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Energy Reconstruction of the ATLAS Tile Calorimeter under high pile-up conditions using the Wiener filter

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Outline

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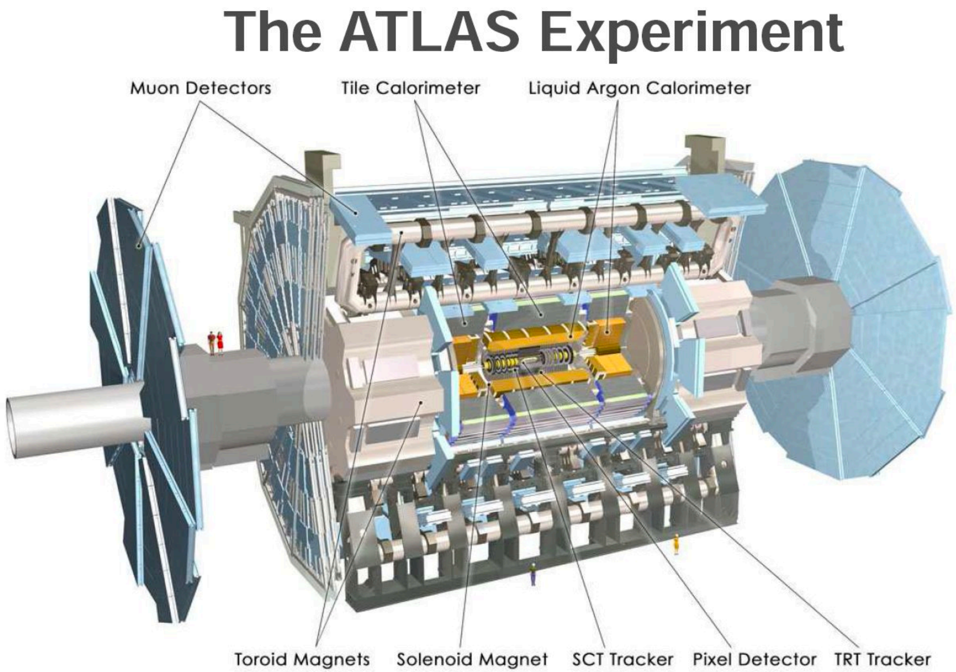
- ✦ Pile-up in the ATLAS Tile Calorimeter (TileCal)
- ✦ TileCal Energy Estimation Method
- ✦ Wiener Filter Estimation Method
- ✦ Performance Evaluation
- ✦ Summary

The ATLAS experiment



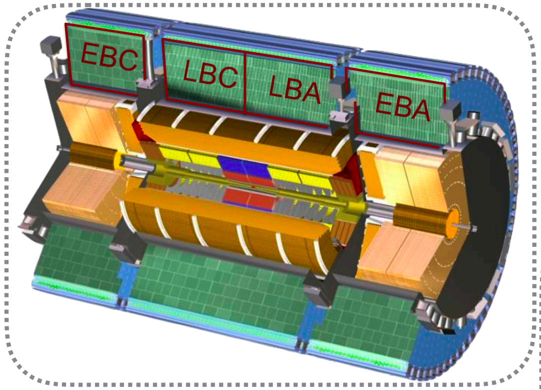
Inner detector

- ✦ Pixel detector
- ✦ SemiConductor tracker (SCT)
- ✦ Transition Radiation Tracker (TRT)

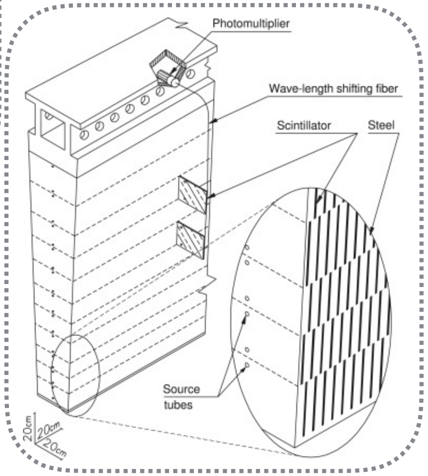
Calorimeter

- ✦ Finely segmented calorimeter system
- ✦ Liquid Argon Calorimeter

- ✦ **Tile Hadronic Calorimeter**



- ✦ **Divided onto long barrel (LBA and LBC) and two extended barrels (EBA and EBC)**



