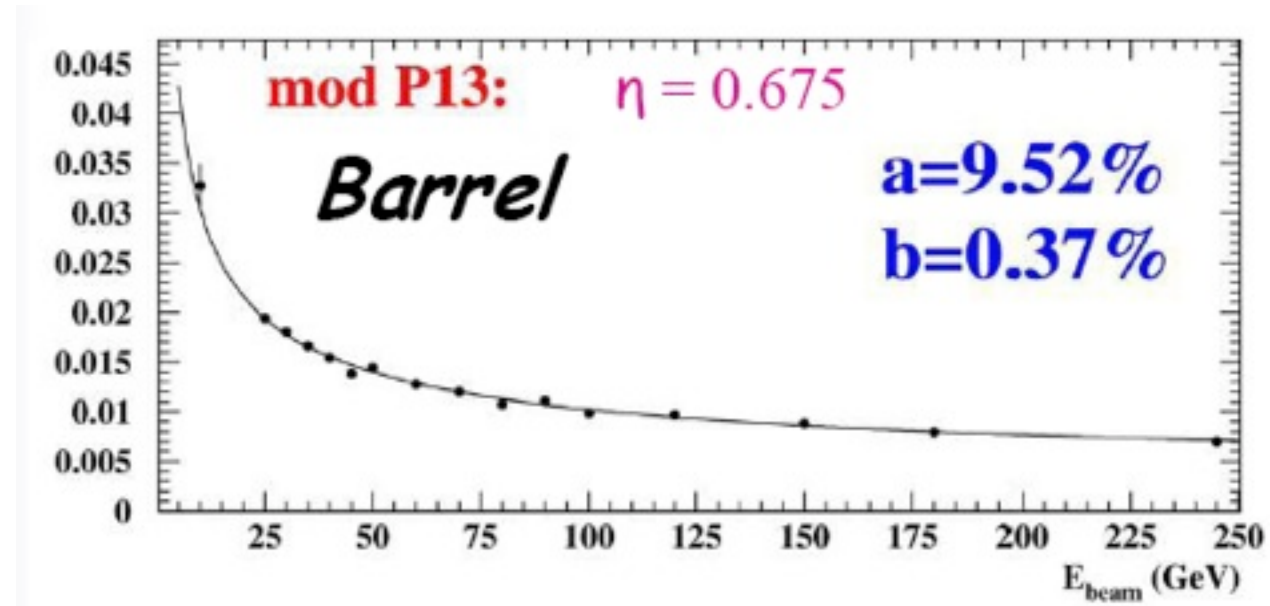
120 GeV electrons

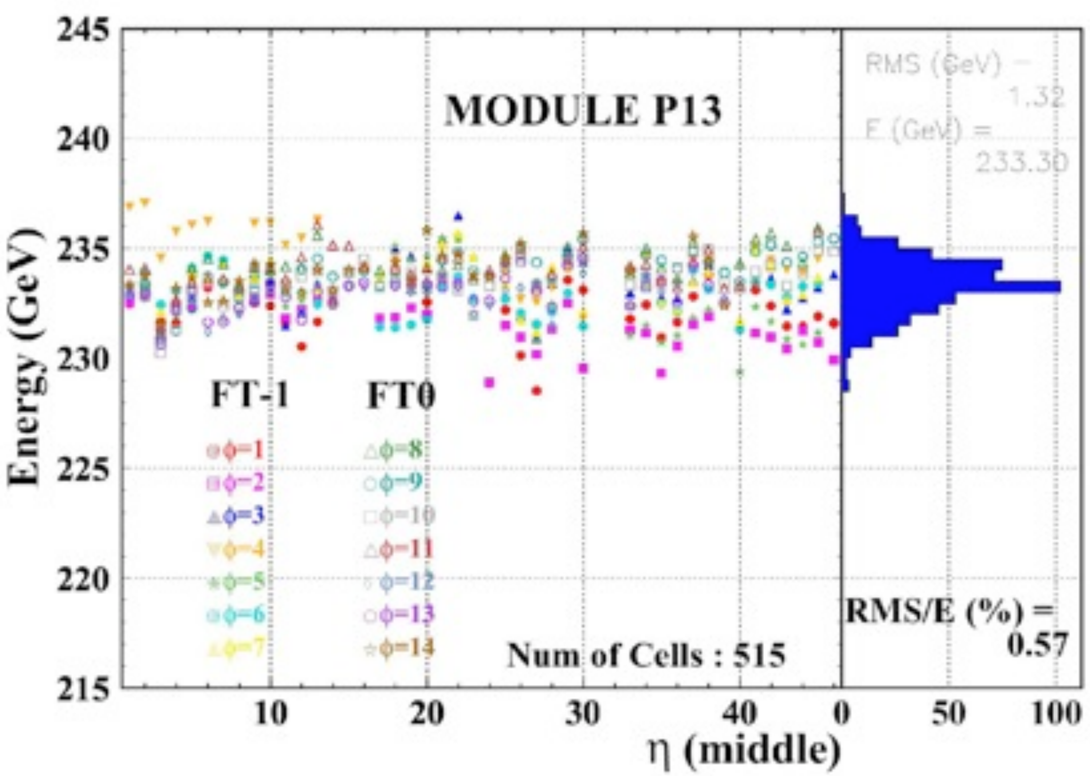


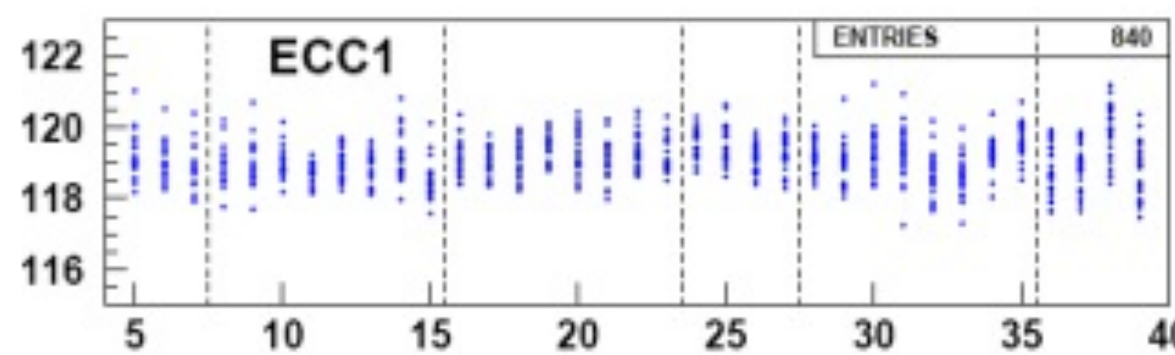


Beam test results: electrons

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



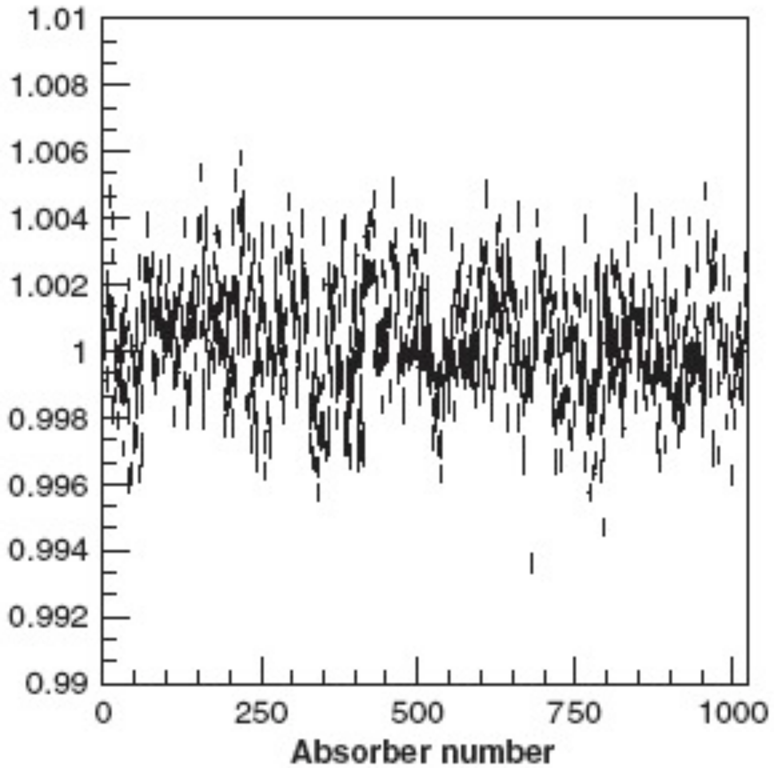




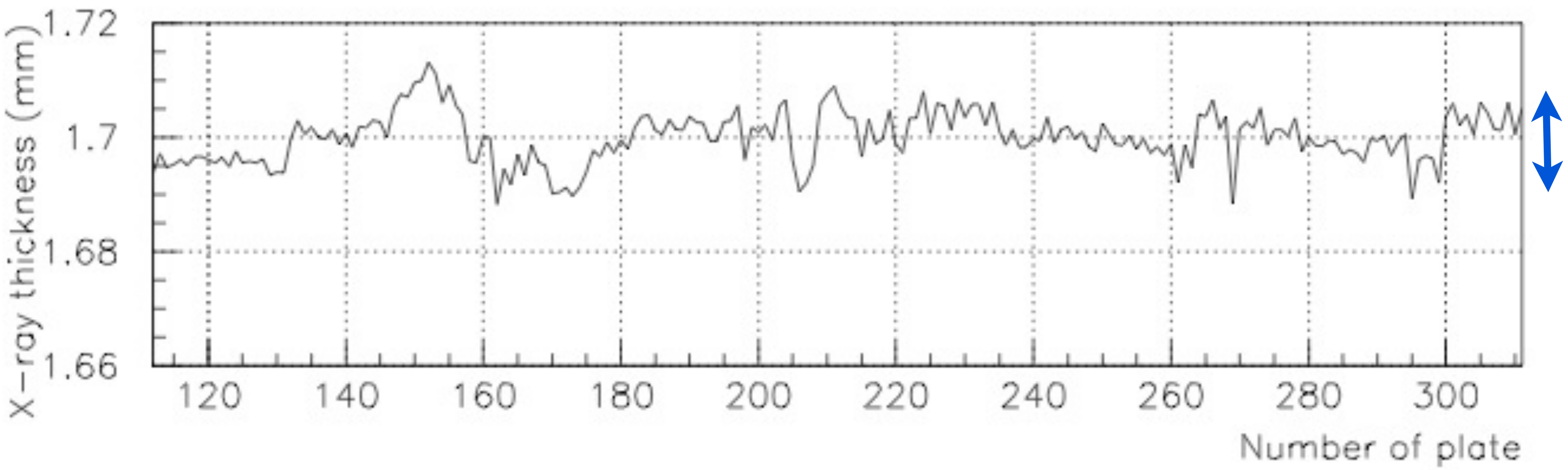
0.55%

Global non-uniformity $\sim 0.6\% \Rightarrow\ b \sim 0.7\%$

