

Ecole de la formation
permanente IN2P3

Du Détecteur à la mesure 2025



Calorimetry Part 2

Marco Delmastro



Lecture plan

YESTERDAY

1. Interactions of electron, photons and hadrons
2. Fundamentals of calorimetry
3. Examples: LHC calorimeters
4. Readout electronics and energy reconstruction for calorimeters

TODAY

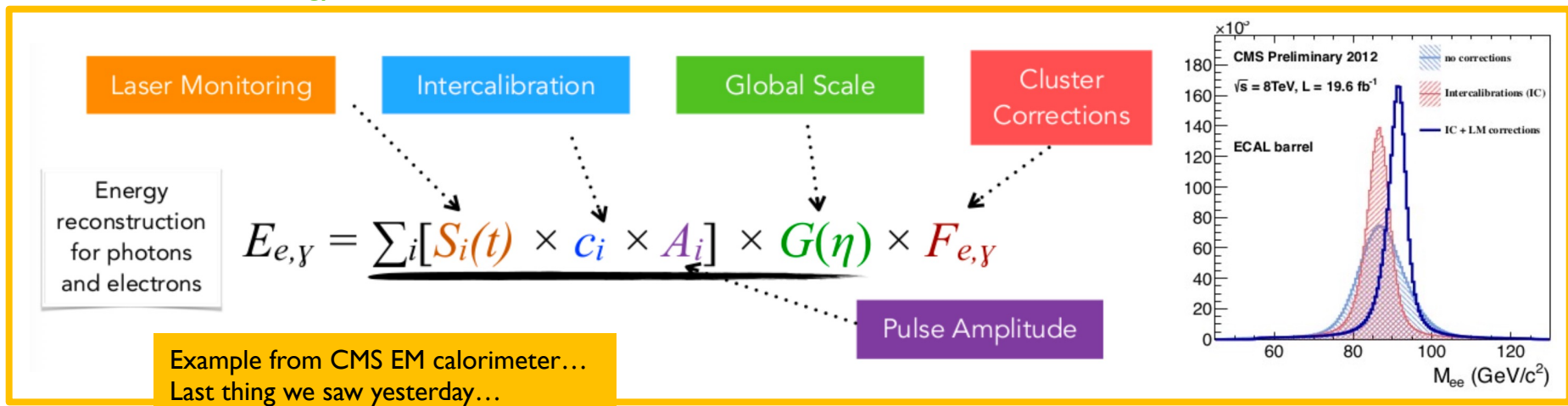
5. From detector to measurement: the case of the ATLAS EM calorimeter
6. Future calorimeter technologies

5.

From detector to
measurement: the case of
the ATLAS EM calorimeter

Calorimeter energy reconstruction and calibration

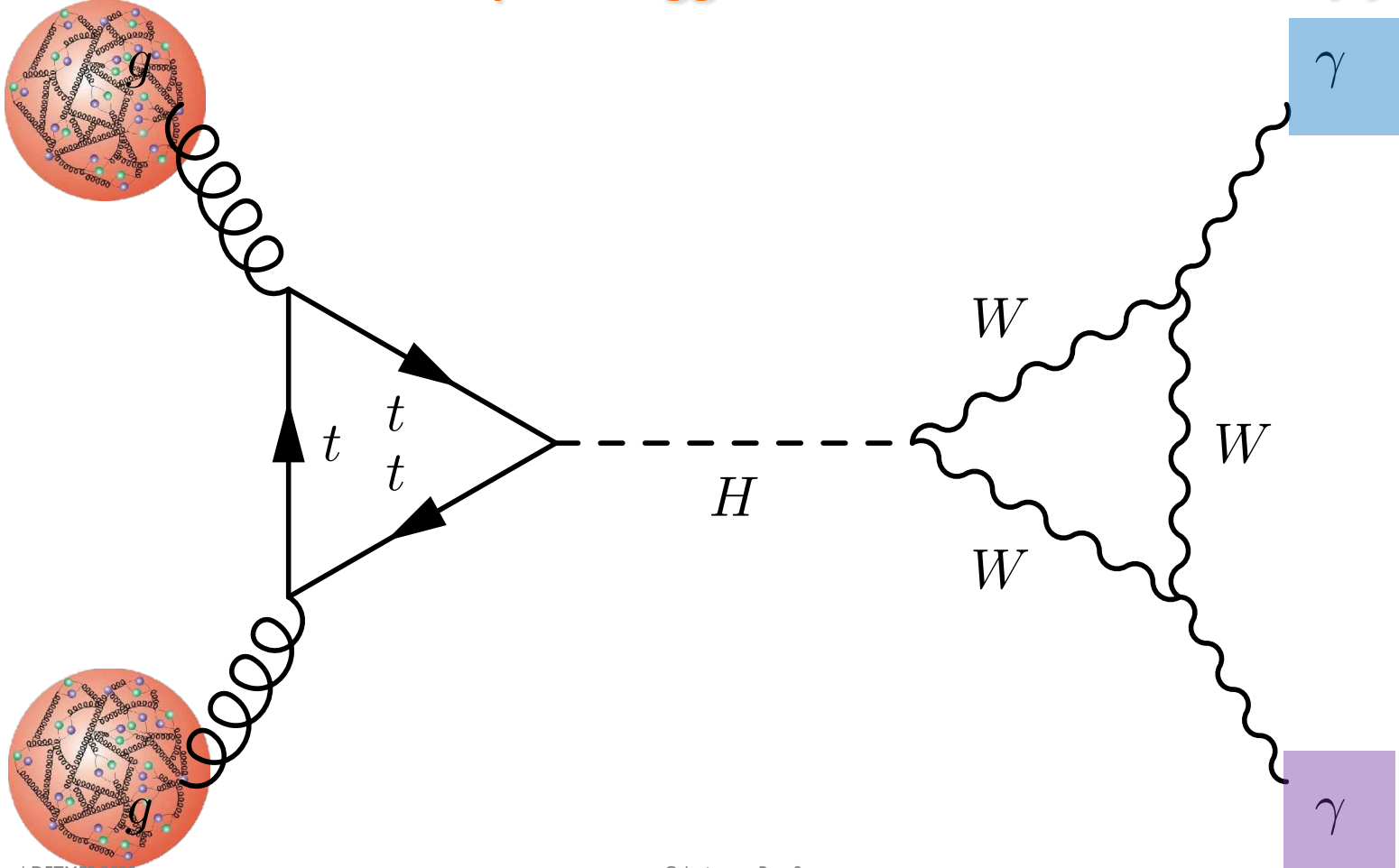
- Typical reconstruction + calibration chain
 - ✓ Pulse amplitude reconstruction
 - ✓ Pulse → energy: correct response effects from monitored parameters (detector, electronics)
 - ✓ Clustering (i.e. grouping cells belonging to same shower)
 - ✓ Intercalibration
 - Correct differences of response in different detector places: mechanics, electronics, ...
 - ✓ Leakage corrections (energy lost outside of cluster)
 - ✓ Absolute energy scale correction

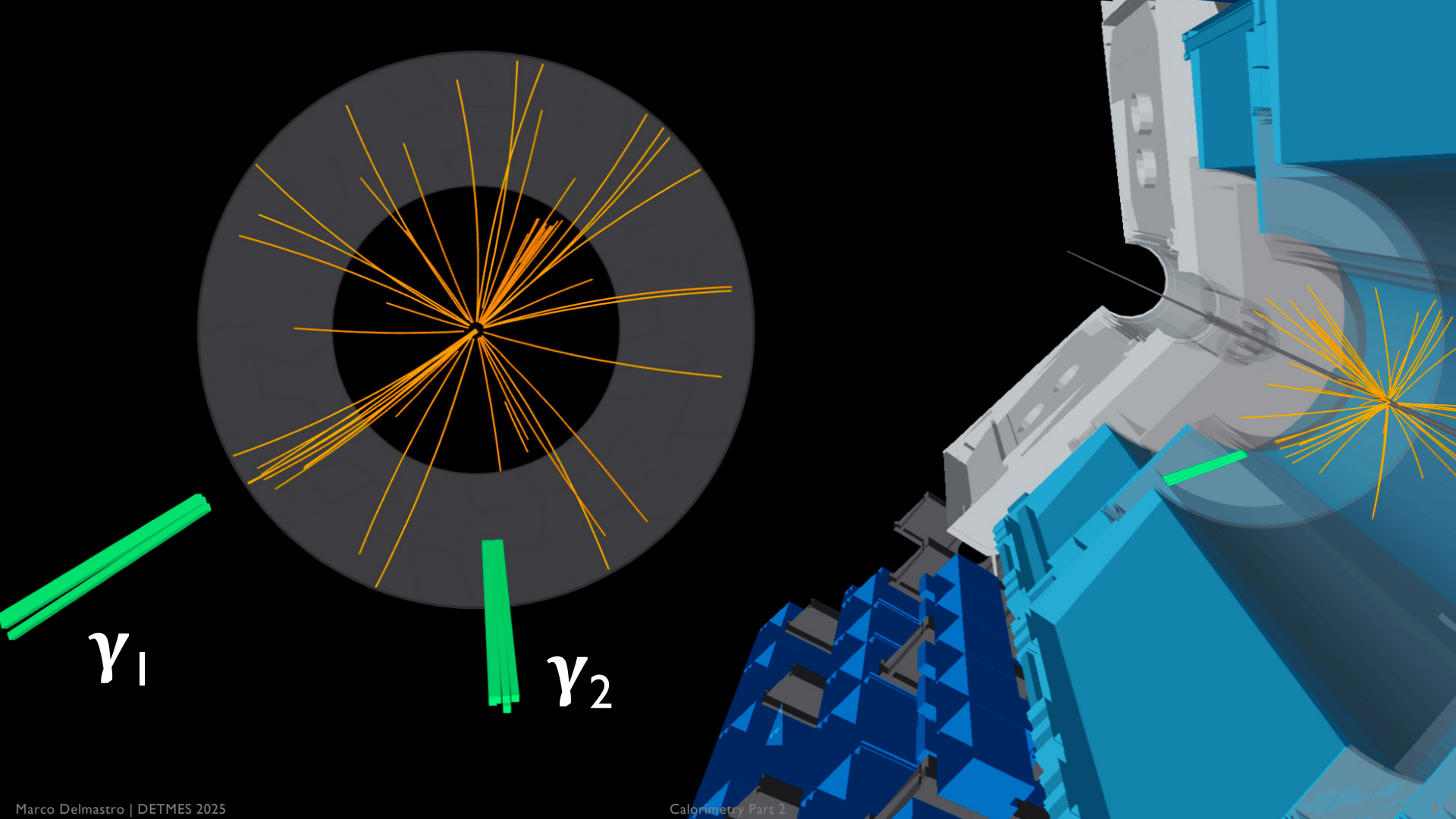


5.1

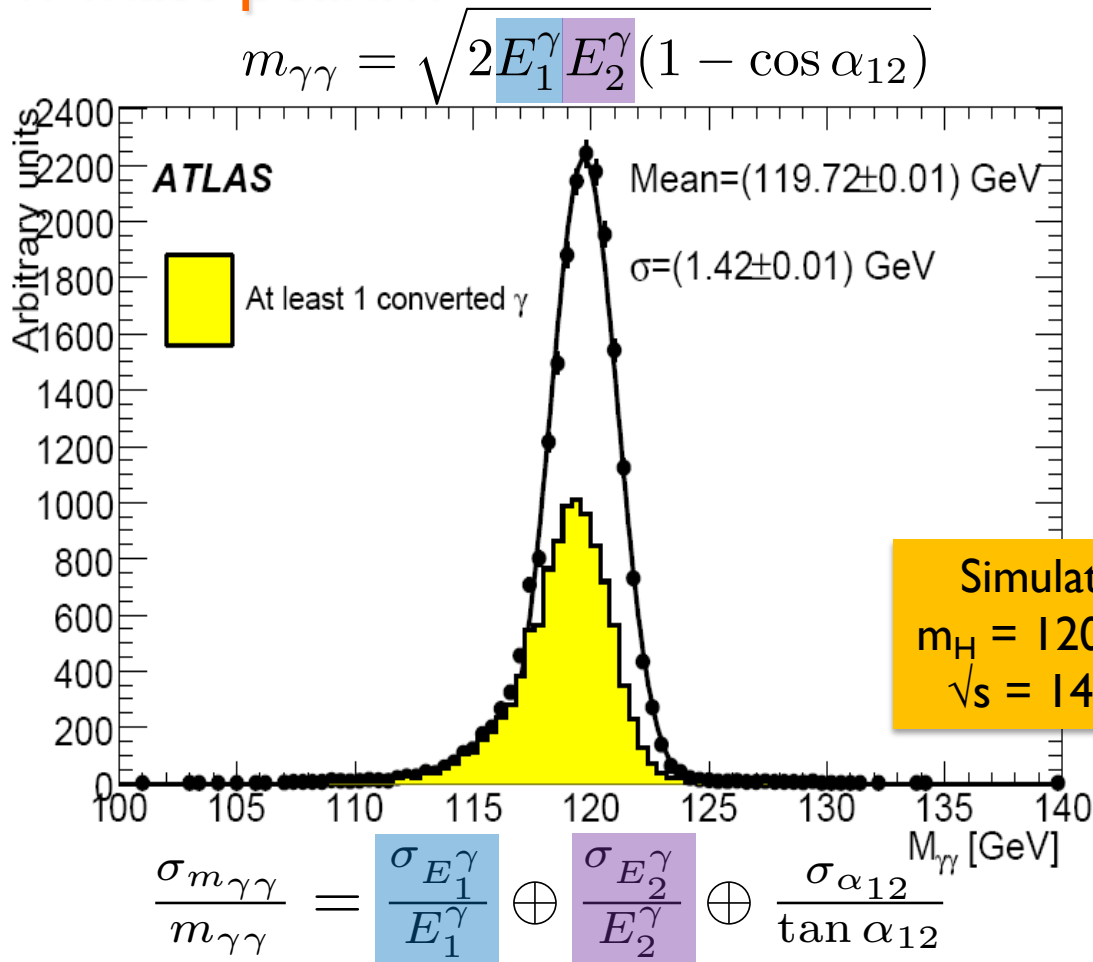
A measurement example:
Higgs boson mass
with $H \rightarrow \gamma\gamma$

A measurement example: Higgs boson mass with $H \rightarrow \gamma\gamma$





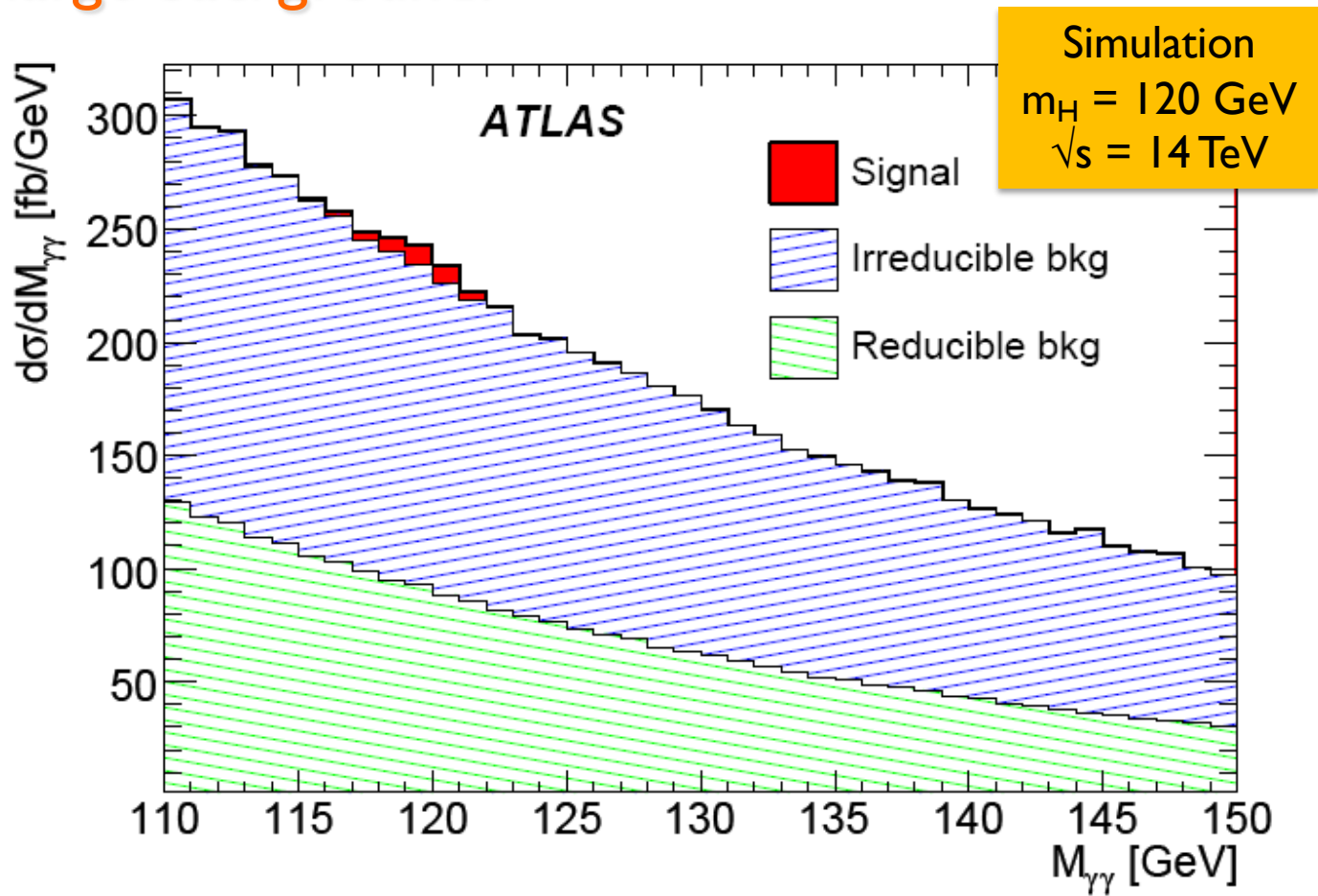
A narrow mass peak...

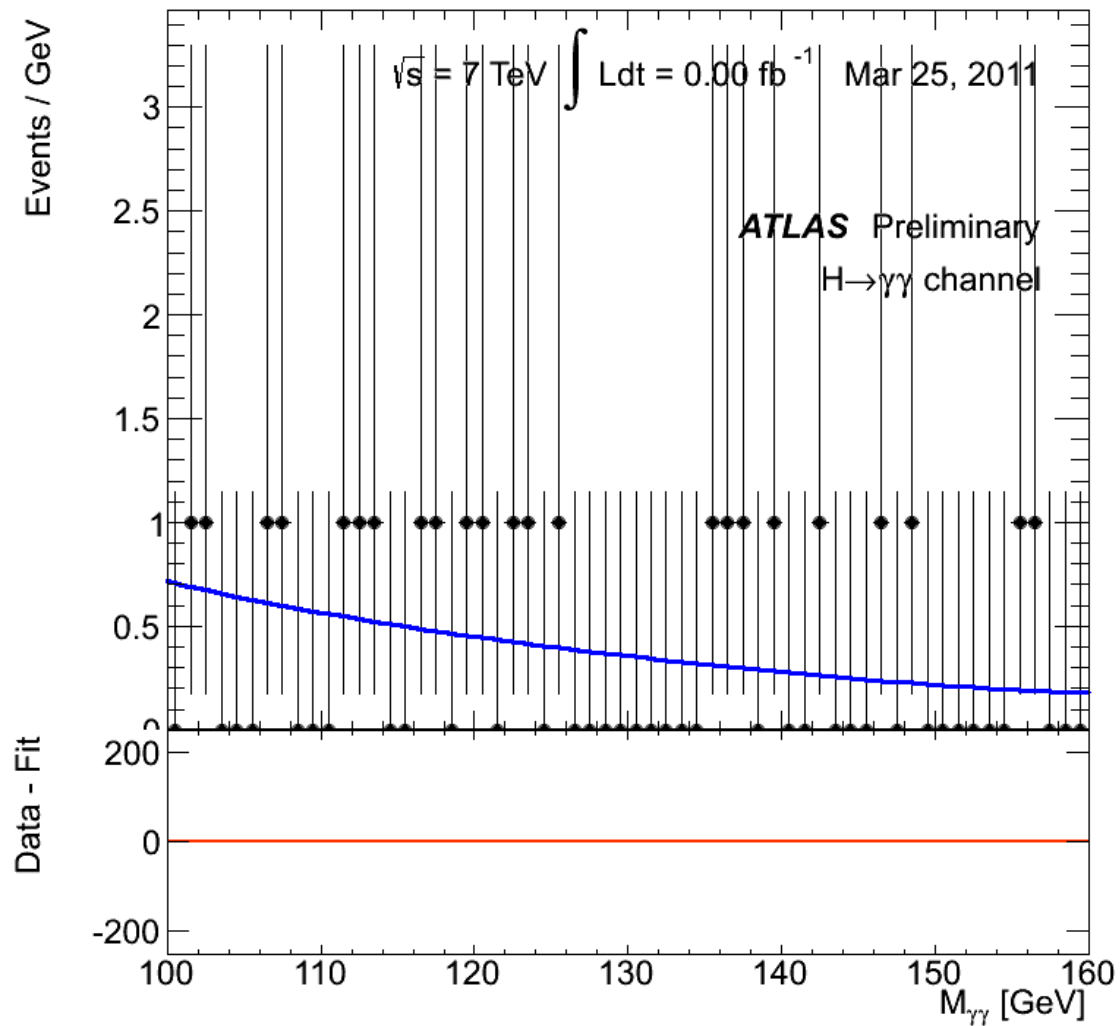


Photon energies and
position from EM
calorimeter

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

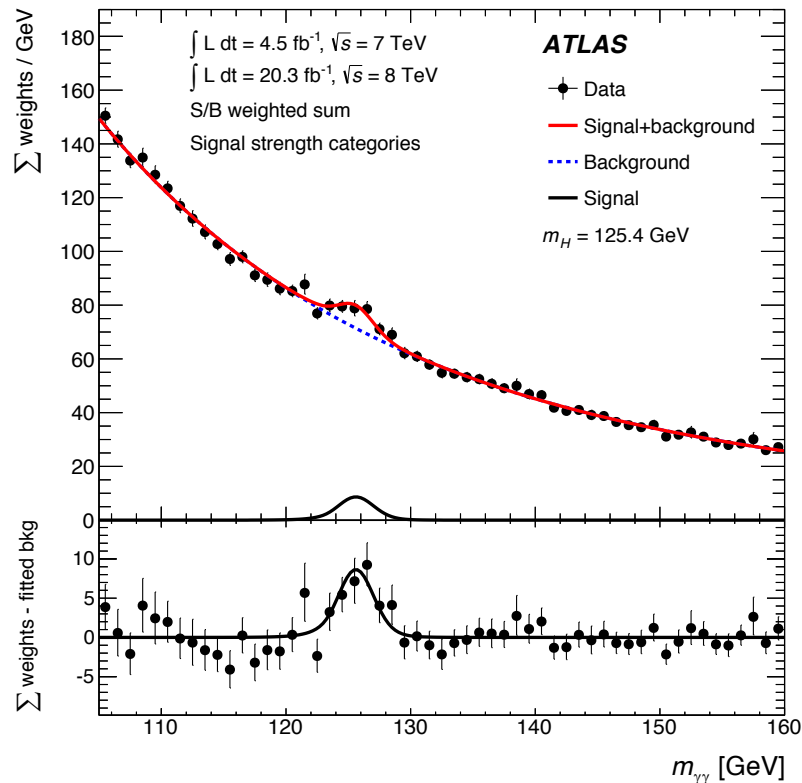
... on a large background!



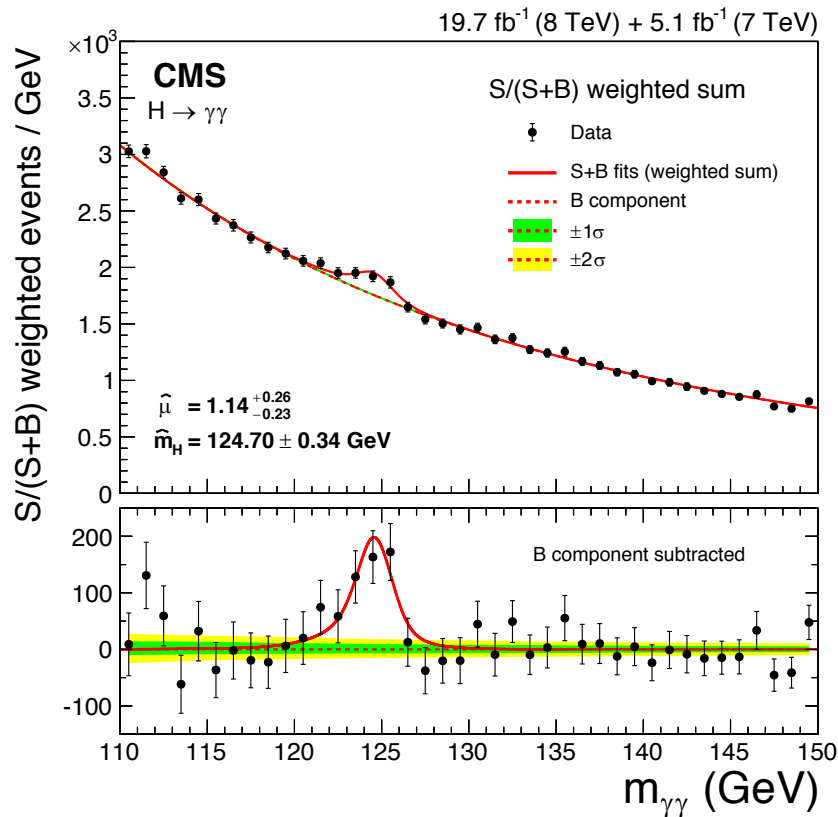


$H \rightarrow \gamma\gamma$ (weighted) mass spectra

ATLAS



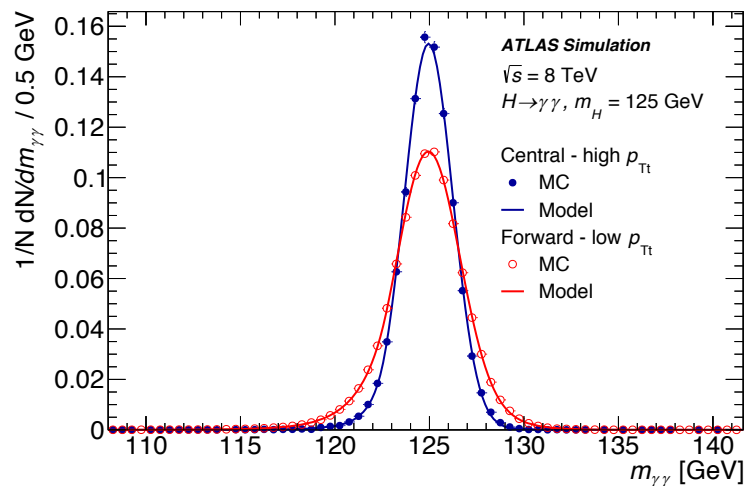
CMS



$H \rightarrow \gamma\gamma$ invariant mass resolution

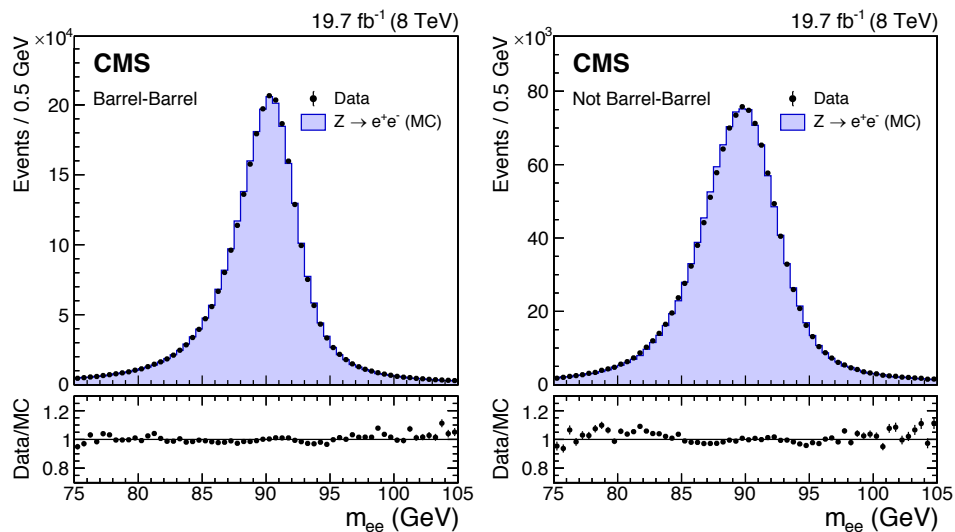
ATLAS

[*Phys. Rev. D. 90, 112015 \(2014\)*](#)

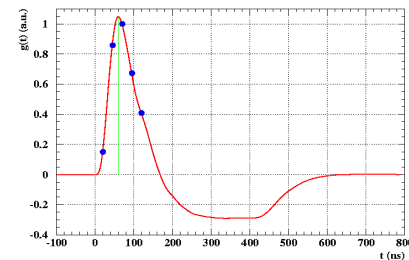
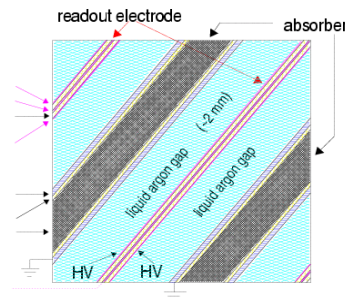
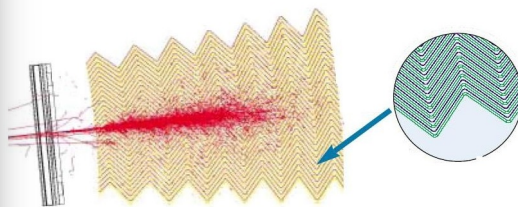
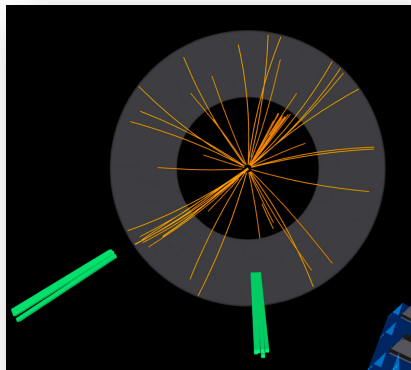
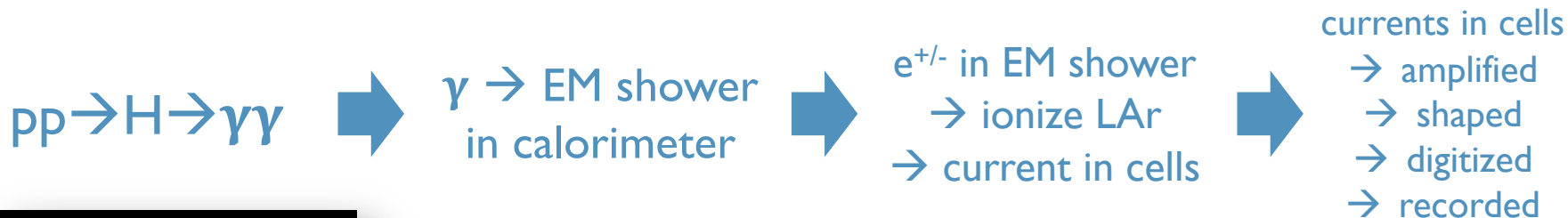


CMS

[*Eur. Phys. J. C 74 \(2014\) 3076*](#)



From physics to detector and back...