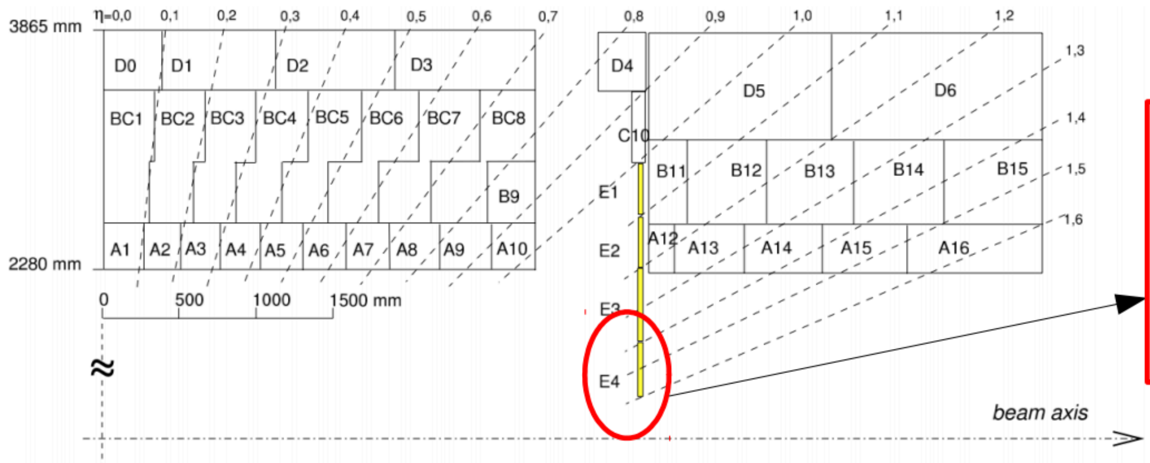
- ✦ **Composed by approximately 5000 cells and 10000 channels, as most of the cells are composed of two readout channels**

Trigger system

- ✦ Reduces event rate to 1kHz from beam crossing rate of 40MHz
- ✦ Based on Region of Interest (ROI) concept
- ✦ Software based High Level Trigger is seeded by hardware based Level 1 (L1) trigger

Motivation

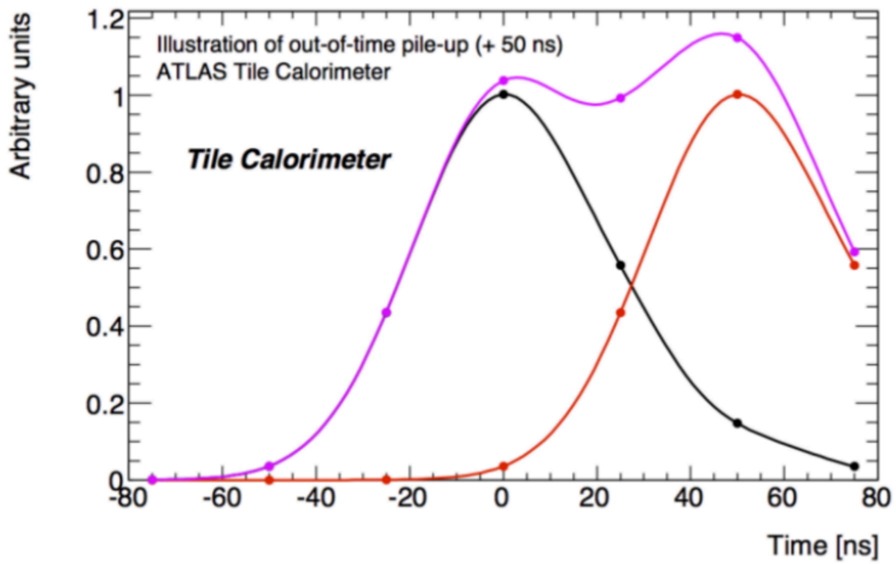
- TileCal cells are divided into 4 layers (A, BC, D and E) according to their physical position with respect to the beam axis
- Most of TileCal cells, especially the ones in layers BC and D, are not severely affected by the signal pile-up, considering the current LHC luminosity
- However, the E layer is strongly affected
- Particularly, the E4 cells are of our interest due to their intense activity (worst case among TileCal cells)



- E4 cells are the worst case in terms of signal pile-up in TileCal.
- Therefore, they are used in this study.

