The TileCal Energy Reconstruction for Collision Data Using the Matched Filter

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On behalf of the ATLAS Collaboration

2013 IEEE NSS/MIC/RTSD

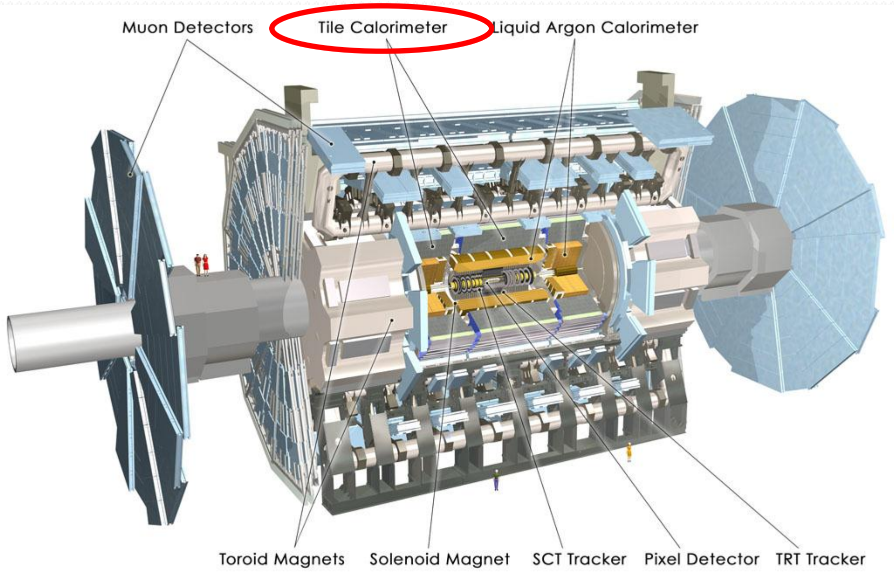
"Beyond Imagination of Future Science"

Agenda

- The ATLAS Tile Calorimeter (TileCal)
- TileCal Energy Reconstruction Methods
  - Current algorithm used in TileCal
  - The Matched Filter method
- Energy Reconstruction Performance Using Collision Data
- Conclusions