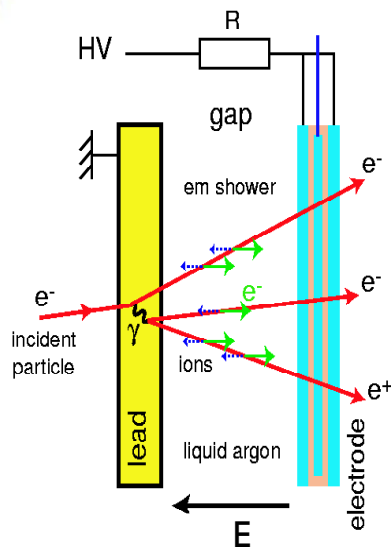
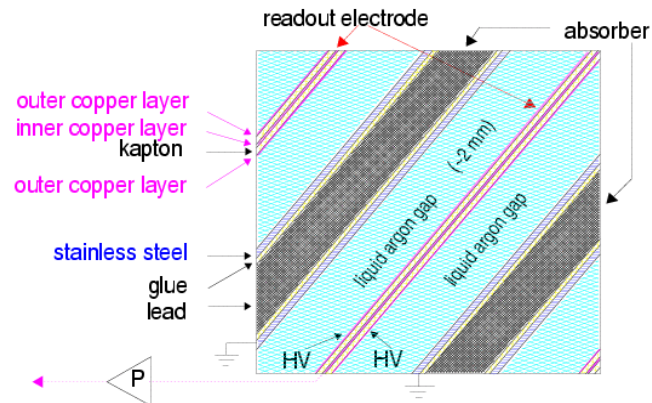
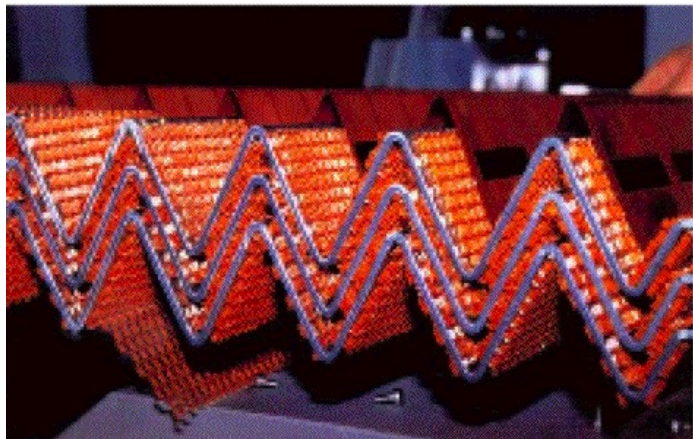
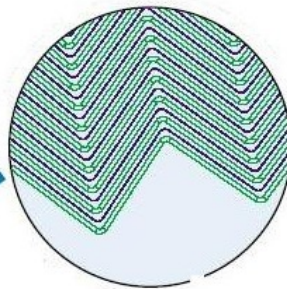
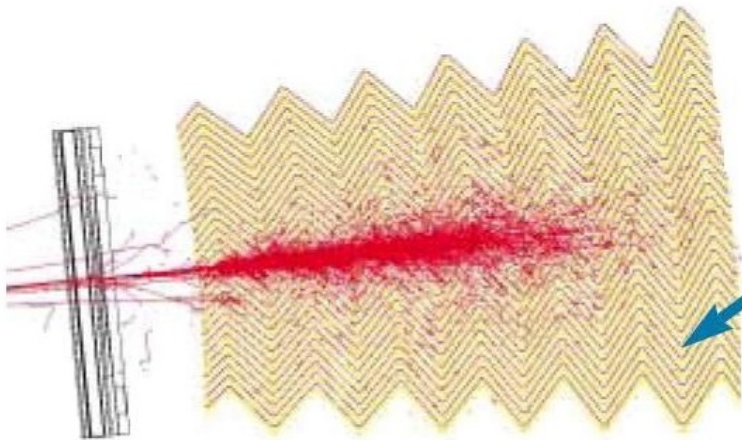
γ energies
 (and positions)
 $H \rightarrow \gamma\gamma \leftarrow$
 $m_H \leftarrow$

$\leftarrow$ cell energies
 $\leftarrow$ cell cluster
 $\leftarrow$ cluster energy
 $\leftarrow$ γ energy

$\leftarrow$ cell current
 $\leftarrow$ cell energy

$\leftarrow$ digitized pulse samples
 $\leftarrow$ pulse amplitude
 $\leftarrow$ cell current

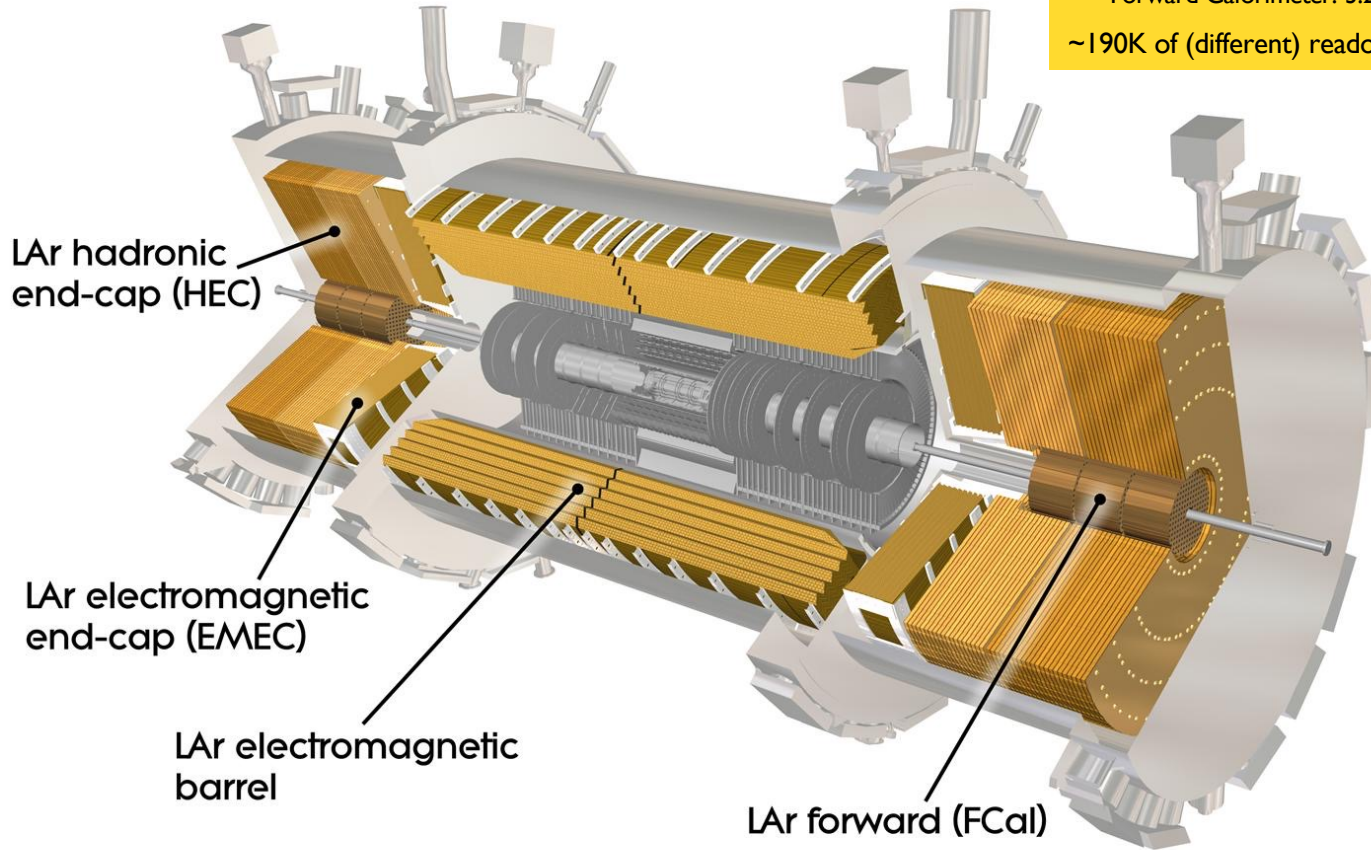
ATLAS EM calorimeter



i(t)

- **EM calorimeter outside inner solenoidal field**
 - ✓ More material in front, energy losses, photon conversions
- **Sampling calorimeter (LAr + Pb)**
 - ✓ Worse energy resolution
- **High granularity and segmentation**
 - ✓ better PID and rejection
 - ✓ position measurement for photons
- **Electrical signals**
 - ✓ High stability in calibration
 - ✓ Radiation resistant

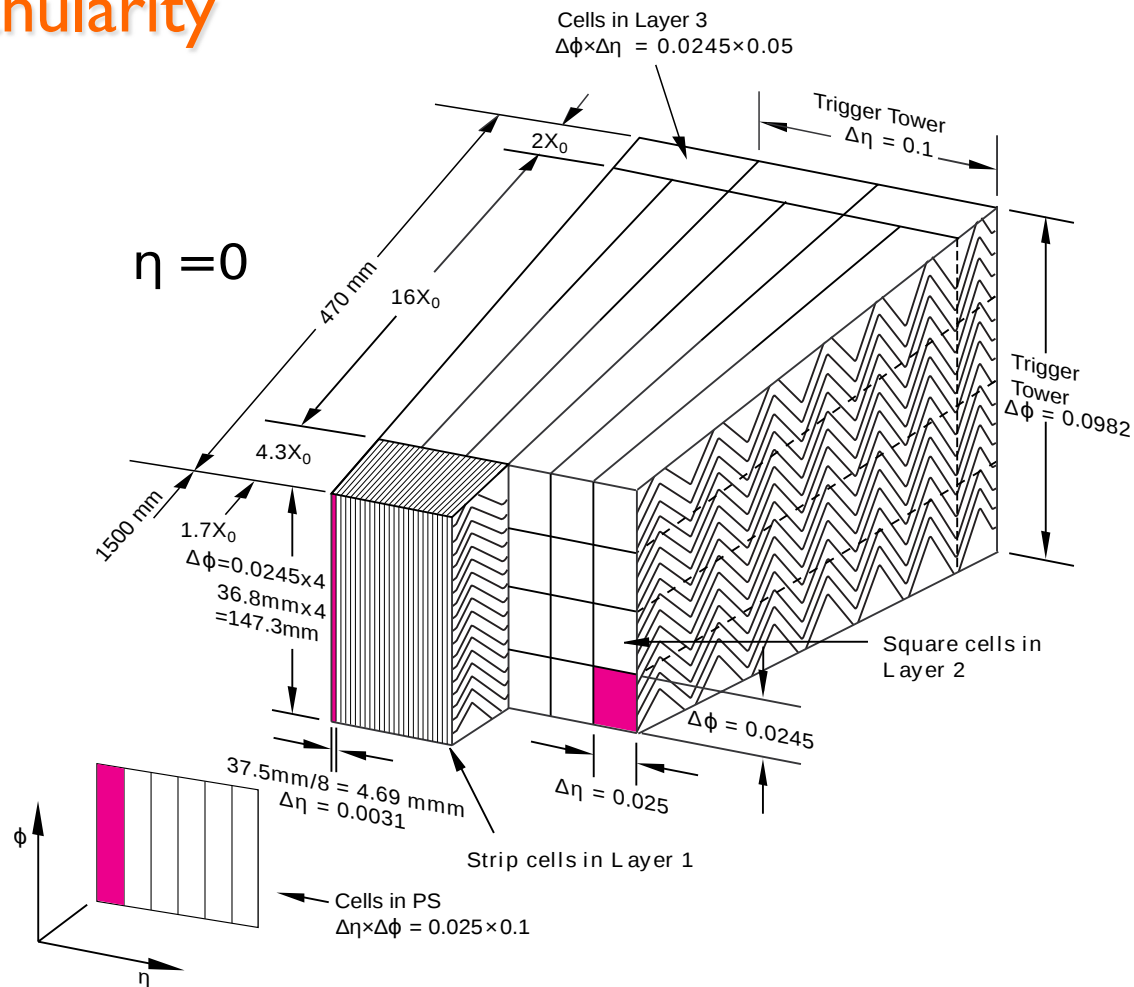
ATLAS LAr calorimeters



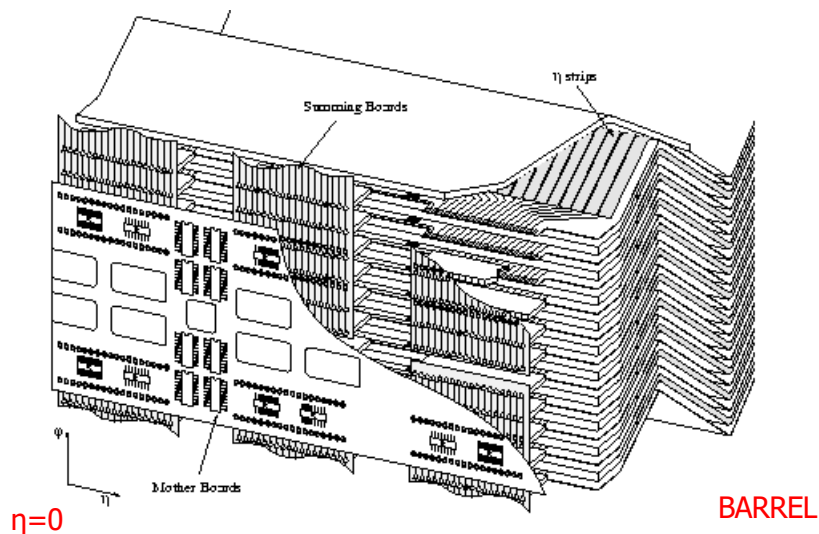
- ✓ EM Barrel : ($|\eta| < 1.475$) [Pb-LAr]
- ✓ EM End-caps : $1.4 < |\eta| < 3.2$ [Pb-LAr]
- ✓ Hadronic End-cap: $1.5 < |\eta| < 3.2$ [Cu-LAr]
- ✓ Forward Calorimeter: $3.2 < |\eta| < 4.9$ [Cu, W-LAr]

~190K of (different) readout channels

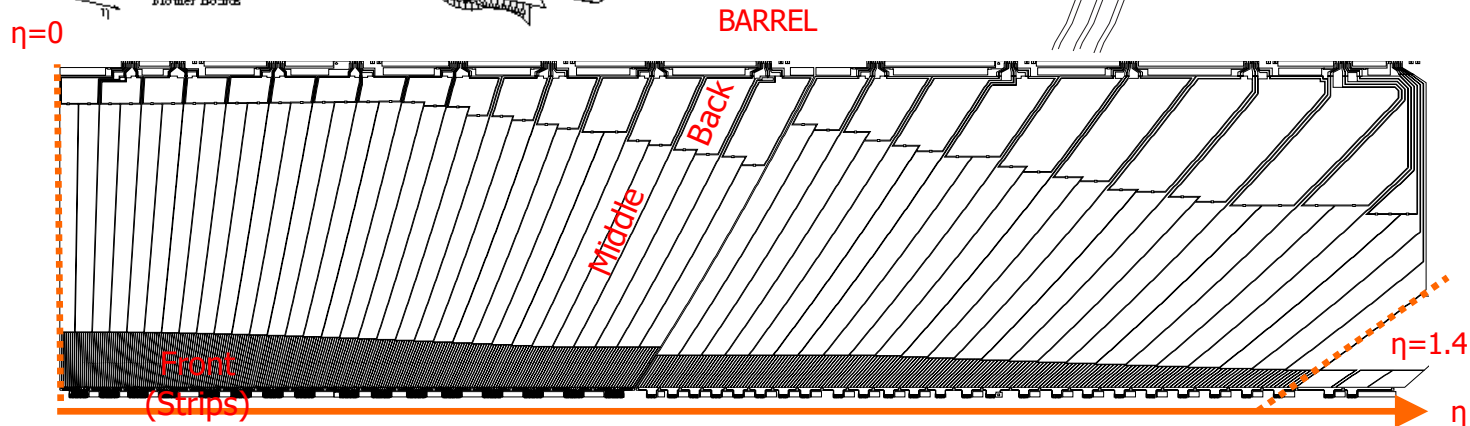
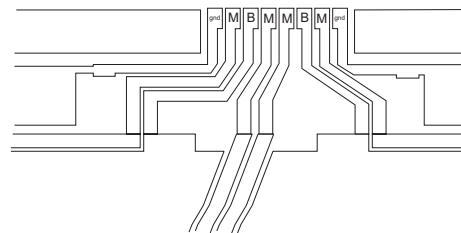
LAr EM granularity



How is LAr granularity achieved?



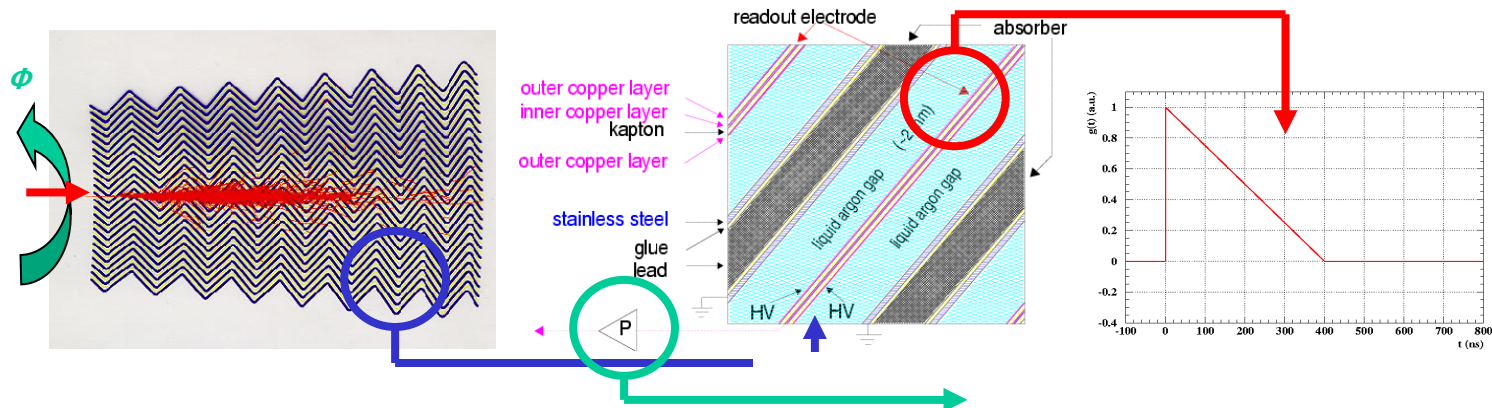
- η : etching of readout electrode
- ϕ : electrode connection via “summing boards”
- Signal from summing boards collected “mother board”, where also calibration resistors are located
 - ✓ Signal path: partly on electrode, then SB+MB, then cables



5.2

Cell energy reconstruction and calibration

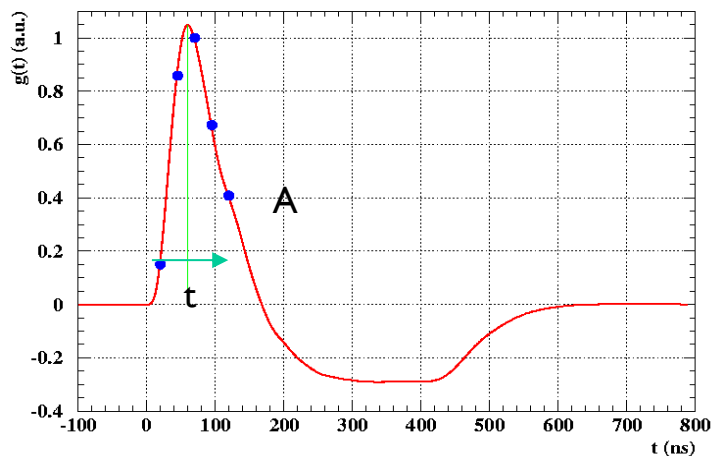
LAr (EM) signal generation and readout



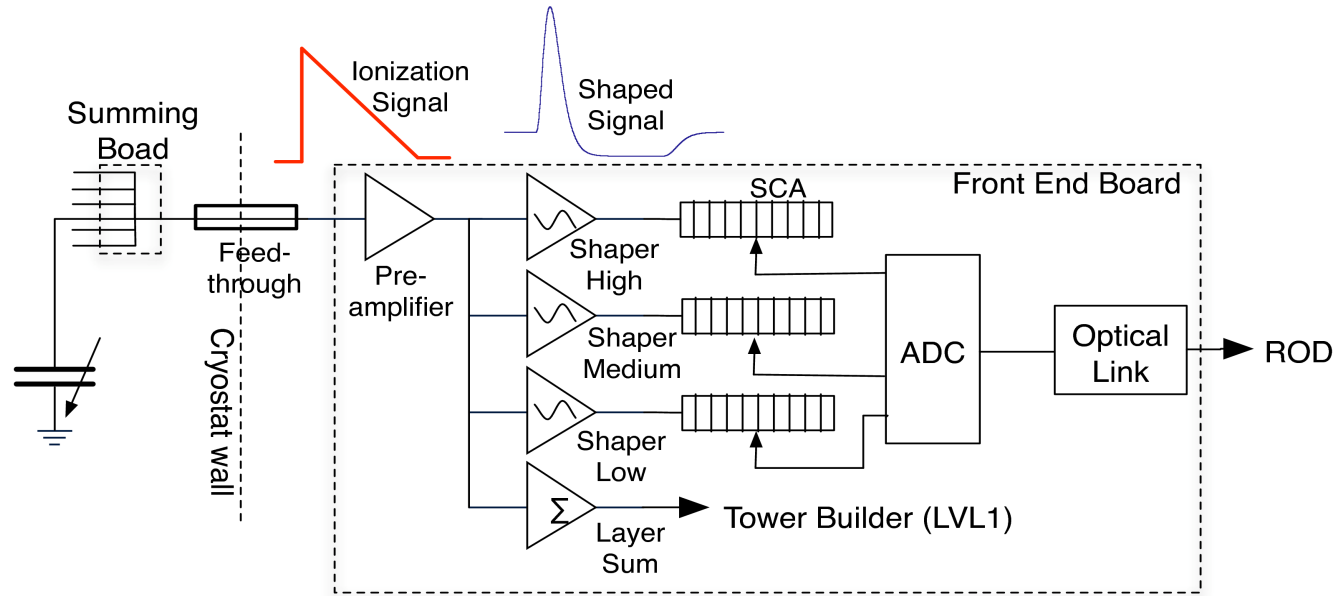
The LAr signal is generated by the ionization electrons drifting in the LAr gap thanks to HV between electrodes and absorbers.

The peak of the ionization current is proportional to the energy released in LAr

The triangular current signal is pre-amplified and shaped (bipolar filter CR-RC²), then sampled at the LHC bunch crossing frequency (every 25 ns) and digitized

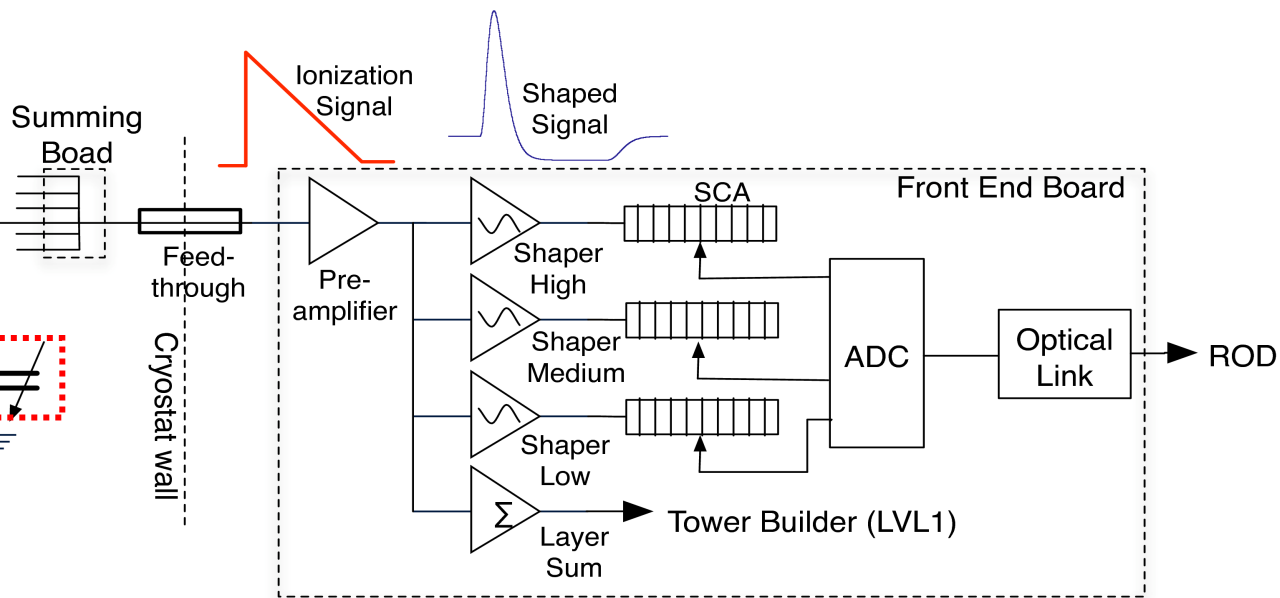


LAr readout electronics in a nutshell

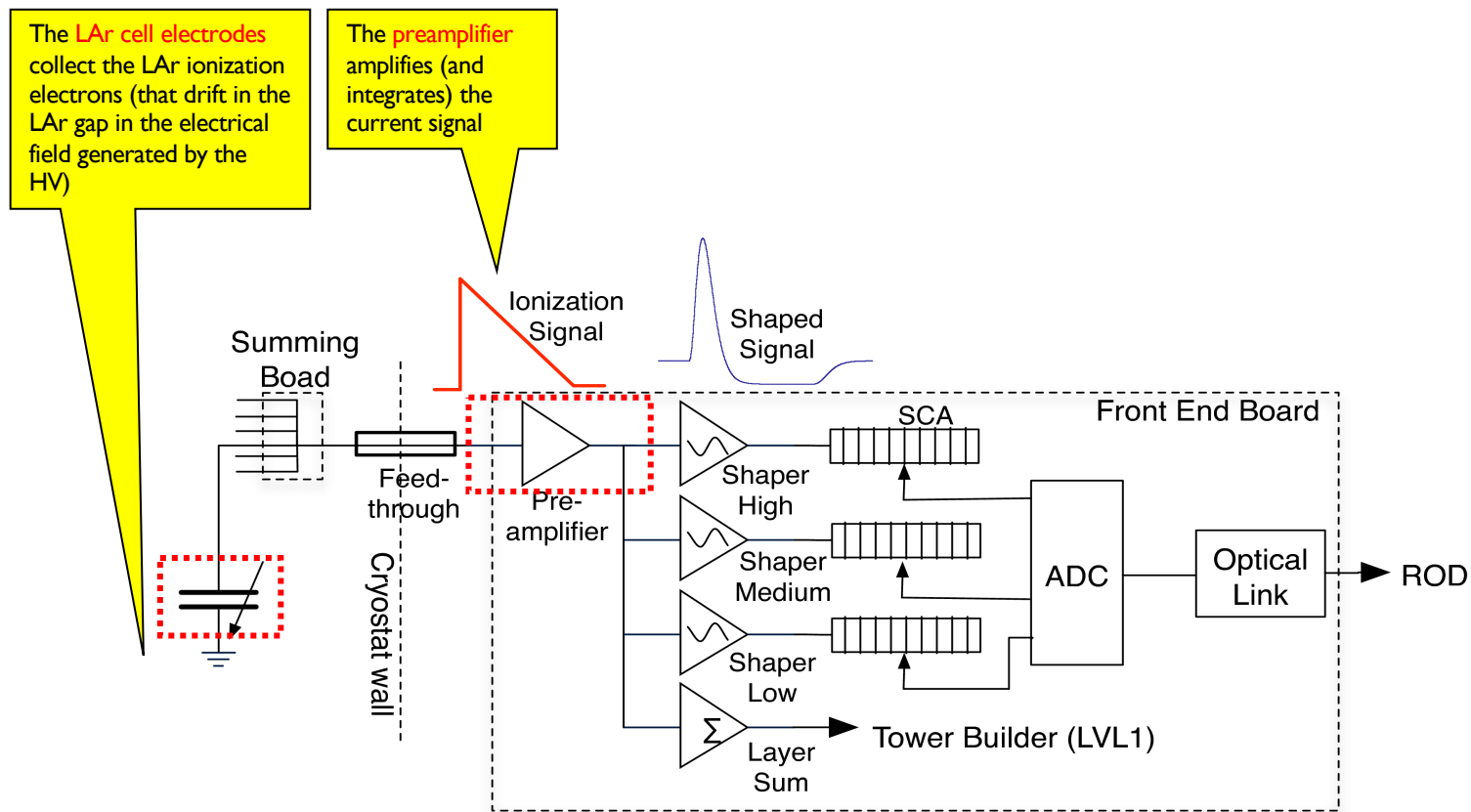


LAr readout electronics in a nutshell

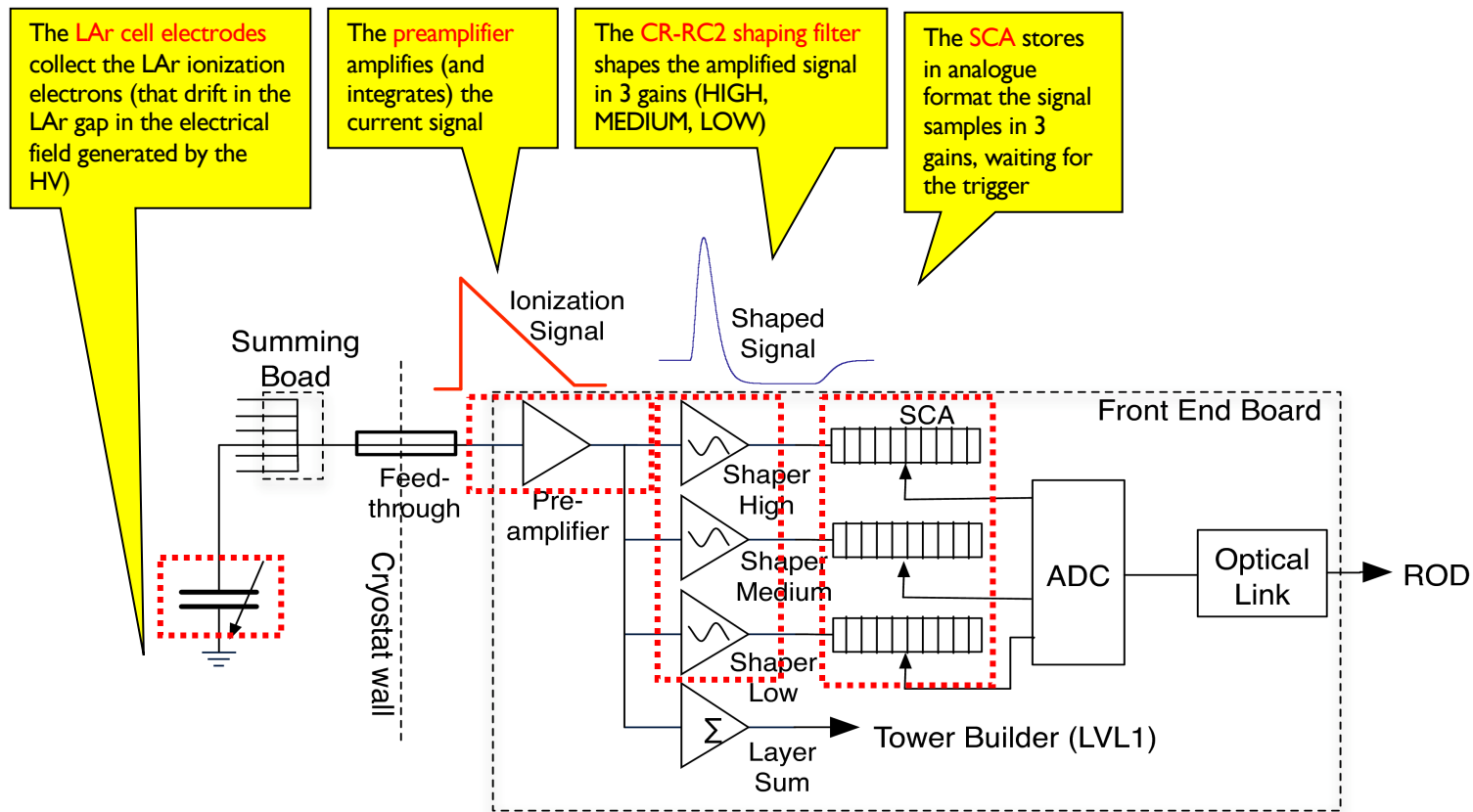
The LAr cell electrodes collect the LAr ionization electrons (that drift in the LAr gap in the electrical field generated by the HV)



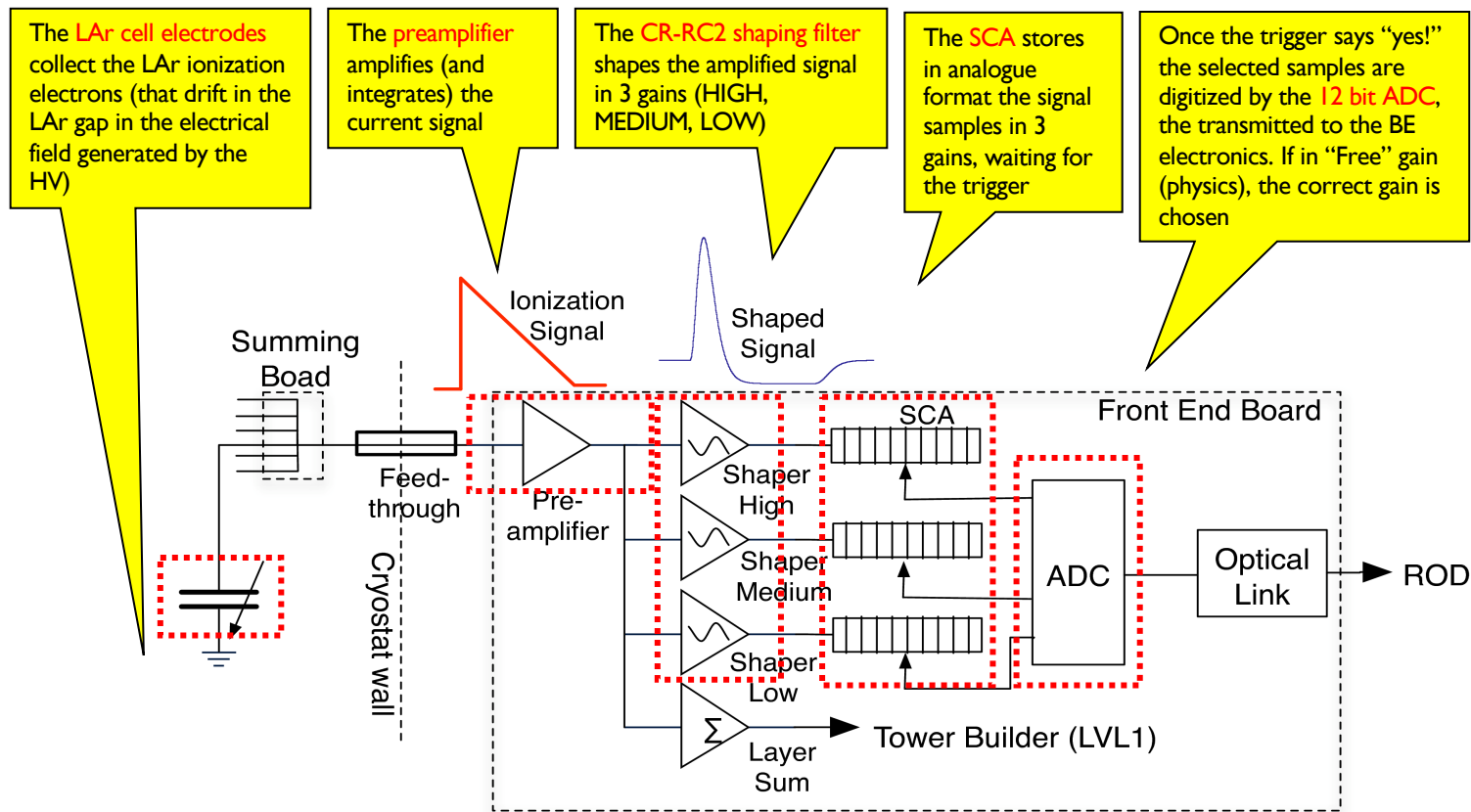
LAr readout electronics in a nutshell



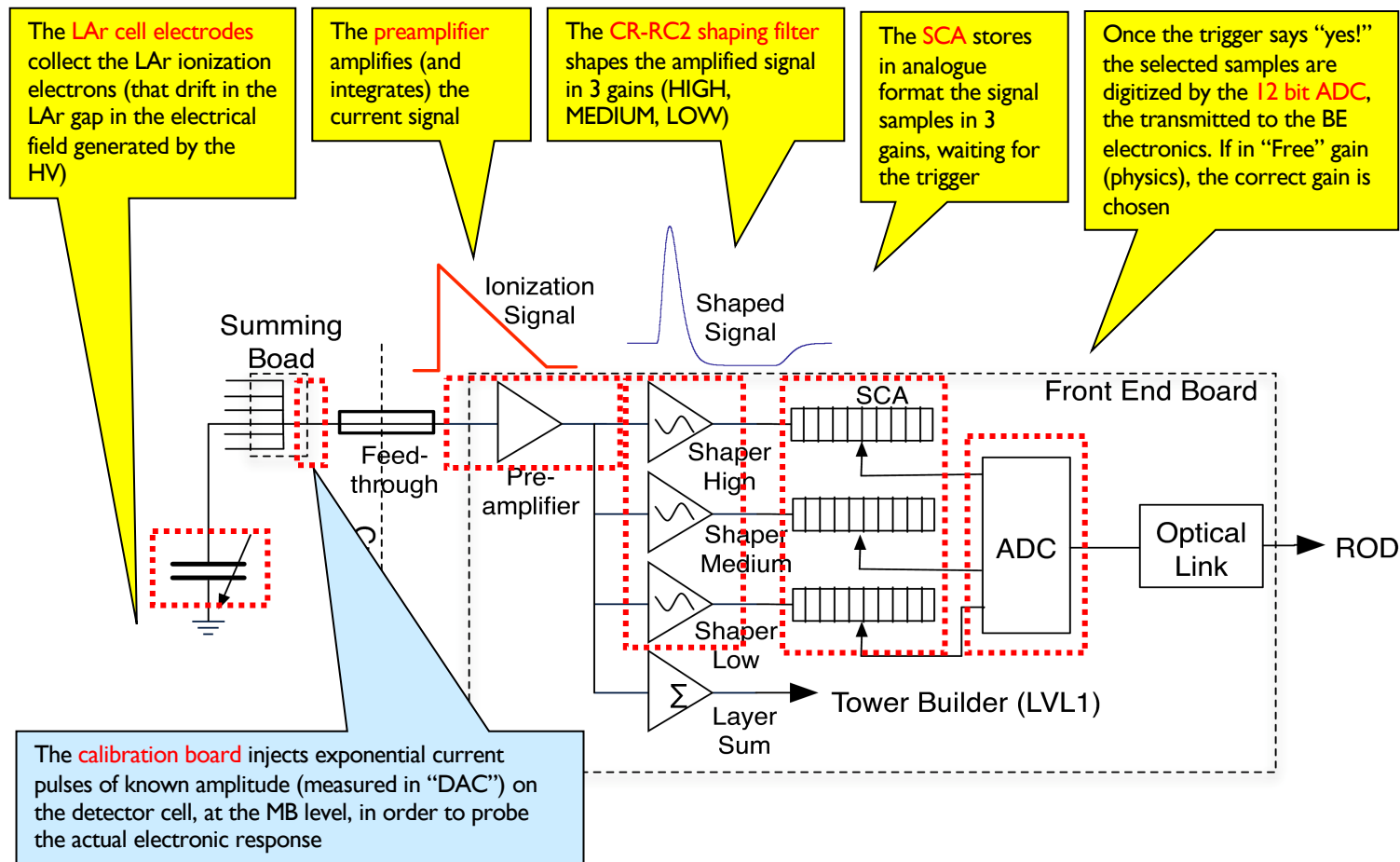
LAr readout electronics in a nutshell



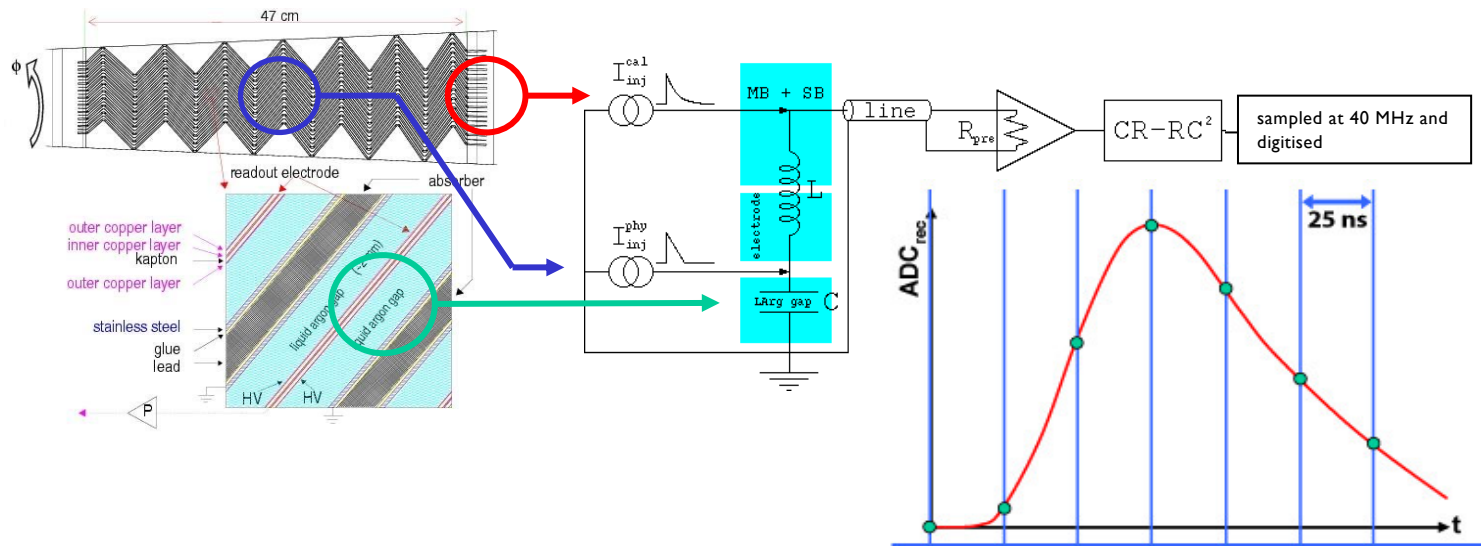
LAr readout electronics in a nutshell



LAr readout electronics in a nutshell



From digits to “raw” energy in a cell

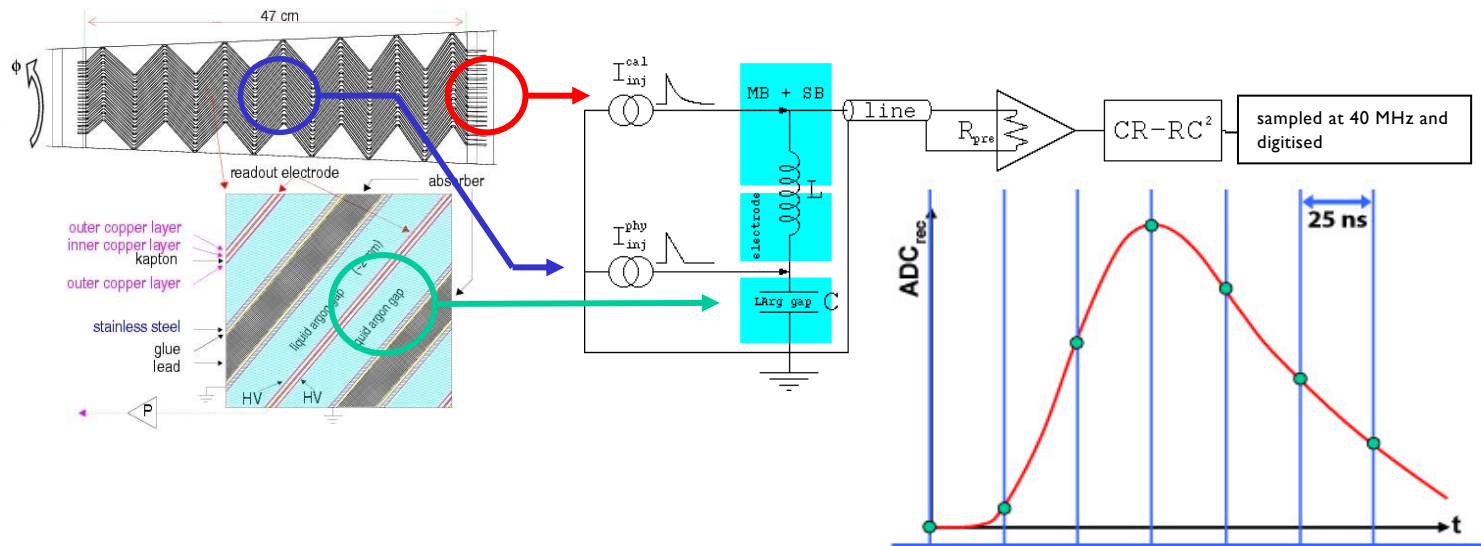


$$E_{\text{cell}} = F_{\text{DAC} \rightarrow \mu\text{A}} \cdot F_{\mu\text{A} \rightarrow \text{MeV}} \cdot \frac{1}{\frac{M_{\text{phys}}}{M_{\text{cali}}}} \cdot G_1 \cdot \sum_{i=1}^{N_{\text{samples}}} a_i (s_i - p)$$

