Signal Reconstruction in ATLAS Tile Calorimeter using Run 3 Real Data and Perspectives for the Phase-II Operation

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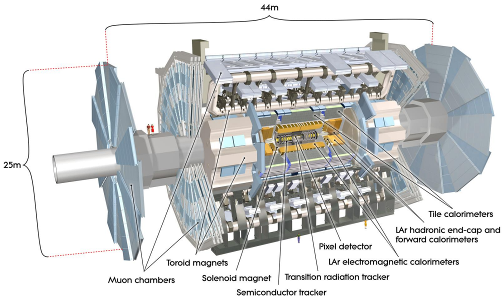
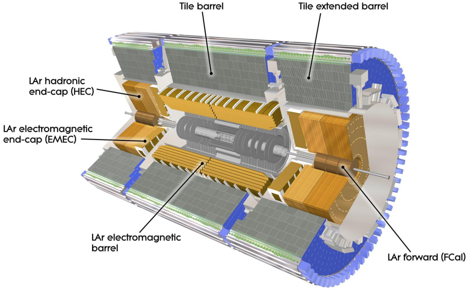
Agenda

The ATLAS experiment at LHC

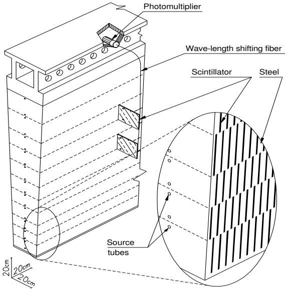
- One of the largest experiments at LHC.
- General purpose, covering a large range of physics program.
- It is divided into three sections: two extended barrels and one central barrel.
- The calorimeter is composed of two systems: electromagnetic and hadronic.

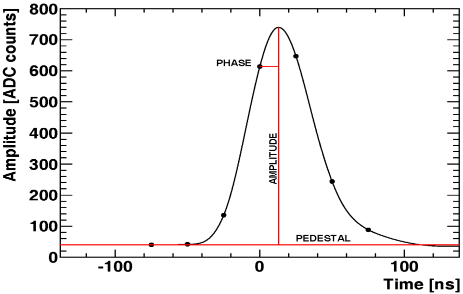




The ATLAS Tile Calorimeter (TileCal)

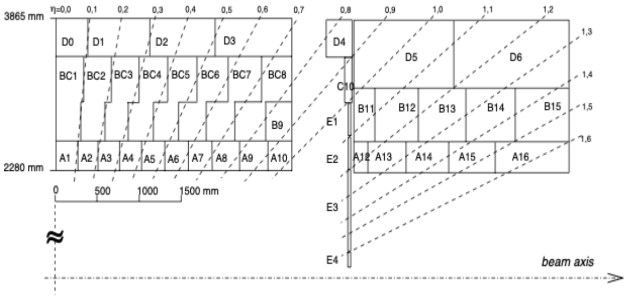
- TileCal: main hadronic calorimeter at ATLAS ($|\eta| < 1.7$).
- Sampling calorimeter: energy is absorbed and sampled by scintillating tiles.
- Light is converted into electric signals (PMT) that is conditioned and digitized in such a way that the amplitude is proportional to the energy.
- Energy is reconstructed by estimating the amplitude of the digitized pulse using an Optimal Filter (OF) algorithm (approximately 5,000 cells with double readout).

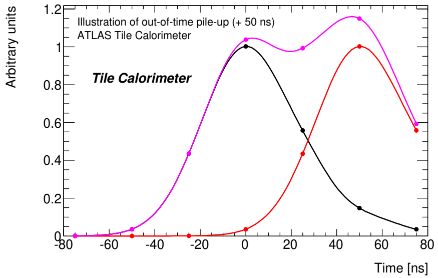




The Calorimetry energy reconstruction task

- Challenge: Increase of luminosity (LHC upgrade program) leads to signal pile-up which distorts the expected pulse shape.
- The pile-up effect introduces correlations and nonlinearities to the noise, degrading the efficiency from typical OF approaches.
- How can we mitigate the pile-up in the readout signal considering the cell segmentation?