Lead thickness and energy resolution



Barrel
rms < 0.007 mm



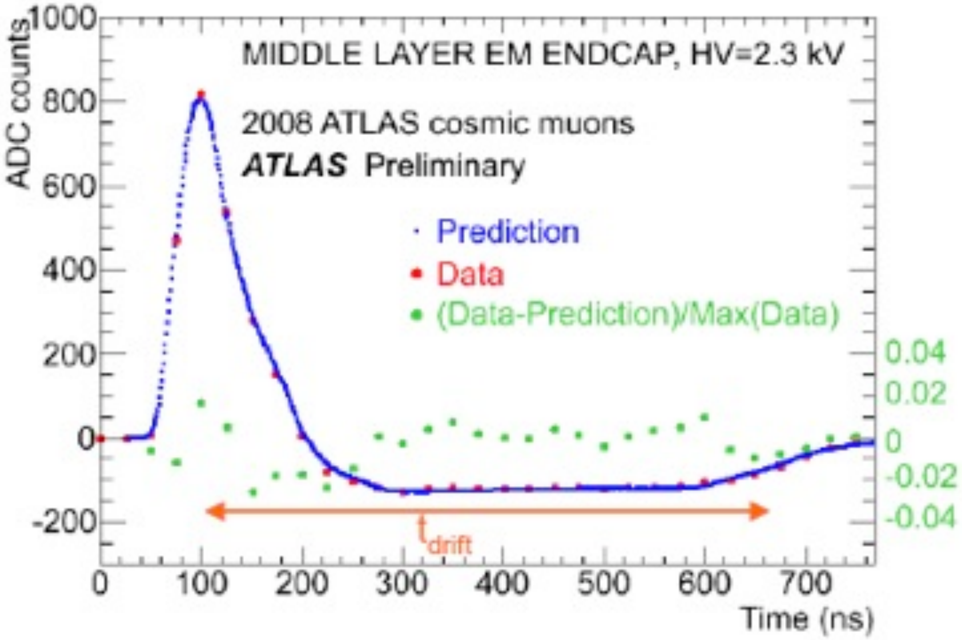
Endcaps
rms < 0.01 mm

Lead plate thickness
EMB = 1.5 and 1.3 mm

EMEC OW = 1.7 mm
EMEC IW = 2.2 mm

Eresol constant term b$\sim$0.18%

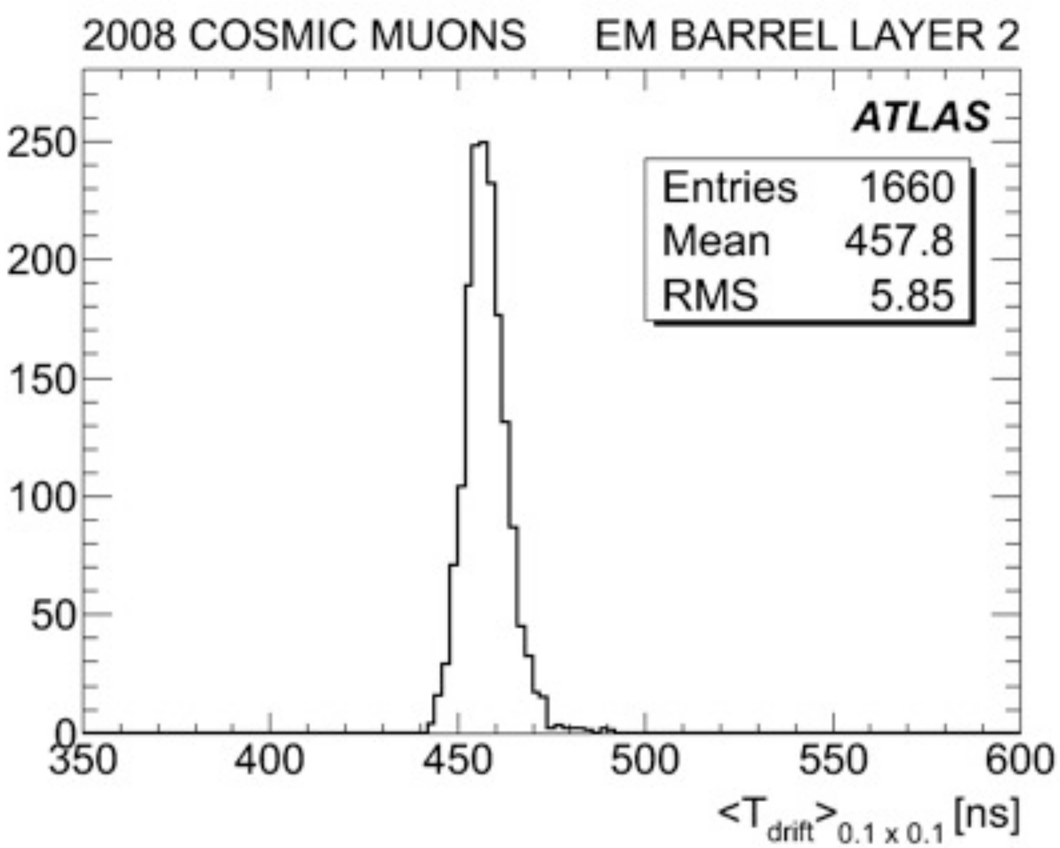
LAr gap size and uniformity



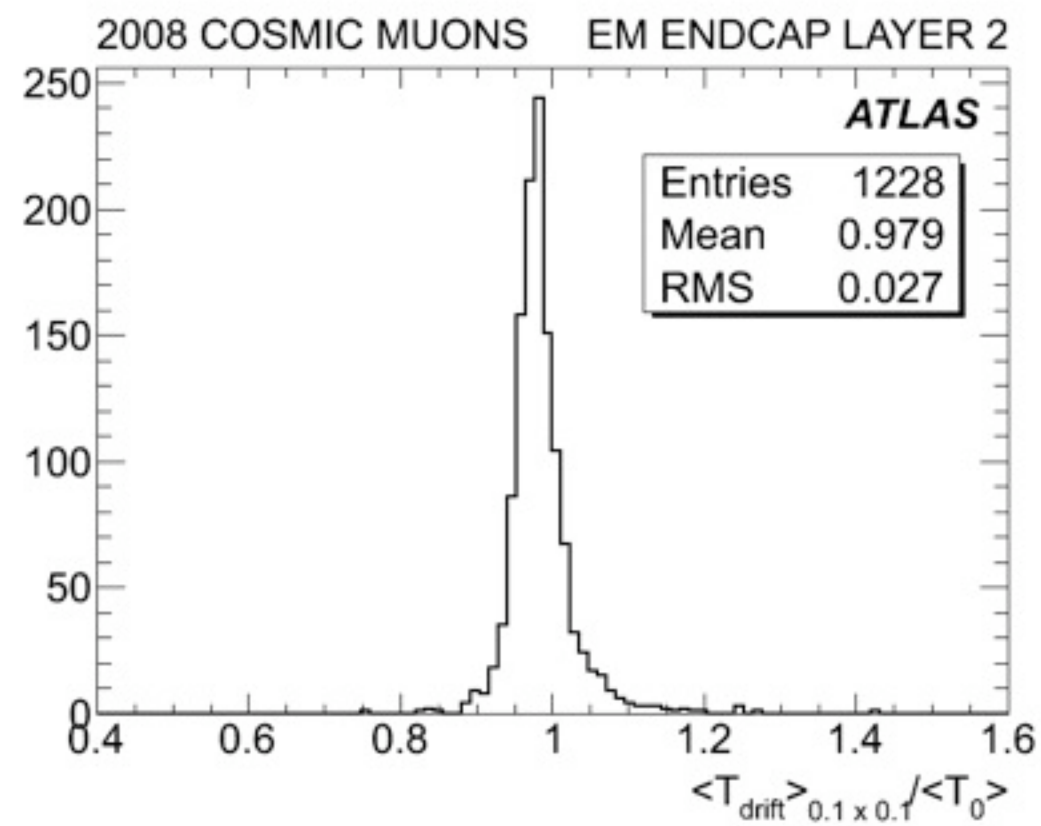
$$I(t) = I_0(1 - \frac{t}{T_D}) \;\; ; I_0 = \rho V_D \;\; ; \;\; T_D = \frac{g}{V_D}$$

$$V_D = K(\frac{U}{g})^{\alpha} \sim g^{-\alpha} \Rightarrow T_D \sim g^{1+\alpha}$$

$$(\alpha \sim 0.3)$$



uniformity $\sim 0.3\%$



uniformity $\sim 0.5\%$

Reasons for gap size variation

Absorber thickness var.

abs = Pb + 2*adhesive + 2*steel
abs_th = Pb_th + 2*0.15 mm + 2*0.2 mm
defined by a mold