Pile-up in TileCal

- At high occupancy channels (such as E4) adjacent collisions are observed within same readout window, causing signal pile-up
- In such conditions, noise comprises typical electronic noise plus pile-up noise, which degrades energy estimation efficiency
- A higher pile-up rates are expected with the increase of LHC luminosity in 2023



TileCal Energy Estimation Method

✦ The Optimal Filter (OF2) is the current energy reconstruction method used in TileCal

It performs the optimisation procedure subjected to the following constraints:

$$\sum_{i=1}^{N} g_i w_i = 1$$

- Regarding the energy scale factor

$$\sum_{i=1}^{N} g'_i w_i = 0$$

$$\sum_{i=1}^{N} w_i = 0$$

- Make the estimation procedure immune against phase and baseline fluctuations

g and g' are the TileCal reference pulse shape and its derivative
w corresponds to the OF2 weights

N is the number of TileCal reference pulse shape samples

TileCal Energy Estimation Method

The weights can be found by solving the following matrix system using Lagrange multipliers:

$$\begin{pmatrix} C_{1,1} & \dots & C_{1,7} & -g_1 & -g'_2 & -1 \\ \vdots & \ddots & \vdots & \vdots & \vdots & \\ C_{7,1} & \dots & C_{7,7} & -g_7 & -g'_7 & -1 \\ g_1 & \dots & g_7 & 0 & 0 & 0 \\ g'_1 & \dots & g'_7 & 0 & 0 & 0 \\ 1 & \dots & 1 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} w_1 \\ \vdots \\ w_7 \\ \lambda \\ \xi \\ \upsilon \end{pmatrix} = \begin{pmatrix} 0 \\ \vdots \\ 0 \\ 1 \\ 0 \\ 0 \end{pmatrix}$$

Where λ, ξ, υ are the Lagrange multipliers and C is the noise covariance matrix

The amplitude estimation is given by:

$$\hat{A} = \sum_{i=1}^{N} s_i \, w_i$$

Where s_i correspond to the received ADC samples

The Optimal Filter method assumes:

- Deterministic pulse model
- Additive Gaussian noise

The method efficiency degrades with the increasing of luminosity because of the pile-up effect!

Wiener Filter Estimation Method

- The Wiener filter calculates optimal weights by using the statistics of the input and output signals

The idea is to minimize the expected value of the squared error:

$$J = E[(\hat{A}-A)^2]$$

Let R denote the N-by-N correlation matrix of the inputs $u(n), u(n-1), \ldots u(n-N+1)$:

$$R = E[u(n)u^H(n)]$$

Correspondingly, p is denoted as N-by-1 cross-correlation vector between the inputs of the filter and the desired response d(n):

$$p = E[u(n)d(n)]$$

Wiener Filter Estimation Method

The wiener equation can be rewritten in the compact matrix form:

$$Rw = p \quad \longrightarrow \quad \boxed{w = R^{-1}p}$$

Inclusion of an additional weight in the optimization procedure:

In order to absorb bias (mean of the error) an element "1" is added to each input signal, as last element.

