Correlated noise unfolding on a Hadronic Calorimeter

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Abstract—The correlated noise component of TileCal, the barrel hadronic calorimeter of the ATLAS experiment at the Large Hadron Collider, is studied and an algorithm is used to parametrize and unfold it from the response of the photomultipliers. It is shown that the correlated noise component can be significantly reduced and mostly removed not only for pedestal runs, but also in the presence of physics signals like minimum bias events in 900 GeV collisions and 7 TeV simulated top quark pair production events.

I. INTRODUCTION

The ATLAS detector [1] is a general purpose detector designed to explore the physics potential of the Large Hadron Collider (LHC). ATLAS consists of several layers, each with a specific purpose on the reconstruction of particles. The main detector components are the Inner Tracker, the Electromagnetic and Hadronic Calorimeters and the Muon Spectrometer. The Tracker and the Muon Spectrometer are embedded in two powerful Magnet Systems. The central Hadronic Calorimeter (TileCal) [2], is composed by steel as the absorber and scintillating tiles as the active material.

The Tile Calorimeter consists of one central barrel (separated in LBA and LBC) and two extended barrels (EBA and EBC) composed of 64 wedges, also known as modules. The light produced by the particles that cross the TileCal tiles is collected at the two edges of the scintillating tiles by wavelength shifting (WLS) fibers which are bundled together to form cells with three sampling depths (A,BC and D) and with a transverse granularity of $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ (0.1×0.2 for the last layer). Every cell is readout from both sides by different channels in order to provide redundancy. The channels reading out a wedge are grouped in assemblies (drawers) of 48 readout units hosted inside the girder at the outer radius of the calorimeter. The signal pulse produced by each photomultiplier is shaped, amplified with two gain factors (low gain and high gain), whose nominal ratio is 1:64, by fast and low-noise front-end electronics. The amplified signals are sampled and digitized at 40 MHz by two 10-bit Analog to Digital Converters. During this process undesirable signal interference effects might occur as it has been reported in a previous study [3]. This will result in a correlated noise pattern between different channels which may have a negative impact on the TileCal performance. Finally, digitized samples - high-gain or low-gain depending on the signal amplitude,

are sent via optical links to off-detector back-end electronics. The correlated noise seems to manifest itself in regions of 6 or 12 channels, which is the extent of the digitizers and motherboards cards, respectively. There are “sensitive” areas in the drawer front-end (FE) assembly where the electromagnetic interference between the Low Voltage Power Supply (LVPS) and FE is pronounced, i.e. the area close to the LVPS (channels > 42) and the border between the two sub-assemblies (channels around 24). This effect is enhanced by the fact that switching DC-DC converters are used as LVPS.

II. TILECAL CORRELATED NOISE

The correlated noise in TileCal plays an important role in the pedestal fluctuations’ degradation. To address the problem, it is desirable to consider a general approach based on first principles which does not depend on the specific source of the problem. The approach presented assumes that the observed noise measurement (x_i) in a particular channel i of the TileCal module, is a combination of a genuine intrinsic noise component (β_i) plus a contribution which depends on the response of all readout channels in the module as a whole and it is probably dominated by the closest neighbors. The simplest approach to describe the noise measurement in channel i is then to consider x_i as being a linear combination between the intrinsic noise component (β_i) and a weighted sum of the signals of all the other readout channels (N) in the module i.e.,

$$x_i = \beta_i + \sum_{j \neq i}^N \alpha_{i,j} x_j. \quad (1)$$

where x_i and x_j are the noise signals for channels i and j respectively. These signals refer to the pulse amplitudes reconstructed by the non-iterative Optimal Filter method [4], [5] using the 7 digitized measurements of the pulse. The $\alpha_{i,j}$ unknown parameters ensure measurements from other readout channels are taken into account with different weights. Given the fact that pedestal subtracted signals around zero are used, the β_i values are expected to be zero. For each channel, the measured noise can be compared with the model above using

the usual χ^2 method,

$$\chi_i^2 = \sum_{\text{Events}} \frac{\left[x_i - (\beta_i + \sum_{k \neq i}^N \alpha_{i,k} x_k) \right]^2}{\sigma_i^2}, \quad (2)$$

which can be minimized (individually for each channel) with respect to each one of the $\alpha_{i,j}$ and β_i of the model,

$$\frac{\partial \chi_i^2}{\partial \alpha_{i,1}} = \frac{\partial \chi_i^2}{\partial \alpha_{i,2}} = \dots = \frac{\partial \chi_i^2}{\partial \alpha_{i,N}} = \frac{\partial \chi_i^2}{\partial \beta_i} = 0. \quad (3)$$

Assuming that the noise correlations are the same independently of the signal amplitude or, in other words, that no cross talk is present, the noise correlations information (embedded in the α matrix) can be extracted from the first out of seven digitized samples and the α matrix itself:

$$\begin{pmatrix} 0 & \alpha_{1,2} & \dots & \alpha_{1,N} \\ \alpha_{2,1} & 0 & \dots & \alpha_{2,N} \\ \dots & \dots & \dots & \dots \\ \alpha_{N,1} & \alpha_{N,2} & \dots & 0 \end{pmatrix}$$

