PROCEEDINGS OF SCIENCE

Performance of the CMS HCAL local reconstruction algorithms with Run 2 data

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We report various energy reconstruction algorithms used by the CMS hadron calorimeter (HCAL) during Run 2 of the LHC. During Run 2 of the LHC, the characteristic bunch-crossing spacing for proton-proton collision was 25 ns, which resulted in overlapping signals from adjacent crossings. The energy corresponding to a particular bunch crossing can be estimated using the known pulse shapes of energy depositions in the calorimeter. In this document, we describe the performance of the algorithms that were developed to mitigate the effects of adjacent bunch crossings on local HCAL energy reconstruction in Run 2.

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1. Introduction

The hadron calorimeter (HCAL) in the CMS detector [1] is vital for event reconstruction. It identifies charged and neutral hadrons, measures their energies, and aids in identifying leptons and photons. The HCAL comprises the brass and scintillator sampling calorimeters HCAL barrel (HB) for $|\eta^{1}| < 1.3$ and HCAL endcap (HE) for $1.3 < |\eta| < 3.0$. The HB has a radial extent ranging from $r = 1.806$ to 2.95 m, with one HE calorimeter positioned on each side, denoted as HE plus and HE minus. The HCAL is divided into η-ϕ[2] units (known as "towers"), with dimensions 0.087×0.087 for $|\eta| < 1.6$ and 0.17×0.17 for $|\eta| > 1.6$. The readouts in HB and HE towers are divided into

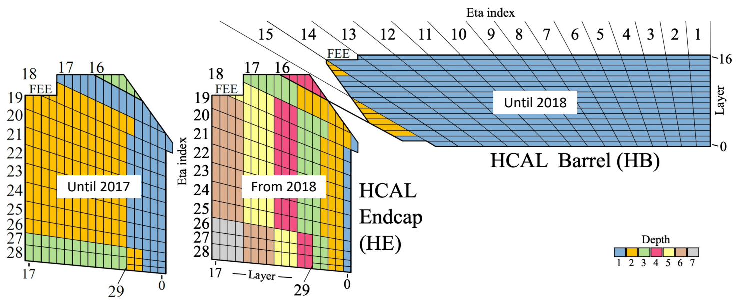

Figure 1: Cross-sectional view of HB and HE in the r-z plane, showing color-coded depth segmentation [2].

different radial "depths", each linked to a series of adjacent scintillator layers. In terms of data processing, a detector "channel" within HB and HE can be distinctively identified by its position in η-ϕ space and its depth. Hybrid photodiodes (HPDs) served as photodetectors in both regions until 2017, when SiPMs replaced HPDs in the HE during a technical halt in 2017-2018. Figure 1 provides a cross-sectional view showing alterations in depth segmentation in the HE region, both before and after the technical stop in 2017-2018.

Particles passing through the detector produce light in plastic scintillator tiles, collected by wavelength-shifting (WLS) fibers, and transformed into analog electric signals by photodetectors. These signals are digitized by a charge integrator and encoder (QIE) ADC chip over a 25 ns interval, known as a "time sample" (TS). The readout chain of HCAL is graphically shown in Fig. 2. The data stream, initially recording ten sequential TSs, was reduced to eight TSs in 2018 to reduce the data volume while maintaining performance. The "sample of interest" (SOI), representing the TS of the triggered event, corresponds to the fourth TS. Pulse shapes, showing signal evolution over time, can be extracted with a 1 ns resolution from test beam and proton-proton collision data. Fluctuations in pulse shape are attributed to factors like nonzero energy readings from photodetectors in the absence of a signal and dark currents due to radiation damage.

[1]We use polar coordinates, with polar angle (θ) measured with respect to the LHC beam line. The massless limit approximation of rapidity, called pseudorapidity ($\eta = -\ln\tan(\theta/2)$).

[2]The azimuthal angle (ϕ) in the (x, y) plane is measured from the x-axis.

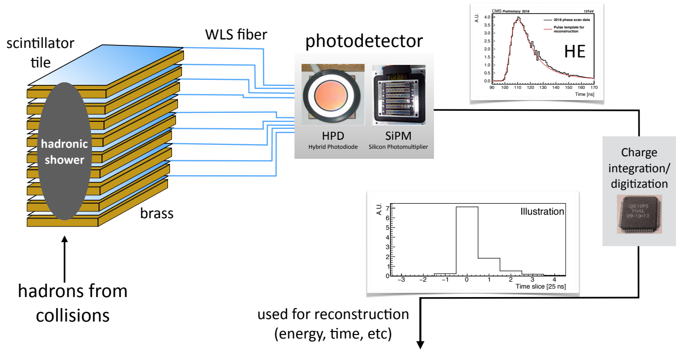

Figure 2: Readout chain of HCAL.