Energy

Pulse Samples

From digits to “raw” energy in a cell

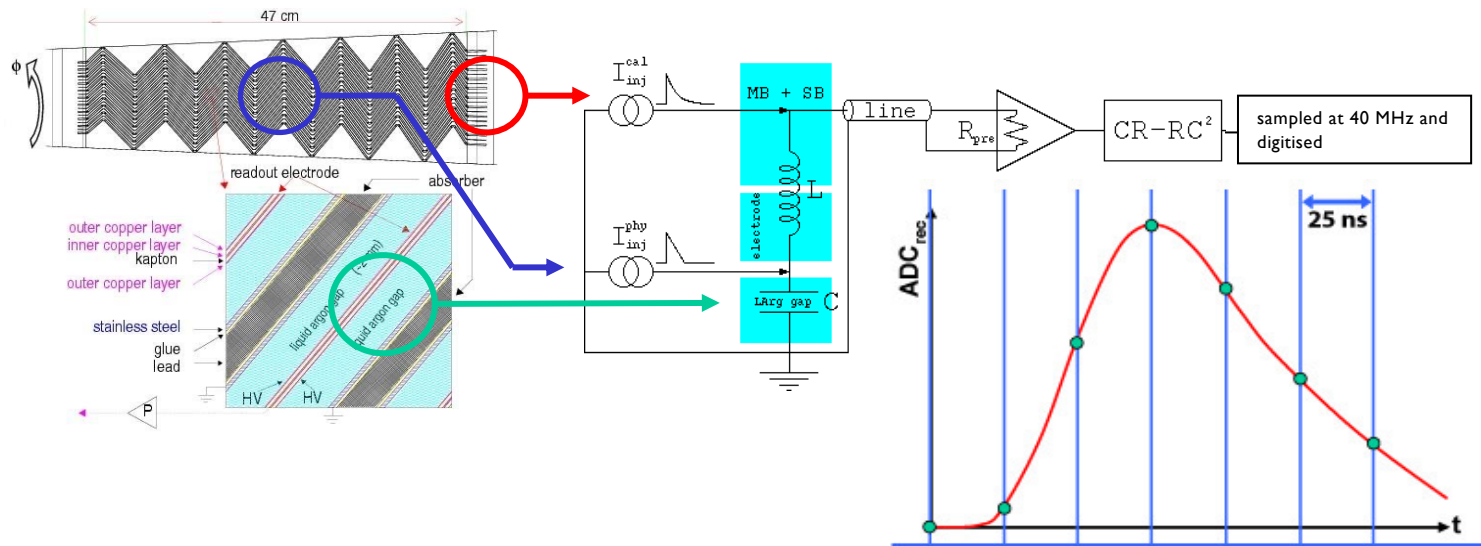


$$E_{\text{cell}} = F_{\text{DAC} \rightarrow \mu\text{A}} \cdot F_{\mu\text{A} \rightarrow \text{MeV}} \cdot \frac{1}{\frac{M_{\text{phys}}}{M_{\text{cali}}}} \cdot G_1 \cdot \sum_{i=1}^{N_{\text{samples}}} a_i (s_i - p)$$

Energy

Pedestals

From digits to “raw” energy in a cell



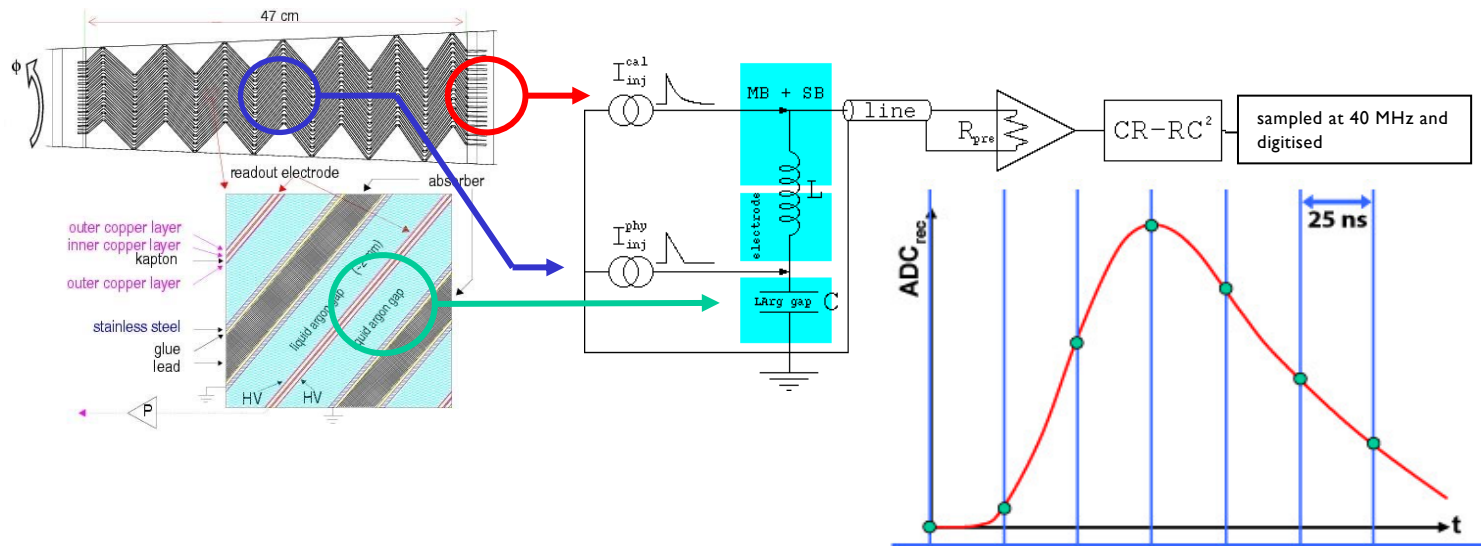
$$E_{\text{cell}} = F_{\text{DAC} \rightarrow \mu\text{A}} \cdot F_{\mu\text{A} \rightarrow \text{MeV}} \cdot \frac{1}{\frac{M_{\text{phys}}}{M_{\text{cali}}}} \cdot G_1 \cdot \sum_{i=1}^{N_{\text{samples}}} a_i (s_i - p)$$

Energy

Optimal Filtering Coefficients

Pedestals

From digits to “raw” energy in a cell



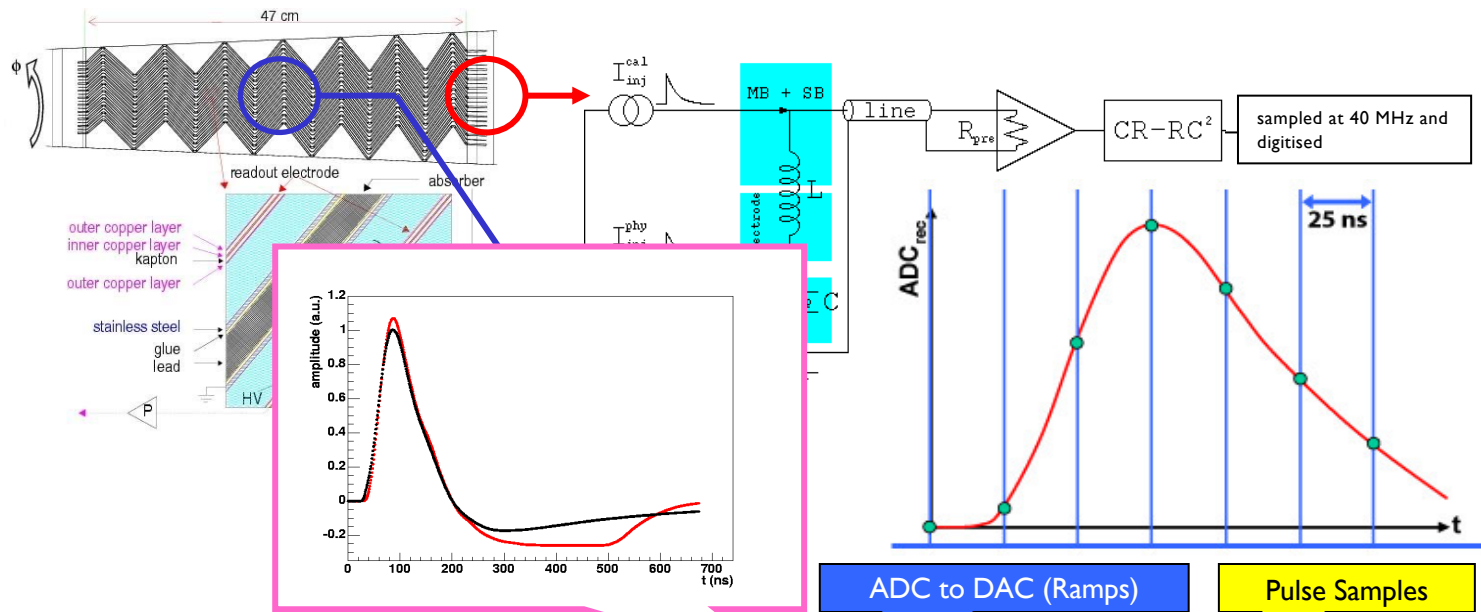
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Energy

Optimal Filtering Coefficients

Pedestals

From digits to “raw” energy in a cell



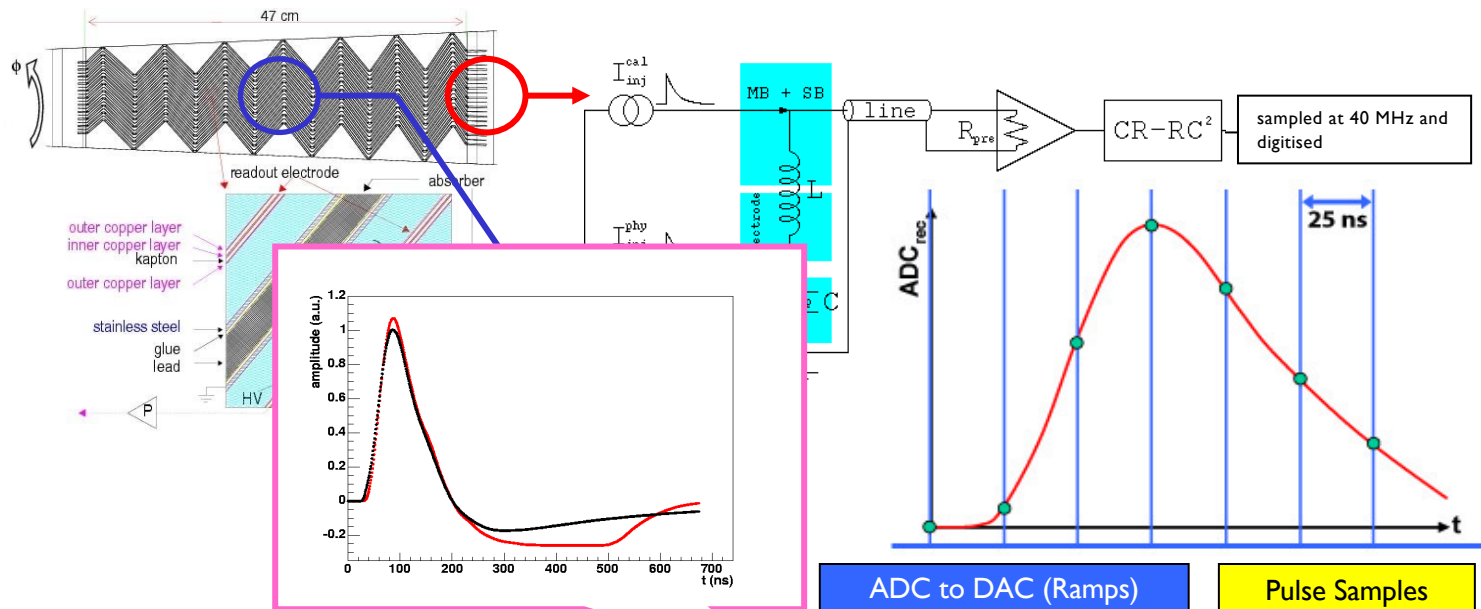
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Energy

Optimal Filtering Coefficients

Pedestals

From digits to “raw” energy in a cell



$$E_{\text{cell}} = F_{\text{DAC} \rightarrow \mu\text{A}} \cdot F_{\mu\text{A} \rightarrow \text{MeV}} \cdot \frac{1}{\frac{M_{\text{phys}}}{M_{\text{cali}}}} \cdot G_1 \cdot \sum_{i=1}^{N_{\text{samples}}} a_i (s_i - p)$$

Energy

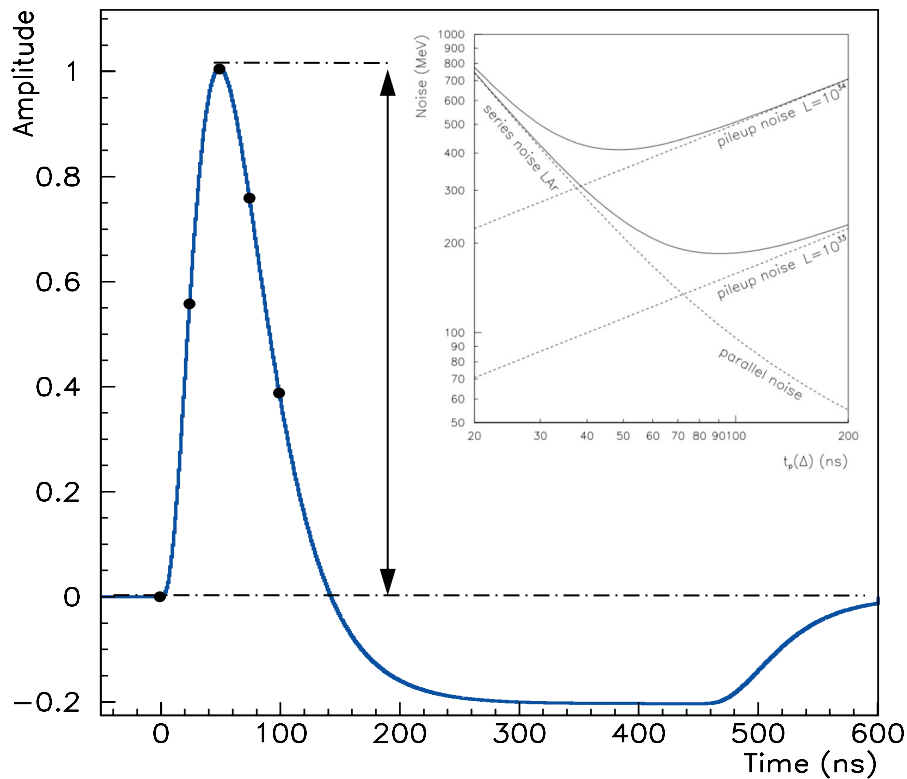
Calibration
board

Sampling
Fraction

Optimal Filtering Coefficients

Pedestals

Why use OF reconstruction?



$$s_i = Ag(t_i) + n_i$$

$$\langle n_i \rangle = 0$$

$$\langle n_i n_j \rangle = R_{ij}$$

$$\tilde{A} = \sum_i a_i s_i$$

$$\tilde{A} = A \underbrace{\sum_i a_i g(t_i)}_1 + \underbrace{\sum_i a_i n_i}_N$$

More details on OFC optimization? Read this!

Nuclear Instruments and Methods in Physics Research A 338 (1994) 467–497
North-Holland

**NUCLEAR
INSTRUMENTS
& METHODS
IN PHYSICS
RESEARCH**
Section A

Signal processing considerations for liquid ionization calorimeters in a high rate environment **

W.E. Cleland *, E.G. Stern ¹

Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA 15260, USA

(Received 13 July 1993)

We present the results of a study of the effects of thermal and pileup noise in liquid ionization calorimeters operating in a high luminosity environment. The method of optimal filtering of multiply-sampled signals to obtain timing and amplitude from calorimeter signals is described. This method has some advantages over the traditional method of sampling the peak of a shaped signal, which include a reduced sensitivity to channel-to-channel variations in the pre-filter shaping parameters and good performance over a wide range of operating conditions. Analytic expressions for the variance of amplitude and timing measurements are found through a frequency domain approach. Implications for the choice of pre-filter shaping time, number and position of the samples, and digitization accuracy are discussed.

Pileup in system with bipolar shaping

3.2.2. Pileup in systems with bipolar shaping

In the situation where pileup noise is continuously distributed in time, Campbell's theorem [8–9] may be used to find the pileup variance. However, at a collider, where the signals are generated at fixed intervals, it is necessary to use a discrete sum in calculating the effect of pileup noise. The expression for this case is derived in the appendix.

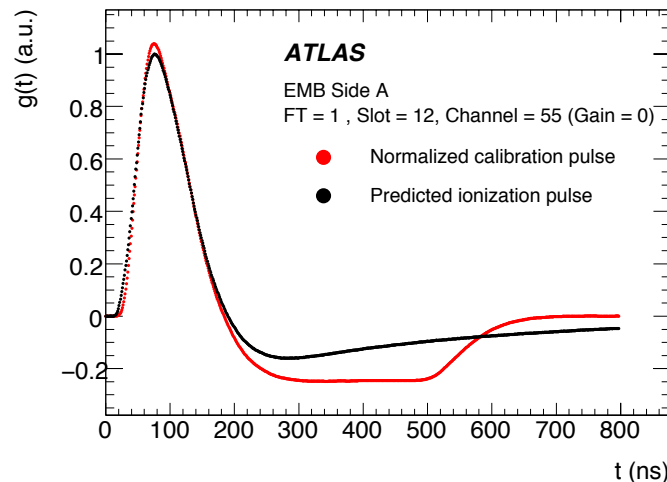
From Eq. (99) we see that the expression for the pileup variance is

$$\sigma_p^2 = \rho_p^2 T_c \sum_{i=-\infty}^{\infty} g^2(t_i) = \rho_p^2 S_p \quad (17)$$

in which $\rho_p^2 = \text{Var}(E)/T_c$ is the variance of the energy deposition in the calorimeter per crossing, T_c is the time between crossings, $g(t)$ is the signal waveform and S_p , called the “pileup sum” in this paper, is the discrete form of the so-called “pileup integral”,

$$I_{2p} = \int_{-\infty}^{\infty} g^2(t) dt. \quad (18)$$

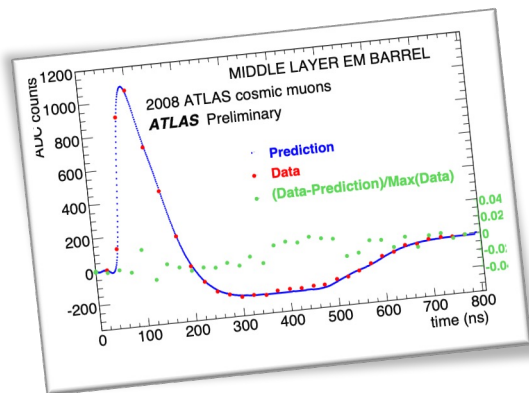
The quantity ρ_p , called the pileup noise density, is that part of σ_p which is independent of the signal processing parameters. The dimensions of ρ_p are $E/\sqrt{T}$ while S_p has dimensions of T , reflecting the time interval



$$\int_{-\infty}^{+\infty} g(t) dt = 0 \quad \left\{ \begin{array}{l} \langle E_{pileup} \rangle = 0 \\ \sigma_{pileup}^2 \propto I_{2p} \\ R^{pileup}(t) \propto \int g(u)g(t-u) du \end{array} \right.$$

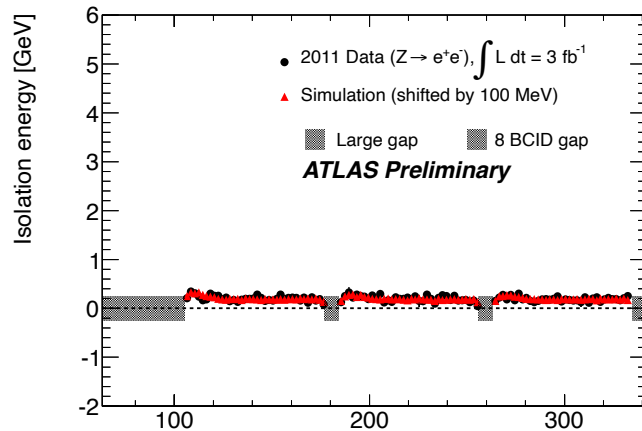
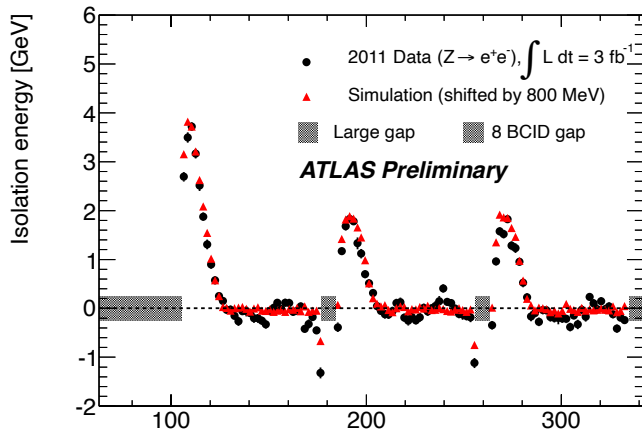
$$\sum_i g(t_i) \neq 0 \rightarrow ?$$

In-time and out-of-time pileup effect



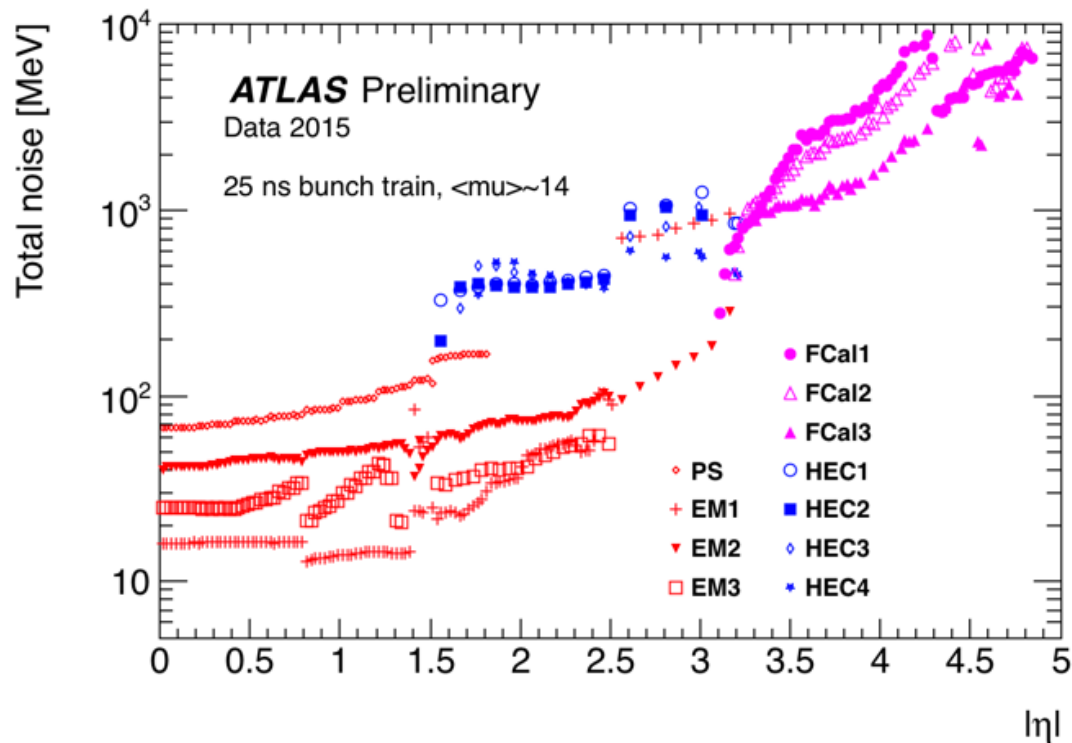
- **Ideally, infinite bunch trains with same luminosity per bunch**
 - ✓ Average energy per cell = 0
 - ✓ Pileup fluctuations translate in noise per cell
 - dominant w.r.t. electronics noise for $\eta > 2.5$
- **In real life, bunch train structure and bunch-to-bunch luminosity variations**
 - ✓ No cancellation of in-time pileup shifts for first bunches
 - ✓ Residual shifts for bunches with luminosity different from average
 - ✓ Only the first effect simulated in ATLAS MC

• **Correction computed from pulse shape, OFC, bunch-per-bunch luminosity (data) or bunch structure (MC), and average energy per cell for in-time only energy deposit**



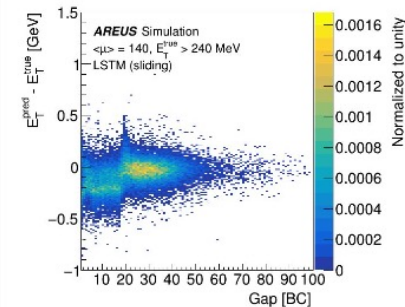
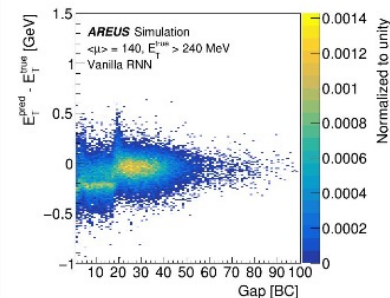
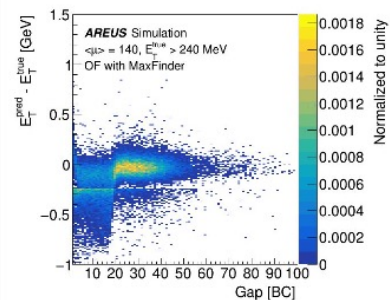
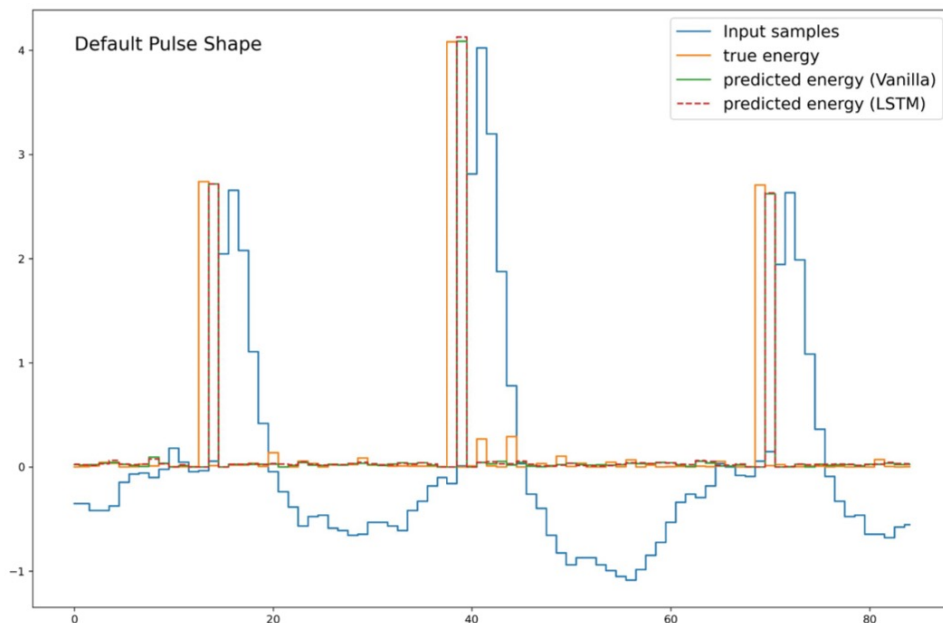
Noise after PU-optimized OFC reconstruction

- All values “at the electron scale”
 - ✓ i.e. assuming the effective sampling fraction for a 100 GeV electron

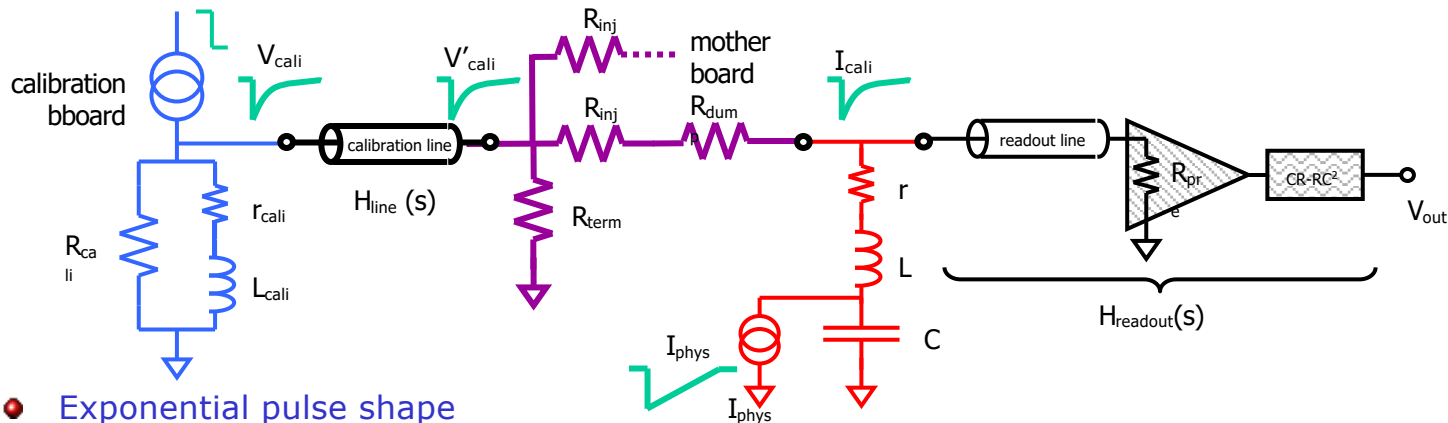


Signal peak reconstruction: alternatives to OFC?

- Extremely high pileup conditions ($\mu \sim 200$) expected at HL-LHC
- Machine-learning-based algorithms could outperform OFC reconstruction in reducing PU effects, while addressing other issues (e.g. pulse jitter)
 - ✓ Currently being studied: Recurrent Neural Network



How can we predict the ionization pulse?