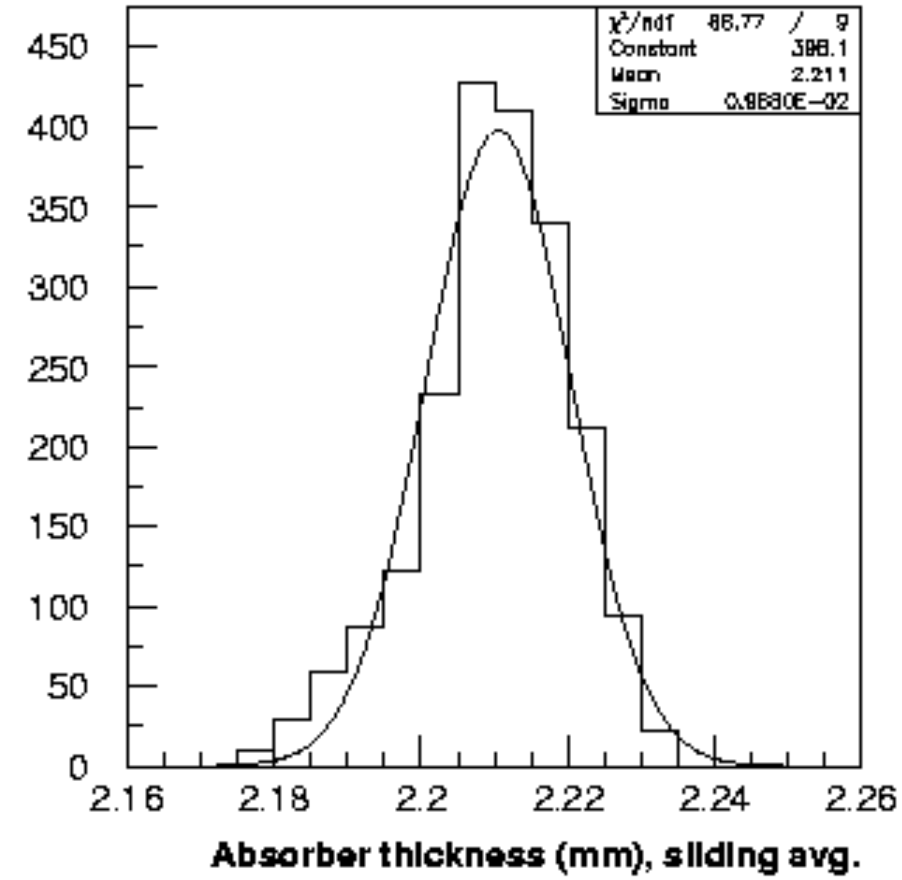
Barrel

$<>\sim 2.21mm$

$\sigma \sim 0.01mm$

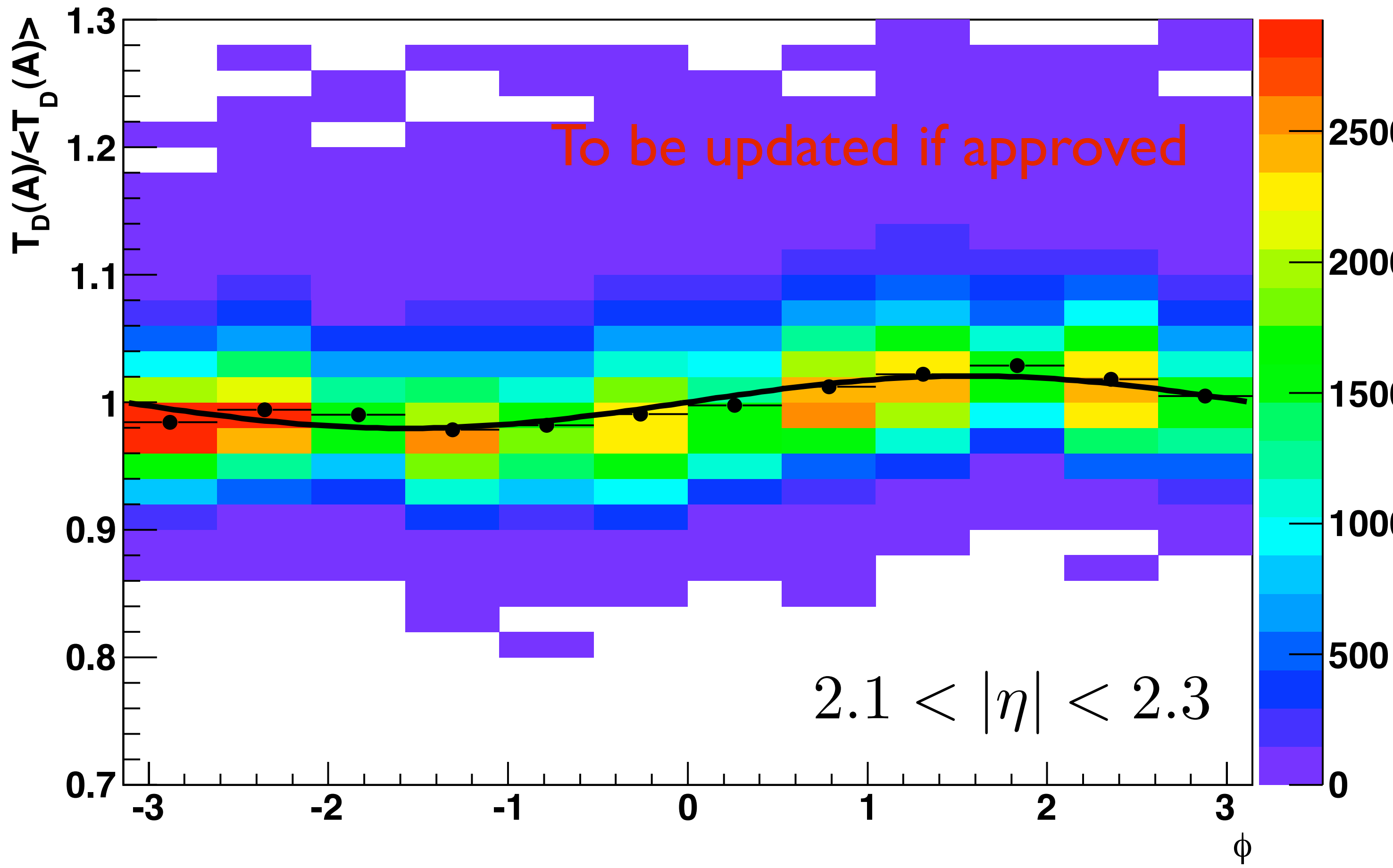
Endcaps

$\sigma \sim 0.03mm$



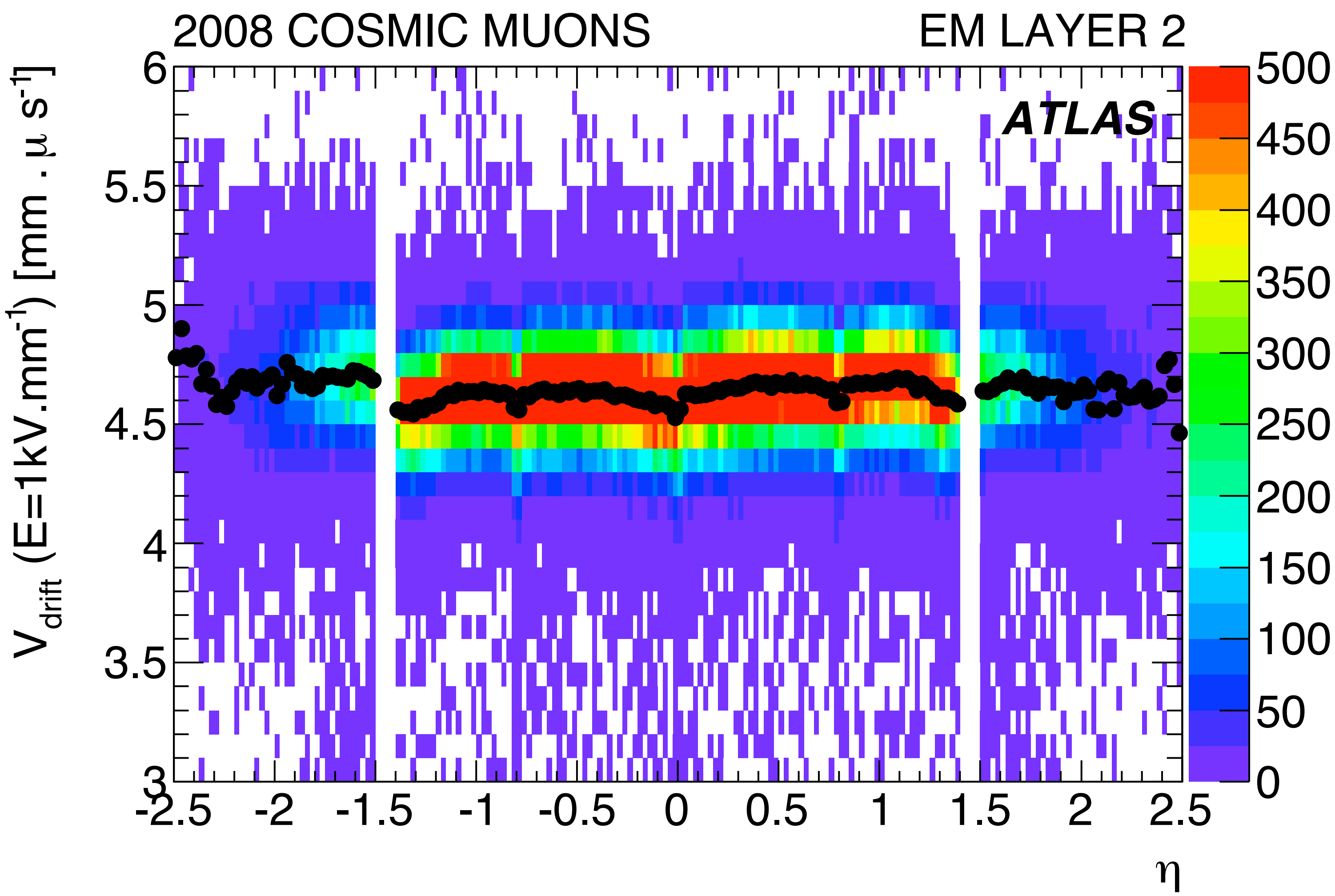