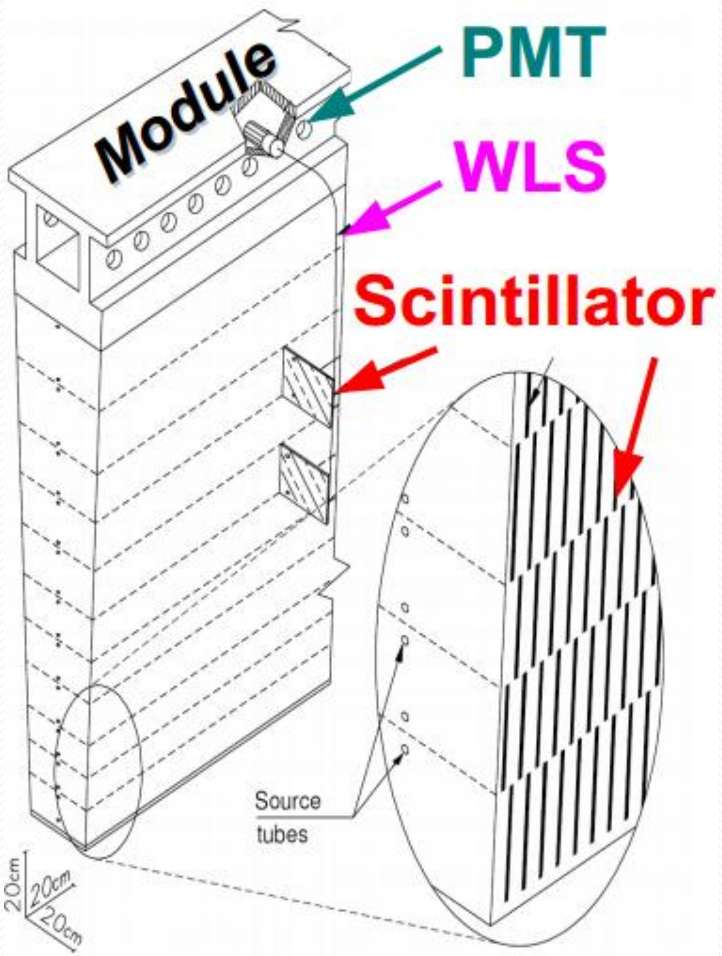
TileCal

- ATLAS central hadronic calorimeter
- Measures the energy and direction of jets and hadrons
- Total length 12 m, diameter 8.8 m, weight 2,900 tons
- Three cyllinders covering $|\eta|<1.7$ (divided in 4 partitions)
- 64 wedges (modules) each partition
    - 48 cahnnels central partition, 32 channels extended partition (aprox. 10,000 signals available)
- TileCal cell comprises two channels (double readout)



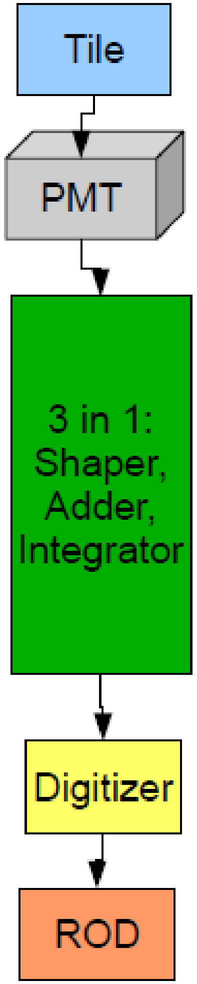
TileCal modules

- Sampling calorimeter
  - Steel plates as absorbing material
  - Plastic scintillating tiles as active medium
- Light produced in scintillators are transmitted by wavelength shifting (WLS) fibers up to PMTs (Hamamatsu R7877)
- Front-end electronics and PMTs located in drawers in the outermost side of the modules