- Exponential pulse shape depends on CB elements

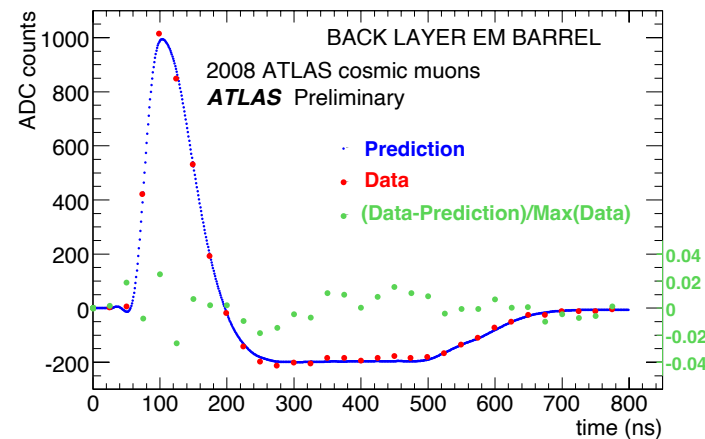
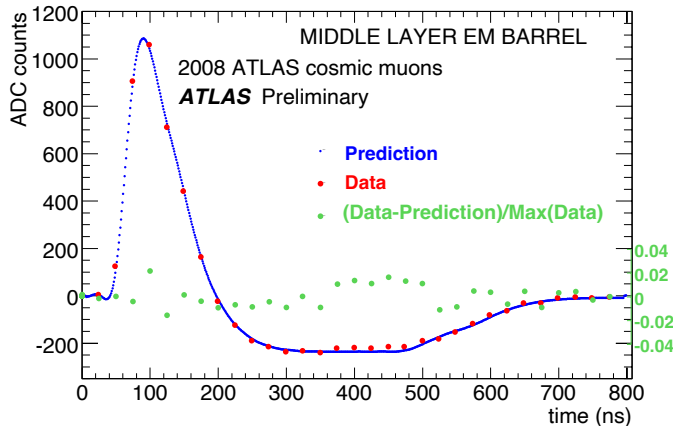
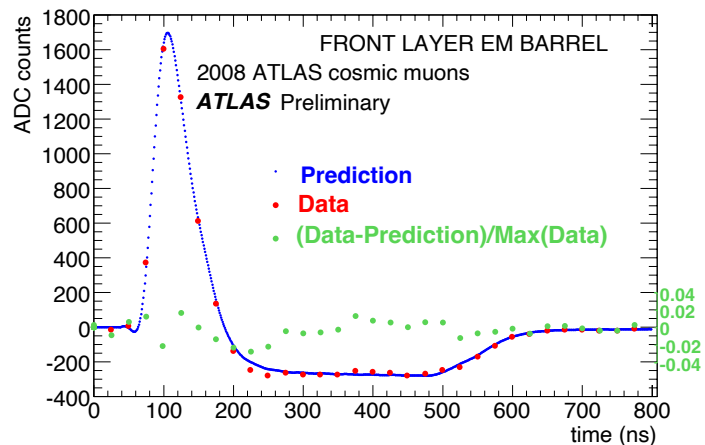
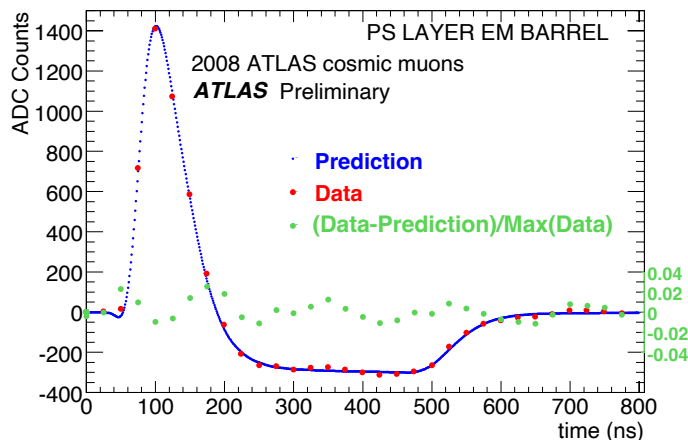
$$\begin{cases} f_{\text{step}} = \left(\frac{r_{\text{cali}}}{r_{\text{cali}} + \frac{R_{\text{cali}}}{2}} \right) \\ \tau_{\text{cali}} = \left(\frac{L_{\text{cali}}}{r_{\text{cali}} + \frac{R_{\text{cali}}}{2}} \right) \end{cases}$$

- R_{term} is such that $1/R_{\text{term}} + n/(R_{\text{inj}} + R_{\text{dump}}) = 1/R_{\text{cali}}$
- The injected calibration current is $I_{\text{cali}} = V'_{\text{cali}}/(R_{\text{inj}} + R_{\text{dump}})$

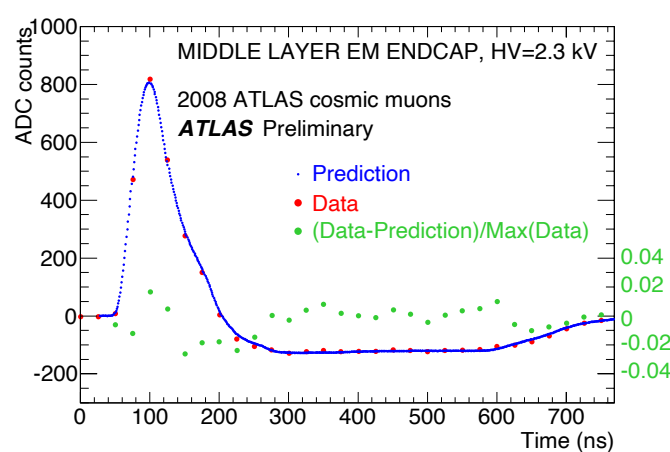
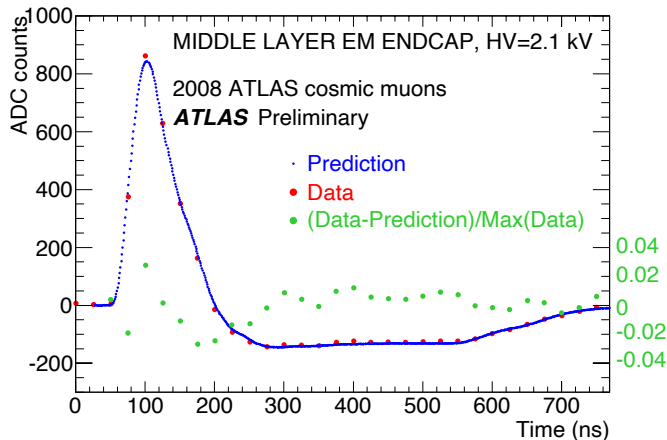
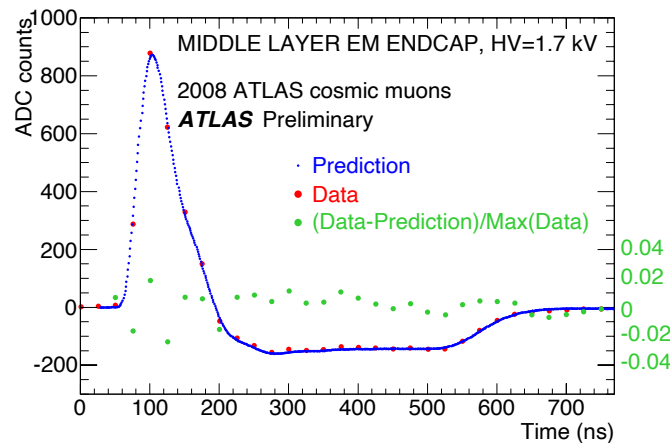
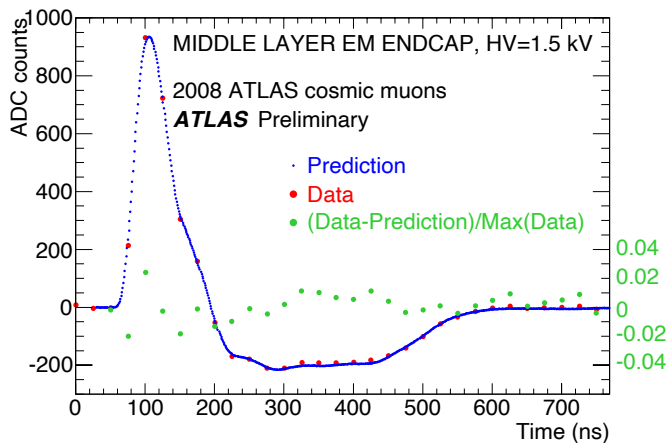
- The ionization pulse is (currently) predicted as:

$$I_{\text{phys}}(s) = I_{\text{cali}}(s) \times \left(\frac{(1 + s\tau_{\text{cali}})(sT_d - 1 + e^{-sT_d})}{sT_d(f_{\text{step}} + s\tau_{\text{cali}})} \right) \times \left(\frac{1}{1 + srC + s^2LC} \right)$$

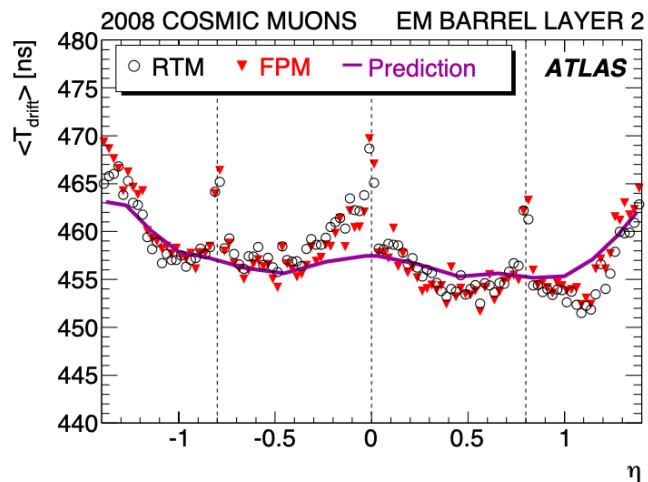
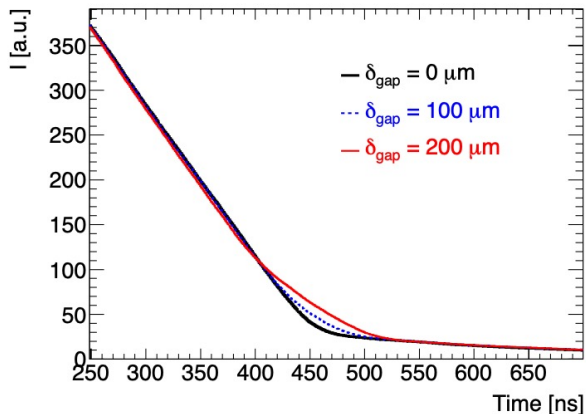
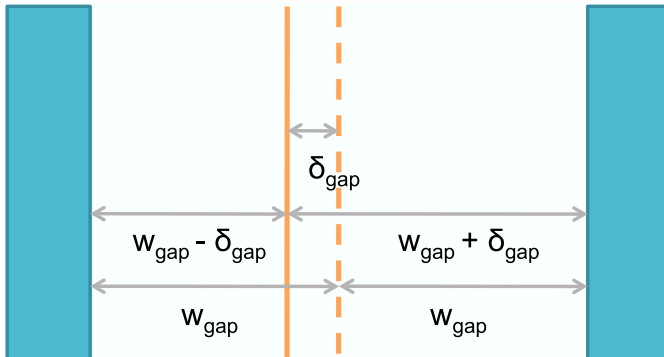
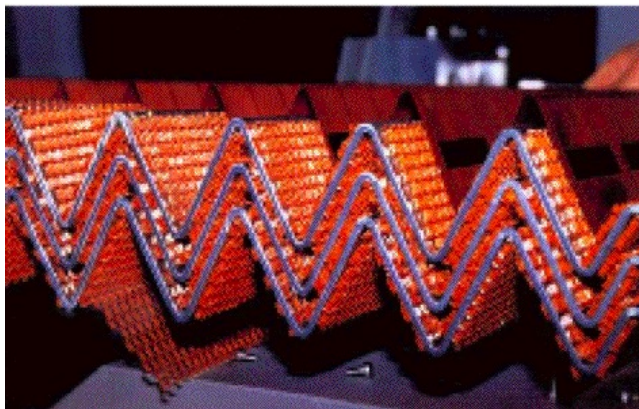
A quick view to the ionization pulses: EM Barrel



A quick view to the ionization pulses: EM EndCap



Pulse shape details depend on electrode position

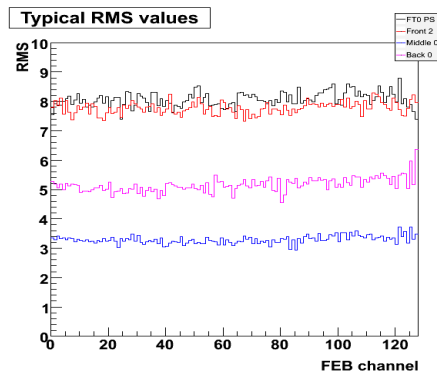


Electronic calibration “runs”

pedestals and noise

FEB are read with no input signal to obtain:

- Pedestal
- Noise
- Noise autocorrelation (OFC computation)

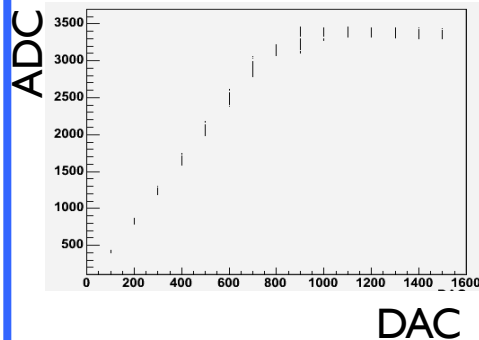


PEDESTAL

ADC → MeV conversion

$$F = \text{ADC2DAC} \times \text{DAC2}\mu\text{A} \times \mu\text{A2MeV}$$

- Scan input current (DAC)
- Fit DAC vs ADC curve with a first (second) order polynomial, outside of saturation region

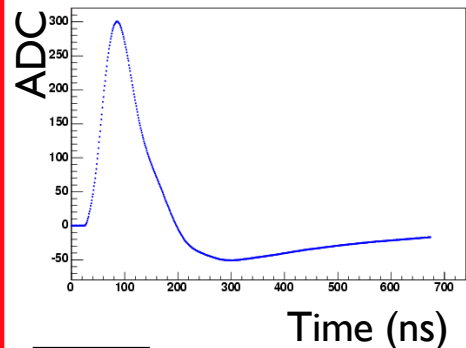


RAMP

response to current pulse

All cells are pulsed with a known current signal:

- A delay between calibration pulses and DAQ is introduced
- The full calibration curve is reconstructed ($\Delta t = 1\text{ ns}$)

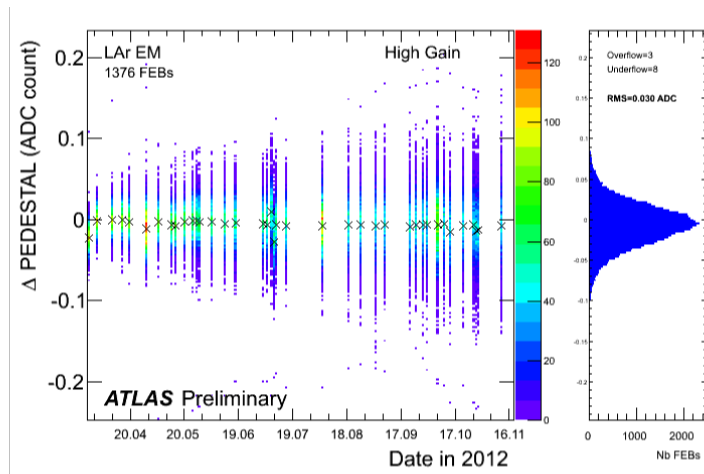


DELAY

- Executed routinely (pedestal/ramp: daily; delay: ~weekly)
 - ✓ Monitor stability over time (temperature changes, ...)

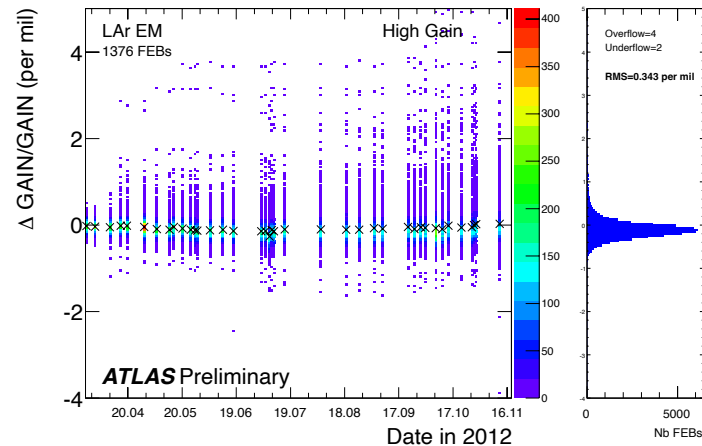
Electronic calibration constants vs time

$$G_1 \cdot \sum_{i=1}^{N_{\text{samples}}} a_i (s_i - p)$$



PEDESTAL

p



RAMP

G_1

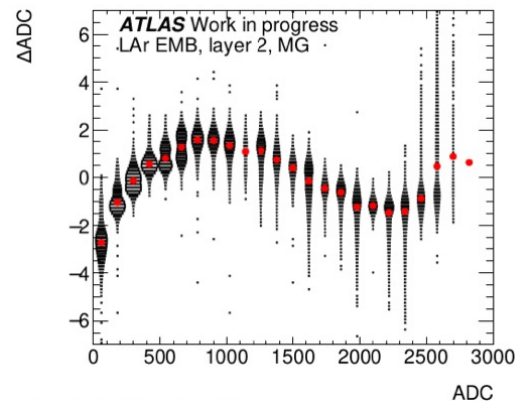
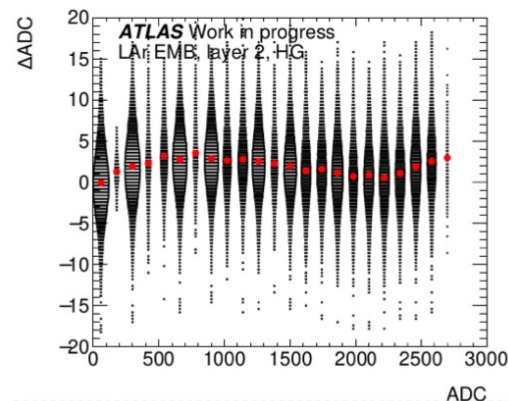
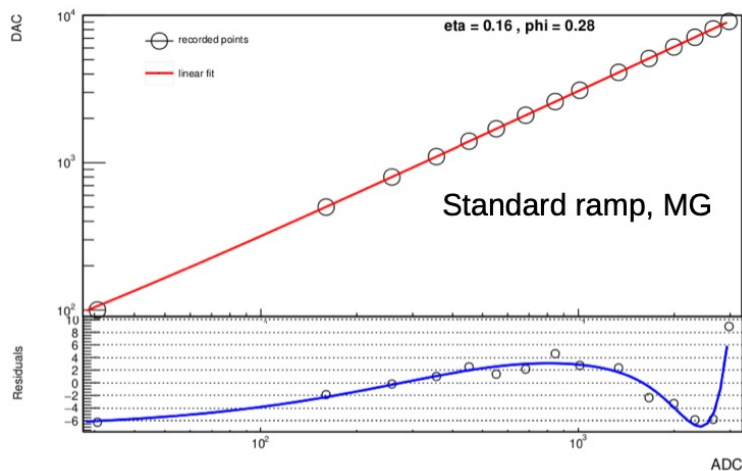
Electronic gain might be less linear than expected

- Standard reconstruction assumes linear response of readout electronics

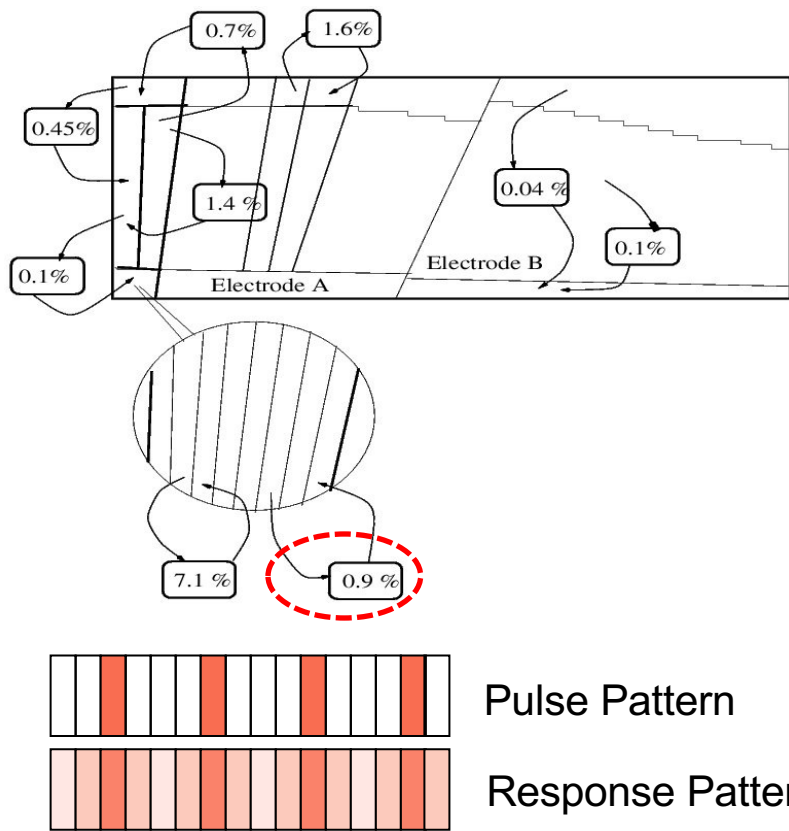
$$E_{\text{cell}} = \dots \cdot G_1 \cdot \sum_{i=1}^{N_{\text{samples}}} a_i (s_i - p)$$

- Things can be more complicated...

- ✓ Residual (non-linear) effect can (should) be corrected for

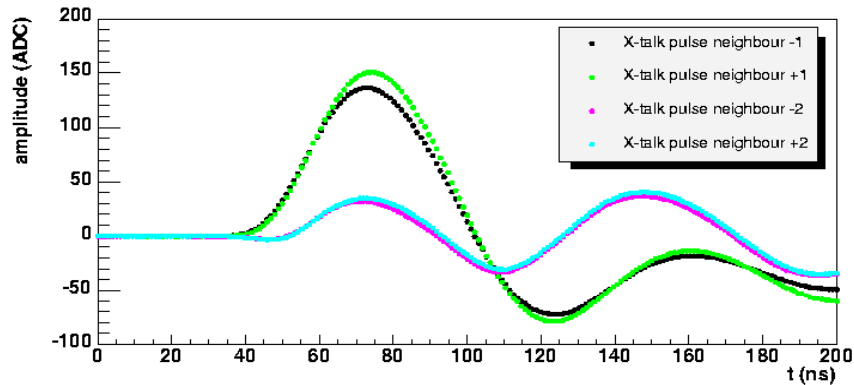
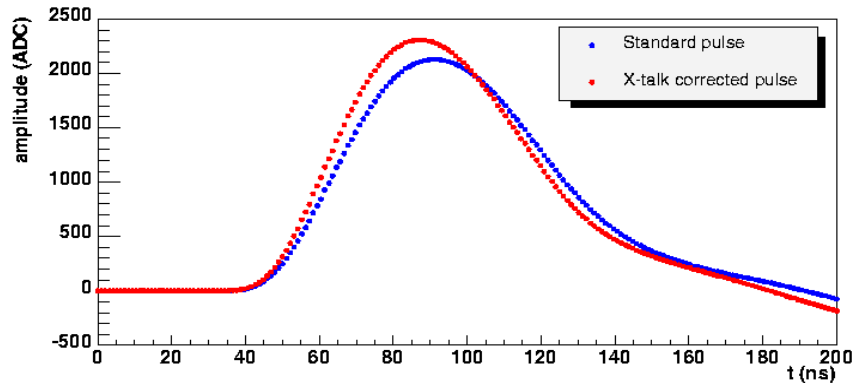


Cross-talk on LAr readout electrode



- The EMC cells share part of their collected current because of cross-talk
 - ✓ In general the effect is negligible, and anyway compensated by the clustering algorithm
- The effect is non negligible for the first sampling (front compartment a.k.a. Strips)
 - ✓ The actual electronic gain is overestimated ($\sim 9\%$)
 - ✓ The pulse shapes obtained injecting the calibration current are “wrong” w.r.t. the one generated by a particle shower (cluster)
 - If these shapes are directly used to compute OFC, the use of these “wrong” OFC lead to a underestimation of the ADC peak ($\sim 1-3\%$)
 - ✓ The combined effects lead to a global overestimation of the first sampling cluster energy of $\sim 7\%$
 - ✓ We have an effective recipe to treat the effect (gain correction + proper OFC)

A recipe for cross-talk correction



● Prescription

$$\tilde{E}_{w/o \text{ } X\text{-Talk}} = E_{pulsed} + E_{1st \text{ Nghb.}}^1 + E_{1st \text{ Nghb.}}^2 + \frac{E_{2nd \text{ Nghb.}}^1 + E_{2nd \text{ Nghb.}}^2}{2}$$

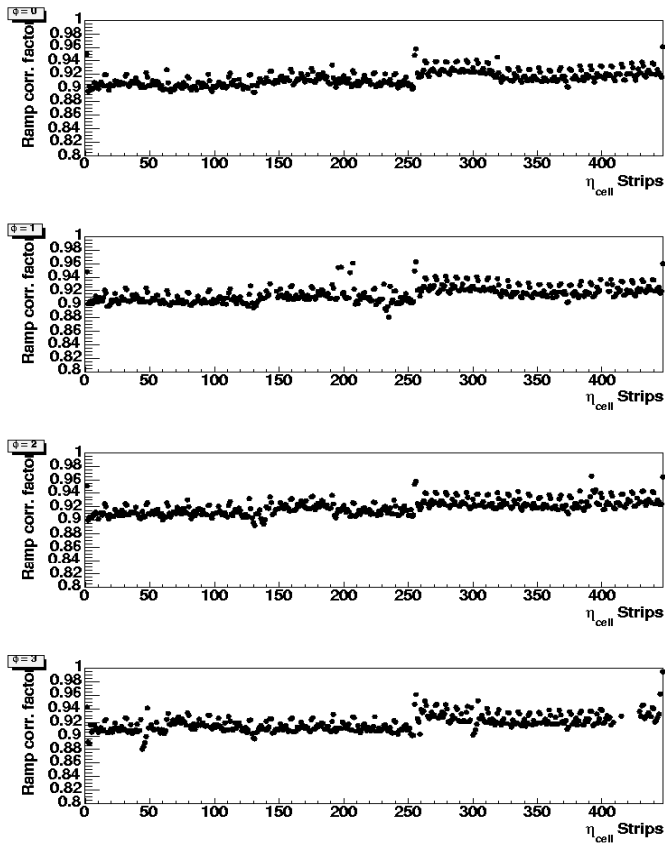
● Gain correction

- ✓ Ration between delay pulse peaks without an with X-talk prescription

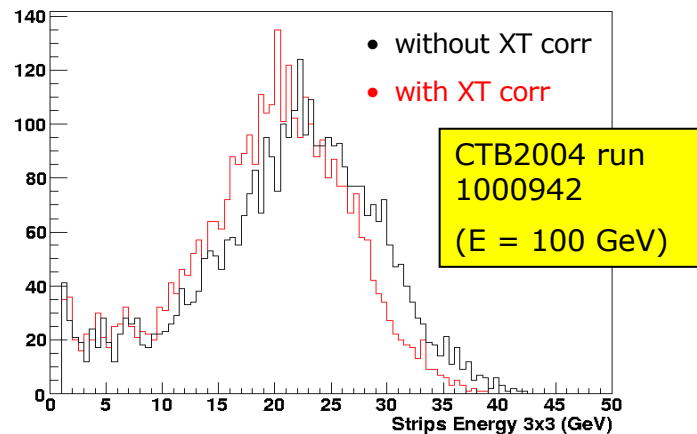
● OFC correction

- ✓ Use X-talk corrected pulses to computed MW, predict physics pulses, compute OFC

Cross-talk effect on energy reconstruction



- The correction is (weakly) η -dependent...
- ... but the variation along η may affect the clustering algorithm results!



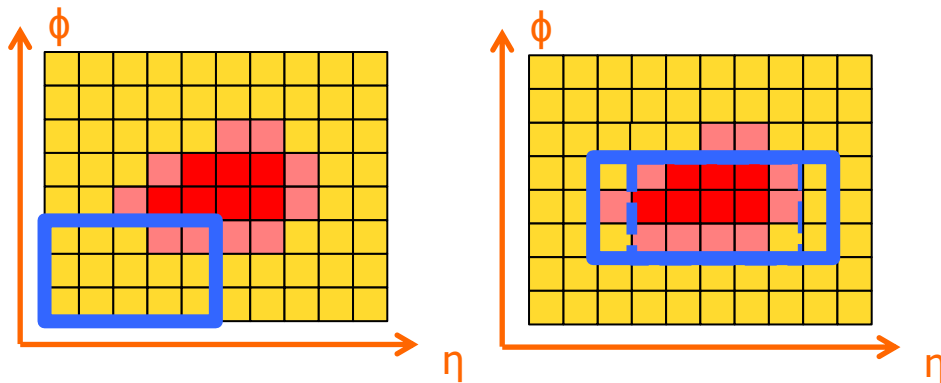
5.3

From cells to cluster

Sliding-window clustering

The historical approach to EM clustering in ATLAS used a “sliding window” **fixed-size rectangular clusters**:

- ✓ $\Delta\eta \times \Delta\phi(\text{Middle}) = 3 \times 5, 3 \times 7, 5 \times 5$
- ✓ Size is trade-off between energy leakage and noise pickup (electronics and pileup)

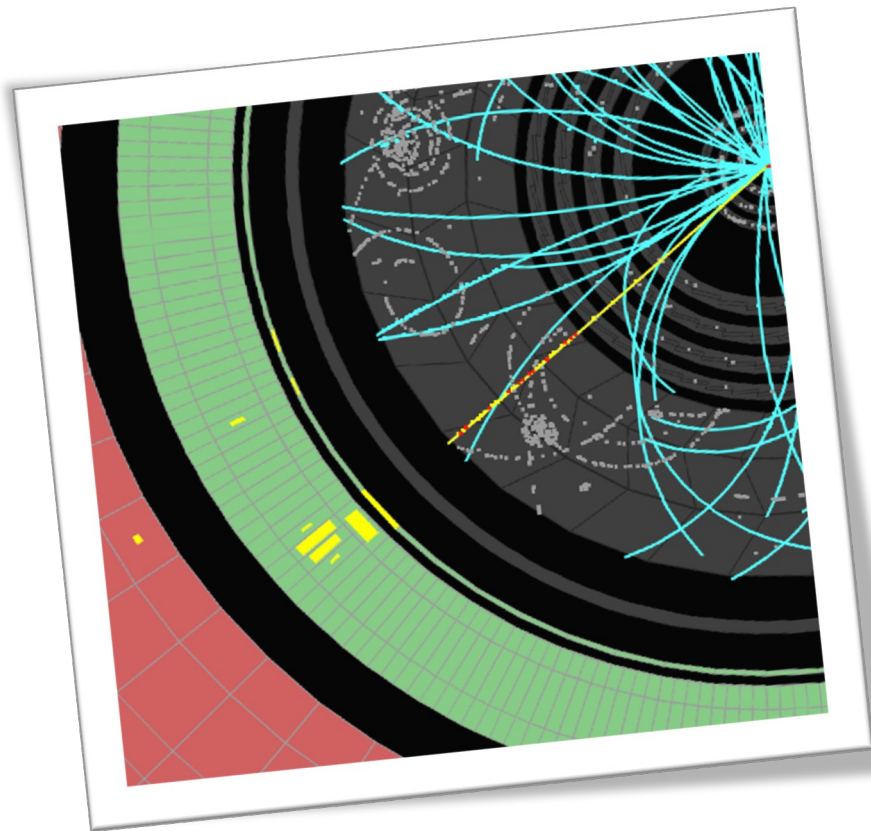


- **Pros**

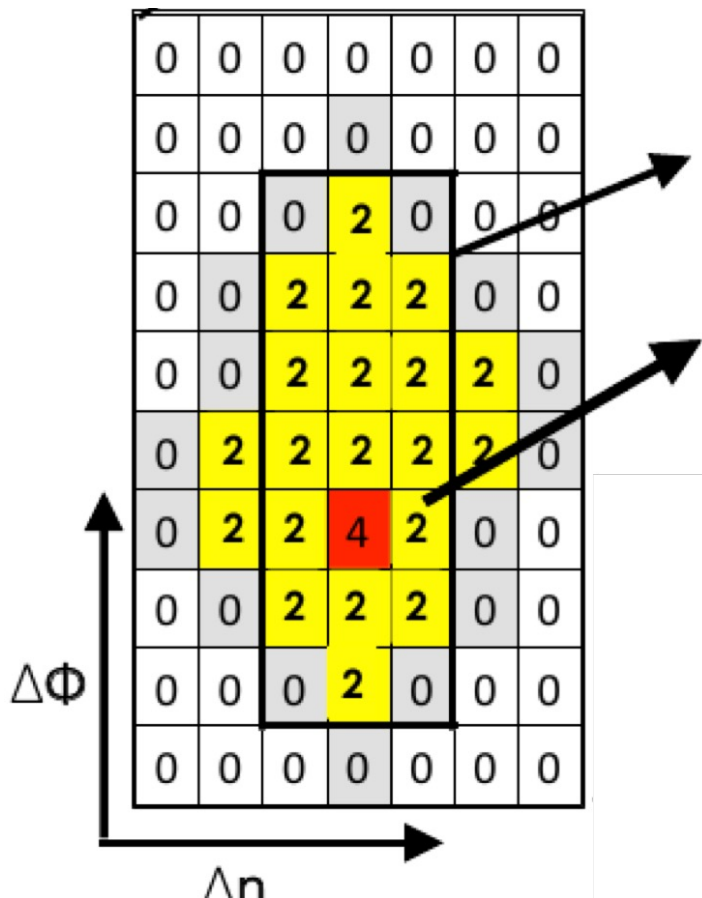
- ✓ “Fixed” noise contribution
- ✓ Easier to calibrate with “traditional” approaches

- **Cons**

- ✓ Difficult to recover energy loss by low energy photons radiated due to bremsstrahlung in ID



Topological clustering



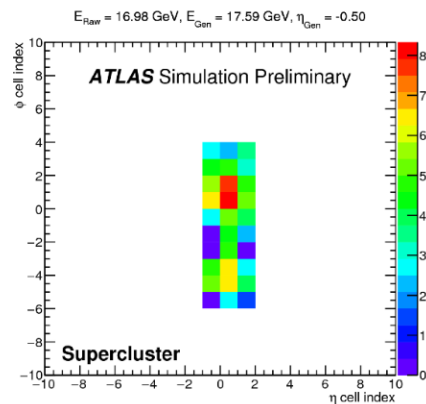
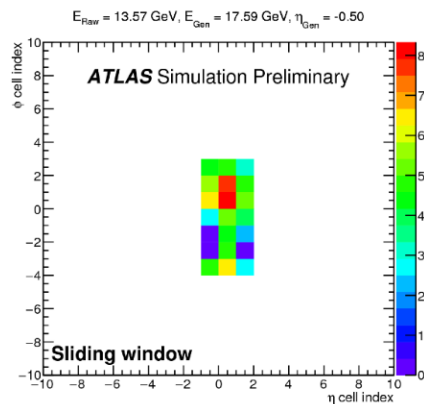
- Originally developed for jet reconstruction, now adapted also for EM objects (electrons and photons)
- Topo-clusters formed by growing-volume algorithm starting from calorimeter cell with a highly significant seed signal
 - ✓ Seeding, growth, and boundary controlled by parameters $\{S, N, P\}$

$$S_{\text{cell}}^{\text{EM}} = \frac{E_{\text{cell}}^{\text{EM}}}{\sigma_{\text{noise,cell}}^{\text{EM}}}$$

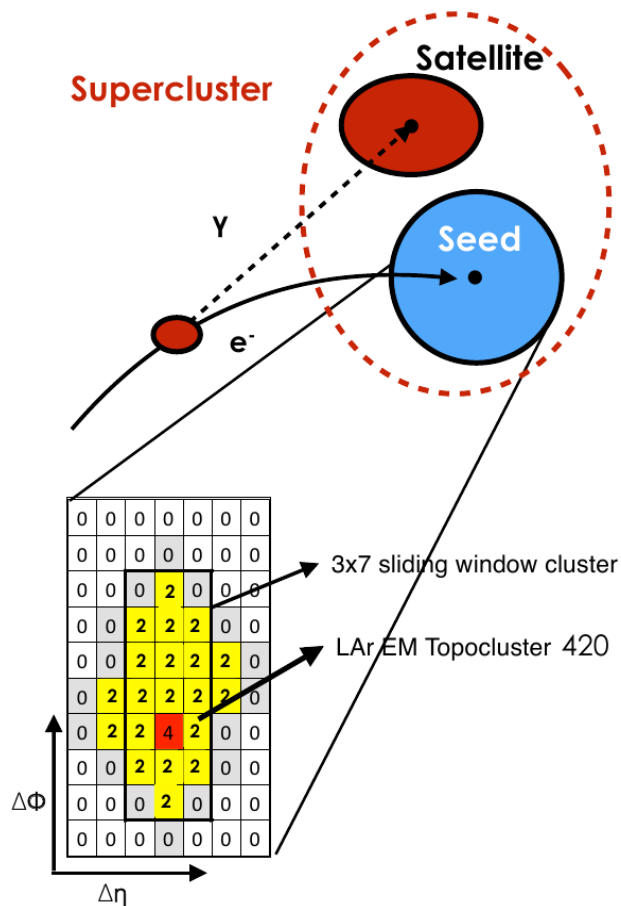
$$|E_{\text{cell}}^{\text{EM}}| > S \sigma_{\text{noise,cell}}^{\text{EM}} \Rightarrow |S_{\text{cell}}^{\text{EM}}| > S$$

$$|E_{\text{cell}}^{\text{EM}}| > N \sigma_{\text{noise,cell}}^{\text{EM}} \Rightarrow |S_{\text{cell}}^{\text{EM}}| > N$$

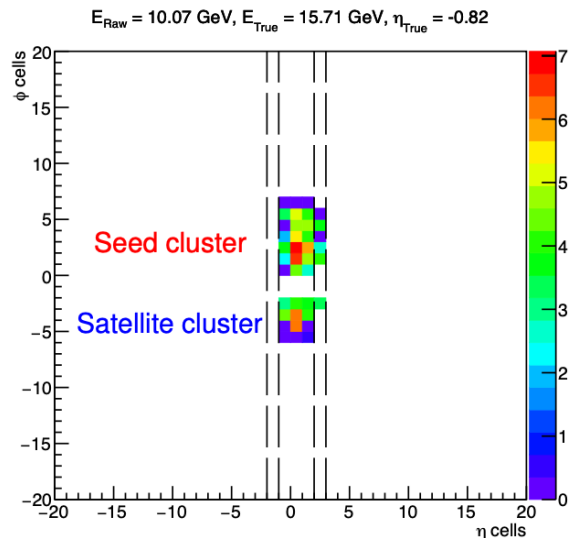
$$|E_{\text{cell}}^{\text{EM}}| > P \sigma_{\text{noise,cell}}^{\text{EM}} \Rightarrow |S_{\text{cell}}^{\text{EM}}| > P$$



Topological clusters and superclusters

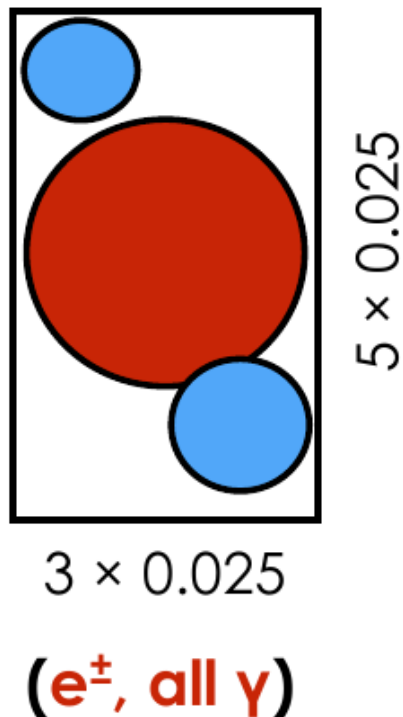


- Include radiative losses from bremsstrahlung into cluster to improve energy measurement
- “Superclusters” built from
 - ✓ Primary (“seed”) electron cluster
 - ✓ Nearby, secondary (“satellite”) clusters
- Cluster reconstruction uses 420 topo-clusters
- Example:



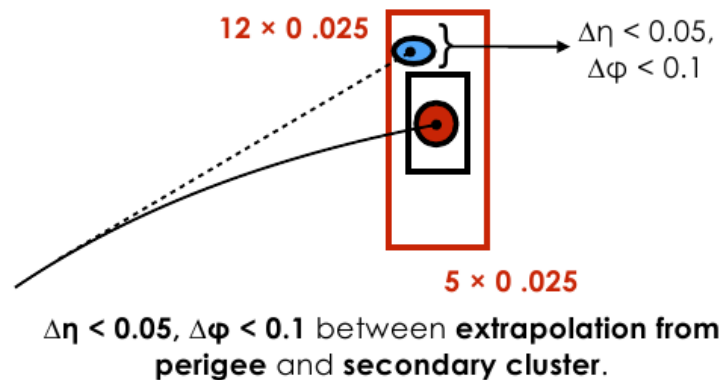
Superclusters for electrons

1. Add all clusters within 3×5 window around seed cluster.

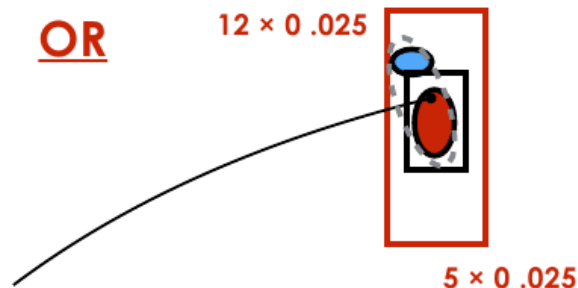


Electrons only:

2. For clusters with $\Delta\eta, \Delta\phi$ **outside 3×5 window**, but **within 5×12 window**, add to seed cluster if:



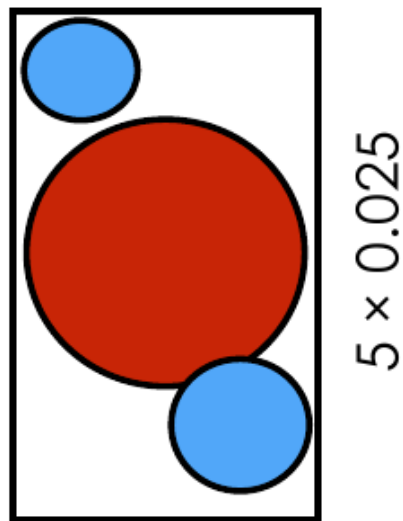
OR



Seed, secondary cluster **match the same track**.

