Performance of the CMS Zero Degree Calorimeters in the 2016 pPb run

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Abstract. Two neutral particle detectors, Zero Degree Calorimeters (ZDCs) at the LHC-CMS experiment, cover the $|\eta| > 8.5$ region. The ZDCs are Cherenkov calorimeters that use tungsten as the absorber and quartz clad quartz fibers as the active medium. They have a five element electromagnetic section followed by a hadronic section divided into four depth segments. For the 2016 pPb run, the ZDCs were calibrated using test beam data and the single spectator neutron peak at 2.56 TeV. Peaks corresponding to 1, 2 and 3 neutrons are visible in the ZDC total signal distribution. The effect of pileup is corrected by a Fourier deconvolution method. Using this, the spectator neutron number distribution can be unfolded by a linear regularization method. This information serves as a strong constraint to models of pPb collisions and has the potential to produce an unbiased measure of centrality in pPb collisions.

1. Introduction

The Zero Degree Calorimeters (ZDCs) at the LHC-CMS experiment are Cherenkov calorimeters that observe very forward ($|\eta| > 8.5$) neutral products [1]. In heavy ion and hadron-nucleus collisions the main contribution is due to the spectator neutrons, which can be used as a centrality estimator [2]. The centrality variables $N_{\text{part}}$ (number of participants) and $N_{\text{coll}}$ (number of binary collisions) are important in many heavy ion analyses like the measurement of nuclear modification factor. The ZDCs are also used for the tagging of intact nuclei in ultraperipheral collisions [3]. The newly developed reaction plane detector (RPD) element will be used to measure the event plane for flow analyses in heavy ion collisions.

2. The CMS Zero Degree Calorimeter

The two CMS ZDCs are located in the neutral particles absorbers (TANs) between the two beampipes (Figure 1), 140 m on either side of the interaction point. It measures forward neutral particles at $|\eta| > 8.5$, since there is a dipole magnet used to steer the beams to the interaction point, that removes the charged products. The coordinate system is defined as so: $z$ stands for the beam direction, while $x$ is the horizontal and $y$ is the vertical direction.

The ZDC has three main parts: the electromagnetic section, the reaction plane detector and the hadron section. The electromagnetic section (EM) consists of 33 vertical tungsten plates and quartz fibers. This equals to 19 radiation lengths or one nuclear interaction length. The EM section is divided into 5 segments in the $x$ direction, but due to space limitations it is not possible to place read-out for $y$-segmentation. The hadron section (HAD) is built up from 24 tungsten...
plates corresponding to 5.6 hadronic interaction lengths. The plates are tilted by 45°, which maximizes the light that a fiber can pick up, since the Cherenkov photons exit at this angle. The HAD section is divided into four segments in the z direction, denoted as HAD1-4. The RPD is the newest part of the CMS ZDC, which was tested in 2016 and will be fully integrated in the PbPb data collection in 2018. This detector element is read out by Si-based photodetectors, which are more compact providing an opportunity for simultaneous x-y segmentation. The RPD is divided into 4 × 4 quartz tiles. This spatial resolution makes it possible to calculate the event plane in heavy ion collisions.

3. Calibration
The ZDC has continuous readout with 25 ns timeslices (TS), in a total of 10 timeslice window. The timing of the detector is set so that the signal always shows up at TS3 (Figure 2). For the studied proton lead runs there was a 100 ns bunch spacing, which can result out-of-time collisions in TS7 and the timeslice before TS0.

Therefore the ZDC signal for a given $i$ channel is defined as

$$Q_i = Q_{i,TS3} - \frac{1}{2}(Q_{i,TS2} + Q_{i,TS6}),$$  \hspace{1cm} (1)

where the signal in TS3 is saturated, the following expression is considered:

$$Q_i^* = R \cdot Q_{i,TS4} - \frac{1}{2}(Q_{i,TS2} + Q_{i,TS6}),$$  \hspace{1cm} (2)

where the $R$ factor is calculated from non-saturated events in the following way:

$$R = \left\langle \frac{Q_{i,TS3} - \frac{1}{2}(Q_{i,TS2} + Q_{i,TS6})}{Q_{i,TS4} - \frac{1}{2}(Q_{i,TS2} + Q_{i,TS6})} \right\rangle. \hspace{1cm} (3)$$

This method ensures a good resolution for the whole energy range of the ZDC calorimeter.

First, the difference in the gains of the channels is compensated by introducing a $w_i$ weight factor for all channels:
Figure 2. An example of a typical ZDC signal.

Figure 3. Comparing the distributions of shower shape variable HAD3/HAD1 for 2010 PbPb (left) and 2016 pPb (right) data.

\[ Q_{ZDC} = \sum_i w_i Q_i, \]  

where \( i \) goes over all of the channels. These weights are calculated from variables like HAD2/HAD1, HAD3/HAD1, HAD4/HAD1, which are characteristic for the shower shape, thus should not depend on the detector configuration. The distribution of these variables are compared in the present 2016 and a 2010 dataset (Figure 3), when the gain matching was performed using a test beam. Then \( w_i \) factors are calculated to match the maximum of the pairs of these distributions.

