The performance of the CASTOR calorimeter during LHC Run 2

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Abstract. CASTOR is an electromagnetic and hadronic tungsten-quartz sampling Cerenkov calorimeter located at the Compact Muon Solenoid experiment at the Large Hadron Collider. The detector has pseudorapidity borders at -5.2 and -6.6. An overview is presented on the various aspects of CASTOR’s performance and their relations during LHC Run 2. The equalisation of CASTOR’s channels is performed using beam-halo muons. Thereafter, CASTOR’s pedestal spectrum is studied. It is shown that noise estimates which are extracted using a fit, give on average a 10% lower threshold than statistical estimates. Gain correction factors, which are needed for the intercalibration, are obtained using a statistical, in-situ applicable method. The results of this method are shown to be reasonably consistent with laboratory measurements. Penultimately the absolute calibration is discussed, with emphasis on the relation between the scale uncertainty and CASTOR’s alignment. It is shown that the alignment’s contribution to the systematic uncertainty is decreased by over 50% in LHC Run 2 w.r.t. LHC Run 1. Finally generalisations of the conclusions to other subsystems and future improvements are discussed.

1. Introduction

At collider experiments, forward calorimeters contribute to numerous physics measurements. By their kinematical acceptance, they allow for dedicated QCD studies. But forward calorimeters also complement the central detectors. At the LHC experiments the hermeticity of the calorimetric systems has enabled measuring the missing transverse energy, allowing searches for new physics.

Various aspects of calorimetry, for example the design and hardware, the electronics, and the detector performance provide a unique set of challenges at forward rapidities. A quantitative, well understood estimate of the performance is vital for being able to interpret the measurements of the calorimeter.

In this paper we discuss the performance of the CASTOR calorimeter, which is installed at the Compact Muon Solenoid (CMS) experiment [1] at the Large Hadron Collider (LHC). CASTOR is a unique detector since it is the most forward calorimeter deployed at the LHC (except for Zero-Degree calorimeters). It has pseudorapidity ($\eta$) acceptance [-6.6,-5.2]. Many conventional techniques (for example to establish the inter and absolute calibration) have still not been applied successfully at CASTOR. This paper aims to describe not only the methods to assess the performance, but also to emphasise the relationships between the various aspects of CASTOR’s performance. The key numbers obtained with the design and improvements w.r.t. LHC Run 1 are stated throughout the text.
2. The design of CASTOR
To measure at the aspired very forward \( \eta \), CASTOR (which weighs approx. 2 tonnes) is installed at only 1 cm from the beampipe, at 14.4 m from the interaction point. Moreover, when the CMS magnet is turned on, CASTOR becomes displaced from its initial position by approx. 3 mm. These factors make the installation a very delicate task. Constant monitoring of the position sensors during the first magnet cycle is required. Given a fixed initial position, the movements in subsequent cycles have proven to be well predictable though.

CASTOR consists of 16 transversal sectors, 14 longitudinal modules, and has no \( \eta \) segmentation [2]. A channel consists of tungsten plates interleaved with quartz; CASTOR is a Cerenkov calorimeter. The Cerenkov photons are guided to fine-mesh PMTs (Hamamatsu R5505 and R7494), where the signal is collected and amplified. The design was motivated by the relative fast response and radiation hardness. CASTOR is equipped with LED fibers, which can illuminate the PMTs. This has proven to be a very useful tool for various commissioning purposes. The relative energy resolution achieved for pions is \( 18.3 \pm 187/\sqrt{E} \) [2].

3. Intercalibrating CASTOR
3.1. Equalising channels with beam-halo muons
The LHC beam causes beam-halo muons, which traverse the CASTOR sectors longitudinally. The muons were collected during the circulating beam periods of the LHC (a period during which circulating beams are present in the LHC but no collisions take place). One can infer that a MIP (Minimally Ionizing Particle) causes on average approx. one photoelectron per channel.

To maximally distinguish the minute muon signals from the electronic noise background, the muons are collected at the maximal gain settings (1800V, corresponding to an amplification factor of approx. 1M). For most PMT-related sources of noise, the signal-to-noise ratio on contrary is flat as function of the gain on the range considered in this paper. Muons are collected online by demanding exclusive activity in one sector. The offline selection further requires minimally three channels in three different longitudinal sections of the sector to be above a channels-specific threshold. In fig. 1 the signal and noise spectrum after the offline selection are displayed for a particular channel. The good description between the PMT model and data indicates MIPs are indeed mainly measured, as opposed to showering muons. The black dotted vertical line indicates the channel-specific noise threshold. To obtain an event sample which is both statistically relevant and sufficiently pure, it is indispensable to pick this threshold correctly.

3.2. Determining CASTOR’s noise threshold per channel
To obtain a precise estimate of the baseline and noise in CASTOR’s channels, the pedestal signal spectrum was studied at the maximal gain (see fig. 2 for a typical CASTOR channel). Three different sources of noise are identified:

(i) The Gaussian, fitted peak at the left hand side, corresponding to \( \mathcal{O}(0.1) \) GeV, is due to electronic noise. The signal is gain independent

![Figure 1. Signal spectrum for a typical CASTOR channel after an offline isolated muon event selection. The overlaid noise distribution is measured from non-colliding bunch data. The model line corresponds to a mesh-type PMT with an average number of photoelectrons \( \langle N_{p.e.} \rangle \) of 0.5. The selection threshold used to identify channels above noise is shown as vertical line. Plot from [3]](image-url)
(ii) The shoulder around 100 fC (corresponding to $O(1)$ GeV) is due to thermal photoelectrons. The signal depends strongly on the gain.