Superclusters for converted photons

1. Add all clusters within 3×5 window around seed cluster.

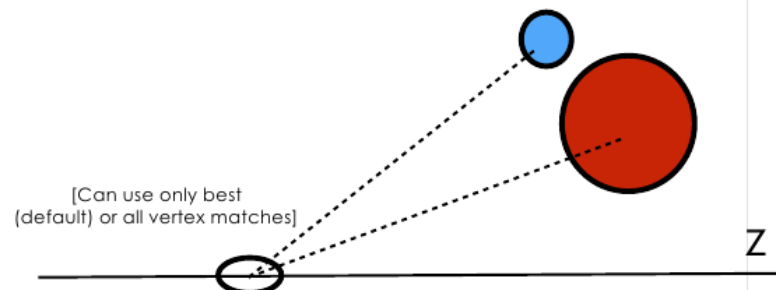


3×0.025

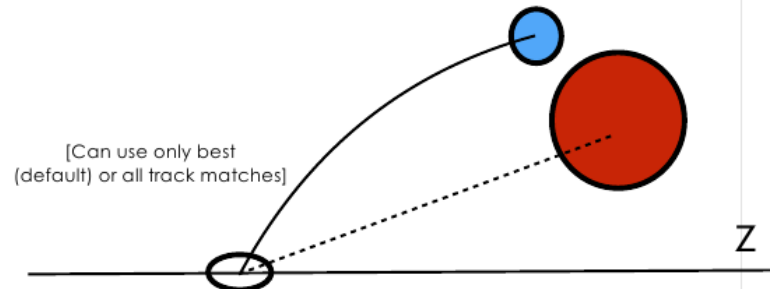
$(e^\pm, \text{all } \gamma)$

Conversions only:

2. Add topoclusters that have the **same conversion vertex** matched as the seed cluster.

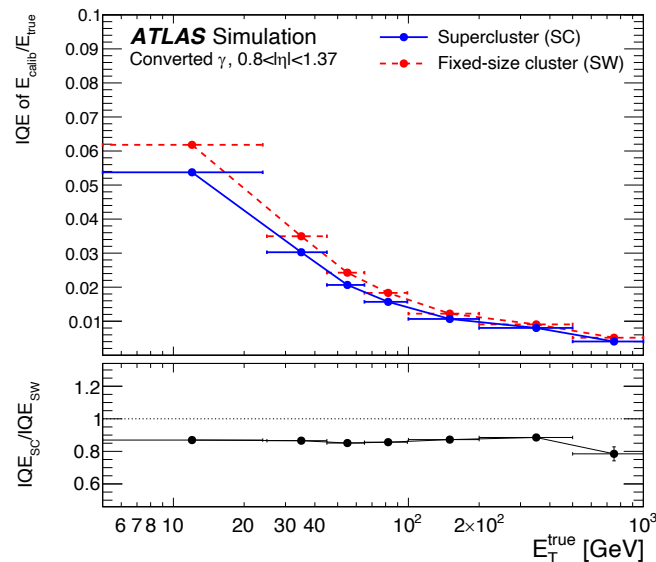
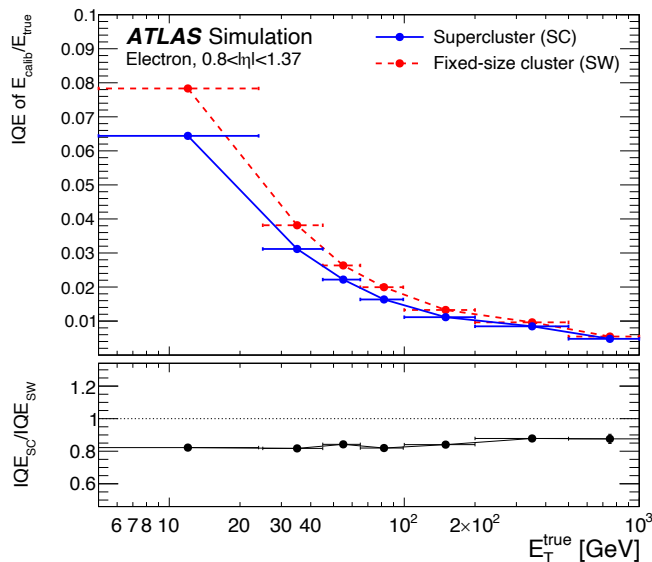
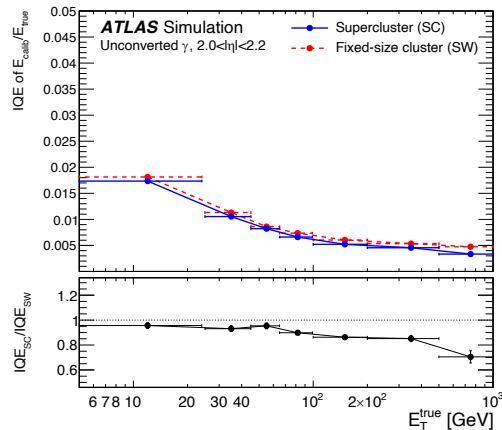


3. Add topoclusters that **have a track match** that is a **part of the conversion vertex** matched in the seed cluster.



SW vs supercluster

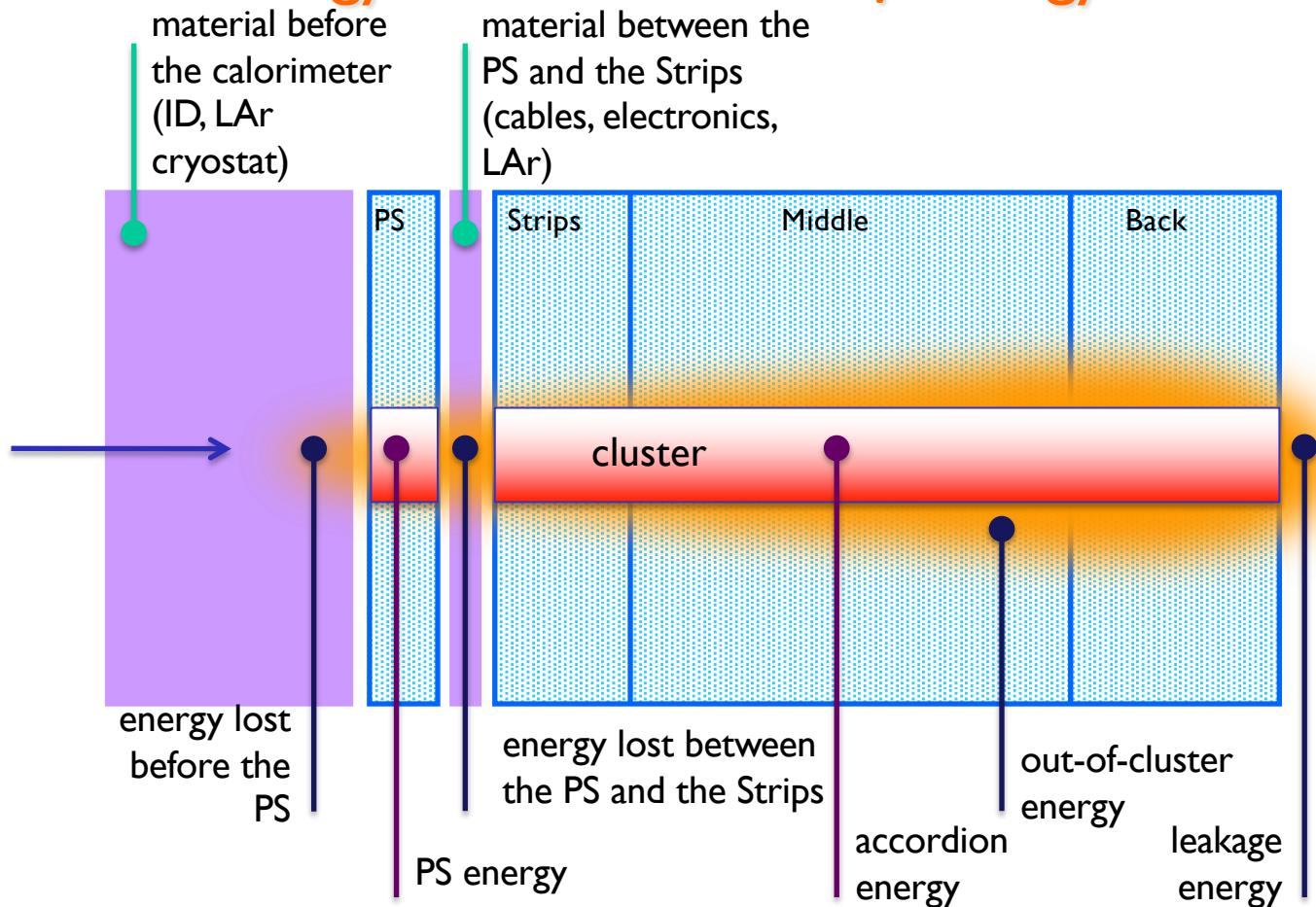
- After calibration supercluster algorithm shows significant improvement for electrons and converted photons
 - ✓ In absence of pile-up 20–30% in EMEC and at low ET
- Negligible improvement for unconverted photons due to the generally narrower shower width.
 - ✓ Some improvement is observed at high ET bins in EMEC



5.4

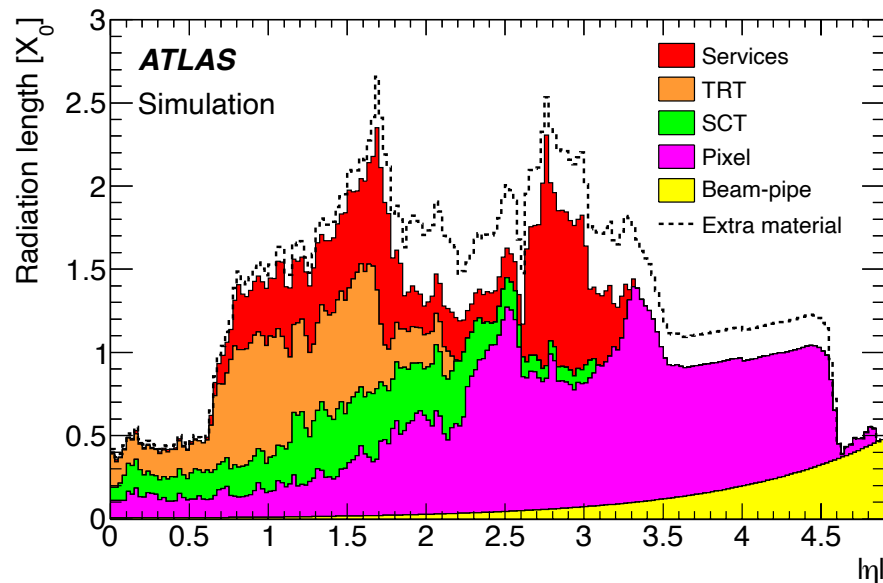
From cluster energy
to calibrated energy

From cluster energy to electron and γ energy

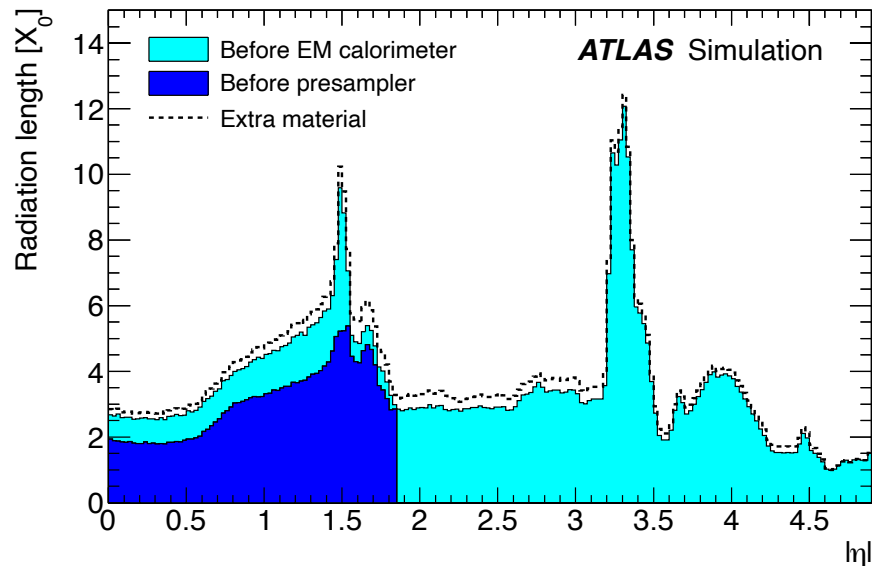


How much material do we have in front of EMC?

up to ID boundaries



before EMC



How do we calibrate electron and γ energies?

calibrated energy

visible energy in cluster layers
calibrated for 100 GeV electrons

Information about photon
conversion, ...

$$E_{e/\gamma} = f(E_i^{\text{cluster}}, \eta, \phi, R_{\text{conv}}, \dots)$$

some complicated function
obtained from simulation,
different for electrons and photons

- **“Calibration hits”**

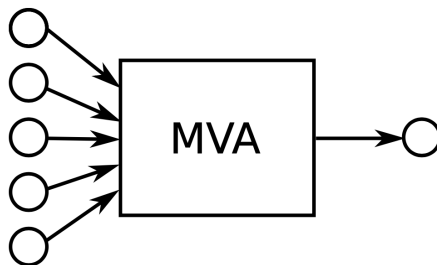
- ✓ Parameterize energy deposits as accounted by G4 vs. visible energy information

$$E_{\text{reco}}^{\text{cal}} = a(E_{\text{reco}}^{\text{acc}}, |\eta|) + b(E_{\text{reco}}^{\text{acc}}, |\eta|)E_{\text{ps}}^{\text{cl LAr}} + c(E_{\text{reco}}^{\text{acc}}, |\eta|)(E_{\text{ps}}^{\text{cl LAr}})^2$$

$$+ f_{\text{acc}}(X, |\eta|) \times (1 + f_{\text{out}}(X, |\eta|)) \times \left(\sum_{i=1}^3 E_i^{\text{cl LAr}} \right) \left(1 + f_{\text{leak}}(X, |\eta|) \right) \times F(\eta, \varphi)$$

- **“MVA”**

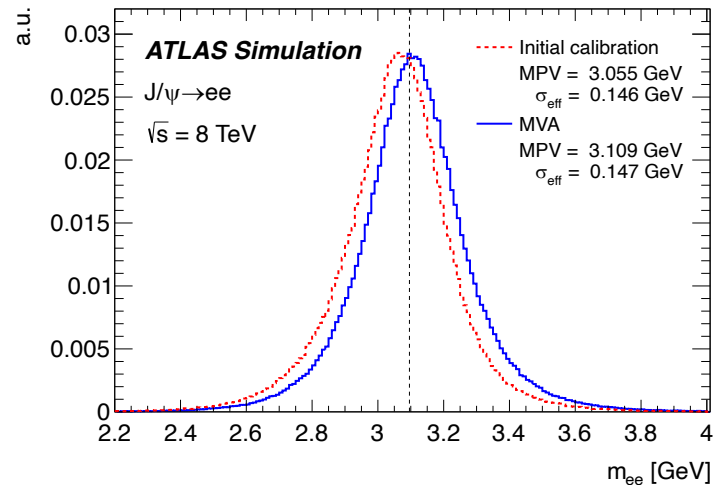
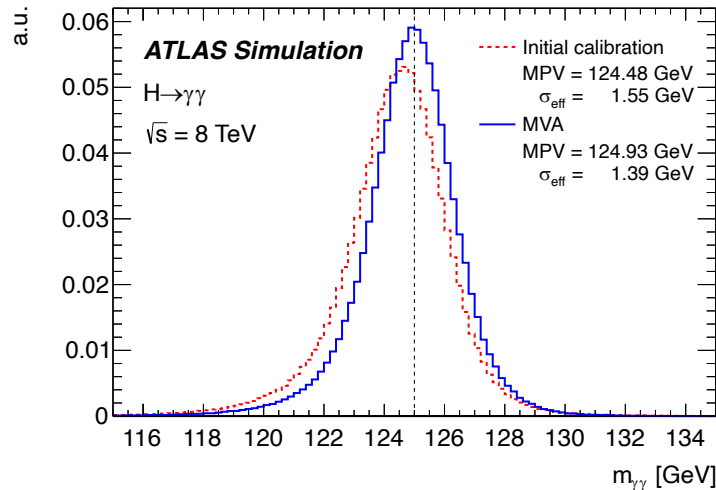
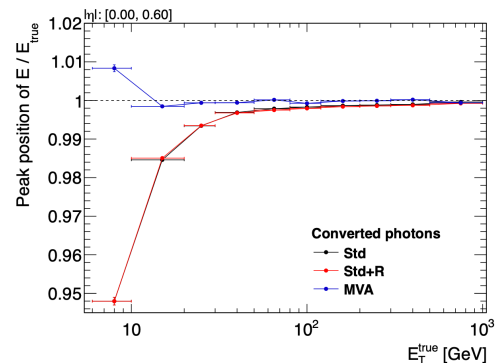
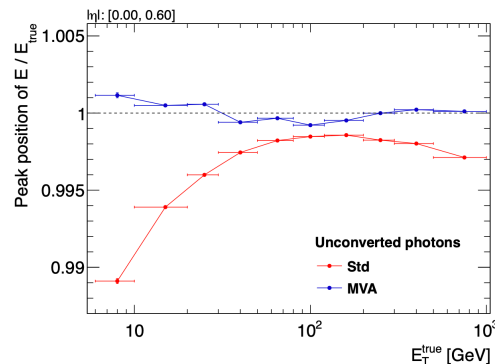
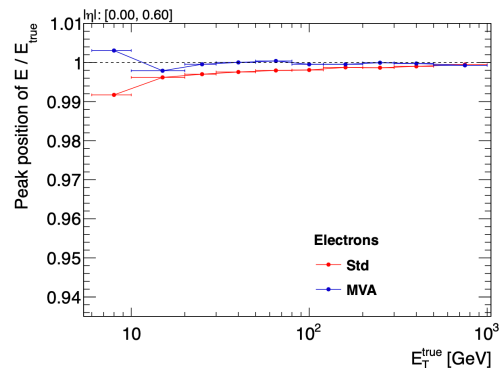
- ✓ Train BDT with visible energy information to return best energy response



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

$X_0 (\eta=0) \sim 1.1 X_0$
 $X_1 (\eta=0) \sim 3.7 X_0$
 $X_2 (\eta=0) \sim 13.8 X_0$
 $X_3 (\eta=0) \sim 23.3 X_0$

Calibration regressions from MC



What if MC description is imperfect?

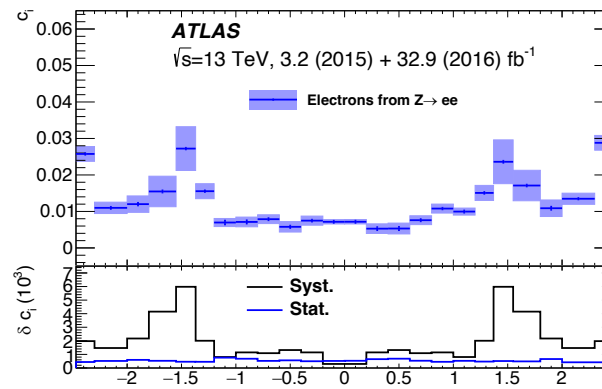
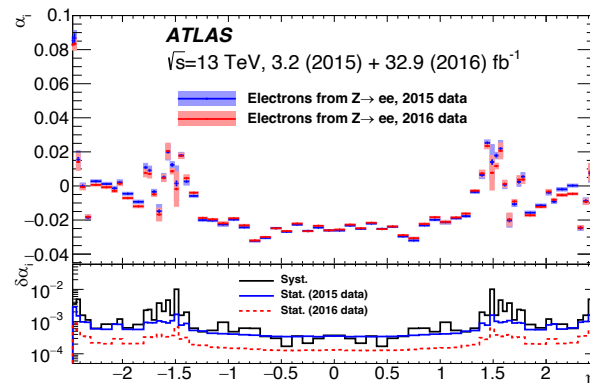
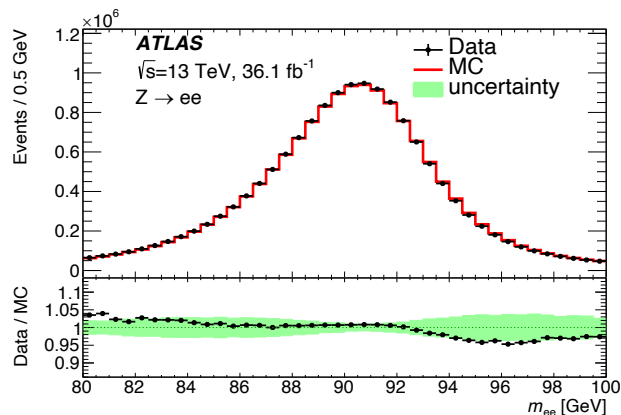
- In-situ correction of global energy scale using $Z \rightarrow ee$ events

$$E^{\text{data}} = E^{\text{MC}} (1 + \alpha_i)$$

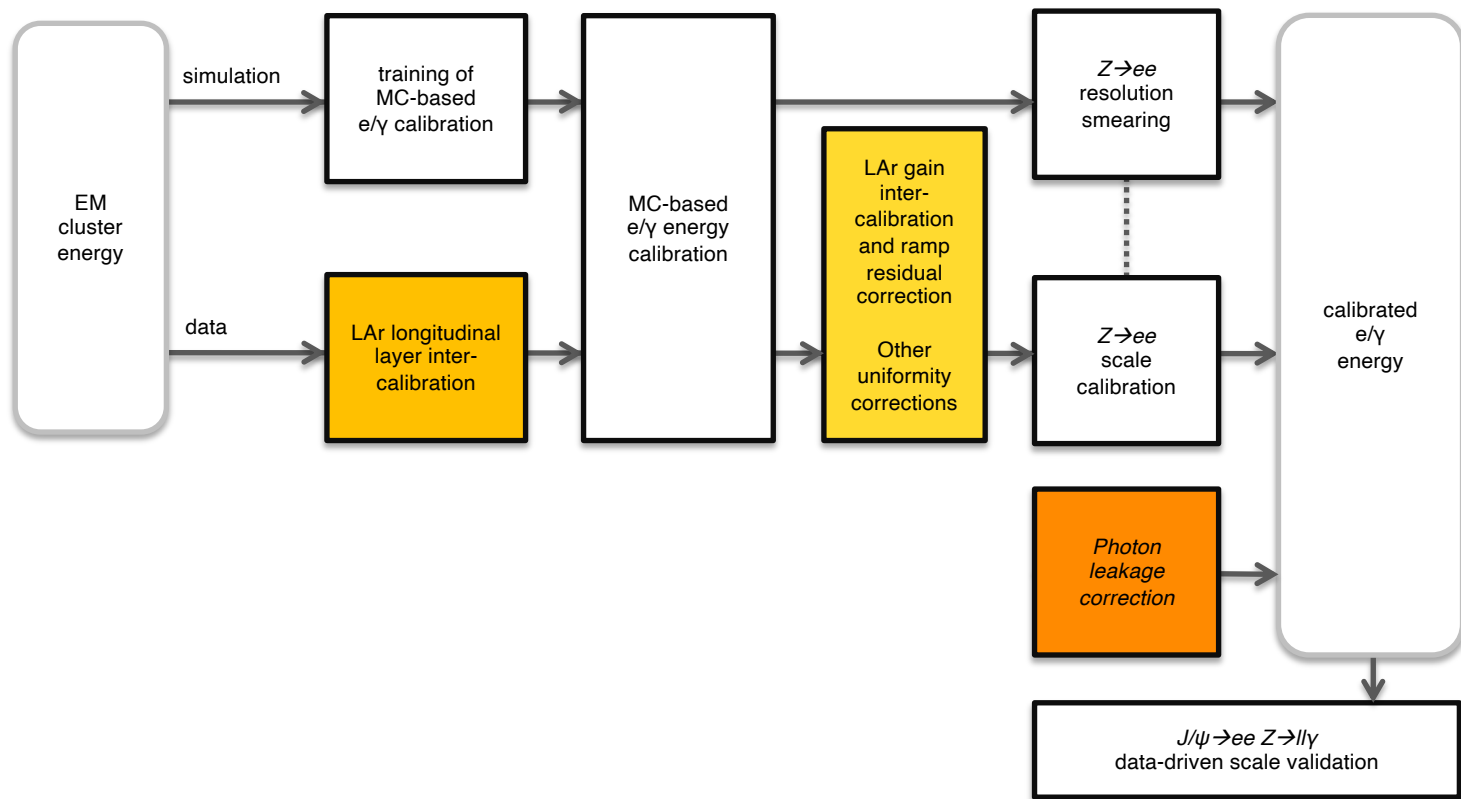
$$\left(\frac{\sigma_E}{E}\right)^{\text{data}} = \left(\frac{\sigma_E}{E}\right)^{\text{MC}} \oplus c_i$$

$$m_{ij}^{\text{data}} = m_{ij}^{\text{MC}} (1 + \alpha_{ij}) \quad \alpha_{ij} = (\alpha_i + \alpha_j)/2$$

$$(\sigma_m/m)_{ij}^{\text{data}} = (\sigma_m/m)_{ij}^{\text{MC}} \oplus c_{ij} \quad c_{ij} = (c_i \oplus c_j)/2$$

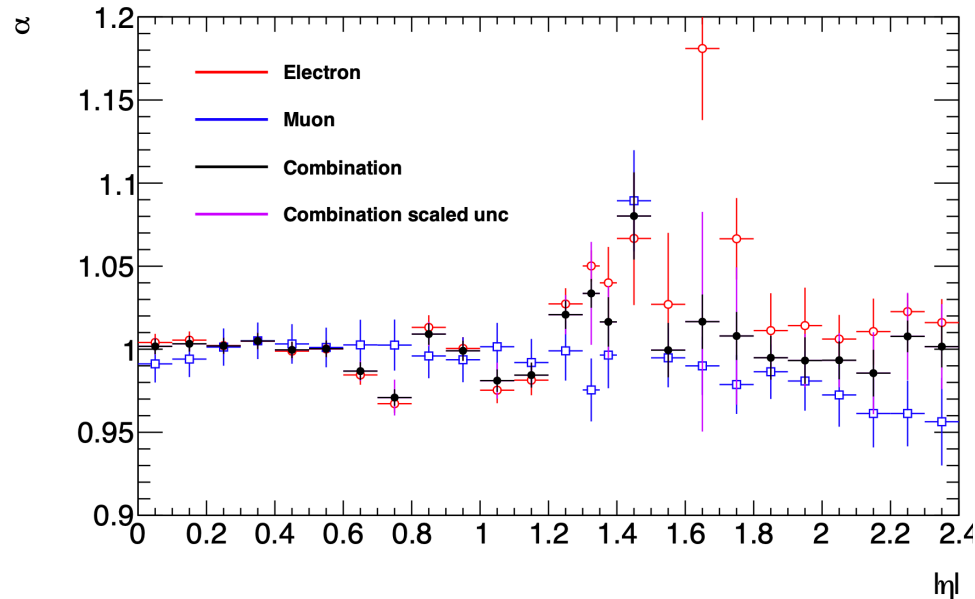


ATLAS e/γ “full” calibration scheme

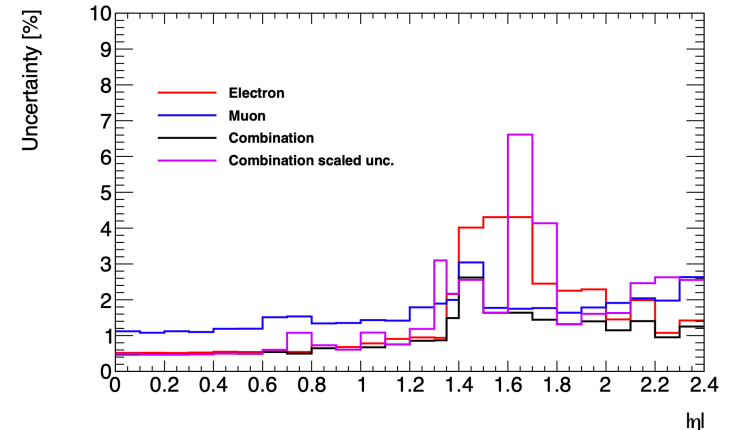


LAr longitudinal layer intercalibration

- Relative calibration of LAr longitudinal layers (Front, Middle, Back) might not be perfect
 - ✓ e.g. imperfect electronics calibration (gain from Ramp, $M_{\text{phys}}/M_{\text{cali}}$, cross-talk)
- It *can* be corrected in-situ using data (muons, electrons)
- It *should* be corrected since E_i energies in longitudinal layers are inputs to the calibration regression (sensitive to longitudinal shower development)!



$$\alpha_{1/2} = \frac{E_1^{\text{data}} / E_2^{\text{data}}}{E_1^{\text{MC}} / E_2^{\text{MC}}}$$



LAr electronic gain intercalibration

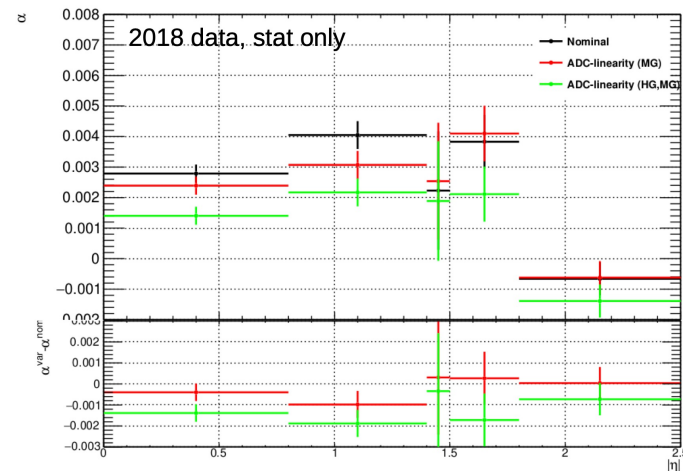
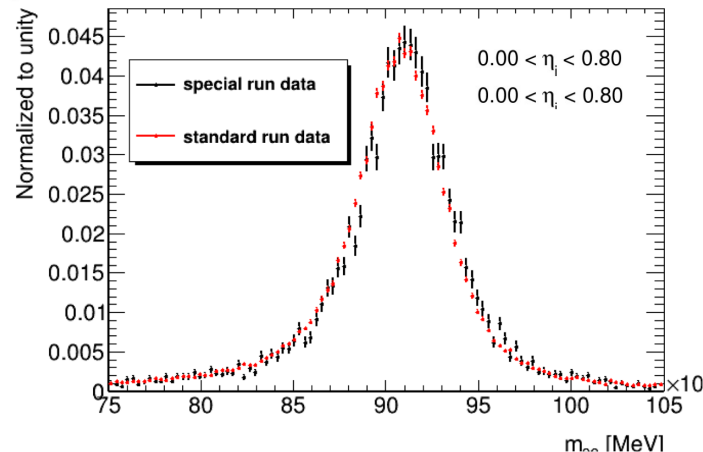
- Global data/MC energy scale adjusted with $Z \rightarrow ee$
- Clusters from $Z \rightarrow ee$ mostly reconstructed in High gain
- Clusters from photon from $H \rightarrow \gamma\gamma$ have cell(s) reconstructed in Medium gain
 - ✓ Possible bias if HG and MG not properly inter-calibrated!
- Effect measured with **special $Z \rightarrow ee$ with lowered gain-switching threshold**
 - ✓ **After correction for ramp non-linear effects!**

$$E^{spec} = (1 + \alpha) E^{stand}$$

$$m_{ee}^{spec} = m_{ee}^{stand} \sqrt{(1 + \alpha_i)(1 + \alpha_j)}$$

$$\frac{\Delta E}{E} = \alpha(\eta) \cdot \frac{1}{\delta_Z(\eta)} \cdot \delta_p(\eta, E_T)$$

- $\delta_Z(\eta)$ is how much the electron energy changes between the medium gain special run and standard runs for a given change in layer 2 medium gain energy. This is estimated injecting a 1% change in medium gain layer 2 energy in both the special and standard runs.
- $\delta_p(\eta, E_T)$ is how much for a given particle p the total energy changes for a given change of medium gain layer 2 energy, as a function of η and E_T . This is estimated using single particle simulated samples.