Deformations

EMEC-A



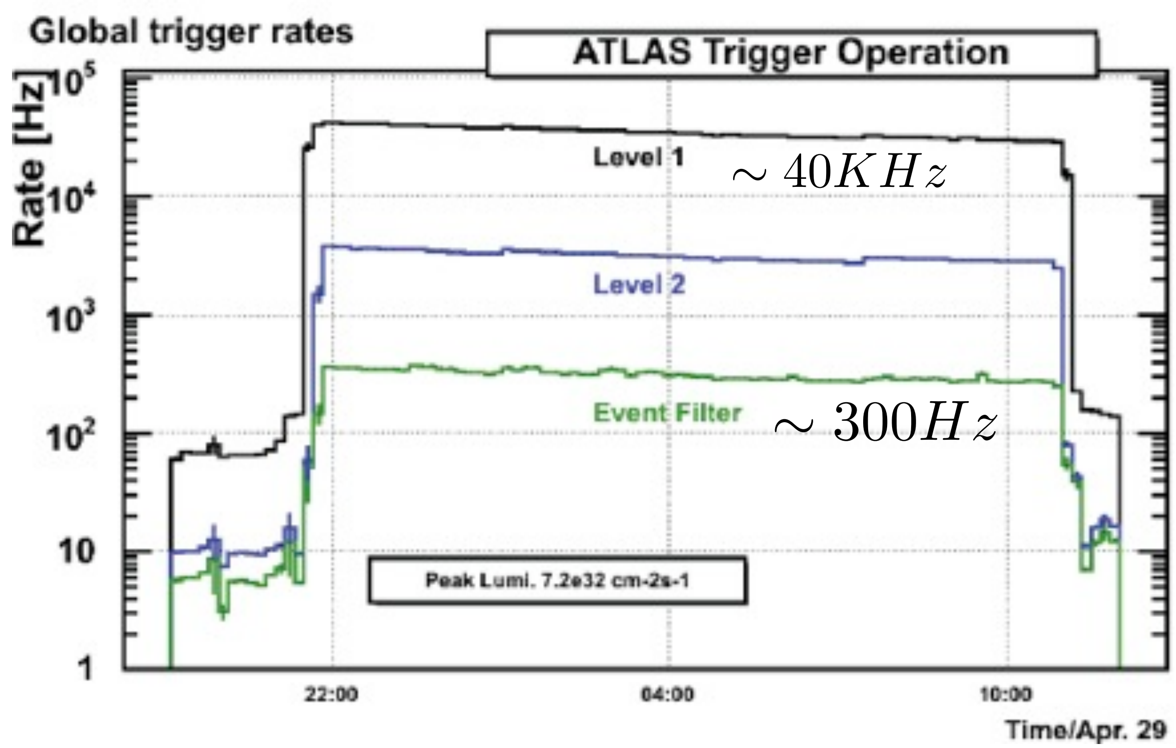
Measurement of drift velocity

T_D from cosmic data $\longrightarrow V_D(1KV/mm) = \frac{g}{T_D}(\frac{1000V}{U}\frac{g}{1mm})^{\alpha}$