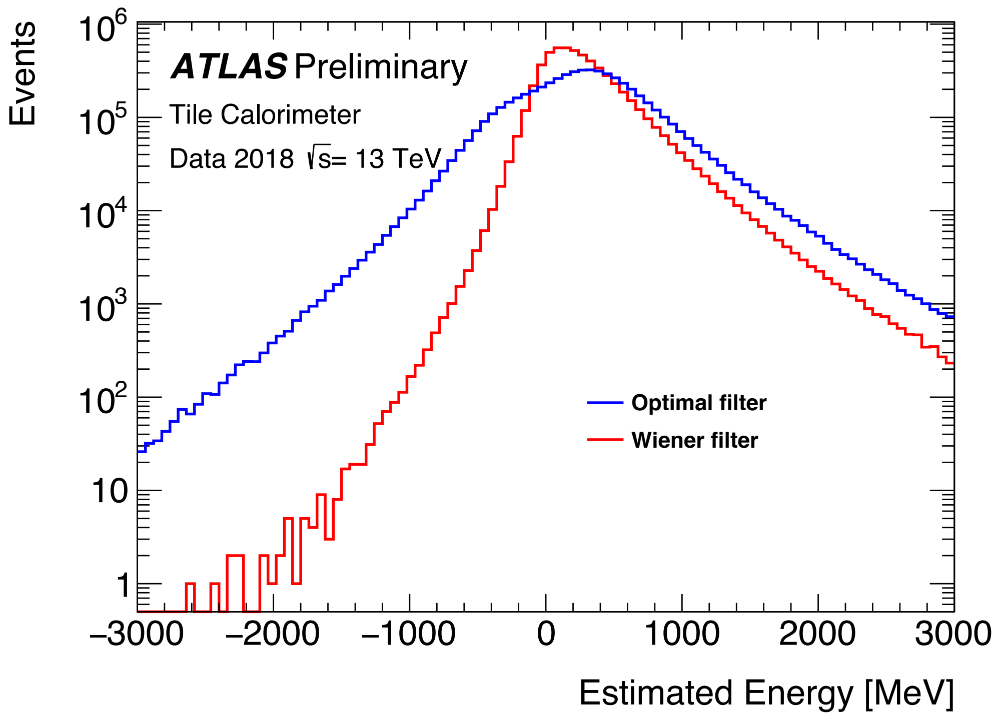
The amplitude estimation is given by:

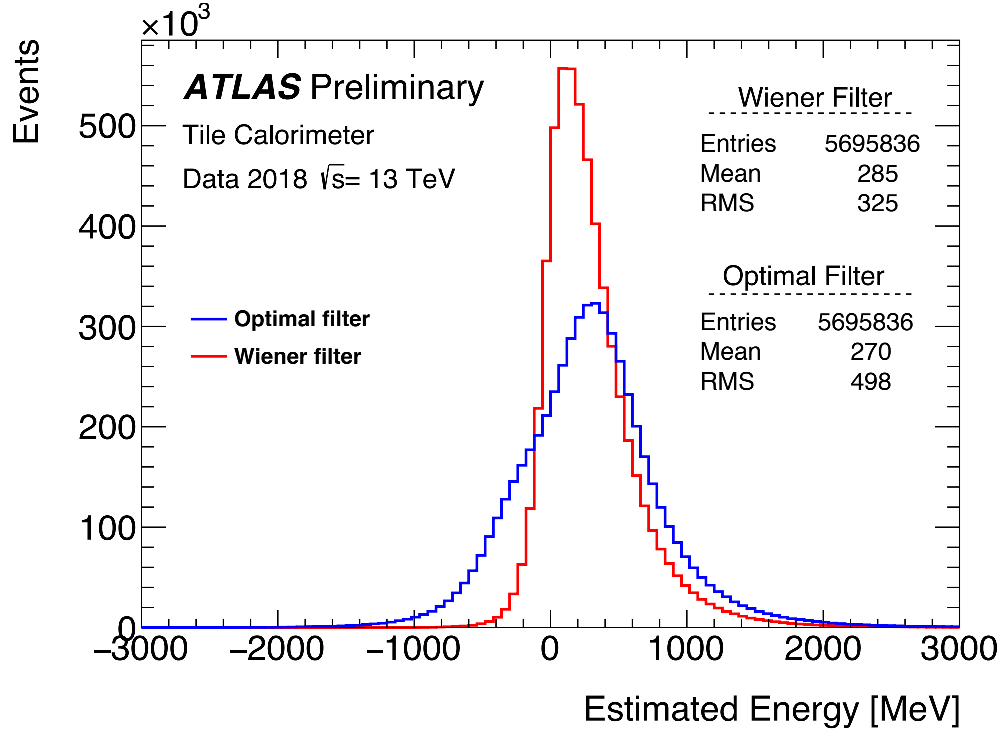
$$\hat{A} = \sum_{i=1}^{N} s_i w_i + w_{N+1}$$