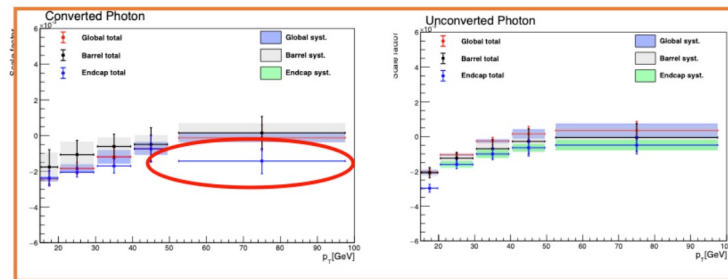
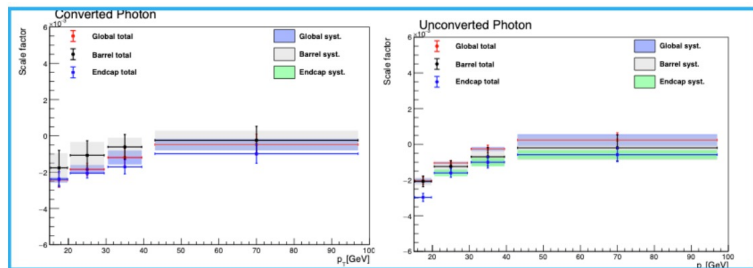
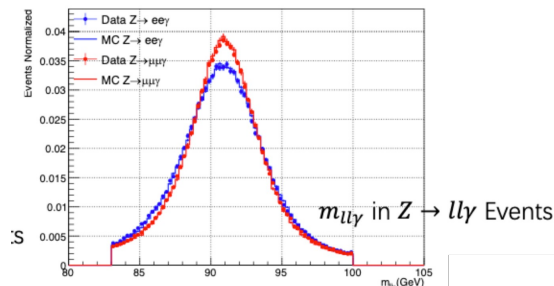
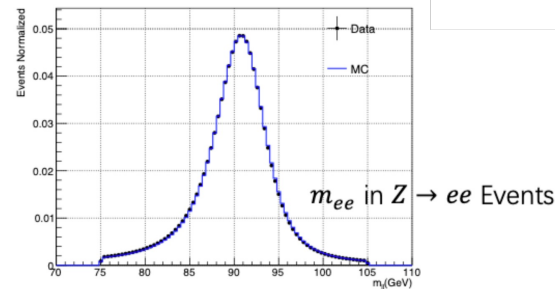
Photon leakage correction

- Global data/MC energy scale adjusted with $Z \rightarrow ee$
- Need to take into account different lateral shower development
- Studied using electron from $Z \rightarrow ee$ and photons from $Z \rightarrow ll\gamma$

- **Double data/MC difference of out of cluster energy between electrons and photons**

$$\Delta((e - \gamma)^{data} - (e - \gamma)^{MC}) = (I^e - I^\gamma)^{data} - (I^e - I^\gamma)^{MC}$$

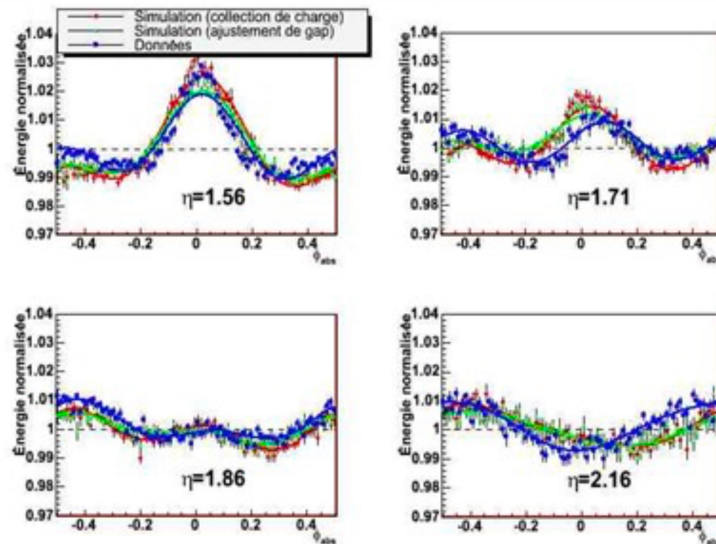
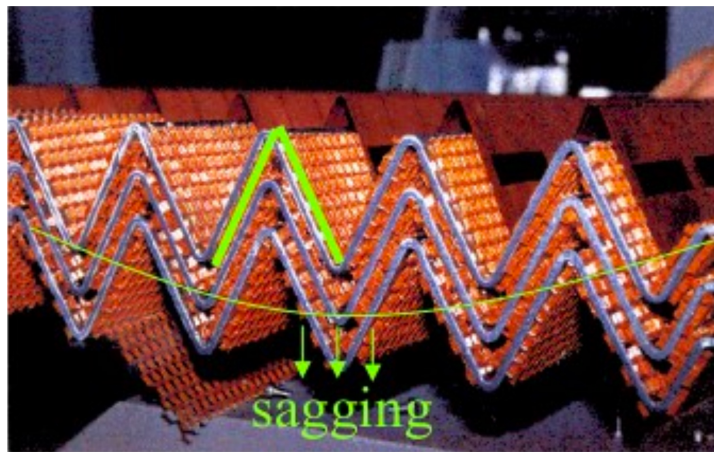
$$I = \frac{E_{S_2}(7 \times 11) - E_{S_2}(nominal)}{E_{S_2}(nominal)}$$



Other uniformity corrections

- Mechanical effects can alter calorimeter structure, thus local response

- ✓ Sagging (gravity) locally change sampling fraction

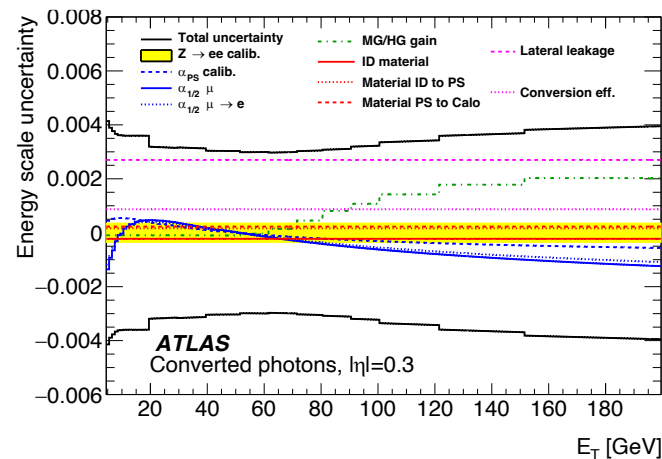
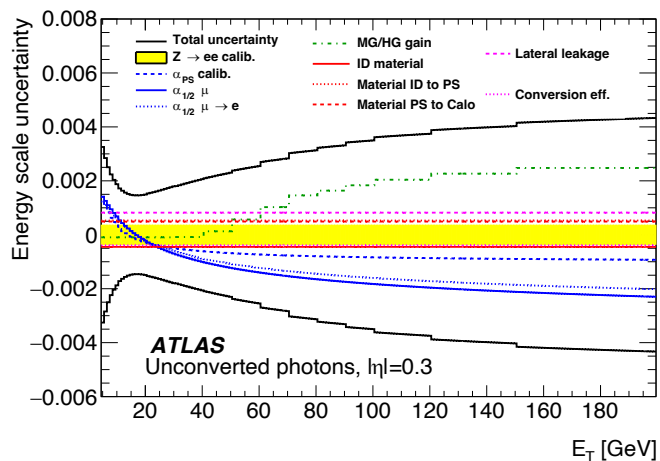
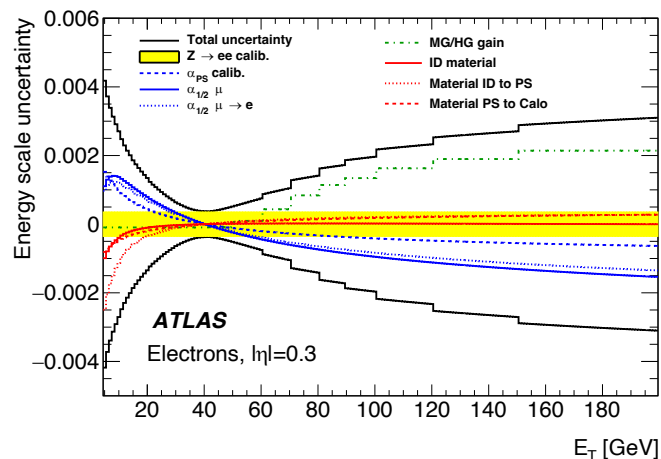


- Instrumental failure can have similar effects

- ✓ Local High Voltage failures

- Short on one LAr gap $\rightarrow$ disable HV $\rightarrow$ halve response
- Intermittent HV sparks $\rightarrow$ reduce HV $\rightarrow$ reduce response

(Current) e/ γ calibration performance...

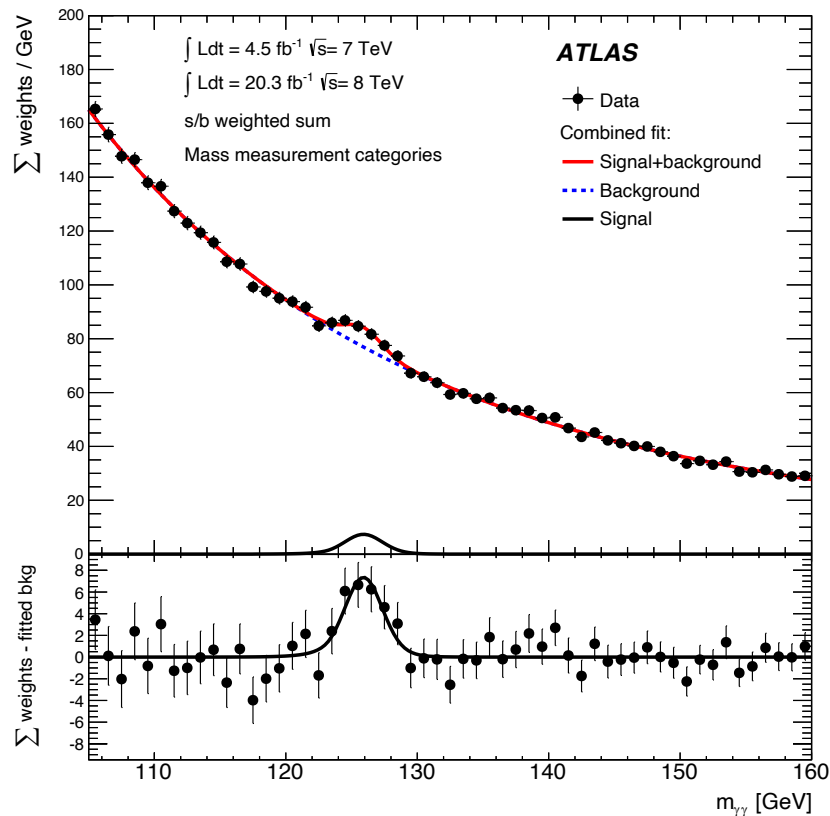


5.5

Results:

Higgs boson mass
with $H \rightarrow \gamma\gamma$

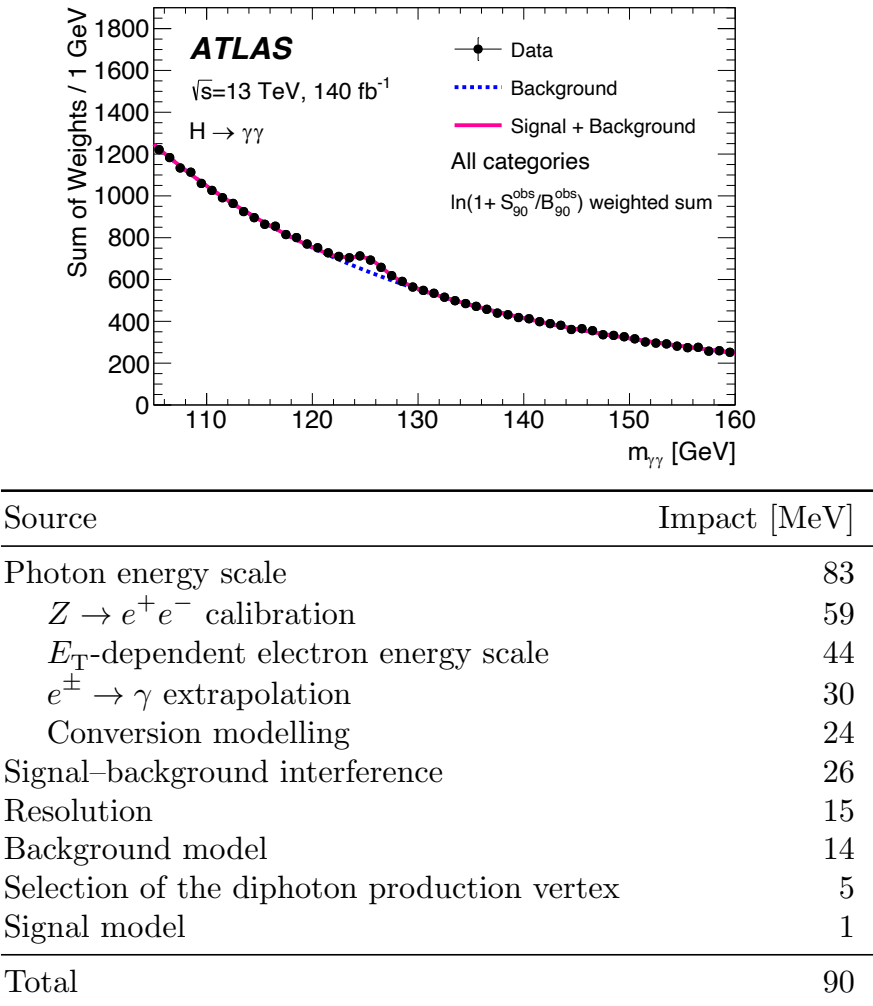
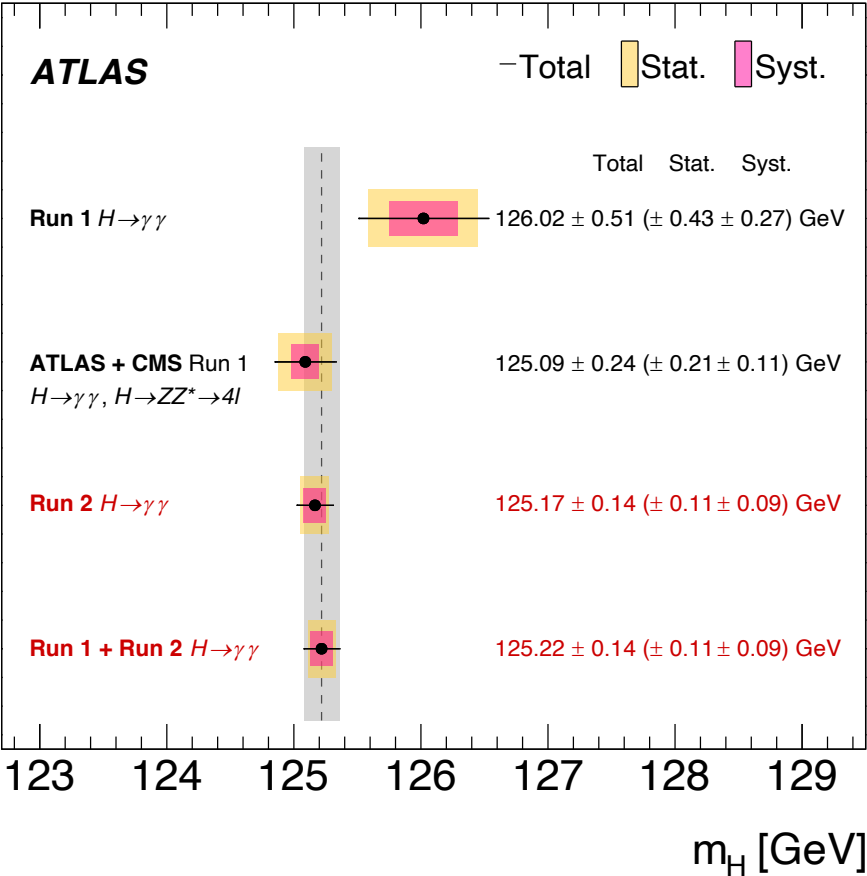
H $\rightarrow\gamma\gamma$ Run I Higgs mass



Channel	Mass measurement [GeV]
$H \rightarrow \gamma\gamma$	$125.98 \pm 0.42 \text{ (stat)} \pm 0.28 \text{ (syst)} = 125.98 \pm 0.50$

Systematic	Uncertainty on m_H [MeV]
LAr syst on material before presampler (barrel)	70
LAr syst on material after presampler (barrel)	20
LAr cell nonlinearity (layer 2)	60
LAr cell nonlinearity (layer 1)	30
LAr layer calibration (barrel)	50
Lateral shower shape (conv)	50
Lateral shower shape (unconv)	40
Presampler energy scale (barrel)	20
ID material model ($ \eta < 1.1$)	50
$H \rightarrow \gamma\gamma$ background model (unconv rest low p_{Tt})	40
$Z \rightarrow ee$ calibration	50
Primary vertex effect on mass scale	20
Muon momentum scale	10
Remaining systematic uncertainties	70
Total	180

H→γγ Run 2 Higgs mass

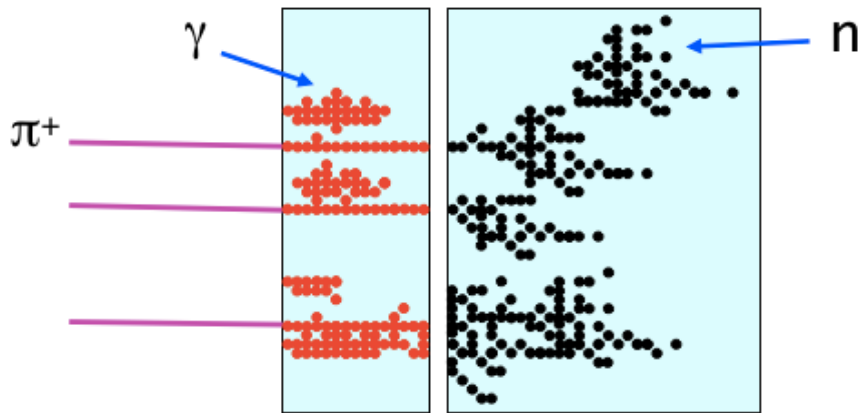


6.

Future calorimeter technologies

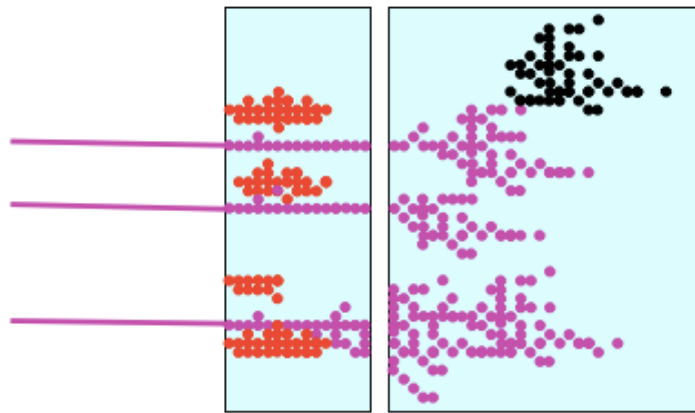
Particle flow

- Typical jet energy composition
 - ✓ ~62% carried by charged particles (mainly hadrons)
 - ✓ ~27 % carried by photons
 - ✓ ~10% by long-lived neutral hadrons
 - ✓ ~1.5 % by neutrinos.
- Traditional approach to calorimetry: measure jet energy via energies deposited in the electromagnetic and hadronic calorimeters (ECAL and HCAL)
 - ✓ **72 % energy measured by HCAL** → $\sim 50\%/\sqrt{E/\text{GeV}}$



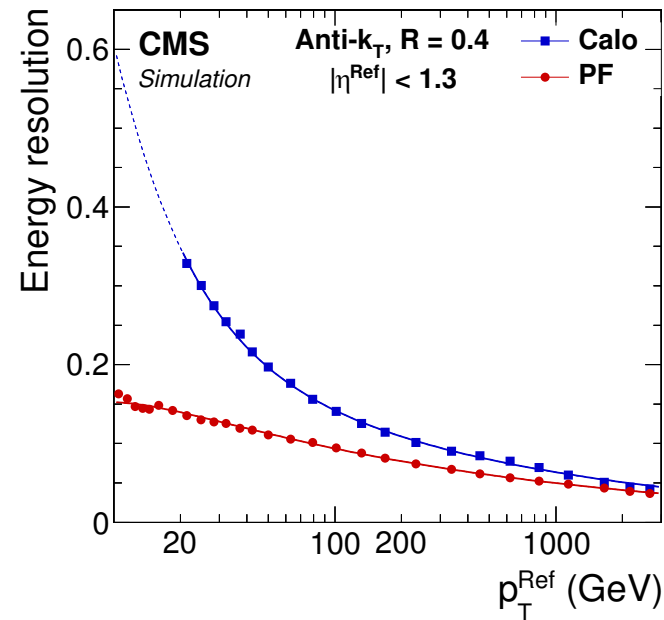
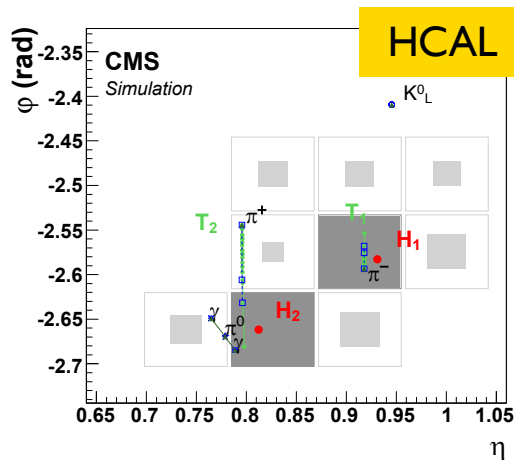
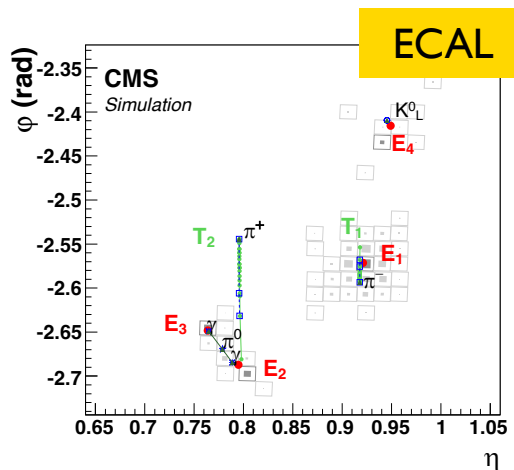
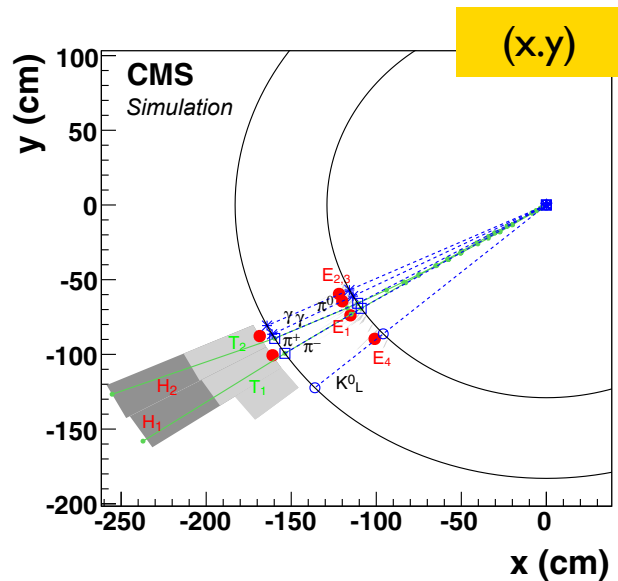
$$E_{\text{JET}} = E_{\text{ECAL}} + E_{\text{HCAL}}$$

- Particle flow calorimetry: trace paths of individual particles through detector, collecting energy deposits left in each subdetector system
 - ✓ Energy and momentum for each particle extracted from subdetector system most accurate in measuring that kind of particle
 - Charged particles → Tracker
 - Photons → ECAL ($\sim 10\%/\sqrt{E/\text{GeV}}$)
 - **Long-lived hadrons (only 10% of jet energy) → HCAL**
 - ✓ Significant improvement to jet energy measurements!
 - ✓ It relies on **accurate pattern recognition** techniques to collect energy deposits from individual particles
 - ✓ **Segmentation + resolution**



$$E_{\text{JET}} = E_{\text{TRACK}} + E_{\gamma} + E_n$$

Example: CMS particle flow

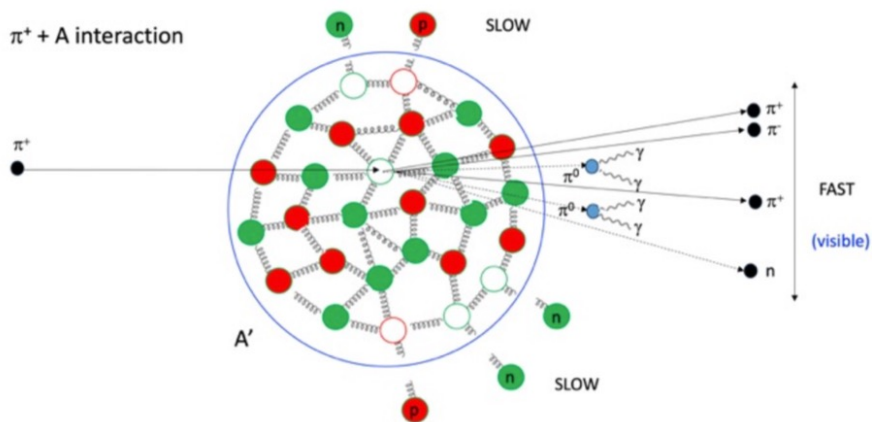


- True particles in blue; Reconstructed tracks and tracker hits (+extrapolation) in green;
- Cluster seeds in dark grey; Other cluster cells in light grey; Cluster position in red;
- Symbols indicate the positions of the true particles

Main criteria for a particle-flow friendly detector

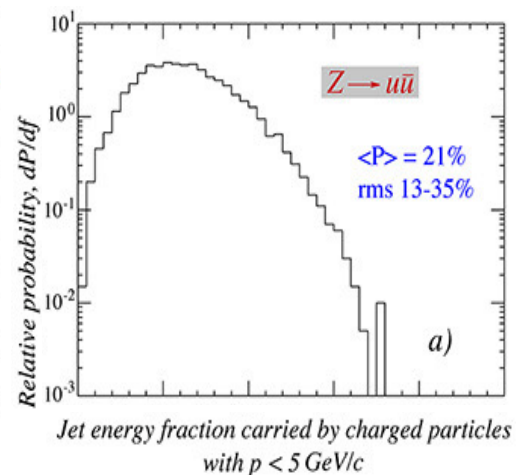
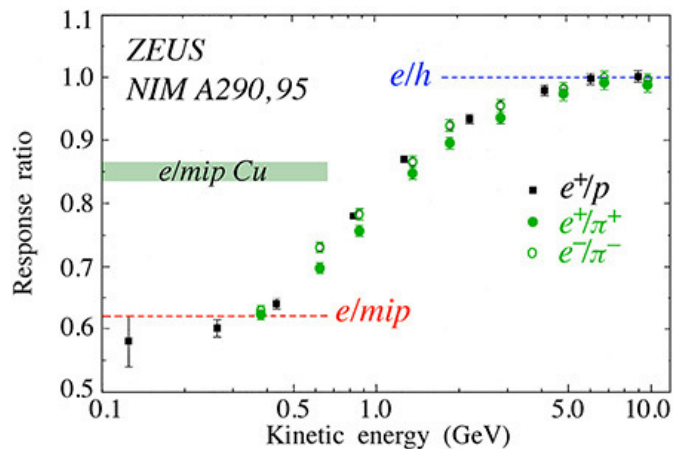
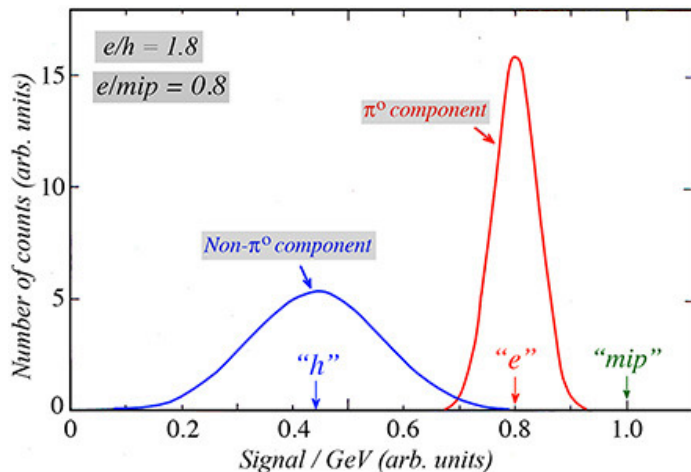
- **Simplicity: as many sub-detectors as needed, but not more**
 - ✓ The more sub-detectors, the more tedious the linking procedure
- **4π hermeticity (including the separation between sub-detector modules)**
 - ✓ Every missing particle (or information) affects the physics interpretation reliability
- **Fine 3D granularity/segmentation of all sub-detectors (+shower compactness in calos)**
 - ✓ To minimise overlapping tracks and showers from different particles in jets
 - ✓ **Calorimeter energy resolution is a valuable bonus, but granularity comes first**
 - Too fine granularity may resolve secondary particles inside showers and defeat the purpose
 - Too many readout channels also increase the electronics noise accordingly (higher thresholds)
- **Sufficiently large magnetic field (and/or tracking volume)**
 - ✓ To separate showers from charged particles in jets
 - ✓ Too large B field would bend many particles towards the end-caps and defeat the purpose
- **Little material in front of the calorimeters (e.g., light tracker, solenoid coil behind the calos)**
 - ✓ To avoid several tracks and showers for one particle due to secondary interactions
- **Measurement redundancy (e.g., with pads and wires) in each sub-detector**
 - ✓ Very instrumental for noise/fake identification, but not compulsory

Compensation and its drawbacks



- In general, e/h differs from 1
 - ✓ Nuclear binding energy losses
 - ✓ Invisible energy fluctuations
- Compensation in HAD calorimeter = $e/h \rightarrow 1$
 - ✓ **Achieved with high Z absorber (Pb, U)**
 - Reduce EM response
 - Generate large number of neutrons
 - ✓ Drawback: e/mip gets smaller (~ 0.6)!
 - Large response non-linearities for low energy hadrons
 - **Worse response for jets than for single hadrons!**

arXiv:1712.05494



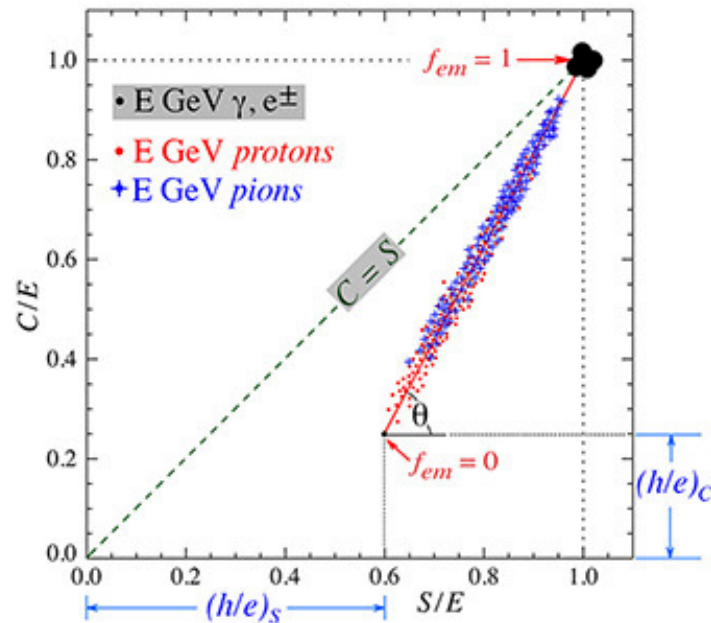
An alternative to compensation: dual readout calorimeter

- Idea: measure f_{EM} directly exploiting **Cerenkov vs Scintillation light**
 - ✓ Electrons in hadronic shower are relativistic down to 200 keV → Cerenkov
 - ✓ Most non-EM energy in hadronic shower from protons from nuclear reaction → Scintillation
- Advantages
 - ✓ No need for high Z absorber (e.g. Cu has $e/mip \sim 0.86$)
 - ✓ Can select any sampling fraction
 - ✓ Method does not rely on measuring neutrons (smaller volume, faster integration time)

$$S = E \left[f_{\text{em}} + \frac{1}{(e/h)_S} (1 - f_{\text{em}}) \right]$$

$$C = E \left[f_{\text{em}} + \frac{1}{(e/h)_C} (1 - f_{\text{em}}) \right]$$

$$f_{\text{em}} = \frac{(h/e)_C - (C/S)(h/e)_S}{(C/S)[1 - (h/e)_S] - [1 - (h/e)_C]}$$

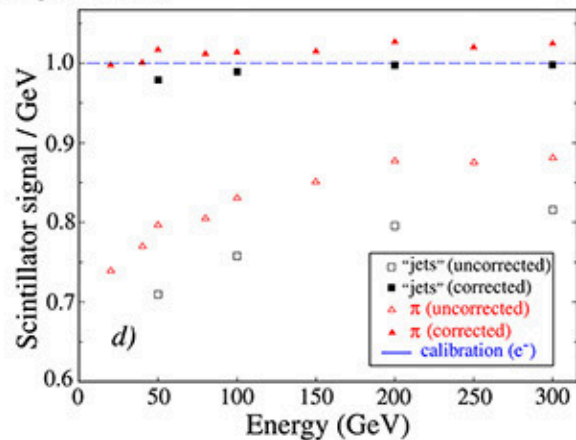
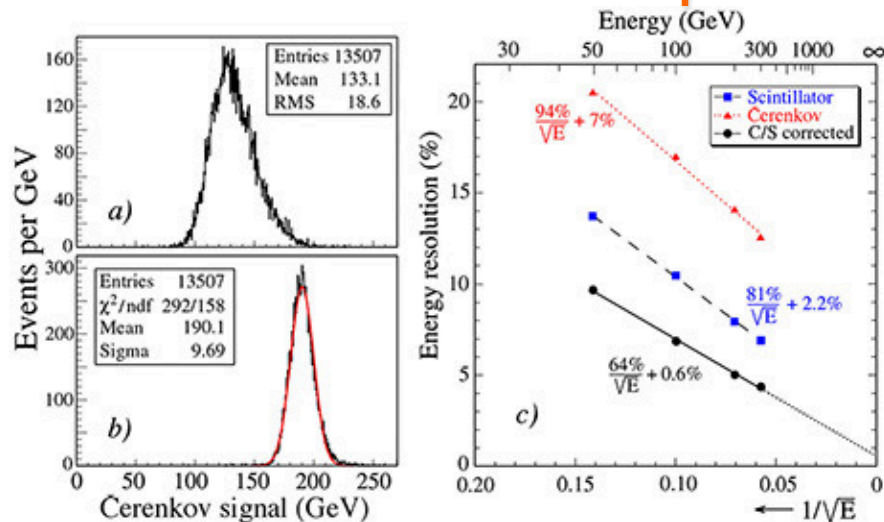
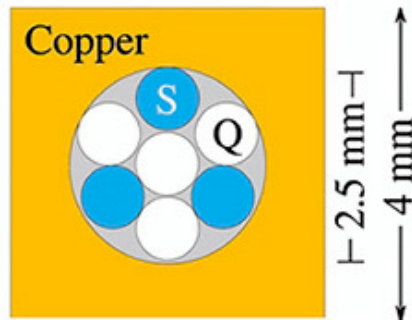
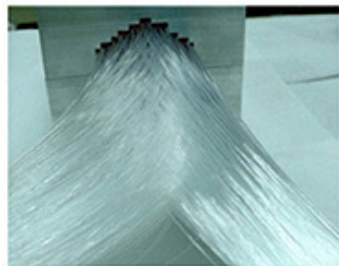
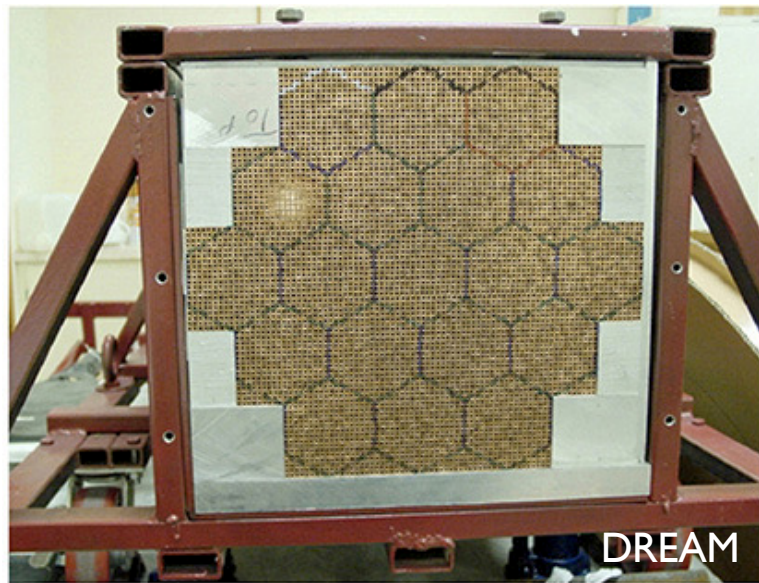


$(e/h)_S$ and $(e/h)_C$ need to be known

$$\cot \theta = \frac{1 - (h/e)_S}{1 - (h/e)_C} = \chi$$

$$E = \frac{S - \chi C}{1 - \chi}$$

How is a dual readout calorimeter realized? An example



Requirements on detectors for HET* factories

CERN-ESU-2025-001

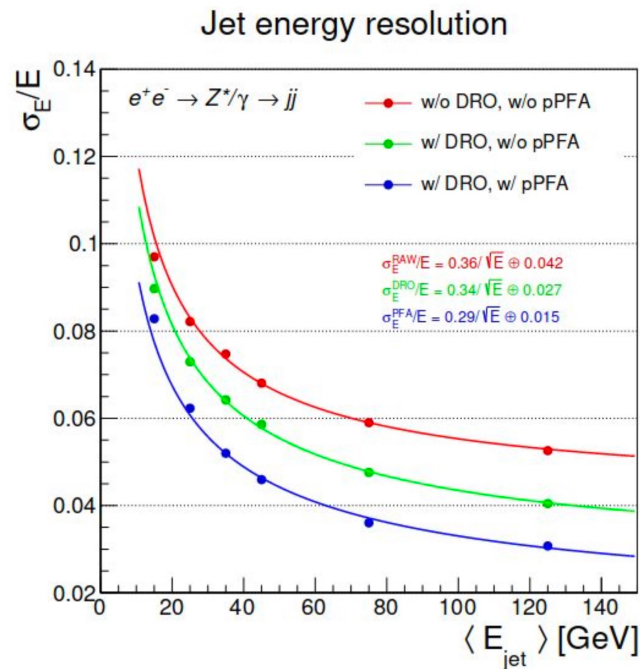
* HET: $e^+e^- \rightarrow$ Higgs/Electroweak/Top

Performance indicator	Requirement	Physics motivation
Vertex hit resolution and material budget	$\approx 3 \mu\text{m};$ $\approx 0.1\% X_0$ per layer	B -meson, Higgs-boson and τ lepton physics
Momentum resolution	$\sigma(p_T)/p_T \approx 2 \times 10^{-5} \cdot p_T(\text{GeV}) \oplus 0.2\%$	$\delta M_H = 4 \text{ MeV}; \delta M_Z = 15 \text{ keV}$
ECAL	$\sigma(E)/E \approx \text{few}\% / \sqrt{E(\text{GeV})}$ and high granularity	B -meson, τ and EW physics, π^0 and γ reconstruction
Jet energy resolution	$\approx 30\% / \sqrt{E(\text{GeV})}$	Higgs and multi-jet events
Magnetic field stability/mapping	better than 10^{-6}	Point-to-point energy uncertainty in $\delta\Gamma_Z$
Timing resolution	tens to 100 ps per track	Particle identification; δM_{HNL}
Particle identification	> 3 standard deviation π - K separation 1 GeV to 30 GeV; standalone muon ID	$H \rightarrow s\bar{s}; b \rightarrow s\nu\bar{\nu};$ long-lived particle searches
Luminosity detector alignment	Position along beam line: $\delta z = 110 \mu\text{m};$ Inner radius: $\delta R_{\text{min}} = 1 \mu\text{m}$	$\delta\mathcal{L} = 10^{-4}$ from Bhabha events at the Z pole energy
Data acquisition and trigger	50 MHz trigger rate and up to 25 Gbit s^{-1} module readout	Processing of beam-induced backgrounds at the Z pole

Specific requirements on calorimeters for HET* factories

- Energy coverage (dynamic range): **200 MeV - 180 GeV**
 - ✓ vs LHC: up to 6 TeV jets !
 - ✓ moderate depth: **22 X_0 , 6-8 λ_{int}**
- Energy resolution: **3-4 % di-jet mass resolution**
 - ✓ Differentiate W vs Z origin of di-jet systems
 - ✓ Implication for jet energy resolution: $\delta E_{\text{jet}}/E_{\text{jet}} \approx 30\% / \sqrt{E [\text{GeV}]}$
 - ✓ Particle flow for jets!
 - Resolution “only” for photons and neutral hadrons (but ideally photons as low as 200-300 MeV)
- Granularity
 - ✓ PID
 - ✓ Disentangle showers for particle flow
- Hermeticity, uniformity, stability
 - ✓ Low systematics for precision measurements
 - ✓ Complex system-level engineering questions
- No need to be particularly fast

* HET: $e^+e^- \rightarrow \text{Higgs/Electroweak/Top}$



Some unique challenges at HET factories!