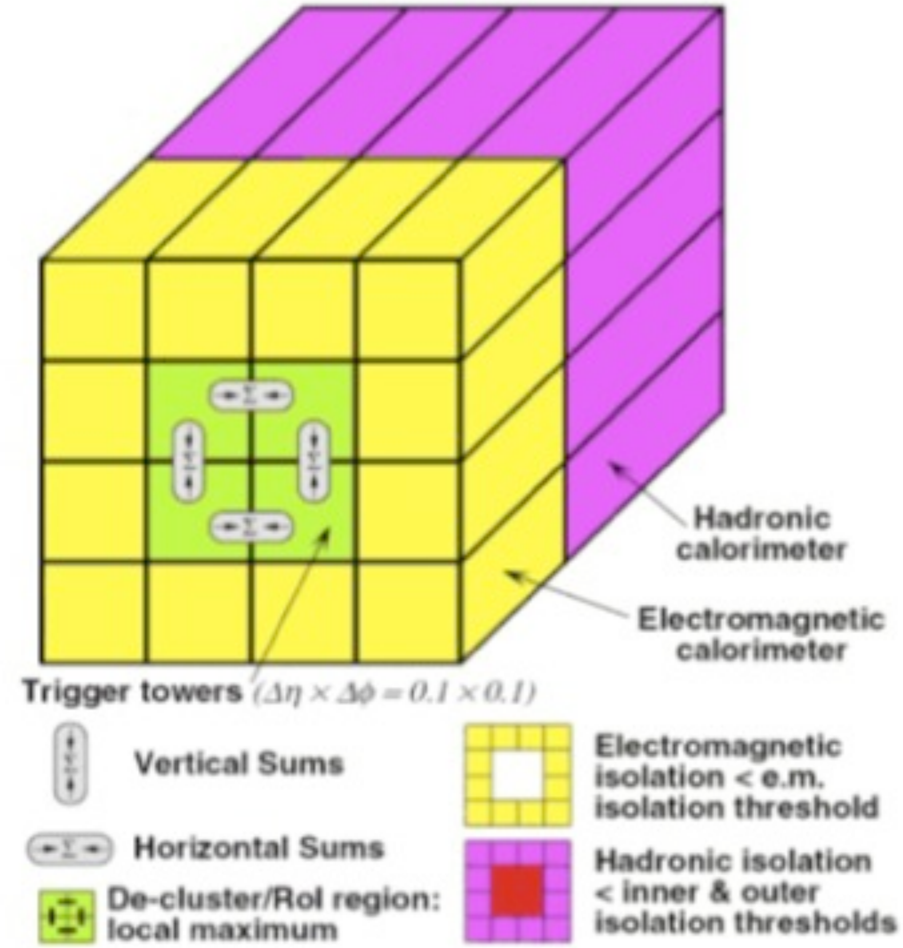


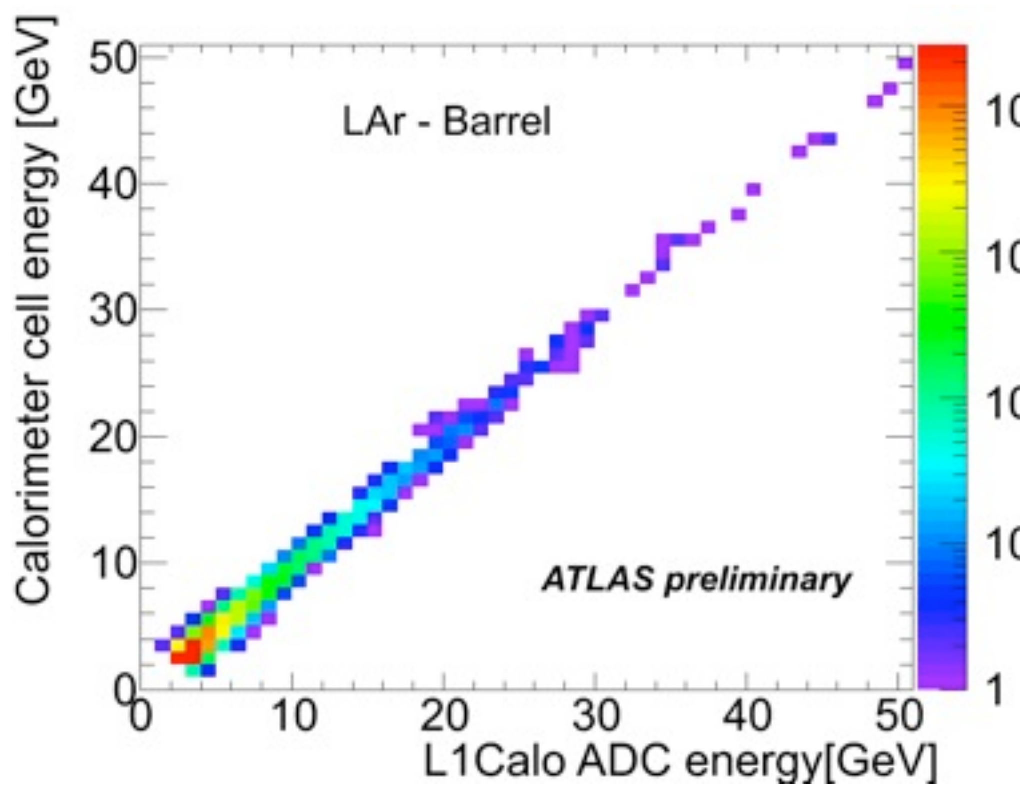
$$< V_D >= 4.63 \pm 0.12\ mm/\mu s \quad ; \quad (1000V/mm\ ,\ 88.5^o K)$$