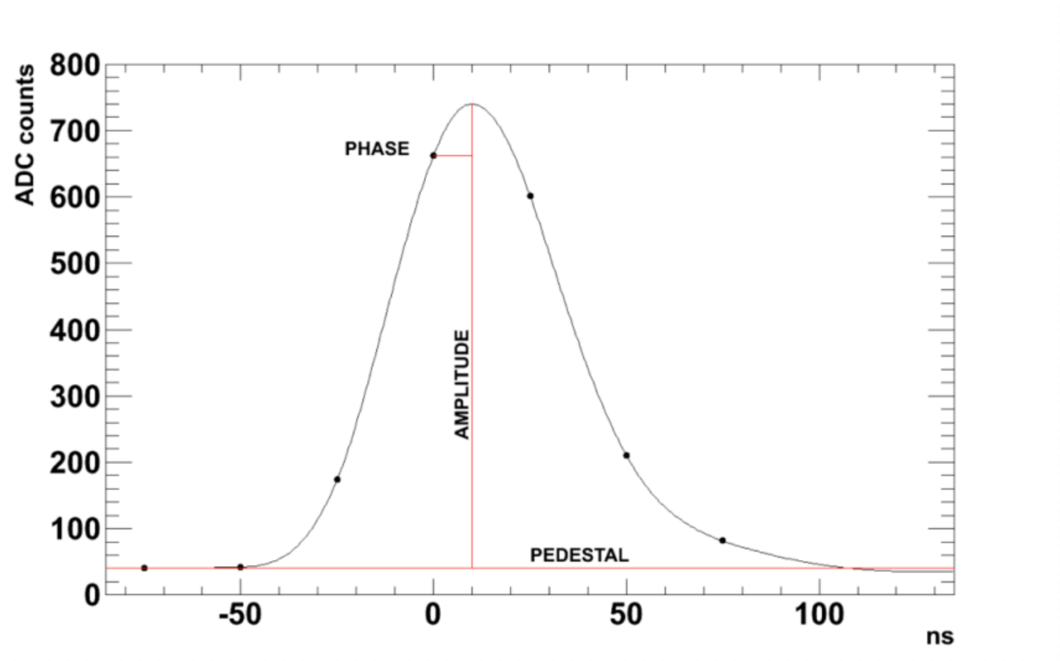
TileCal signal processing

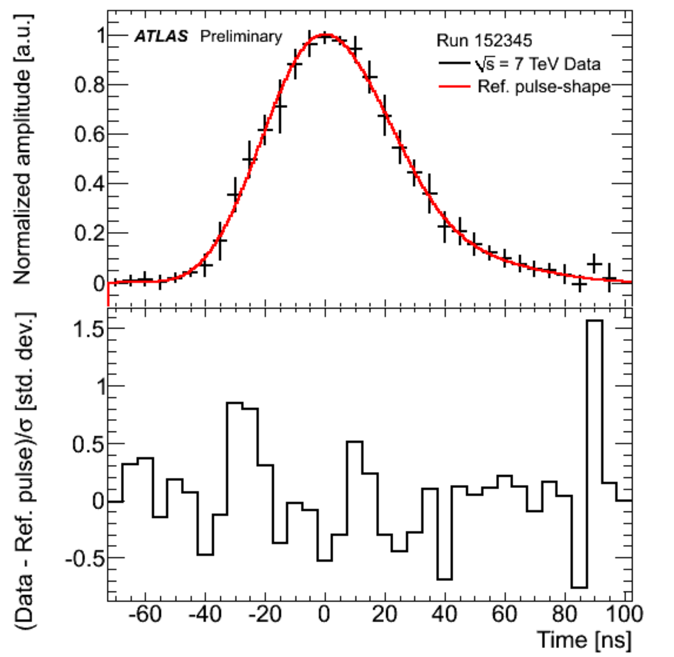
- PMT output signal is shaped and amplified with two different gains (1:64)
- Pulse amplitude is proportional to signal energy
- Signals are sampled at the LHC clock frequency (40 MHz) and digitized samples are sent to ROD (7 samples) for Level-1 accepted events
- Digital signal processing is carried out at ROD level
- Raw data from all signals above 5 ADC counts (approximately 70 MeV) are recorded for offline analysis (zero suppression)



TileCal signal characteristics

- Stable pulse
- Tolerance in the electronics leads to small variations
- Energy and time (phase) estimated from amplitude estimation





Energy Reconstruction

- Currently, the Optimal Filter (OF) algorithm is used online and offline
- Amplitude recovered from weighted sum operation:

$$\hat{A}_{OF} = \sum_{i=0}^{N-1} r_i a_i$$

r are the received samples and ***a*** the OF weights

- Variance minimization approach
- Constraints are applied for weights computation:

$$1)\ \sum_{i=0}^{N-1} a_i g_i = 1, \qquad 2)\ \sum_{i=0}^{N-1} a_i g'_i = 0, \qquad 3)\ \sum_{i=0}^{N-1} a_i = 0$$

g and ***g'*** are the reference pulse shape and its derivative, respectively

A Matched Filter (MF) for TileCal

- Signal detection filter based on the likelihood ratio test (known to be optimum detector in the SNR sense):

$$L(\boldsymbol{r};\boldsymbol{R}) = \frac{f_{\boldsymbol{r}|H_1}(\boldsymbol{R}|H_1)}{f_{\boldsymbol{r}|H_0}(\boldsymbol{R}|H_0)} \underset{H_0}{\overset{H_1}{\gtrless}} \gamma$$

H1 and *Ho* corresponds to the "signal+noise" and "only noise" hypotheses, respectively, ***r*** the received sample from observation **R**, and γ the detection threshold. $f_{\boldsymbol{r}|H_1}$ is the Probability Density Function for H_1 case, while $f_{\boldsymbol{r}|H_0}$ is for H_0 case.