2. HCAL local reconstruction algorithms

The primary objective of the HCAL local reconstruction algorithms is to determine the energy deposited in a given channel in the SOI. A challenge is that the width of the pulses obtained from the scintillator tile through WLS fiber is wider than one TS. Before 2015, the LHC maintained a 50 ns bunch-crossing interval during regular data collection. This allowed for an accurate representation of the energy deposited in the SOI by summing the charge in the SOI with its subsequent TS. To improve the precision, the total charge is adjusted by subtracting the average pedestal and then multiplied by a corrective factor, addressing 10-15% of the energy outside of the two TSs. This Method 0 (M0) algorithm became unsuitable with a 25 ns bunch-crossing interval due to potential additional contributions from neighboring crossings. To address this, Method 2 (M2) was introduced for offline reconstruction, while Method 3 (M3) was utilized for online reconstruction in the High-Level Trigger (HLT) from 2016 to 2017.

M2 calculated SOI energy using a chi-square (χ^2) minimization approach, considering pulse amplitudes, arrival times, and pedestals. The algorithm employs up to three different pulse shapes: one for the SOI and two for adjacent TSs (SOI−1and SOI+1). The fit extracts amplitudes and arrival times along with the pedestal. The minimization is performed using the MIGRAD algorithm implemented in MINUIT.

M3 was introduced to address the computational constraints of M2, including fixed pulse arrival times, focusing on specific time samples (SOI−1, SOI, and SOI+1), and omitting stochastic uncertainties. This simplification transformed the problem into solving a system of linear equations involving QIE measurements, pulse amplitudes, and predefined pulse template fractions.

Despite using similar pulse-shape templates, M2 and M3 algorithms diverged significantly, resulting in challenges arising from the discrepancy in using M3 for online reconstruction and M2 for offline reconstruction. This divergence impacted trigger thresholds and the reliability of algorithms for electron and photon identification. In 2018, the "Minimization At HCAL, Iteratively" (MAHI) algorithm replaced M2 and M3 for both online and offline reconstructions. MAHI, suitable for offline reconstruction while meeting HLT timing requirements, employed an 8×8 covariance matrix, considering pulse-shape uncertainties and noise. The algorithm utilized pulse templates to generate covariance matrices, which were combined into a final matrix **V** along with μ_j amplitudes. A non-negative least squares algorithm minimized a χ^2 value constrained by positive μ_j, ensuring precise HCAL energy measurements, especially amidst Out-of-Time Pileup (OOTPU). MAHI includes M2 information and considers more pulse shapes (from 3 to 8), within HLT time limits. It is around $O(10)$ times faster than M2, and $O(10)$ times slower than M3.

3. Performance of algorithms

The effectiveness of different methods employed for reconstructing HCAL energy can be assessed using various techniques. The impact of removing contributions from OOTPU is especially notable at lower transverse momentum (p_T) and higher absolute pseudorapidity ($|\eta|$). To assess this, the reconstruction of isolated charged hadrons is studied. Figure 3 illustrates the ratio of HCAL clustered energy to track momentum minus ECAL clustered energy for different algorithms. The Gaussian fit to the core of the distributions is predominantly influenced by HCAL resolution, with M2 and MAHI exhibiting comparable performance, as they both offer OOTPU subtraction. Notably, M0 shows a higher response at larger η due to OOTPU contributions, with its energy response displaying more noticeable non-Gaussian tails.

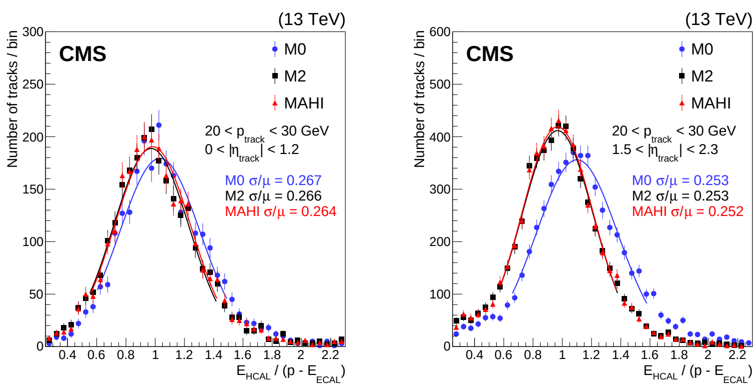

Figure 3: HCAL energy responses of M0, M2, and MAHI algorithms, measured using an electron/photon-triggered dataset with isolated tracks having $20 < p_{\text{track}} < 30$ GeV. The left plot displays data for tracks within $|\eta_{\text{track}}| < 1.2$, while the right plot shows tracks within $1.5 < |\eta_{\text{track}}| < 2.3$ [2].

