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Use of time information in the High Granularity Calorimeter at the CMS experiment

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Abstract. The High-Luminosity phase of the Large Hadron Collider (HL-LHC) starting in 2029 poses unprecedented challenges in terms of data acquisition and event reconstruction. Significant upgrades are planned for both detectors and software to tackle these challenges. Among the strategies adopted by the Compact Muon Solenoid (CMS) experiment there is the incorporation of time-related information from sub-detectors, facilitated by advancements in technology and faster electronics.

The forthcoming High Granularity Calorimeter (HGCAL) is set to replace the current electromagnetic and hadronic calorimeters in the Endcaps. Apart from its exceptional spatial resolution, HGCAL will introduce precise time measurements for high-energy deposits, allowing for a comprehensive 5D reconstruction (x, y, z, t, E) of particle showers. The front-end electronics will measure the time of arrival of pulses above a charge threshold, achieving a resolution as fine as 25 ps for high individual energy deposits.

This research highlights the integration of timing information from the High Granularity Calorimeter into event reconstruction and its use in combination with the information coming from the dedicated timing layer, the MIP Timing Detector, heading towards an enhanced global event interpretation in the high pileup environment of the HL-LHC.

1 Introduction

To deliver an integrated luminosity of about 3000 fb^{-1} and extend its physics capabilities, the Large Hadron Collider (LHC) will undergo a major upgrade before starting the High Luminosity Phase of the LHC (HL-LHC). The consequences of this upgrade will be higher luminosity (up to $7.5 \cdot 10^{34}$ cm^{-2} s^{-1}) and pileup (up to 200), a higher radiation environment, and an increase in the event complexity, necessitating extensive detectors and software upgrades.

One of the strategies adopted by the Compact Muon Solenoid (CMS) experiment to tackle these challenges is the introduction of sub-detectors capable of performing precise time measurements. Since collision vertices within a bunch crossing are spread in a time interval with a σ of 180-200 ps, the time information would allow us to disentangle those interactions, providing a new handle to keep pileup effects under control.

A new detector dedicated to precision timing measurements will be added, the MIP Timing Detector (MTD). It will achieve a resolution of 30-40 ps for charged particles. The electronics of the current electromagnetic barrel calorimeter will be replaced, and the new one's resolution is estimated to be 30 ps for showers greater than 50 GeV. Finally, the current endcap calorimeters will be replaced entirely with the High Granularity Calorimeter (HGCAL), which, in addition to an excellent spatial resolution, will provide timing information at single-hit level, such that particles with $p_T > 5$ GeV will have a resolution better than 30 ps. [1] [2]

Regarding the physics reach, the amount of data collected will allow reaching percent-level precision for most Higgs coupling measurements. Studies on the Higgs self-coupling and measurements of the Higgs coupling to charged leptons (muons and taus) will also be possible. In addition, the novel track-time reconstruction will open new possibilities for CMS allowing it to look for phenomena that are outside the capability of the current detector. Searches for long-lived particles (LLP) will be tackled since heavy particles that travel in the tracking volume before decaying into lighter standard model particles produce delayed signals in the MTD. Moreover, time-of-flight between the collision vertex and the MTD can be used to differentiate among low momentum charged hadrons, such as pions, kaons, and protons, providing new opportunities in Heavy Ions collision studies.

This work presents the initial effort to integrate the time information from the High Granularity Calorimeter in the CMS event reconstruction and to use it in combination with the information from the dedicated timing layer, the MIP Timing Detector, heading towards a time-aware global event interpretation.

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2 The Iterative CLustering

The Iterative Clustering (TICL) is a modular software framework integrated into the CMS software (CMSSW) whose aim is to reconstruct particle showers in HGCAL starting from single hits to the final particle candidates and their properties [3]. TICL starts with the hits clustering on each HGCAL layer with the CLUE algorithm [4] to create 2D clusters (layer clusters), followed by the pattern recognition and linking across full detector to create 3D clusters (tracksters). The final step is the Particle Flow reconstruction and interpretation, which consists of several steps: track linking with calorimeter objects, energy regression, and particle identification to obtain the final candidates.

To monitor the performance of TICL at every step of the reconstruction, dedicated simulated objects have been developed and a sensor-by-sensor matching between simulation and reconstruction is performed to exploit the granularity of HGCAL. In particular, the final particle flow candidates can be compared to the simulated TICL candidates, which are reconstruction-like objects created from Monte Carlo (MC) truth representing the best possible Particle Flow interpretation that can be achieved with the available reconstructed objects. These also include the true timing information from the MTD Endcap Timing Layer (ETL) and the time the particle was produced.

3 Time information in the HGCAL reconstruction

Reconstructed hits

When a particle passes through a silicon sensor in the HGCAL and deposits a charge above a set threshold, currently 12 fC, the front-end readout ASIC of the HGCAL, known as HGCROC, can record the time of arrival (ToA). This measurement is carried out using a constant threshold discriminator and a time-to-digital converter (TDC) operating at 40 MHz.