The values of the α_{ij} and of the offset β_i are obtained with the minimization procedure. The reconstruction of the signal in channel i (s_i^{rec}) is performed by removing the offset evaluated during the minimization procedure β_i and by applying the α matrix to the measured values of all the other channels of the module according to,

$$s_i^{rec} = s_i - (\alpha_{i,1}x_1 + \alpha_{i,2}x_2 + \dots + \beta_i + \dots + \alpha_{i,N}x_N) \quad (4)$$

If the method provides a good description of the correlations in the noise pattern, one may expect that the noise distribution will be narrower after correcting any undesirable effects, closer to the intrinsic noise distribution. The level of noise correlation was studied using 10,000 events from a bi-gain pedestal run during 2009 data taking. In Figure 1 (top), correlations between channels are clearly visible in high-gain for the TileCal module LBA9. Regions of high and low correlation values are visible reflecting the configuration of the TileCal hardware with clear clusters of neighbor channels determining the signal responses, the behavior in magnitude and shape is typical for TileCal drawers. These correlations were significantly reduced after applying the correlated noise χ^2 unfolding, Figure 1 (bottom).

In Figure 2, the reconstructed energy from channel 19 (top) and channel 47 (bottom) of the TileCal LBA23 module are shown in ADC counts before (red dots) and after (blue line) applying the χ^2 unfolding. Channel 19 is an example of a non-correlated channel and the signal remains uncorrelated after applying the method. Channel 47 is an example of a highly correlated to its neighbors channel and the tails are significantly reduced after applying the method.

In Figure 3, the reconstructed energy from LBA23 channel 46 is plotted against the one from channel 47 before (top) and after (bottom) unfolding the correlated noise component with the χ^2 method. A clear improvement is observed i.e., the correlation between both readout channels are very much reduced after applying the unfolding.

Fig. 1. Correlation plot of the noise value (evaluated as explained in the text) for all the channels in module LBA9 before (top) and after (bottom) the unfolding of the noise correlation effect.

Fig. 2. LBA23 channels 19 (top) and 47 (bottom) before and after applying the χ^2 unfolding.

Fig. 3. LBA23 channel 46 against channel 47 before (top) and after (bottom) applying the χ^2 unfolding.

III. CALIBRATION RUN ANALYSIS

The correlation matrices calculated for the third¹ of the seven digitized samples of a channel signal pulse are shown in Figure 4 before (top) and after (bottom) applying the correlated noise χ^2 unfolding. A calibration run where a charge of 100 pC is injected, per event, by the Charge Injection System in each read-out channel of the drawer was used. A total of 1000 events per channel were analyzed when channel 3 of LBA48 was fired. The information from the first out of seven digitized samples (only sensitive to pedestal noise) is successfully used to unfold the noise correlations in the presence of physics signals. The correlated noise component is significantly reduced for third sample. The unfolding was applied to all samples with similar results to validate the performance of the unfolding method in the presence of a controlled injected signal.

IV. METHOD PERFORMANCE WITH PHYSICS SIGNALS

The validation of the method, in the presence of physics signals, is presented using a simulated sample with realistic correlations added and a collisions' data sample from Minimum Bias events. The information from the first out of seven digitized samples of a channel signal pulse (only sensitive to pedestal noise) is used to unfold the noise correlations in the presence of physics signals, only possible because no additional cross-talk was observed in the presence

¹The peak of the pulse is timed to be between the third and the fourth samples.

Fig. 4. Correlation matrices for LBA48 using the third out of seven digitized samples before (top) and after (bottom) applying the χ^2 unfolding.

of controlled injected signals using special calibration runs. The reconstructed cell energy for 10,000 $t\bar{t}$ simulated events generated at 7 TeV with MC@NLO [6] is presented in the Figure 5 (top) for three different situations: without channel-to-channel correlations (black dotted line), with correlations before the noise correlations unfolding (red dashed line) and with correlations after noise correlations unfolding (blue full line). The reconstructed energy for Minimum Bias trigger data taken at a centre-of-mass energy of 900 GeV [7] (10,000 events collected in December 2009) is shown in the Figure 5 (bottom). The red dashed line is before the noise correlations unfolding and the blue full line is after the unfolding. All readout channels were included in the figure and the signal region is shown for both. No visible bias is introduced by the noise correlations unfolding method. The correlations seen in the pedestal region can be successfully unfolded with the χ^2 method without affecting the signal distribution.

V. CONCLUSIONS

The method proposed to remove the correlated noise component of the TileCal has been tested and approved through this systematic survey of the TileCal modules as a powerful solution to the coherent noise presence in pedestal runs. This approach shall be regarded as well as an effective diagnosis tool to the general behaviour of TileCal modules.

The analysis of special calibration runs, where only one channel is fired at a time, excluded the presence of cross-talk allowing the method described herein to be applied in the

Fig. 5. Reconstructed energy for $t\bar{t}$ simulated events generated at 7 TeV (top) and real 900 GeV collisions data (bottom) before and after applying the χ^2 unfolding.

presence of physics signals. No degradation of the signal was observed. The results on Minimum Bias and simulated $t\bar{t}$ events show a clear improvement on the pedestal noise distribution and again the signal is not degraded as one would expect. In conclusion, the method proved to be very effective and reliable for different kinds of events, both real and simulated.

ACKNOWLEDGMENT

The work of M.C.N. Fiolhais has been supported by Fundação para a Ciência e Tecnologia (FCT), grant SFRH/BD/48680/2008.

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