(iii) The rare discharges (maximally at $O(100)$ GeV) in the tails are likely due to ion feedback. These also depend strongly on the gain.

The channel thresholds, for distinguishing the muon signals from noise, were determined with the parameters of the Gaussian fits to the electronic noise (see the red line in fig. 2). The width of the Gaussian is on average 10% lower than the statistical width (which was taken as noise estimate instead during LHC Run 1). This is mainly due to the rare, high energetic deposits, to which the fit is insensitive, but which significantly affect the statistical average. Actually, comparing the statistical and fitted width has proven to be a useful method of identifying noisy channels.

3.3. Results on statistical gain correction factors

The intercalibration constants were determined at the maximal gain settings (corresponding to 1800 V). Physics events, however, were recorded with a gain recipe optimised to the dynamic range. Gain correction factors were therefore needed to scale the gain recipe optimised to the dynamic range. Gain intercalibration constants from the maximal gain to the physics gains.

A statistical method can be performed by analysing a pedestal and LED spectrum per channel.

For the latter, one first needs to obtain a corrected signal $S_c$ by subtracting the pedestal signal $S_p$ from the LED signal $S_t$. $S_c$ equals the electronic gain $G_{el.}$ times the number of photoelectrons $N_{p.e.}$: $S_c = S_t - S_p = G_{el.} \cdot N_{p.e.}$. The relative width of $S_c$ consists of a contribution of the gain fluctuations and the Poissonian fluctuations of the conversion of photons to photoelectrons and is given by: 

$$\frac{\sigma_{S_c}}{S_c} = \frac{\sigma_{N_{p.e.}}}{N_{p.e.}} \oplus \frac{\sigma_G}{G_e}.$$ 

The first contribution is $\frac{1}{\sqrt{N_{p.e.}}}$. The number of photoelectrons is a much smaller number than the electronic gain, therefore the width in corrected signal can be approximated as: $\sigma_{S_c} = G_e \cdot \sqrt{N_{p.e.}}$ and thus $G_e = \frac{\sigma_{S_c}}{\sigma_{S_c}}$.

In fig. 3 the weighted difference between the gain correction factors obtained by both methods is displayed. The statistical properties of the fit to the distribution reveal reasonable consistency between the methods.

Overall, collecting muons at the maximal gain instead of the physics gain recipe significantly improved the collection efficiency, but did not yield smaller uncertainties on the final intercalibration constants. The latter were found to be on average 16%.
4. CASTOR’s absolute calibration and alignment

A fully data-driven calibration has still not been successfully performed at CASTOR. Generally, conventional methods (for example using the invariant mass of a resonance or applying a jet-balance) have proven nontrivial at CASTOR, due to its peripheral nature and lack of $\eta$ segmentation. CASTOR is currently calibrated by extrapolating the energy measurement (on particle level) of a nearby subsystem to CASTOR’s acceptance and equating this to CASTOR’s total energy measurement [4]. Regrettably, the uncertainty due to the model-dependent extrapolation factors is large and the overall uncertainty of this calibration is 15%.

The uncertainty on CASTOR’s position contributes also to the overall uncertainty, and for an energy-flow measurement can literally be interpreted as a scale-uncertainty. CASTOR is, among others, equipped with infrared sensors which measure the distance w.r.t. the beampipe. CASTOR, the position sensors, and the beampipe have been schematically depicted in fig. 4.

A better calibration during LHC Run 2 of the infrared sensors w.r.t. a curved object reduced the alignment’s contribution to the systematic error by over 50% w.r.t. LHC Run 1; the alignment’s final contribution to the uncertainty is 2%.

5. Conclusion

We reviewed the main aspects of CASTOR’s performance during LHC Run 2. Collecting beam-halo muons at the maximal gains significantly increased the collection efficiency, though no improvement was found on the intercalibration constants’ final uncertainty. As a consequence, various noise contributions were also maximally amplified. Therefore, the noise per channel was estimated with a fit. Two methods on obtaining gain correction factors were compared. The results were found to be reasonably consistent. Improving the calibration of CASTOR’s infrared sensors reduced the alignment’s contribution to the systematic uncertainty by over 50%.

Naturally, the LHC provides a unique operating environment and not all lessons learned apply at other forward calorimeters. Three generally applicable conclusions can be drawn through:

(i) Especially at high gains the noise threshold may need to be determined with a fit
(ii) The statistical method on obtaining gain correction factors, which has a broad, polyvalent range of applicability, yields reasonably consistent results
(iii) A reliable, autonomous alignment system is indispensable for very forward calorimeters

The uncertainty on the statistical gain correction factors may be further improved by parameterising the dependence of the gain on the high voltage. Also the fake signals’ contribution from non-electronic noise may be diminished by using CASTOR’s longitudinal segmentation.

References

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