The recorded time is local to the HGCAL, relative to the collision time provided by the LHC. The timing accuracy is determined by the signal-to-noise (S/N) ratio, which is inversely proportional to the deposited energy. For high p_T particles, the timing resolution is expected to reach a floor precision of approximately 20 ps.

In figure 1 the time resolution for K_L^0 showers as a function of the K_L^0 energy is shown, considering the time information only of hits within a cylindrical region of radius $\rho < 3$ cm around the shower axis, at startup and aged (after 3000 fb^{-1} of data taking) conditions.

Layer clusters

Neighboring hits are grouped in clusters on each layer of HGCAL. For each layer cluster, a requirement is set on the minimum number of hits with a ToA to assign a time to the cluster itself, currently set to three. The layer cluster time is computed as the resolution-weighted average of the hits time. To further improve the time resolution by removing outliers' contributions, only a predefined time window containing the highest density of hits is considered.

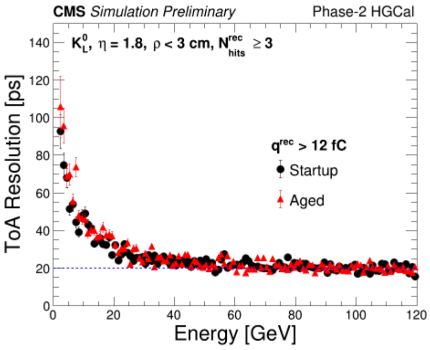

Figure 1. Time resolution of the time-tagged K_L^0 showers obtained by selecting hits within a cylinder with radius $\rho < 3$ cm around the shower axis, as a function of K_L^0 energy. The charge threshold q^{rec} for the time of arrival is set at 12 fC and the time resolution is shown at startup (black) and aged (red) conditions, i.e. simulating the effects induced by the fluence of 3000 fb^{-1} of data taking. The right horizontal blue dashed line shows the constant resolution, derived from a fit of the results at startup conditions. [5]

Pattern recognition

A pattern recognition algorithm runs across the entire detector to group layer clusters together to create 3D clusters, the so-called tracksters. Currently, the default algorithm is CLUE3D, inspired by the already mentioned CLUE, considering the additional longitudinal dimension.

Since the layer clusters in a trackster are located in different positions, a reference surface is used to compute the trackster time. This surface, known as the barycenter plane, is the x-y plane containing the trackster barycenter, which is calculated as the energy-weighted average position of all layer clusters. Each layer cluster with timing information within a trackster is then projected onto this barycenter plane by drawing a straight line from the cluster position to the center of the detector. The layer cluster times are corrected for the propagation at the speed of light to this plane, and the weighted average based on time resolution is then computed. This process is illustrated in figure 2.

Linking with tracks

To create the final particle flow candidates a trackster-to-trackster and a track–to–trackster linking are performed. The track-to-trackster linking is a geometric linking taking into consideration the energy and time compatibility between track and tracksters. The first step is the projection of both tracks and tracksters onto two common surfaces, the first and the last layers of the electromagnetic section of HGCAL (CE-E). Subsequently, the algorithm tries to identify geometric neighbors on these surfaces, searching for tracksters projections that fall in a η window around the track projection of 0.04 for the first CE-E layer and 0.06 for the last. Once the graph of possible links is established, an iterative exploration is undertaken, with additional en-

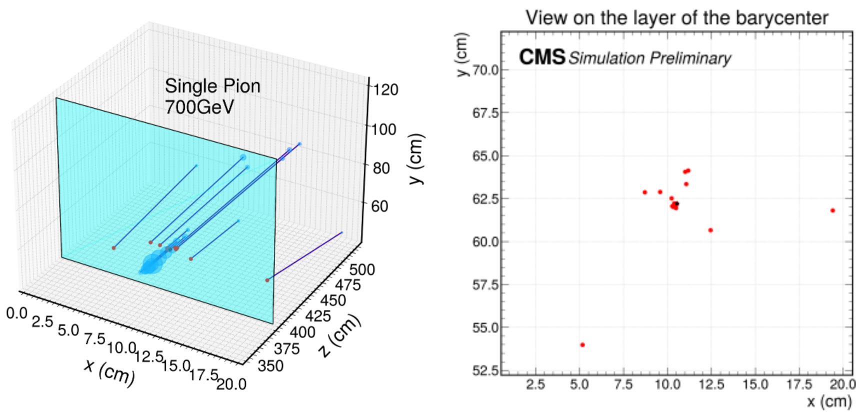

Figure 2. Left: illustration, using a 700 GeV charged pion simulated event, of how the trackster time is computed. The layer clusters (represented by blue circles whose area is proportional to their energy) are projected to the trackster barycenter plane through a straight line, connecting the cluster position to the center of the detector. The plane is represented by the light blue rectangle perpendicular to the beam line, and the red points on it are the layer clusters projections. The individual layer cluster ToA is corrected by the time-of-flight to the plane, assuming the speed of light. The trackster ToA is computed based on a time-resolution weighted average. Right: figure representing the position of the trackster barycenter (black star) and the projected layer cluster positions (red markers, dimension proportional to the logarithm of the layer clusters energy). [6]

ergy and time compatibility requirements, to create the final TICL candidates. The energy compatibility is shown in equation 1 and ensures that the linked trackster energy does not excessively exceed the track energy.