$O(10^{11})$ B and τ at 45 GeV at FCC-ee!

- Some physics channels especially require extreme EM resolution

- τ physics needs to reconstruct τ decays $\rightarrow$ granularity

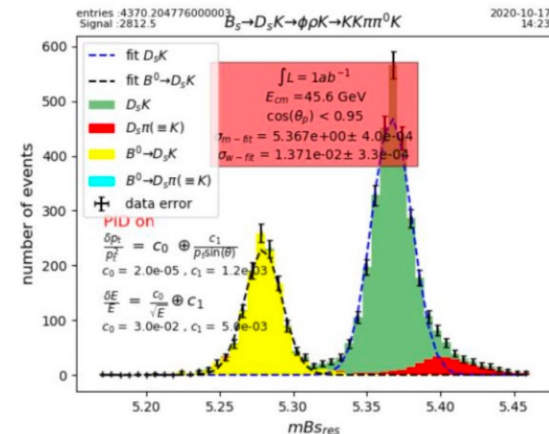
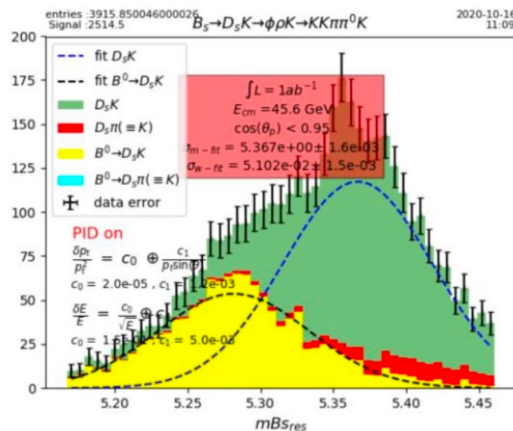
✓ π^0 reconstruction and ID

✓ Count close-by π^0

- BSM with γ in final state (e.g ALP searches)

✓ Photon resolution

✓ Photon direction



Recon $\rightarrow$ Gen $\downarrow$	$\pi^\pm \nu$	$\pi^\pm \pi^0 \nu$	$\pi^\pm 2\pi^0 \nu$	$\pi^\pm 3\pi^0 \nu$	$\pi^\pm 4\pi^0 \nu$
$\pi^\pm \nu$	0.9560	0.0425	0.0010	0.0003	0.0002
$\pi^\pm \pi^0 \nu$	0.0374	0.9020	0.0586	0.0016	0.0002
$\pi^\pm 2\pi^0 \nu$	0.0090	0.1277	0.7802	0.0808	0.0022
$\pi^\pm 3\pi^0 \nu$	0.0036	0.0372	0.2679	0.5972	0.0910

Table: Each row shows the fraction of e.g. $\tau \rightarrow \pi^\pm \nu$ decays classified as each of the considered channels

Calorimetry options being pursued

- All options aim at particle flow reconstruction!
 - ✓ In general, all have good jet energy resolution
 - ✓ Varying ECAL resolution (highest EM resolution required for B physics)
 - ✓ Varying segmentation (impact on PF, shower shapes for γ/π^0 , cluster pointing and γ position)
 - ✓ Varying operational stability and cost

[arXiv:2109.00391](https://arxiv.org/abs/2109.00391)

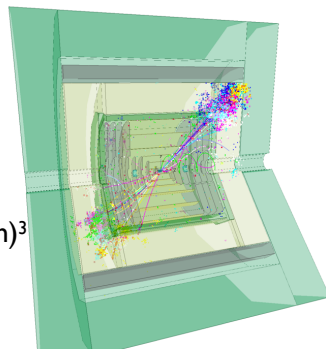
Detector technology (ECAL & HCAL)	E.m. energy res. stochastic term	E.m. energy res. constant term	ECAL & HCAL had. energy resolution (stoch. term for single had.)	ECAL & HCAL had. energy resolution (for 50 GeV jets)	Ultimate hadronic energy res. incl. PFlow (for 50 GeV jets)
Highly granular Si/W based ECAL & Scintillator based HCAL	15 – 17 % [12,20]	1 % [12,20]	45 – 50 % [45,20]	$\approx 6\%$?	4 % [20]
Highly granular Noble liquid based ECAL & Scintillator based HCAL	8 – 10 % [24,27,46]	< 1 % [24,27,47]	$\approx 40\%$ [27,28]	$\approx 6\%$?	3 – 4 % ?
Dual-readout Fibre calorimeter	11 % [48]	< 1 % [48]	$\approx 30\%$ [48]	4 – 5 % [49]	3 – 4 % ?
Hybrid crystal and Dual-readout calorimeter	3 % [30]	< 1 % [30]	$\approx 26\%$ [30]	5 – 6 % [30,50]	3 – 4 % [50]

Table 1. Summary table of the expected energy resolution for the different technologies. The values are measurements where available, otherwise obtained from simulation. Those values marked with "?" are estimates since neither measurement nor simulation exists.

Calorimetry options being pursued

Highly granular Si/W based ECAL & Scintillator based HCAL

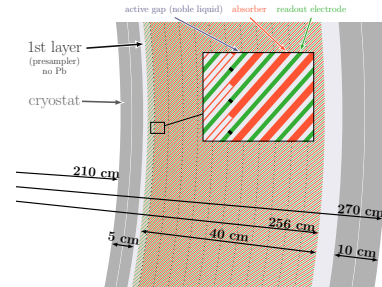
- ECAL: Tungsten-silicon
 - ✓ Extremely fine segmentation: $(0.5 \text{ cm})^3$
- HCAL: Steel-scintillator; SiPM-on-Tile
 - ✓ Fine segmentation: $(2.5 \text{ cm})^3$



EM: $\sigma(E)/E \approx 16\%/\sqrt{E}$
 Jet: $\sigma(E)/E \approx 3\text{-}4\% \text{ @ } 50 \text{ GeV}$

Highly granular Noble liquid based ECAL & Scintillator based HCAL

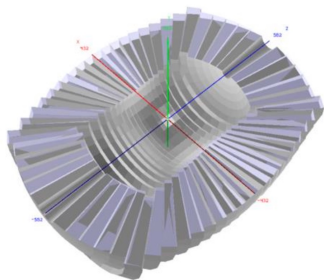
- ECAL: Pb+LAr (or W+LKr); warm or cold electronics
 - ✓ Fine longitudinal sampling (w.r.t. ATLAS, $4 \rightarrow 12$ layers)
- HCAL: Scintillating tile (e.g. CALICE or ATLAS)



EM: $\sigma(E)/E \approx 8\text{-}10\%/\sqrt{E}$
 Jet: $\sigma(E)/E \approx 4\% \text{ @ } 50 \text{ GeV}$

Dual-readout Fiber calorimeter

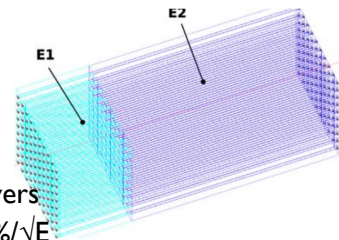
- ECAL + HCAL: Copper or steel matrix; Cherenkov and scintillating fibres, SiPMs
 - ✓ Very fine transverse granularity
 - ✓ Longitudinal information via timing



EM: $\sigma(E)/E \approx 11\%/\sqrt{E}$
 Jet: $\sigma(E)/E \approx 3\text{-}4\% \text{ @ } 50 \text{ GeV}$

Hybrid crystal & Dual-readout calorimeter

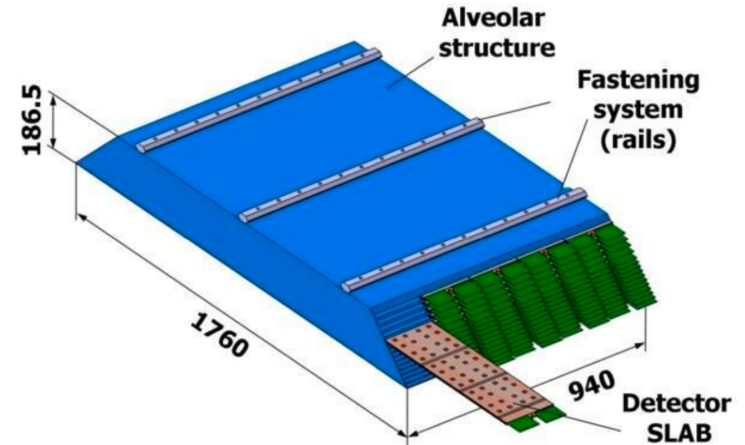
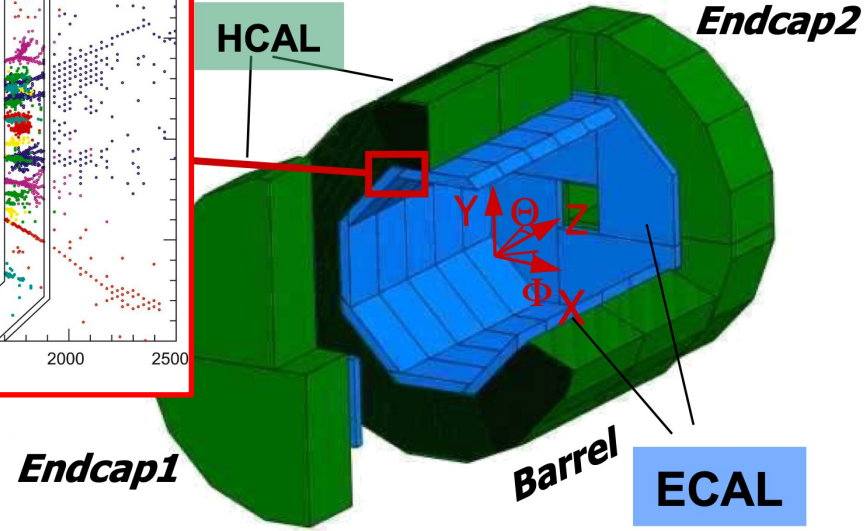
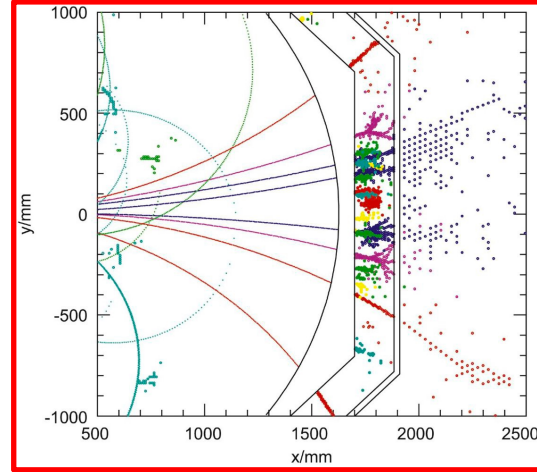
- ECAL: Segmented crystal; SiPMs
 - ✓ Fine transverse segmentation; 2 long layers
 - ✓ Very good EM energy resolution of $\sim 3\%/\sqrt{E}$
- HCAL: fiber-based Dual Readout calorimeter



EM: $\sigma(E)/E \approx 3\%/\sqrt{E}$
 Jet: $\sigma(E)/E \approx 3\text{-}4\% \text{ @ } 50 \text{ GeV}$

SiW ECAL

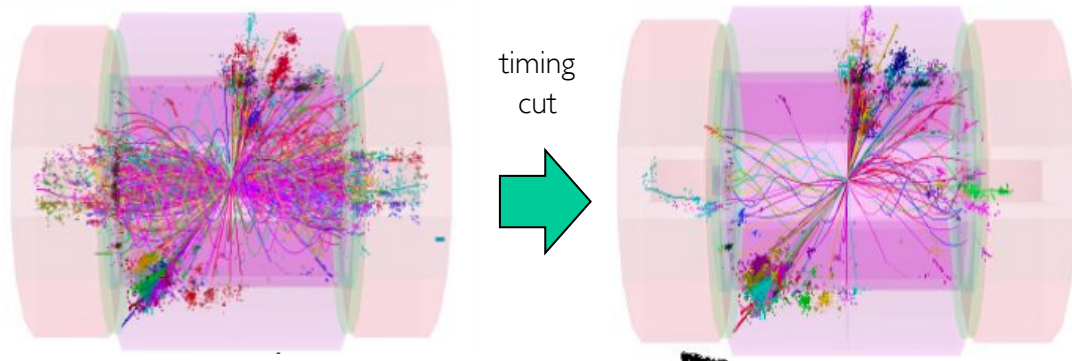
- An “imaging” calorimeter
 - ✓ Tungsten as absorber material
 - $X_0 = 3.5$ mm, $R_M = 9$ mm, $\lambda_l = 96$ mm
 - Narrow showers $\rightarrow$ compact design
 - ✓ Silicon (sensors) as active material
 - Support compact design
 - Sensor + RO < 2mm
 - Allows for $\sim$ any pixelisation
 - Excellent signal/noise ratio > 10
 - ✓ Tungsten–Carbon alveolar structure
 - Minimal structural dead-spaces
 - Scalability
- Optimized for Particle Flow: super high granularity!
 - ✓ 30 layers, 2.8 mm tungsten absorber, $24 X_0$
 - ✓ 0.5 mm thick silicon sensors with 5×5 mm² granularity
 - ✓ $O(10^8)$ cells
 - ✓ Tight integration: compact and hermetic
- EM resolution $\sim 16\%/\sqrt{E}$



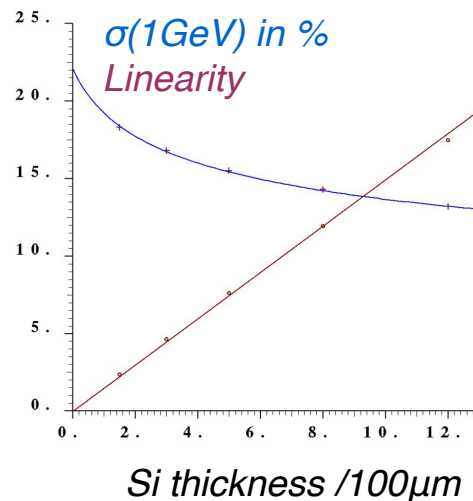
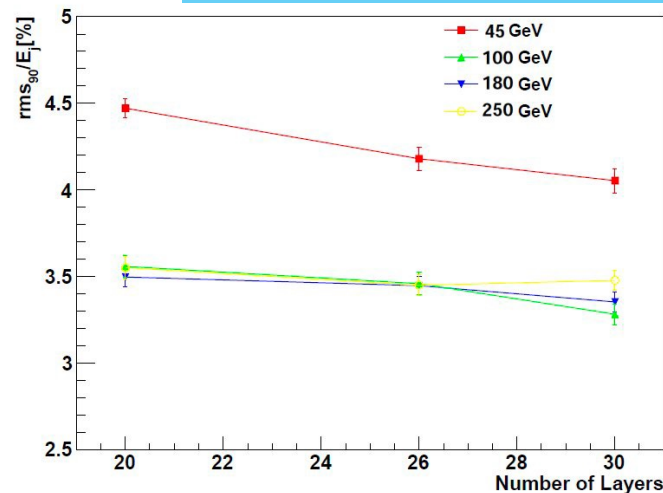
Highly granular Si/W based ECAL

SiW ECAL

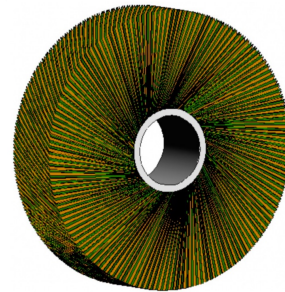
- Originally developed for ILC...
- Adaptation to FCC-ee brings challenges
 - ✓ Granularity re-optimization (e.g. reduce the number of layers + thicker sensors)
 - Going from 30 to 26 layers increase resolution (but reduces cost)
 - Increasing the Si thickness to 725 μ m
 - ✓ Addition of timing
 - From CMS HGCAL



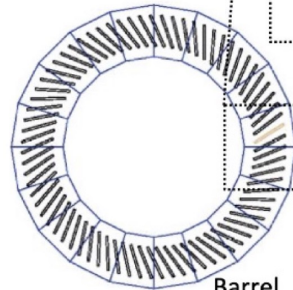
Highly granular Si/W based ECAL



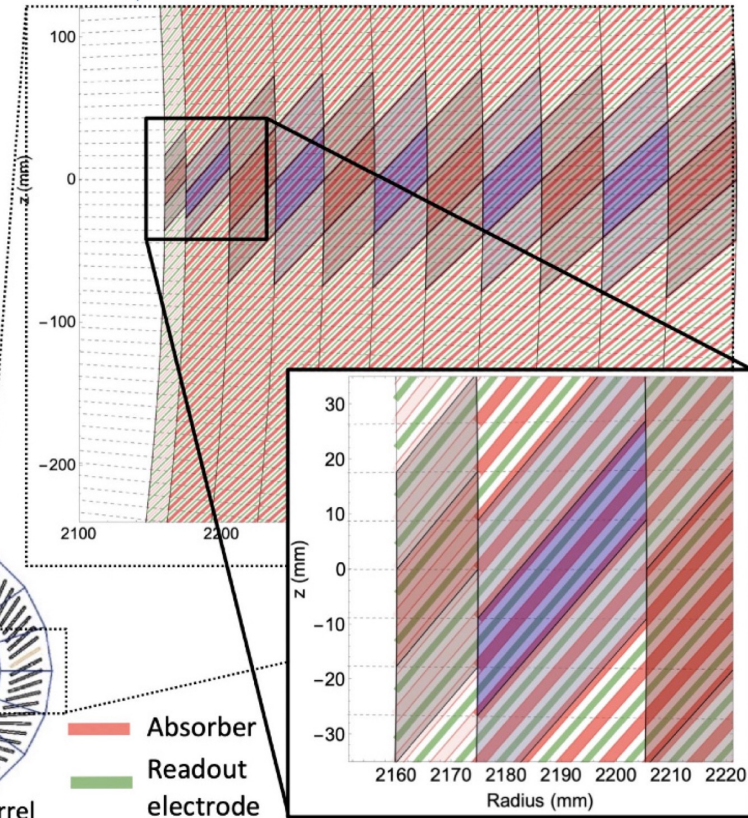
- Noble liquid (LAr/LKr) sampling (Pb/W) sampling calorimeter
 - ✓ Absorber planes inclined in r-phi (barrel) / arranged in turbine-like structure (endcap)
 - ✓ Readout by straight segmented PCB planes alternated to Pb (W) absorbers, gaps in between filled with LAr (LKr)
 - ✓ High granularity via electrode segmentation
 - $O(10^6)$ cells
- Good compromise
 - ✓ Granularity, resolution, stability, uniformity
- EM resolution $5\text{-}8\%/\sqrt{E}$



Endcap

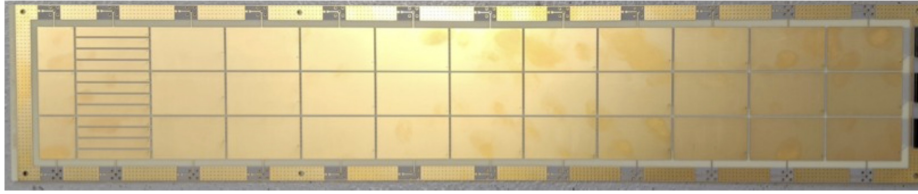


Barrel



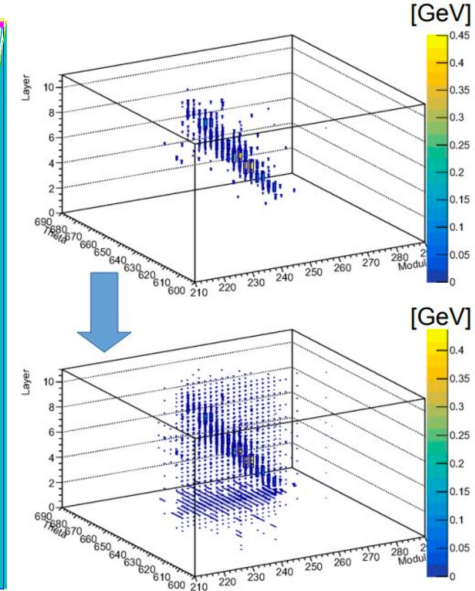
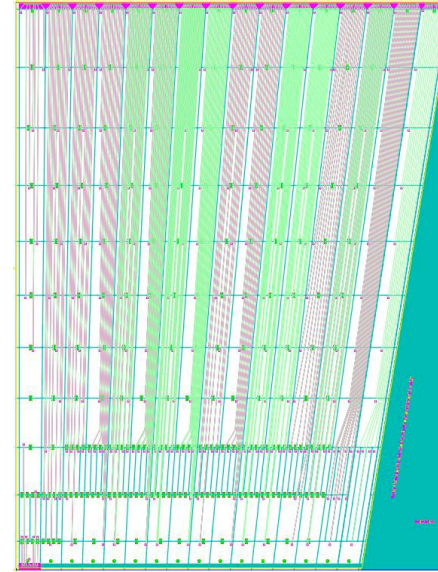
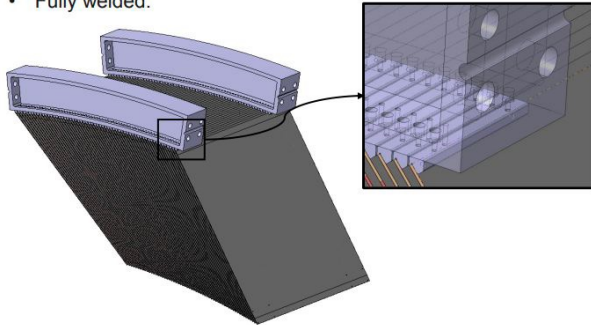
ALLEGRO ECAL

Highly granular Noble liquid based ECAL

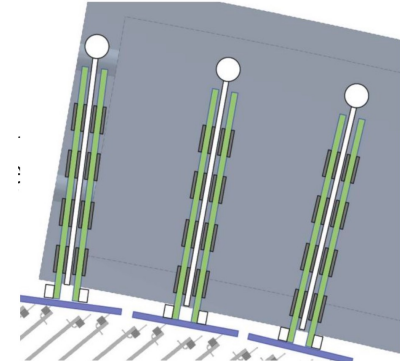


- Granularity achieved by etching readout electrodes
- Collecting signal from inner pads requires long readout lines: cross-talk!
 - ✓ Cross-talk < 0.1% achievable
 - ✓ Negligible impact on γ/π^0 classification

• Fully welded.



- Calorimeter in cryostat: where readout electronics?
 - ✓ Warm electronics: 2M signal cables to route
 - ✓ Cold electronics: need room for boards + HV, powering and signal cables in cryostat
 - Cold FEB along radial direction? RO on PCB?
- Mechanical structure for holding and positioning of absorbers and electrodes

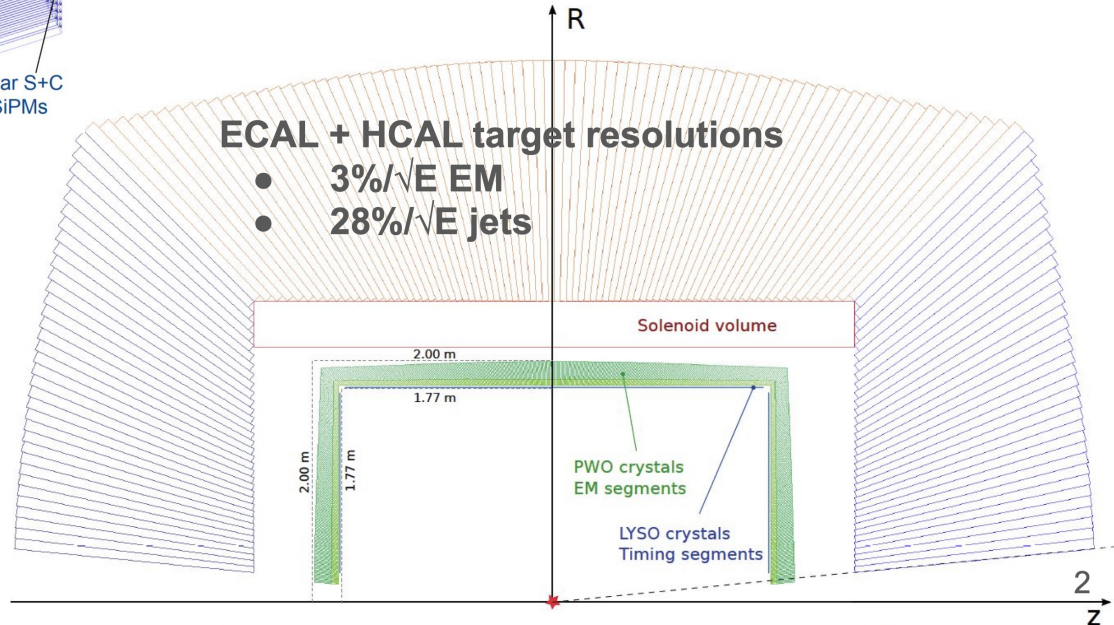
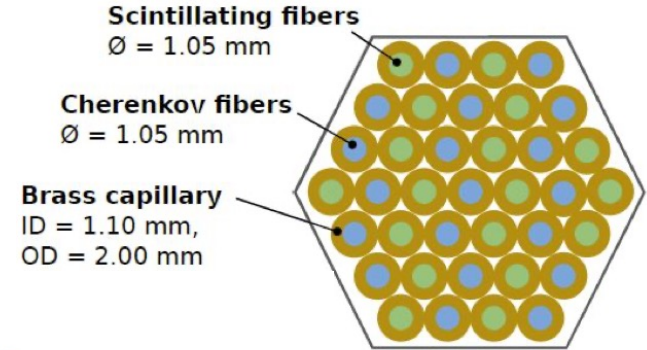
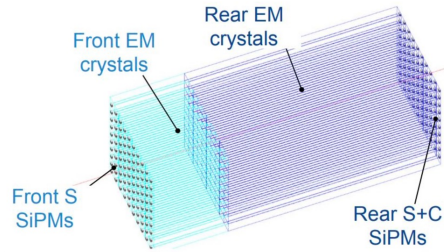


IDEA calorimeter

Hybrid crystal & Dual-readout calorimeter

Dual-readout fiber calorimeter

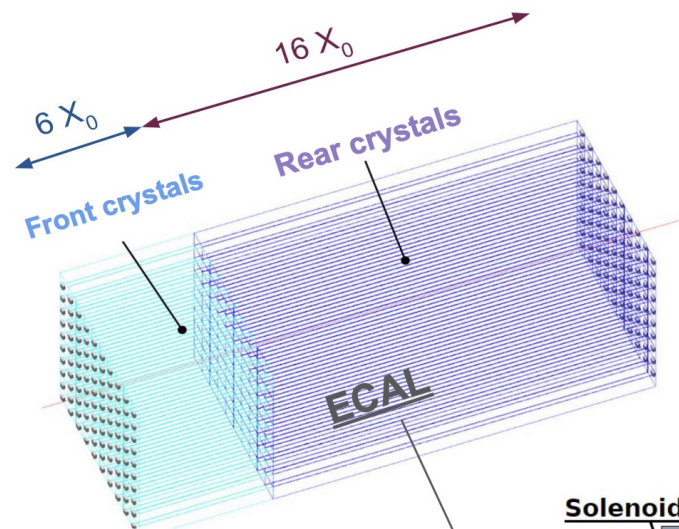
- ECAL: homogeneous dual-readout hybrid crystal
- HCAL: dual-readout fiber hadronic calorimeter



Dual-readout crystal EM calorimeter

Hybrid crystal & Dual-readout calorimeter

Dual-readout fiber calorimeter



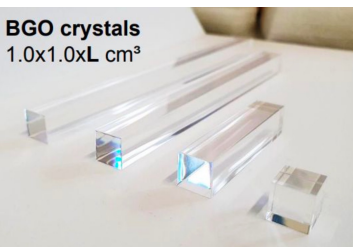
- High density crystals (short X_0 , small R_M)
 - ✓ PbWO₄, BGO, BSO
- Two layers (e.g. 6+16 X_0)
- Fine granularity: $O(\text{cm}^2)$ cross section
- SiPM readout
 - ✓ Front: S
 - ✓ Rear: S + C

Rear crystal ECAL segment

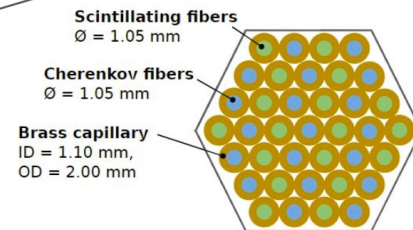
two SiPMs optimized for S and C detection respectively



Front crystal ECAL segment:
one SiPMs optimized for S detection

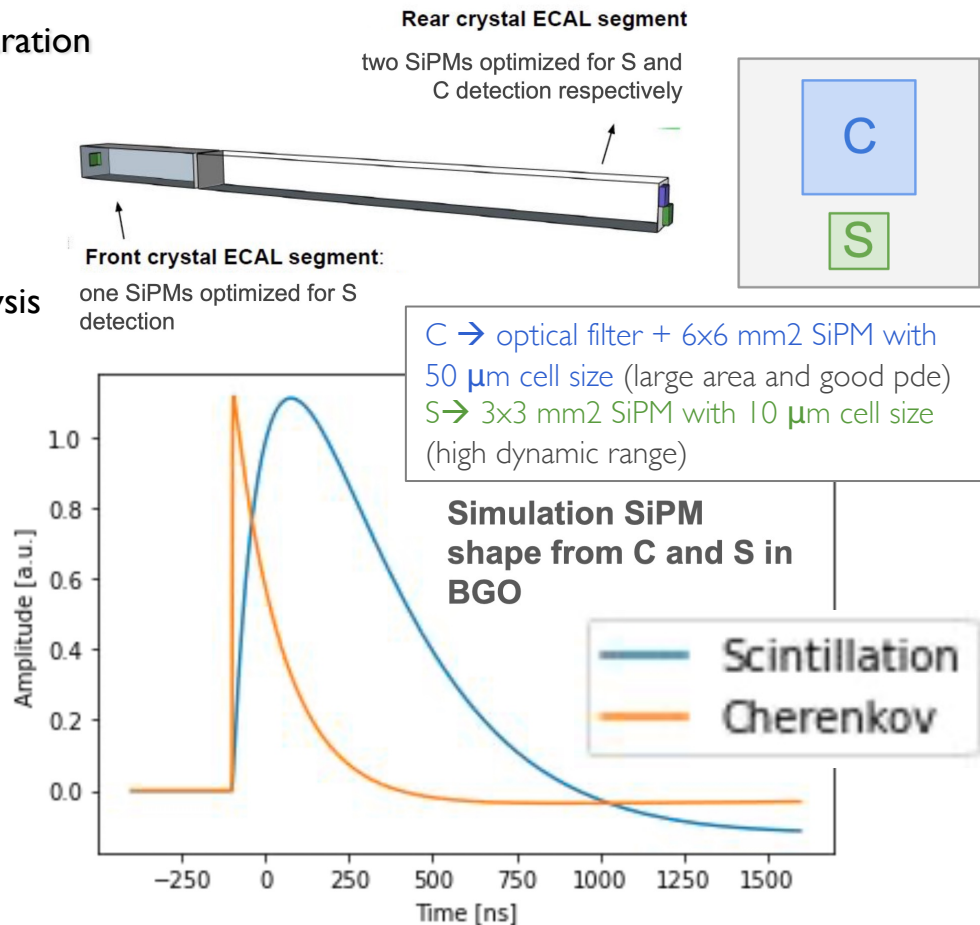
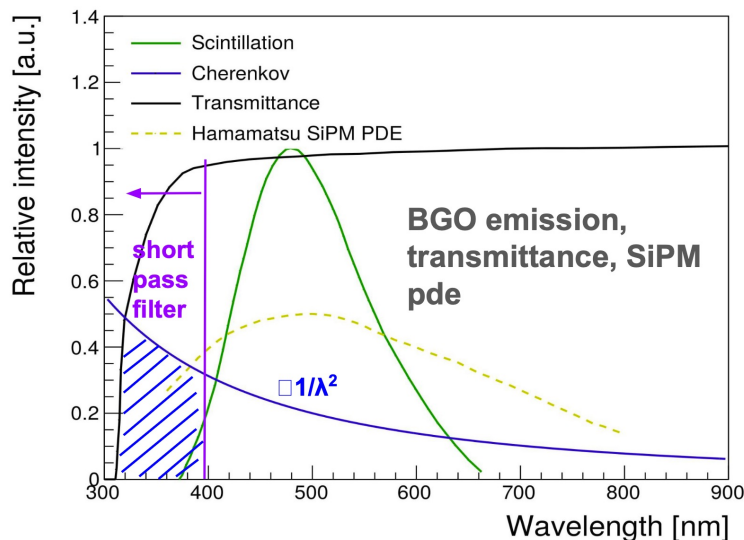


Dual readout HCAL



Dual-readout strategy in crystals

- Cherenkov and Scintillation light detection and separation challenging in homogeneous materials
- C vs S distinctive features
 - ✓ C emission faster than S
 - ✓ C emission spectrum broader than S
 - ✓ C/S separation with filters and pulse shape analysis



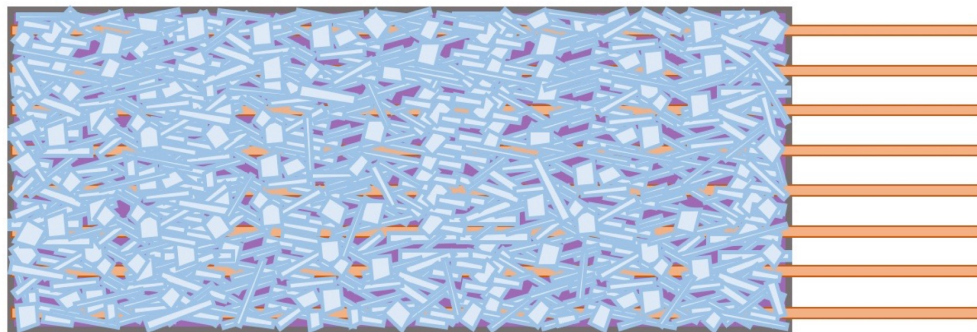
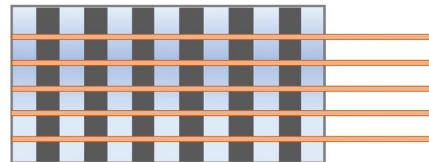
GRAiNITA