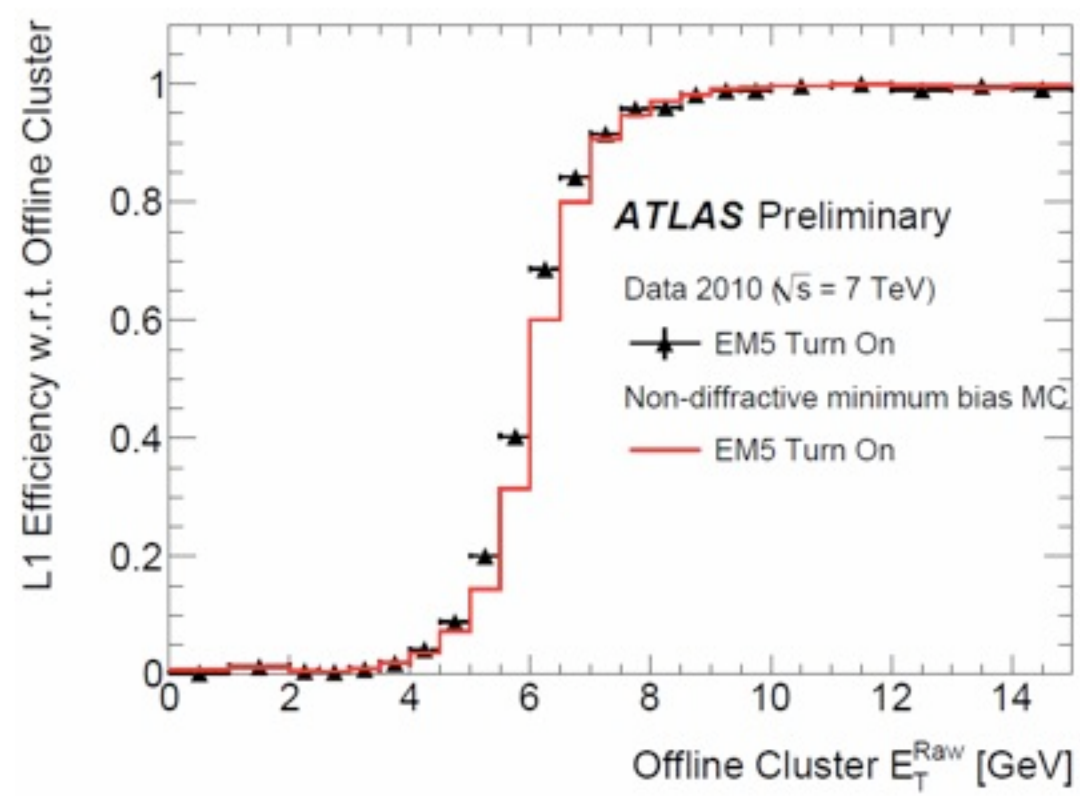
Trigger



L1decision
$\sim 2\mu s$



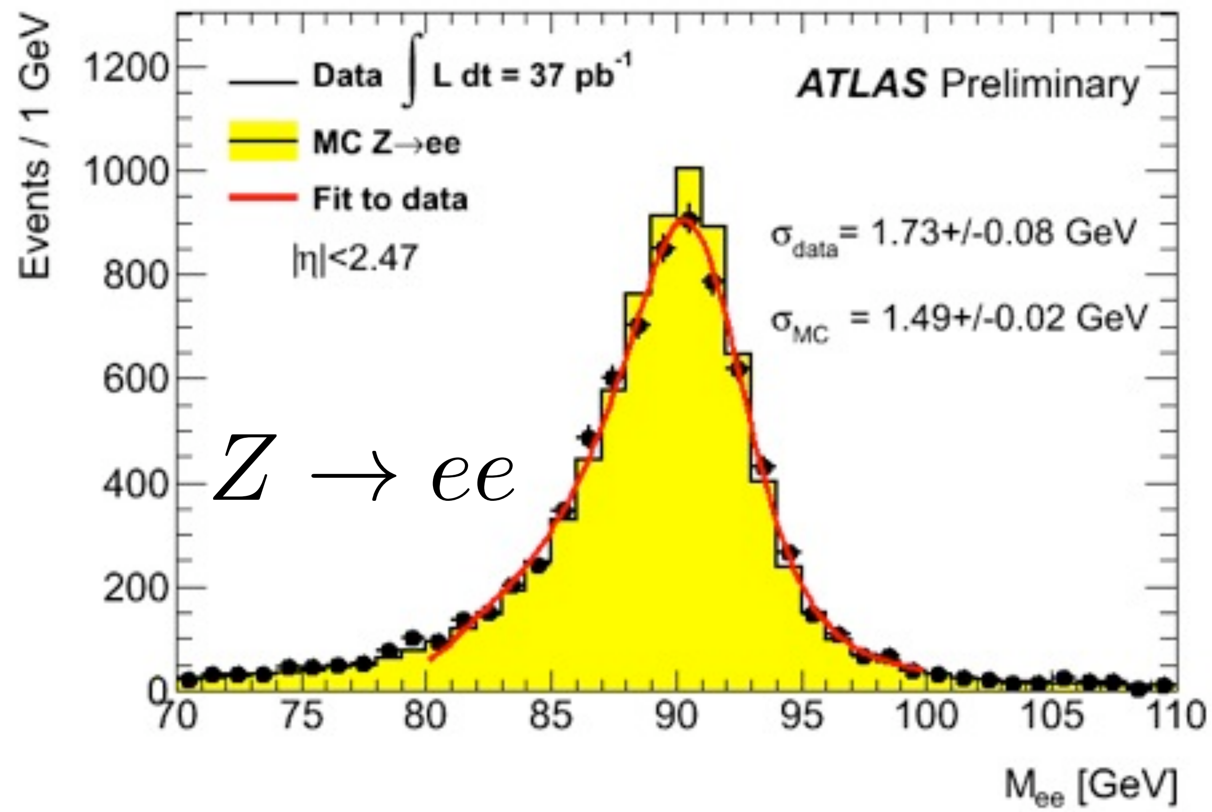




Resonances and energy scale

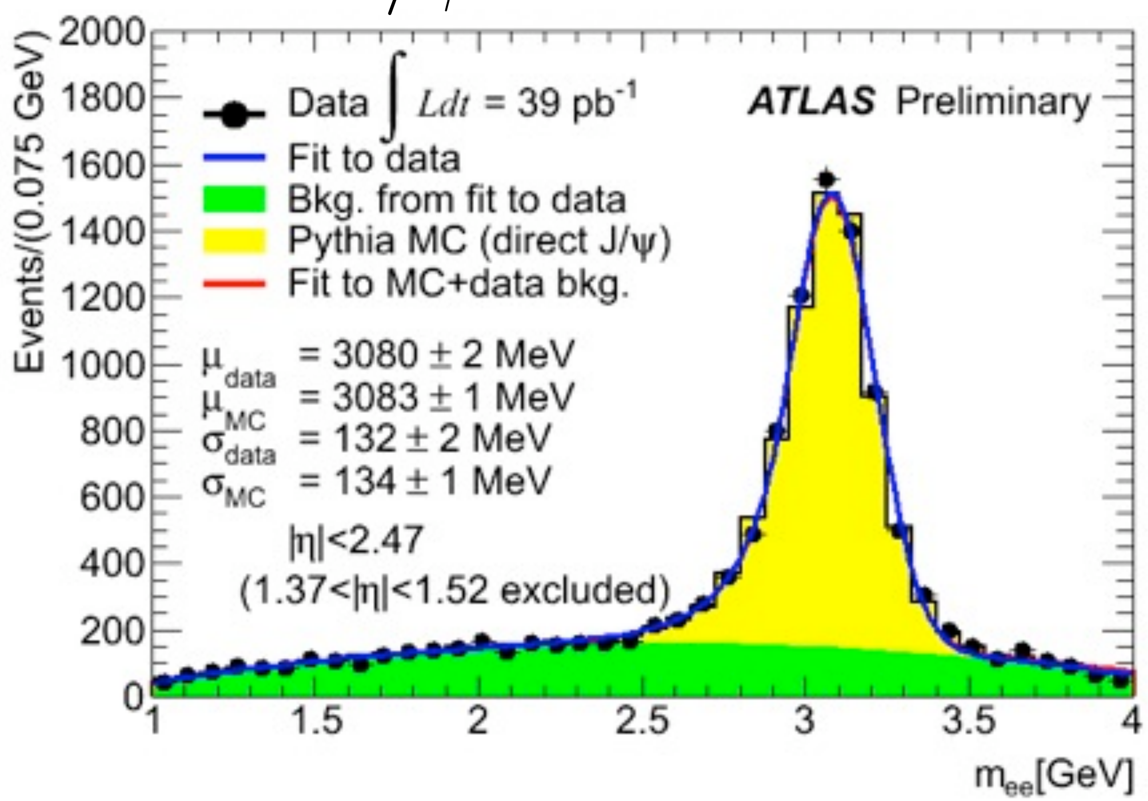
$$E_{corr} = \frac{E_{meas}}{(1+\alpha)}$$

$$M_Z = 91.1876\ GeV \Rightarrow \alpha$$



$Z \rightarrow ee$

$J/\psi \rightarrow ee$



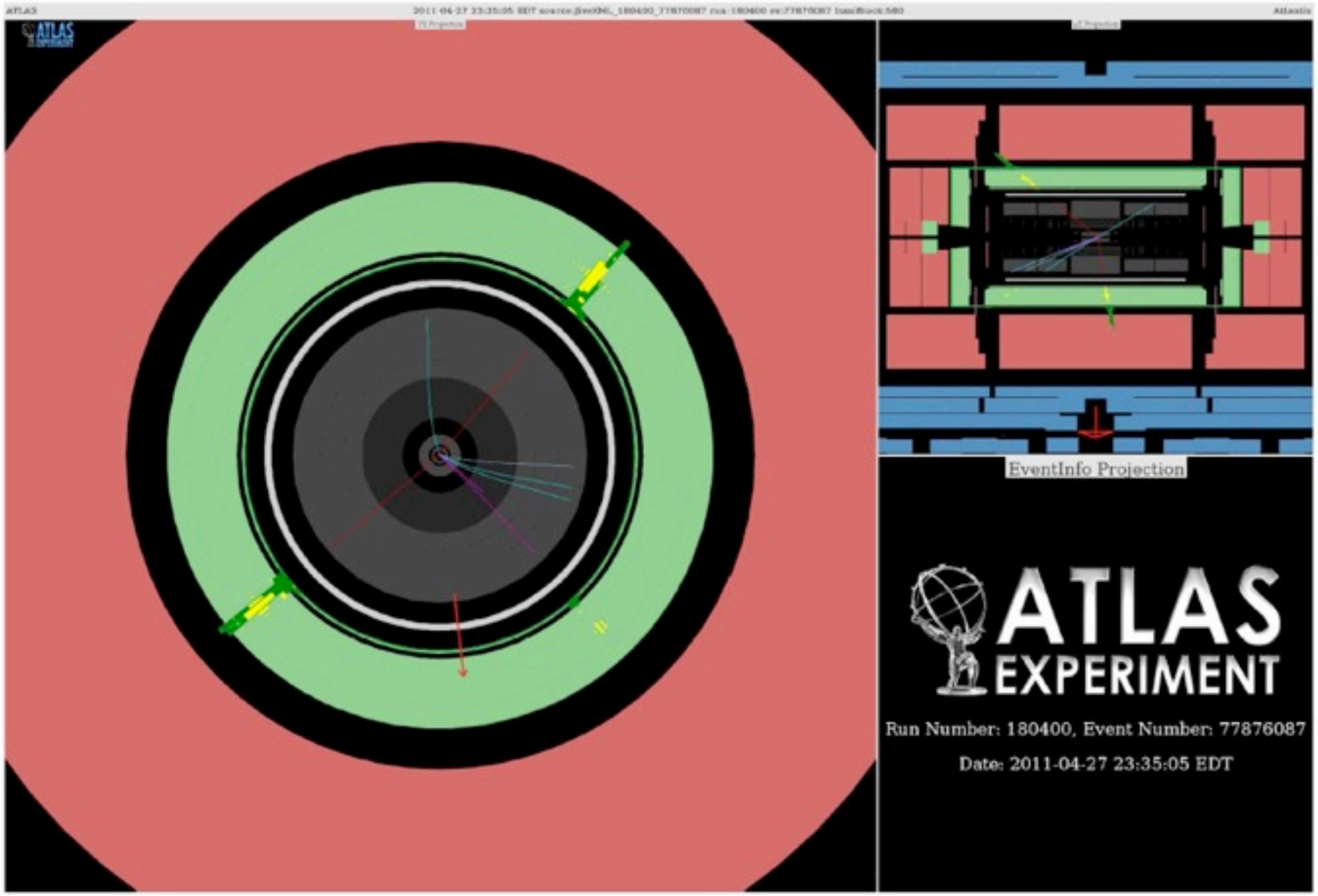


Figure 15: The highest energy electron has an E_T of 390 GeV and an (η, ϕ) of (-1.02, 0.86). The subleading electron has an E_T of 388 GeV and an (η, ϕ) of (0.19, -2.44). The invariant mass of the pair is 920 GeV. The event also contains a photon candidate with a E_T of 36.5 GeV and an (η, ϕ) of ($-1.21, -0.82$).

Conclusion

Almost 20 years have passed since the proposal of the ATLAS LAr calorimeters. Experience gained from the tests during the construction phase and the commissioning after installation in the cavern (2006) has lead to a good understanding of the Calorimeters. During its 5 years of operation in ATLAS the LAr calorimeter performance has been very close to design and has worked as expected, showing the reliability of the LAr technology at the scale of ATLAS.