Optimal Filter (OF) algorithm

- Calorimeter response signal is modeled as:

$$x[k] = Ag[k-\tau] + n[k] + ped$$

and the signal amplitude (energy) estimation is based on:

$$\hat{A} = \sum_{k=0}^{N-1} x[k]w[k]$$

where the filter coefficients $\mathbf{w}$ is calculated in order to minimize the variance of the estimation error subject to a set of constraints.

$$\text{i)} \sum_{k=0}^{N-1} w[k]g[k] = 1 \qquad \text{ii)} \sum_{k=0}^{N-1} w[k]\dot{g}[k] = 0 \qquad \text{iii)} \sum_{k=0}^{N-1} w[k] = 0$$

where $\mathbf{g}$ and $\dot{\mathbf{g}}$ represent the reference pulse (shaper) and its derivative, respectively.

Optimal Filter (OF) algorithm

- Matrix representation of how the set of optimal weights **w** can be computed:

$$\begin{pmatrix} C[1,1] & \cdots & C[1,N] & -g[1] & -\dot{g}[1] & -1 \\ C[2,1] & \cdots & C[2,N] & -g[2] & -\dot{g}[2] & -1 \\ \vdots & \ddots & \vdots & \vdots & \vdots & \vdots \\ C[N,1] & \cdots & C[N,N] & -g[N] & -\dot{g}[N] & -1 \\ g[1] & \cdots & g[N] & 0 & 0 & 0 \\ \dot{g}[1] & \cdots & \dot{g}[N] & 0 & 0 & 0 \\ 1 & \cdots & 1 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} w[1] \\ w[2] \\ \vdots \\ w[N] \\ \lambda \\ \xi \\ v \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ \vdots \\ 0 \\ 1 \\ 0 \\ 0 \end{pmatrix}$$

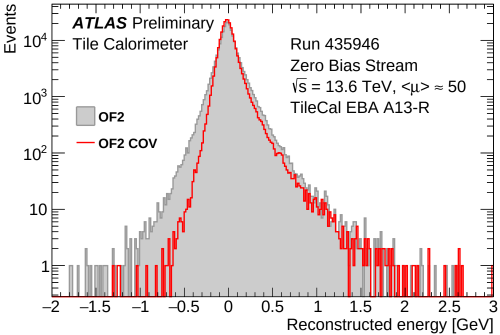
  where C corresponds to the noise covariance matrix, and λ, ξ, and v are the Lagrange multipliers.
- Although the pile-up introduces non-gaussian components to the noise, the noise covariance matrix C improves the OF performance.
- However, currently, C is equal to the identity matrix, assuming a white gaussian noise.

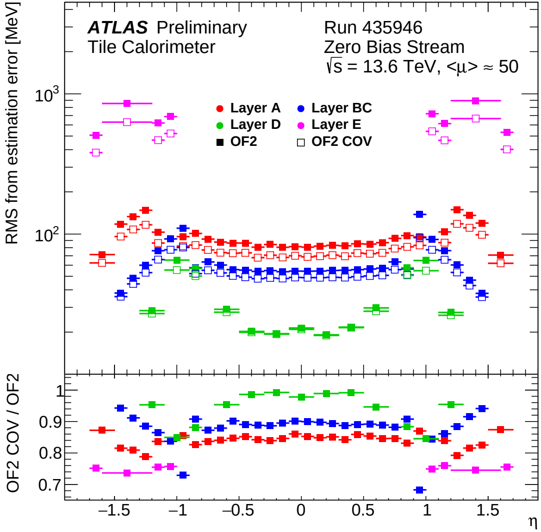
Data set

- The computation of the optimized OF weights (OF2 COV) for all TileCal channels using the noise covariance information was performed, and the improvement with respect to current OF weights was evaluated.
- The improvement was measured by computing the difference between the reconstructed energy and the expected value.
- Real data from October 2022 (Zero Bias Stream Run 438737, $48 \leq \mu \leq 52$) was used for OF weights computation, and another 2022 dataset (Zero Bias Stream Run 435946, $30 \leq \mu \leq 50$) was used for performance evaluation.
- The noise matrix C impacts on the computation of OF weights.