- Assuming the background noise as zero mean Gaussian, and the pulse shape fixed, the likelihood ratio test becomes:

$$L(\boldsymbol{r}) = \frac{e^{-\frac{(\boldsymbol{r}-\boldsymbol{g})^T\boldsymbol{C}^{-1}(\boldsymbol{r}-\boldsymbol{g})}{2}}}{e^{-\frac{\boldsymbol{r}^T\boldsymbol{C}^{-1}\boldsymbol{r}}{2}}} \Rightarrow \boldsymbol{r}^T\boldsymbol{C}^{-1}\boldsymbol{g} \underset{H_0}{\overset{H_1}{\gtrless}} \gamma'$$

where ***C*** is the noise covariance matrix

A Matched Filter (MF) for TileCal

- If the received signal can be modelled as:

$$r_i = A\, g_i + ped + n_i$$

where *ped* is an estimate of the signal baseline and $\boldsymbol{n}$ are the noise samples

- The amplitude of the signal can be extracted from the Matched Filter output:

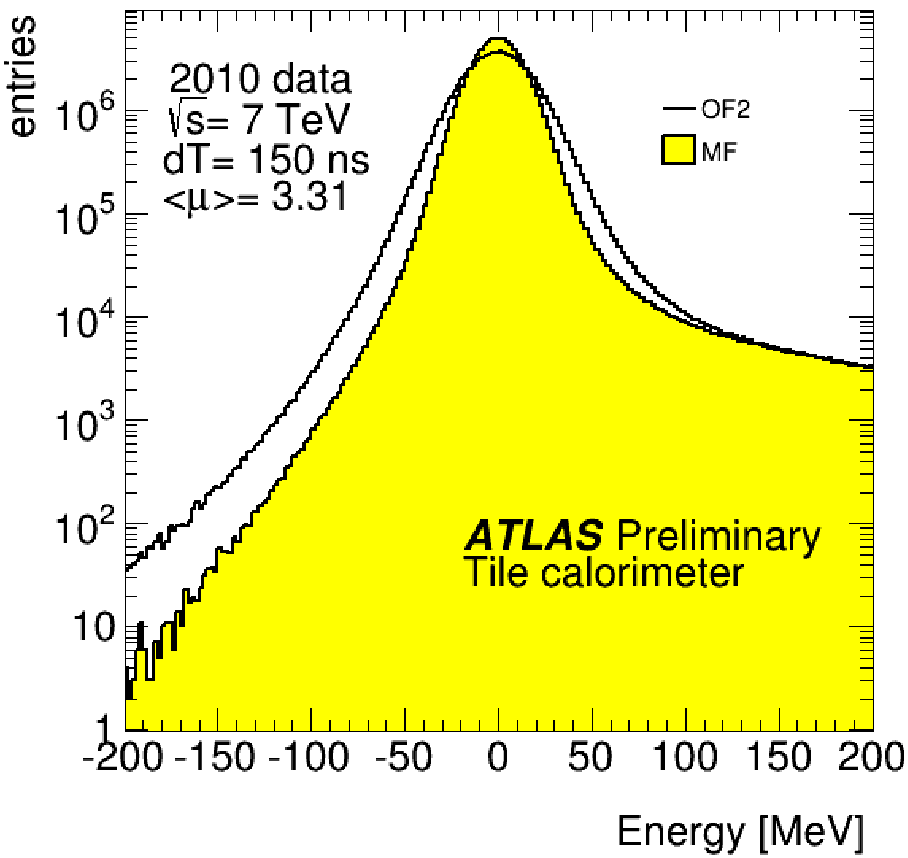
$$\hat{A}_{MF} = \frac{1}{\boldsymbol{g}^T \boldsymbol{C}^{-1} \boldsymbol{g}} \cdot (\boldsymbol{r} - ped)^T \boldsymbol{C}^{-1} \boldsymbol{g}$$