The impact of OOTPU on the mean response is directly evaluated through Monte Carlo simulations. Single pions with varying momenta and pseudorapidities are generated, and their reconstructed energy deposits are clustered. The response, calculated by dividing the clustered energy by the generated energy, is compared with and without the contribution of OOTPU. Figure 4 shows the ratios of the response with OOTPU to a scenario without pileup, where OOTPU corresponds to approximately 30 interactions per bunch crossing without in-time pileup. The M0 algorithm exhibits a more significant discrepancy with respect to the other algorithms at low energy and larger values of $|\eta|$, where the contribution of OOTPU is expected to be more significant. The M2 and MAHI algorithms do not achieve equal responses at low energies because both algorithms are designed not to provide negative energies, which biases the average response in the positive direction.

To highlight the improvements from using consistent local reconstruction algorithms online and offline, the relative difference in missing transverse momentum (p_T^{miss}) in muon-triggered data

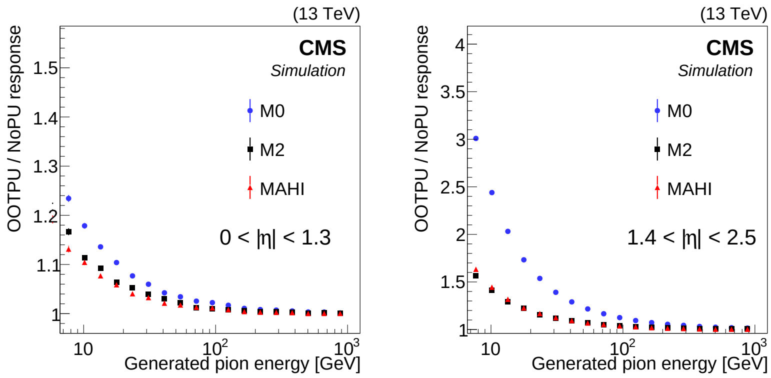

Figure 4: Ratios of responses for simulated charged pions with and without OOTPU, as functions of the generated pion energy for pions in the HB ($|\eta| < 1.3$) in the left plot, and HE ($1.4 < |\eta| < 2.5$) in right plot [2].

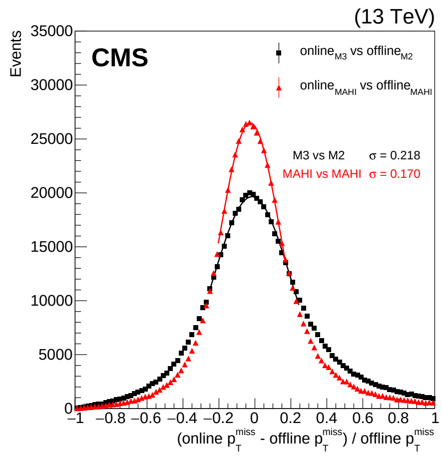

Figure 5: Relative difference of $p_{\mathrm{T}}^{\mathrm{miss}}$ in muon-triggered data events between the online and offline reconstructions [2].

events between online and offline reconstructions is depicted in Fig. 5. The $p_{\mathrm{T}}^{\mathrm{miss}}$ is calculated by summing the negative vector of energies in ECAL, HCAL (including HF), and muon momenta. Two scenarios are compared: one with M3 and M2 used for online and offline reconstruction respectively, and the other with MAHI used consistently at both levels. The consistent usage of MAHI significantly improves the agreement between online and offline $p_{\mathrm{T}}^{\mathrm{miss}}$. The remaining discrepancies with MAHI are mainly due to inconsistent calorimeter calibrations, as updates cannot be applied retroactively to HLT-calibrated systems.

4. Summary

This report discusses four local reconstruction algorithms for HCAL [2]. M0 is suitable for 50 ns bunch-crossing spacing, while pulse-fit algorithms are necessary for 25 ns spacing. M2 is effective in high pileup scenarios but has a long processing time, limiting its use at HLT. M3, although fast enough to be utilized at HLT, introduces online-offline inconsistencies when used together with M2. MAHI suppresses OOTPU, exhibits excellent energy resolution, and is fast enough for HLT. Therefore, MAHI was chosen as the preferred algorithm for Run 2. Recently, more accurate depth and η-dependent pulse shapes have been collected with the QIE clock scan during collisions in June 2023 and we expect to update MAHI in the future with these pulse shapes.

References

[1] CMS Collaboration, "The CMS experiment at the CERN LHC", JINST **3**, S08004 (2008)

[2] CMS Collaboration, "Performance of the local reconstruction algorithms for the CMS hadron calorimeter with Run 2 data", arXiv.2306.10355