Optimal Filter performance evaluation

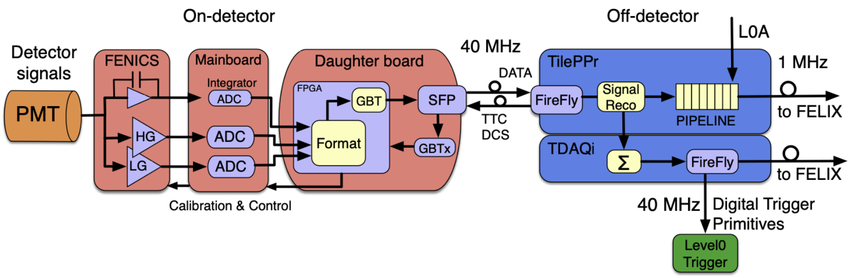
- Zero Bias signals (test set) were applied to the different versions of the OF method.
- The RMS values from the energy histograms are used for performance comparison.
- The optimized version (OF2 COV) produces a smaller dispersion and a smaller negative tail with respect to the usual OF (OF2).





Online energy estimation for HL-LHC operation

- The TileCal electronics will be upgraded for the HL-LHC era.
- Energy estimation to be performed at the TileCal PPr stage in a streaming mode.
- A memory buffer will be available for online energy reconstruction.
- New electronics will allow the implementation of more advanced methods.
- Linear and machine learning strategies to be assessed for bunch crossing assignment and energy estimation.



Online energy estimation for HL-LHC operation

- A linear approach based on the Least Squares (LS) for online energy estimation has been tested using data simulated by the Athena Pulse Simulator (collaboration's official toy).
  - Minimizes the sum of the squares of the residuals.
  - Computation of the LS coefficients θ:

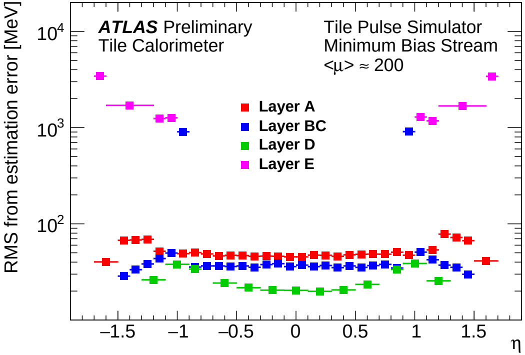
$$\theta = \left(\mathbf{H}^\top \mathbf{H}\right)^{-1} \mathbf{H}^\top \mathbf{y}$$

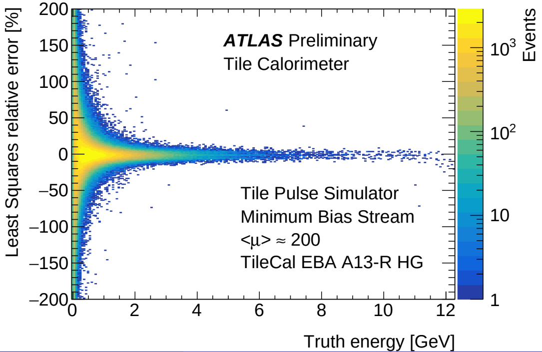
  where **H** is the data matrix, and **y** corresponds to the vector of reference values.

- **Performance evaluation**:
  - Data sets with 1 million events each were generated for various $< \mu >$ values ranging from 10 to 200, simulating different occupancy conditions.
  - Estimation error was evaluated for each order using test datasets by subtracting the LS output from the true amplitude known from the simulation.
  - It has been observed that the LS technique achieves its best performance with a minimum of 15 coefficients, considering different occupancy levels.

Online energy estimation for HL-LHC operation

- The performance is assessed through the estimation error (difference between the reconstructed energy and the truth energy).
- The LS strategy is unbiased regardless the signal energy range.
- Layer E presents the largest error due to its high occupancy condition.
- Also, as expected, the higher the truth energy is, the smaller the relative error becomes.





Conclusions

- The signal pile-up effect can be minimized by computing the correct Optimal Filter coefficients according to the luminosity information.
- The estimation error can be reduced up to 15% in most cells when using the optimized OF method with respect to the non-optimized OF version.
- Considering the ATLAS phase-II upgrade, the digital processing procedure will change, from fixed readout window to streaming mode, where the energy from all bunch crossing will be computed.
- A linear strategy based on Least Squares presents a simple and fast promising alternative.
- Computational intelligence approaches are also being developed and tested within the TileCal upgrade program.

Thank you!

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