- Better than a sampling calorimeter, cheaper than a homogeneous one!

$$\frac{\sigma_E}{E} \sim \frac{\text{sampling } 10\%-15\%}{\sqrt{E}} \longleftrightarrow \frac{\text{homogeneous } 1\%-2\%}{\sqrt{E}}$$

- Idea: mixture of inorganic scintillator grains and heavy liquid
 - ✓ Extremely fine sampling
 - ✓ Scintillation light locally contained by refraction/reflections
 - BGO or ZnWO_4 crystals
 - ✓ Readout by wavelength shifting fibers
- Excellent expected EM resolution: $2-3\%/\sqrt{E}$

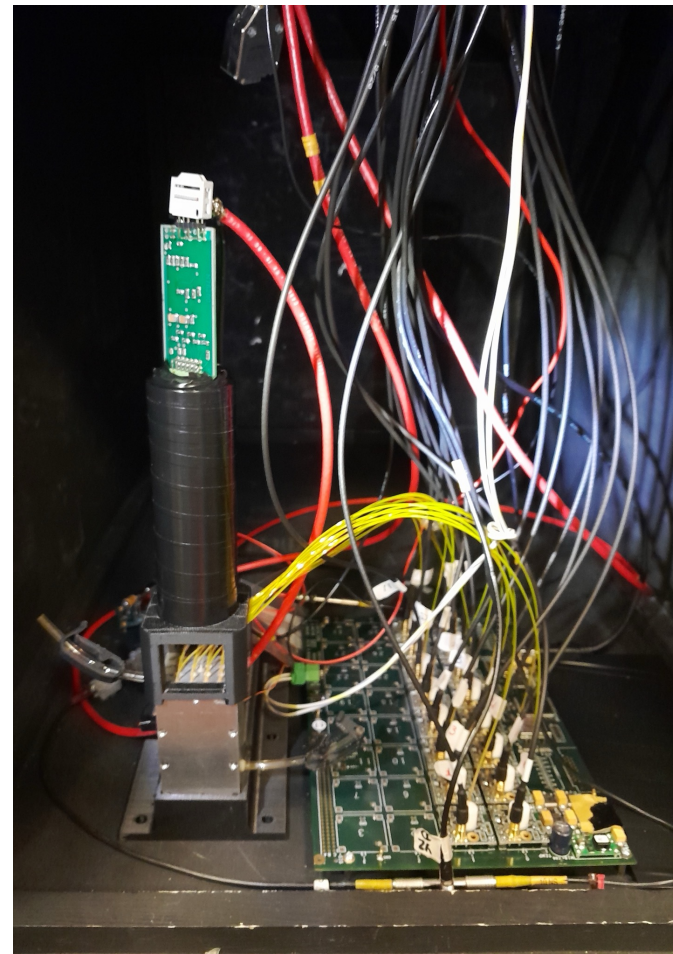
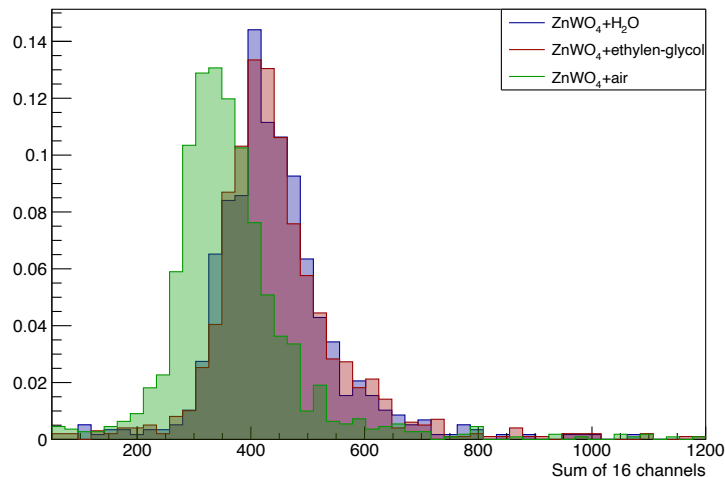
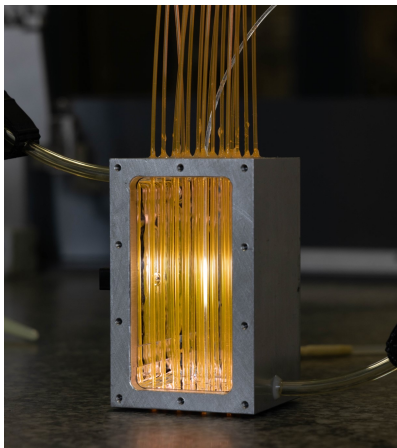
Shashlyk-type calorimeter



	ZnWO ₄
Effective Z	61
Density (g/cm^3)	7.87
Refractive index	2.0 - 2.3
Light yield (photons/MeV)	~ 9000
Peak emission wavelength (nm)	480
Decay time (μs)	20
Radiation length (cm)	1.20
Molière radius (cm)	1.98

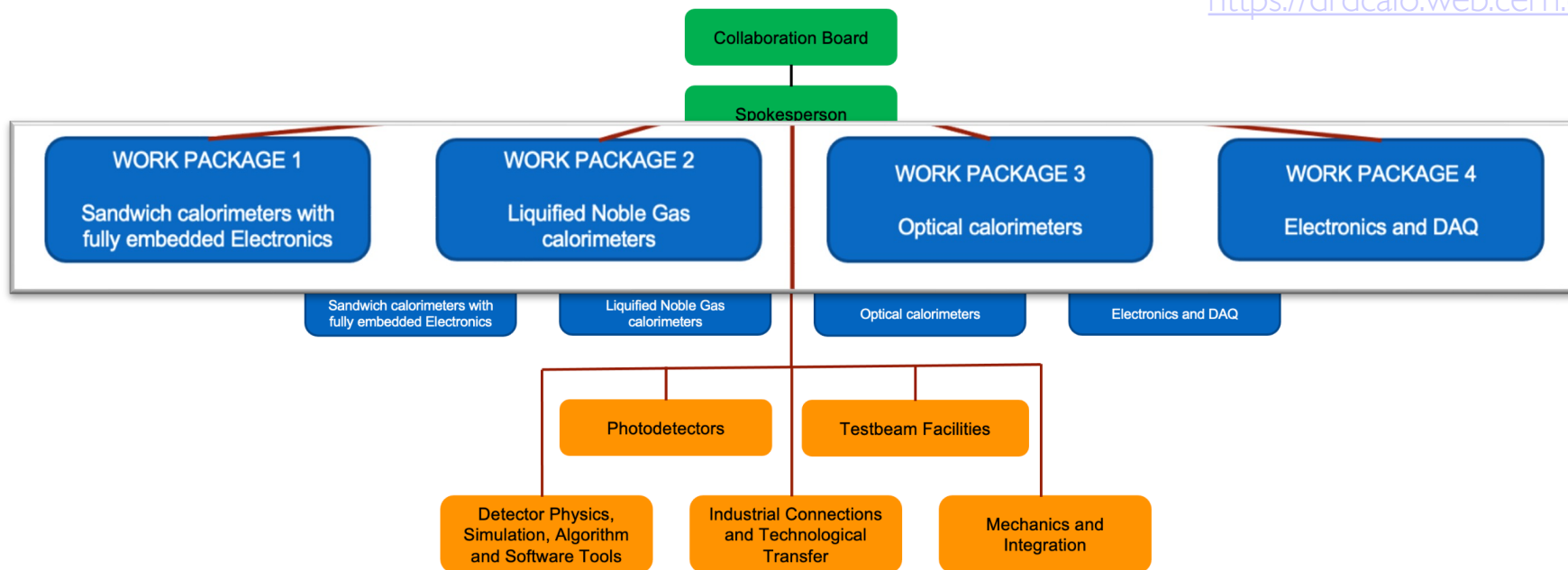


- Small ($2 \times 2 \times 5.5$ cm³) prototype
 - ✓ ZnWO₄ grains + water or Heavy Liquid (e.g. ethylene + glycol)
 - ✓ 16 WLS fibers read out by SiPM and a Wave-Catcher
 - Depolished fiber in the center to allow for green light injection
- Signal yield larger when medium refractive index is better matched with grains
- Light confinement confirmed
- Possibility of $\sim 1\%/\sqrt{E}$ due to photon statistics confirmed
- Currently: uniformity studies (impact on resolution constant term)



drdcalo

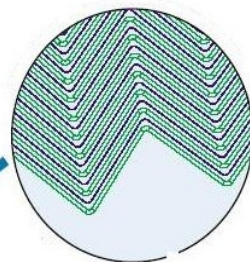
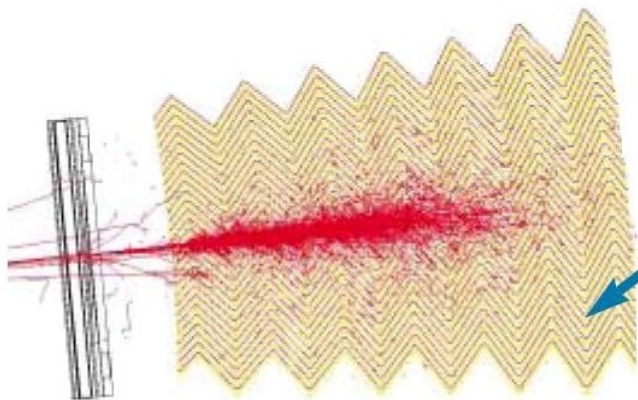
<https://drdcalo.web.cern.ch>



$e^{i\pi}.$

More material

ATLAS liquid argon electromagnetic calorimeters



sampling calorimeter
Pb-LAr

$$\frac{\sigma E}{E} = \frac{10\%}{\sqrt{E}} \oplus \frac{250 \text{ MeV}}{E} \oplus 0.7\% c$$

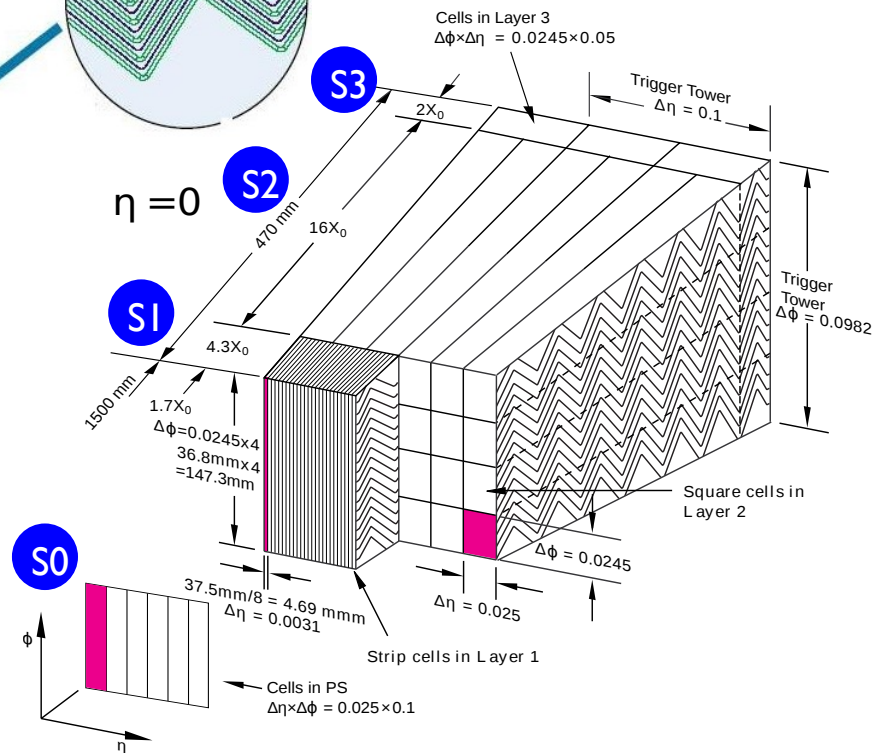
- S0 (Presampler)
- S1 (Strips)
- S2 (Middle)
- S3 (Back)

Energy loss correction

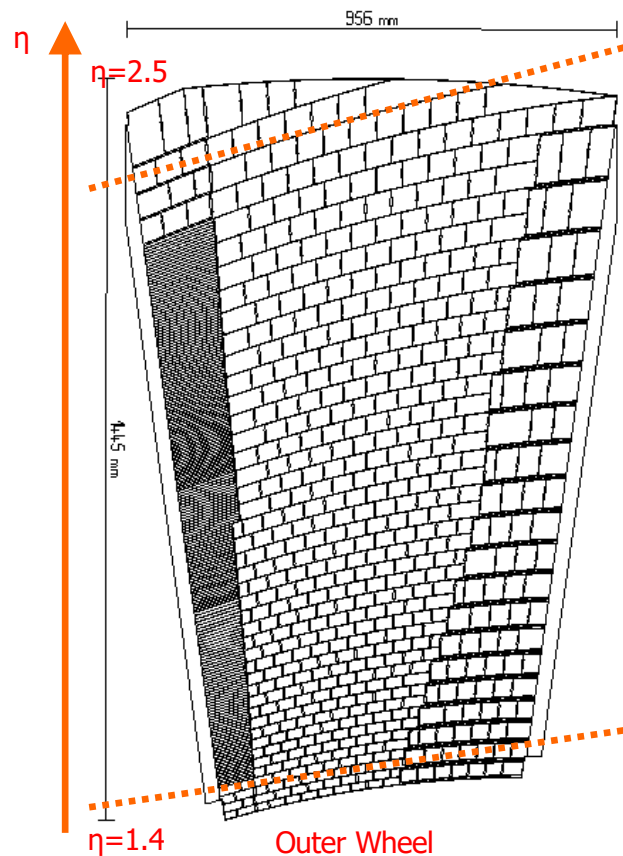
γ/π^0 separation $4.3 X_0$

Main energy deposit $16 X_0$

High energy showers $2 X_0$



LAr EM EndCap granularity



ENDCAP

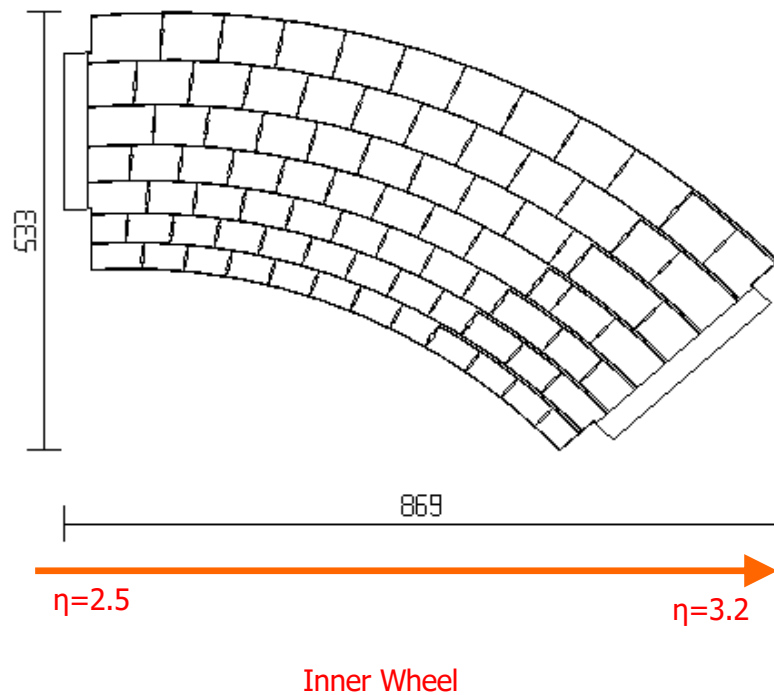
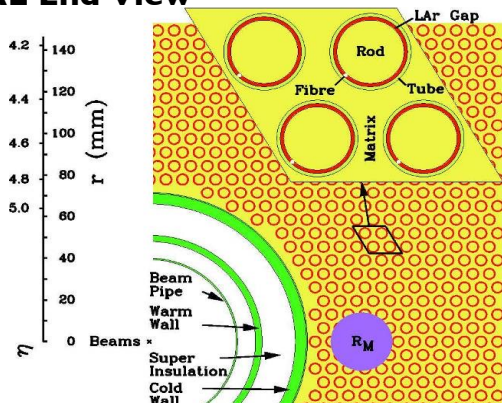


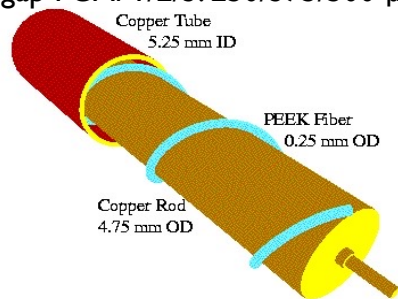
Figure 0-1 High-voltage layer of an electrode of the outer wheel. The signal routing strips and the connectors which are located on both front and back (i.e. left and right) extensions are not drawn here.

The ATLAS Forward and Hadronic Calorimeters

FCAL End View



LAr gap FCAI 1/2/3: 250/375/500 μm



FCAL I Anode Structure

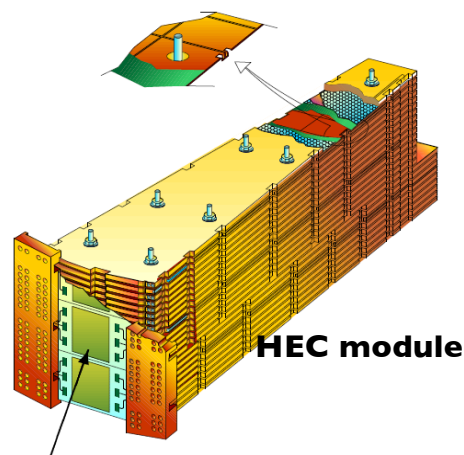
Forward Calorimeter (FCal)

- ✓ 3 wheels per endcap (10λ)
 - Cu matrix for the first wheel (2.6λ , $28X_0$)
 - W matrix for the other two wheels ($2 \times 3.7\lambda$)

Hadronic Endcap Calorimeter (HEC)

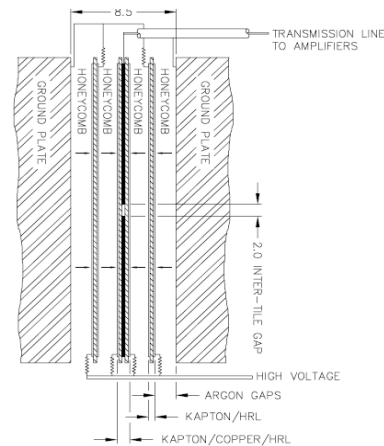
- ✓ 2 wheels per endcap (10λ), 32 modules each
 - Cu absorbers ($25\text{mm}/50\text{mm}$ thick)
 - Each gap consists of 4 sub gaps of 1.85mm

- Since the geometry is different from the EMC, the ionization signals are slightly different...



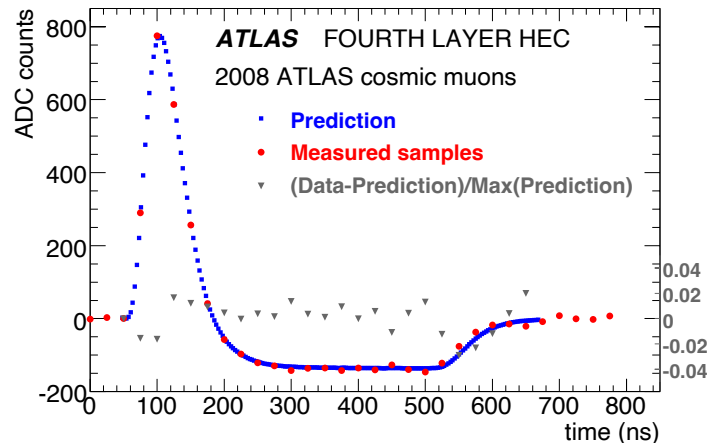
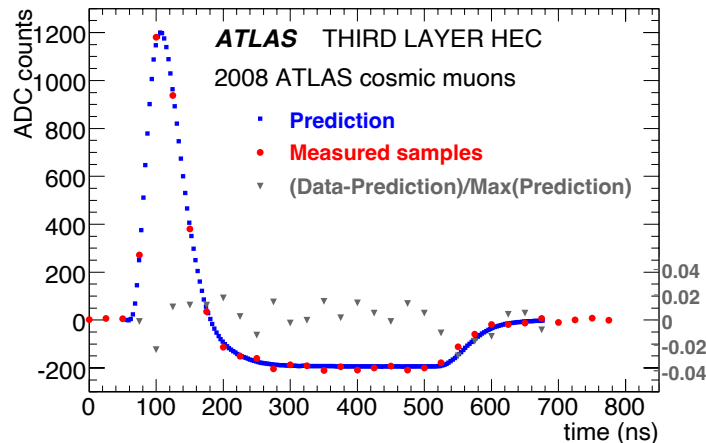
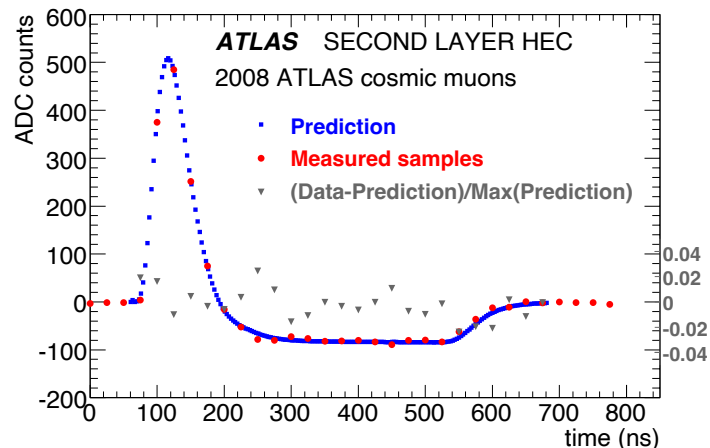
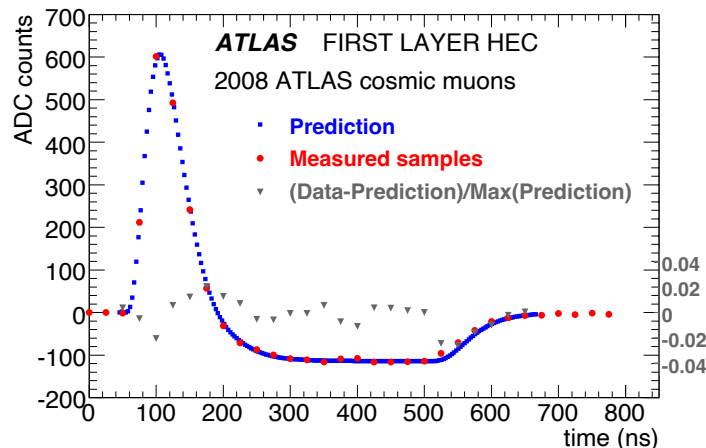
HEC module

cold preamplifiers

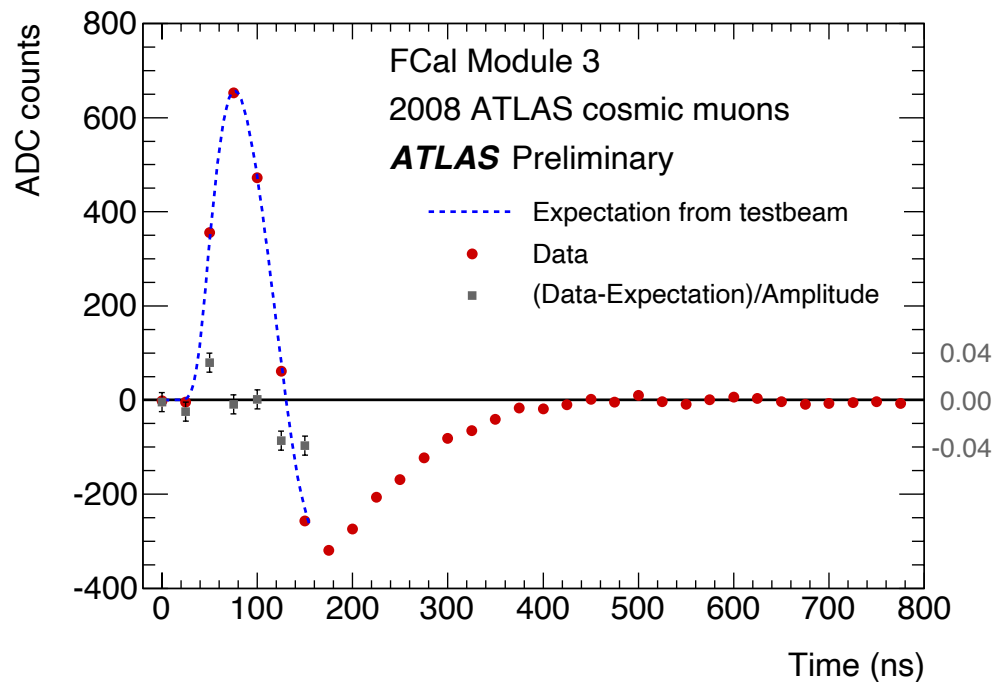


operating HV: 1800V

A quick view to the ionization pulses: HEC



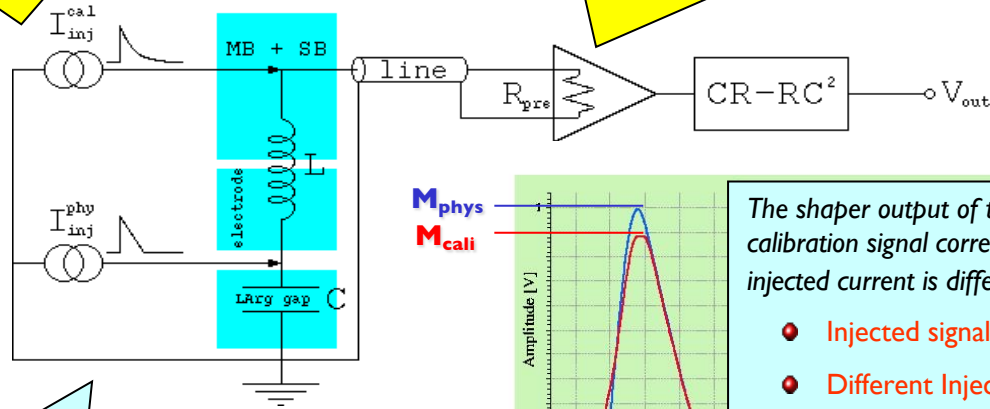
A quick view to the ionization pulses: FCAL



Calibration of the electronic response

A known **exponential** current pulse is injected at the MB level...

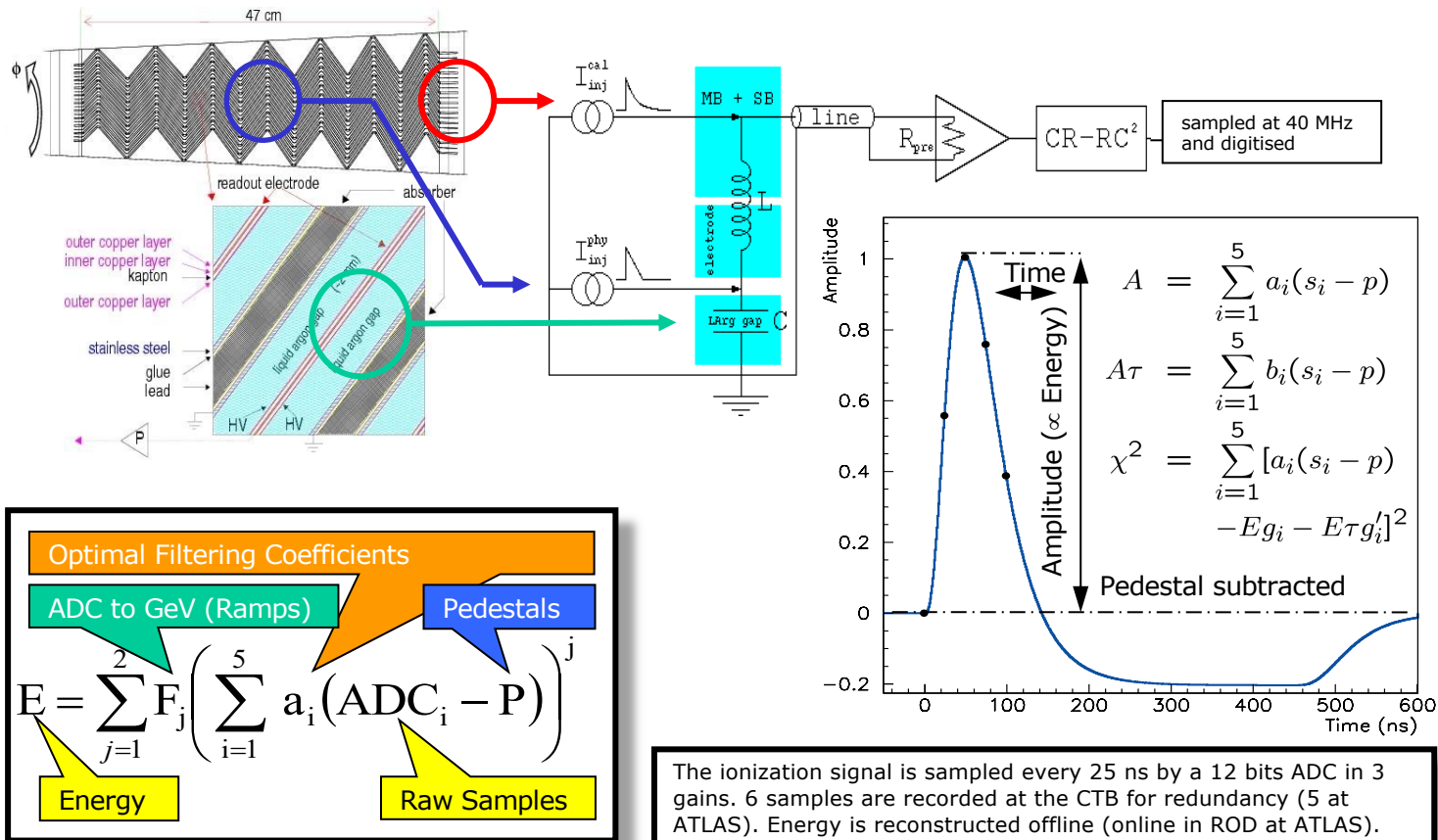
... and reconstructed through the full readout chain. The actual gain of each readout channel is computed.



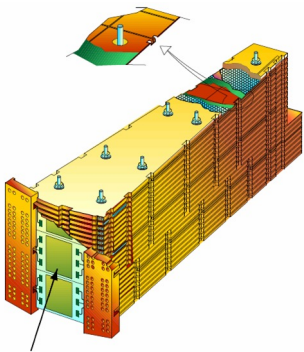
But the **triangular** ionisation signal is generated at the LAr gap level!

- Why can't we directly use the measured ionization signal?
 - It's not easy to measure it (needs asynchronous beam, sensitive to cross-talk, ...)
 - How do we normalize? We do not know the input current...
 - Well, if your performance requirements are not too tight (e.g. FCAL) you can use the pulses measured at the test beams

From digits to “raw” energy, minimizing noise



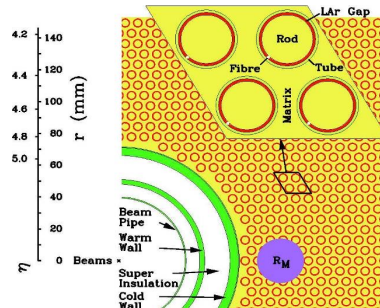
What's common, what's different



The **HEC** cells are pretty large, they are readout by several preamplifier, and **pulsed by 4 different calibration lines**: For this reason, we get **4 separated calibration objects** (Ramps, Delay) from each cell that needs to be averaged later on

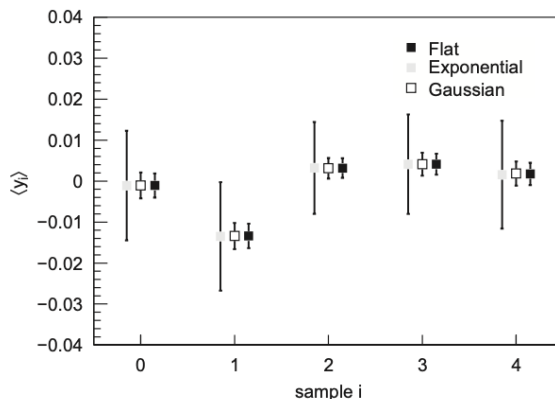
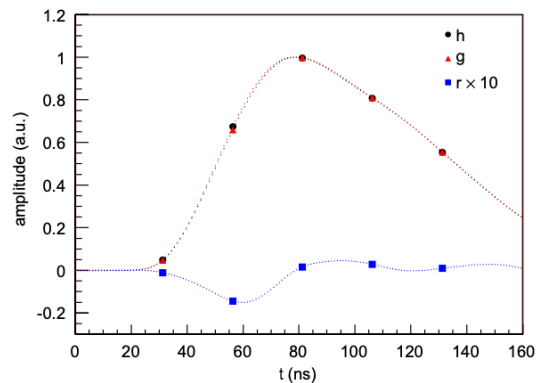
$$E_{\text{cell}} = F_{\text{DAC} \rightarrow \mu\text{A}} \cdot F_{\mu\text{A} \rightarrow \text{MeV}} \cdot \frac{1}{\frac{M_{\text{phys}}}{M_{\text{cali}}}} \cdot G_1 \cdot \sum_{i=1}^{N_{\text{samples}}} a_i (s_i - p)$$

The **FCAL** does not predict its ionization pulse shapes from the calibration ones. Since the performance requirements are more relaxed, it just uses the measured pulses from the beam tests. As a consequence, **$M_{\text{phys}}/M_{\text{cali}} = 1$**



Pulse shape *and* normalization are needed!

- One can derive (correction to) the pulse *shape* from data, but not the *normalization*!



Quality factor analysis and optimization of digital filtering signal reconstruction for liquid ionization calorimeters

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ABSTRACT

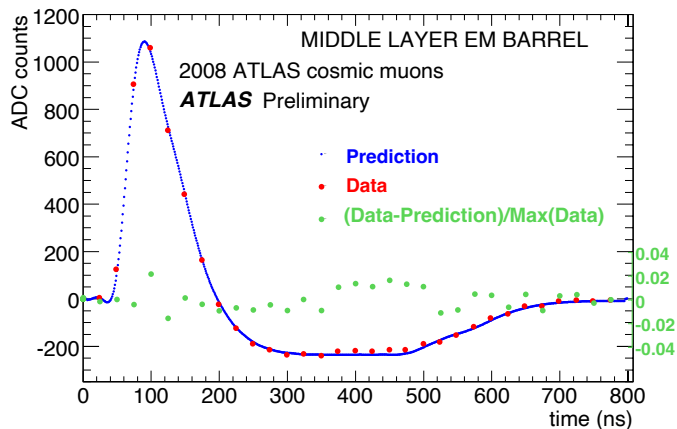
The Optimal Filtering (OF) reconstruction of the sampled signals from a particle detector such as a liquid ionization calorimeter relies on the knowledge of the normalized pulse shapes. This knowledge is always imprecise, since there are residual differences between the true ionization pulse shapes and the predicted ones, whatever the method used to model or fit the particle-induced signals. The systematic error introduced by the residuals on the signal amplitude estimate is analyzed as well as the effect on the quality factor provided by the OF reconstruction. An analysis method to evaluate the residuals from a sample of signals is developed and tested with a simulation tool. The correction obtained is showed to preserve the original amplitude normalization, while restoring the expected χ^2 -like behavior of the quality factor.

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Quality factor

OFC-reconstructed amplitude



$$Q^2 = \sum_i \left(s_i - \tilde{A} g_i \right)^2$$

- Used to reject spurious signals
 - ✓ e.g. noise bursts
- Ideally distributed as a χ^2
- Due to residuals in pulse prediction, has a dependency on energy!

$$\begin{cases} r_i = 0 \\ \epsilon = 0 \end{cases} \Rightarrow Q^2 = \sum_i (n_i + g_i \mathcal{N})^2$$

$$\Rightarrow \frac{Q^2}{(N_{\text{samples}} - 1) \sigma_n^2} = \chi^2 (\text{n.d.f} = N_{\text{samples}} - 1)$$

$$\begin{cases} r_i \neq 0 \\ \epsilon \neq 0 \end{cases} \Rightarrow Q^2 = \sum_i [(n_i + g_i \mathcal{N}) - A(r_i + \epsilon g_i)]^2$$

$$\Rightarrow \frac{Q^2}{(N_{\text{samples}} - 1) (\sigma_n^2 + (kA)^2)} \sim 1$$