After the gain matching, the ZDC total signal distribution on the Pb-going side is shown in Figure 4. In the rest frame of the lead nucleus the neutrons are ejected with a few 10s of MeV
Figure 4. The distribution of total ZDC signal for Pb-going side. The peaks corresponds to single, double and triple neutron final states.

of momenta. Since the lead nucleus has a gamma factor of 2730 in the laboratory frame the neutrons are almost mono-energetic in the laboratory frame. Therefore the peaks in Figure 4 are corresponding to single, double and triple neutrons. Assuming that the response of a single neutron is Gaussian, the signal distribution is fitted with the sum of Gauss distributions:

$$f(x) = \sum_n A_n \frac{1}{\sqrt{2\pi n\sigma_1^2}} e^{-\frac{(x-n\mu_1)^2}{2n\sigma_1^2}}, \quad (5)$$

where $A_n$ amplitudes, $\mu_1$ and $\sigma_1$ single neutron peak position and width are the fit parameters. The absolute energy calibration of the detector is possible by matching the value of $\mu_1$ to the nominal energy value of nucleons, which is about 2.56 TeV in the case if Pb ions in 8.16 TeV pPb collisions.

4. Pileup correction

The ZDC spectrum for large signal values is shown for two different runs with different $\langle \mu \rangle$ pileup values in Figure 5. A larger shoulder can be observed in the run with larger pileup, indicating that this effect is related to the pileup. The distribution corresponding to $\langle \mu \rangle = 0$ case can be calculated by a Fourier deconvolution method. A similar method was used in [4]. Assuming that the $n$ number of pPb collisions in a bunch crossing is Poisson distributed:

$$p_n = \frac{\mu^n}{n!} \frac{e^{-\mu}}{1 - e^{-\mu}}, \quad (6)$$

where $\mu$ is the effective pileup coming from events that yield signal to the ZDC. Here only the $n > 0$ case is considered, thus to ensure the correct normalization the $1 - e^{-\mu}$ expression appears in the denominator. Introduce the random variables $X$ and $Y_i$ describing the $\mu > 0$ and $\mu = 0$ ZDC distributions respectively. One can write up the following equation connecting these two variables:
Figure 5. The full range of ZDC signal distribution for a dataset with smaller (left) and larger (right) pileup.

$$X = \sum_{i=1}^{n} Y_i.$$  \hspace{1cm} (7)

Let $f(x)$ and $g(x)$ be the probability density functions of $X$ and $Y_i$ respectively. The $f(x)$ function is measured directly by the ZDC and the aim is to calculate $g(x)$ from it. Using the total probability theorem one can write

Figure 6. The validation of the Fourier based pileup correction method (left). The result of the correction for real data with different $\mu$ values shows the robustness of the method (right).
The percentiles of the ZDC signal distribution, used for centrality determination.

\[ f(x) = g(x) p_1 + (g * g)(x) p_2 + (g * g * g)(x) p_3 + \ldots, \]  

(8)

where the * operation stands for convolution. After taking the Fourier transform of both sides, the infinite series can be summed up:

\[ F(\omega) = \sum_{k=1}^{\infty} p_k G^k(\omega) = \frac{e^{-\mu}}{1 - e^{-\mu}} \sum_{k=1}^{\infty} \frac{(\mu G(\omega))^k}{k!} = \frac{e^{-\mu}}{1 - e^{-\mu}} \left( e^{\mu G(\omega)} - 1 \right), \]  

(9)

where \( F(\omega) \) and \( G(\omega) \) are the Fourier transforms of \( f(x) \) and \( g(x) \) respectively. After expressing \( G(\omega) \) and doing inverse Fourier transform:

\[ g(x) = F^{-1} \left[ \frac{1}{\mu} \log \left[ 1 + (e^\mu - 1) F(\omega) \right] \right]. \]  

(10)

The method was validated on a simple toy model, that approximated \( g(x) \) as a Gaussian distribution and sampled \( f(x) \) according to (7). The results for this toy model is shown in the left panel of Figure 6, which supports this method. For the calculation on real data the \( \mu \) pileup was approximated by the true pileup measured by the central detectors. The results are shown in right panel of Figure 6.

5. Application for pPb centrality

In pPb collisions the centrality estimators used in heavy ion collisions, like charged particle multiplicity are biased, since they are only loosely correlated with the number of binary collisions \( N_{\text{coll}} \). Instead, it is possibility to use the zero degree energy deposited by spectator nucleons as a centrality measure, which is assumed to be unbiased. The quantiles of the pileup corrected ZDC distribution are shown in Figure 7. In order to use these results in physics analysis a model is needed that connects the number of spectator neutrons observed by ZDC with \( N_{\text{coll}} \). The existing models are valid only for lower energies [2, 5], thus studies of spectator neutrons with ZDC provides useful input for tuning MC event generators to describe slow nucleon production at LHC energies.
6. Summary
The ZDCs are versatile detectors of the CMS experiment used in various fields of heavy ion physics. The detector was used in the 2016 pPb data taking, when the calibration was done by comparison of shower shape variables from the 2010 PbPb data and spectator neutron peaks. The effect of multiple collisions within a bunch crossing is corrected by a Fourier based correction method. The results are used to define centrality percentiles in pPb collisions.

Acknowledgments
The CMS Zero Degree Calorimeter detector is supported by the Office of Science, US Department of Energy. I would like to take this opportunity to thank for my support from the ÚNKP-17-3 New National Excellence Program of the Ministry of Human Capacities, Hungarian Scientific Research Fund (K 109703), National Research, Development and Innovation Office of Hungary (K 124845) and the Hungarian Academy of Sciences "Lendület" (Momentum) Program (LP 2015-7/2015).

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