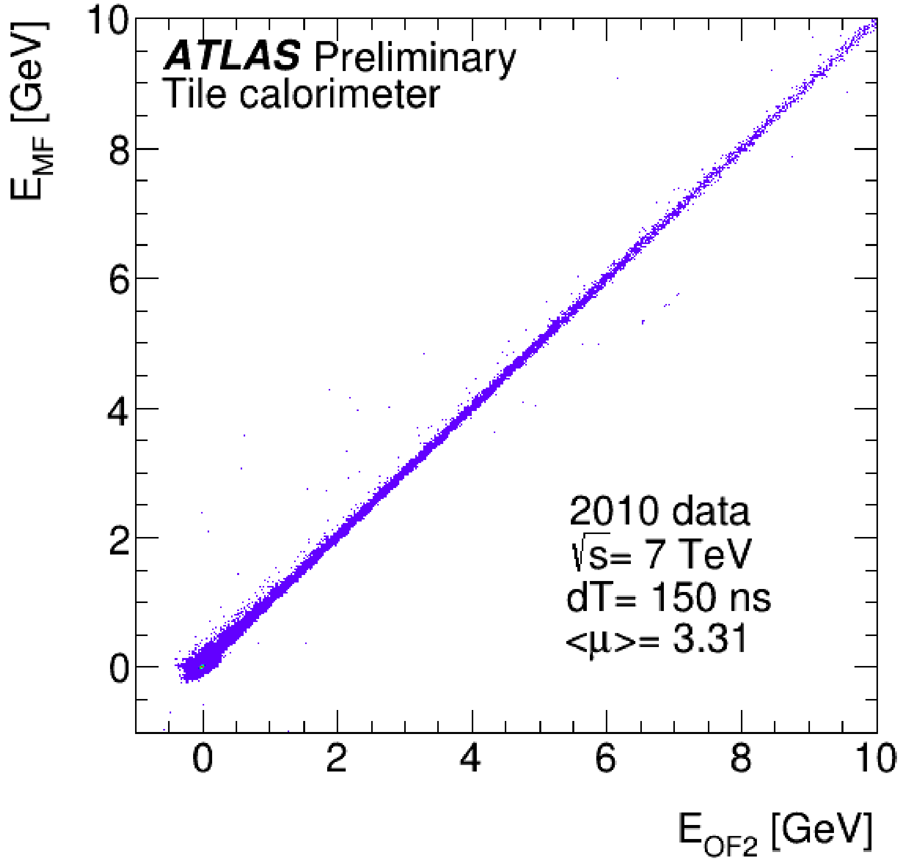
- MF uses the reference pulse shape ($\boldsymbol{g}$), the noise covariance ($\boldsymbol{C}$) matrix and a pedestal estimate (*ped*) to compute the amplitude
- Computing power needed by the algorithm is available offline, although some values could be parametrized and stored in the conditions DB to alleviate the processing

Results (low pile-up)

- Data: 2010 collision run where LHC operated at 150 ns of minimum Bunch Spacing (BS) and $<\mu>=3$, which is mean of the number of *p-p* interactions per Bunch Crossing (BC)
- Under these conditions the reconstruction is almost not affected by Out-Of-Time (OOT) signals
- Therefore, the background comprises only electronic noise (Gaussian like) and the methods operate close to their optimum performance

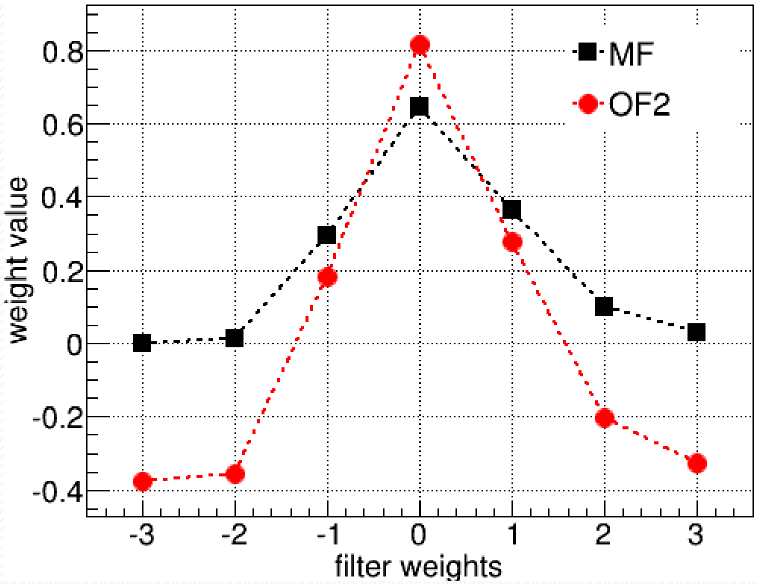
Results (low pile-up)