Where, w_{N+1} corresponds to the bias that is subtracted in each estimation

Performance Evaluation

- Results for EBA E4 cells
  - Proton-proton collision data from a special run with high number of inelastic collisions per beam crossing (<μ>) with peak <μ>=90 collected with ATLAS detector at 13 TeV in October 2018





- The negative tail in OF2 energy distribution corresponds to the out-of-time pileup
  - The current OF2 implementation is not being able to deal with this
- The Wiener Filter method shows smaller RMS of the estimation error

Performance Evaluation

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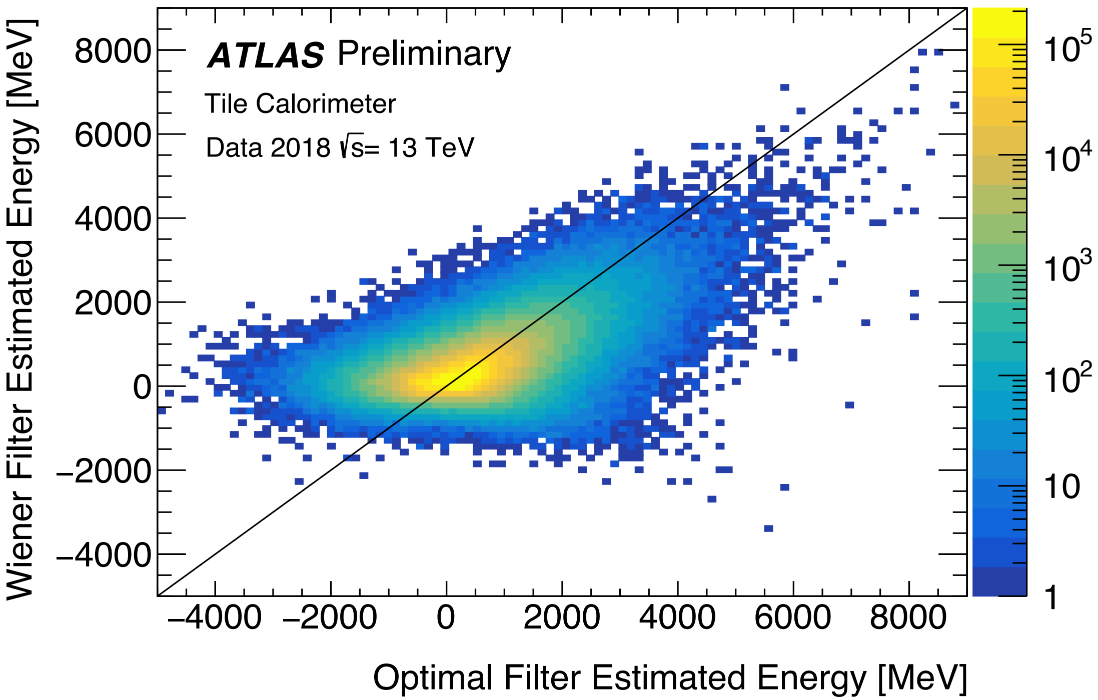

- The OF2 shows a greater dispersion in the negative region of the correlation graph
- The Wiener Filter is based on second - order statistics
  - It does not treat noise optimally, since higher order statistics are not absorbed
  - The method is linear, simple and fast to operate online and offline

Summary

- The Wiener Filter approach has shown to be a good alternative to estimate the energy in high occupancy cells (E4 case)
- Using the Wiener Filter to estimate the energy improves the RMS error of the distribution
- The Wiener Filter efficiency is being evaluated in studies where E cells information is extremely important, such as calibration and objects identifications
- The Wiener Filter is being considered as an alternative to energy reconstruction in TileCal high occupancy cells
  - A tool to reconstruct TileCal signal with Wiener Filter was developed in Athena (ATLAS software framework that manages almost all ATLAS production workflows)
  - Final tests are being done to validate the tool
  - The studies are going to be expanded for the others TileCal E cells