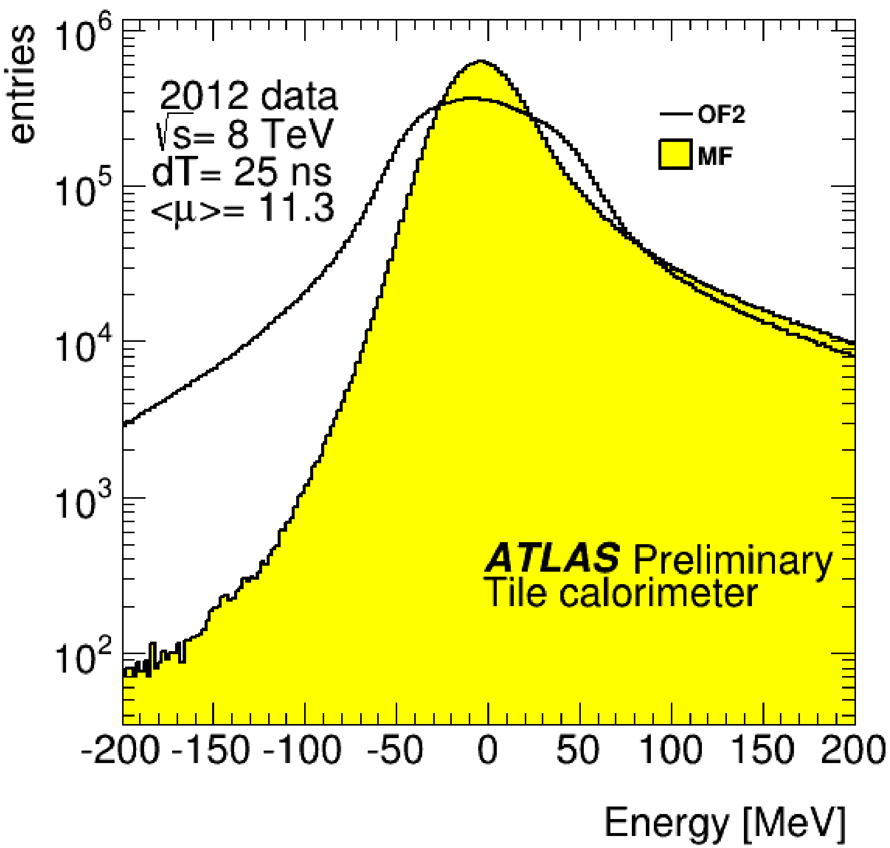


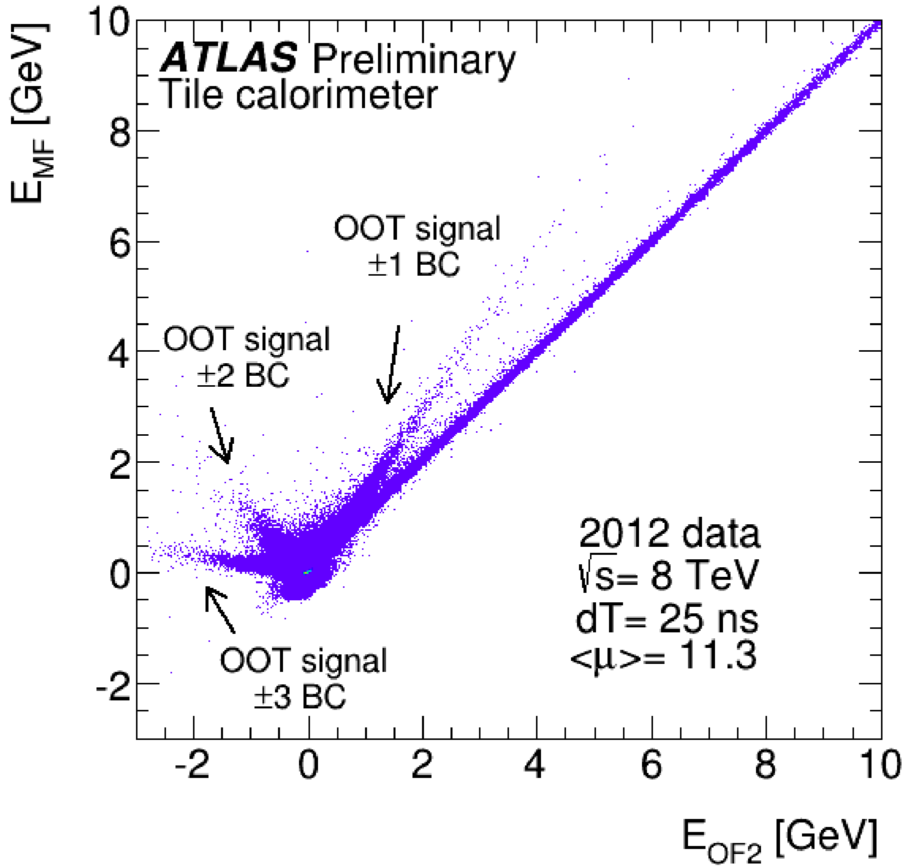
Results (higher pile-up)

- Data: 2012 collision run where LHC operated at 25 ns BS and <μ>=11
- Under these conditions, the background noise comprises the electronic Gaussian convolved with the pile-up (log-normal like)
- As a result of the presence of the OOT signals, both OF and MF decrease in performance: **increase in variance and biased results**
- Filter weights impact on bias



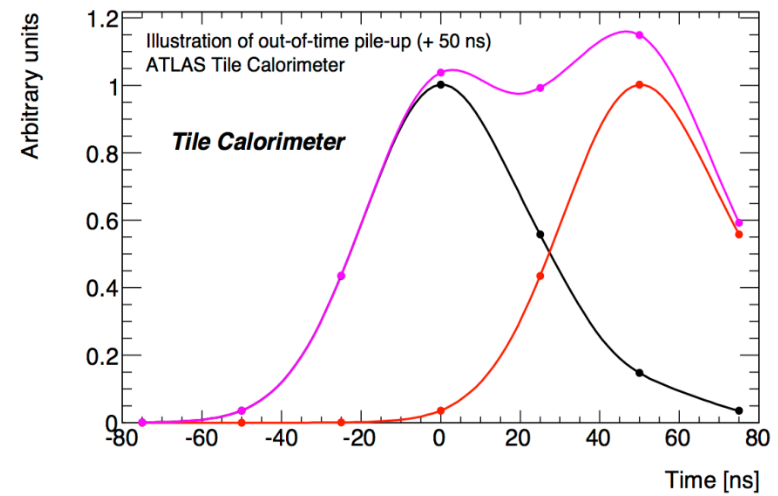
Results (higher pile-up)





Other Reconstruction Techniques

- OF and MF (Finite Impulse Response filters) :
  - The usage of the covariance matrix may reduce the bias introduced by the OOT signals (log-normal like model), however the methods may become "pile-up dependent"
  - Suitable for DSP devices (fast), and simple offline implementation
- Signal deconvolution approach:
  - Considers the pile-up as a linear mixture and finds a transformation that recovers the OOT signals amplitudes (available)
  - Background noise only Gaussian, and it becomes "luminosity independent"
  - Matrix operations (suitable for FPGA devices)
  - However, no restrictions for offline use



Conclusions

- The Matched Filter technique for energy reconstruction was presented
- A comparison with the current method (OF) was performed using collision data recorded during LHC operation
- MF showed lower estimation error (smaller dispersion under non pile-up data) due to stronger optimization approach
- Under pile-up conditions, both OF and MF implementations are biased, but the usage of the covariance matrix for noise description is expected to reduce it
- Alternative reconstructions are under evaluation, like the signal deconvolution method that makes use of a proper description of the OOT signals