$$\mathrm{E}_{\mathrm{trackster}} < \mathrm{E}_{\mathrm{track}} + \min(10\ \mathrm{GeV}, 0.2 \cdot \mathrm{E}_{\mathrm{trackster}}) \qquad (1)$$

Thanks to the presence of the MIP Timing Detector (MTD), the reconstructed tracks linked to a cluster in MTD have timing information assigned to them both locally in the detector and propagated at the vertex using the trajectory, and the mass hypothesis obtained during the vertexing procedure. The local time assigned to the track is used to perform the time compatibility with the trackster as described in equation 2, where $\mathrm{d}_{\mathrm{MTD,trackster}}$ is the distance between the cluster in MTD and the trackster barycenter. The check is skipped if one of the two objects does not have time information.

$$\left|\frac{\mathrm{d}_{\mathrm{MTD,trackster}}}{\mathrm{c}} - (t_{MTD} - t_{trackster})\right| < 3 \cdot \sqrt{\sigma^2_{t_{MTD}} + \sigma^2_{t_{trackster}}} \qquad (2)$$

The track and trackster times are projected one onto the other through a straight line connecting them at the speed of light. The absolute value of the difference between the two times is required to be less than 3 σ to consider track and trackster compatible in time, where σ is the squared root of the sum of the squared time resolutions.

Figure 3 shows the linking efficiency of a track with the correct trackster as a function of the simulated particle (`simTICLCandidate`) energy for a sample of charged pions generated uniformly in the $10 < p_T < 100$ GeV and $1.7 < \eta < 2.7$ ranges. The efficiency is computed as the number of reconstructed tracks correctly linked to a trackster over all the tracks that should have been linked, i.e., they have been reconstructed, passed the cuts used in the linking algorithm and the pions left some energy in HGCAL.

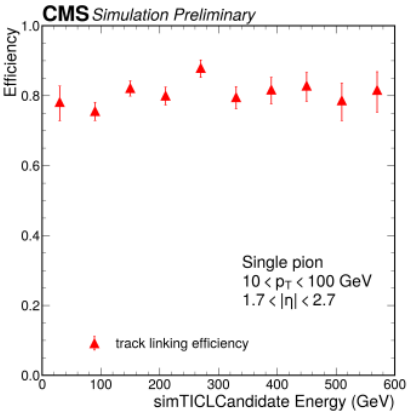

Figure 3. Efficiency in the linking between the tracksters in HGCAL and the tracker tracks. A sample of charged pions generated uniformly in the $10 < p_T < 100$ GeV and $1.7 < \eta < 2.7$ ranges is used. The primary vertex of each pion is produced according to the expected Phase 2 profile. Tracker tracks are used in the linking if they have pT>1 GeV, <5 missing outer hits, and are marked as `high quality`. Tracks and tracksters are projected onto two common surfaces, the first and the last layer of the electromagnetic section of the calorimeter, and geometric compatibility is performed (in a 0.04 (first layer) – 0.06 (last layer) η window). In addition to that, time and energy compatibility with the track are also computed. A track and a trackster are energy compatible if they satisfy equation 1 and time compatible if they satisfy equation 2. The efficiency is defined as the number of tracks correctly linked over the total number of tracks that could have been linked, i.e., they have been reconstructed, passed the cuts mentioned above and the pions left some energy in HGCAL. [6]

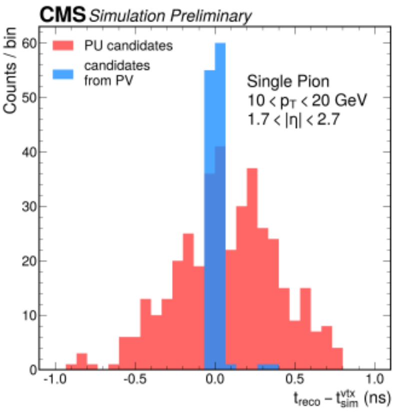

Figure 4. This plot shows the distribution of the difference between the reconstructed TICL Candidate time, t_{reco}, and the simulated time (i.e. referenced to the time of the primary interaction), t^{vtx}_{sim}, for a sample of charged pions uniformly sampled in the $10 < p_T < 20$ GeV and $1.7 < \eta < 2.7$ intervals. Track-only candidates, i.e. those made only of tracks not linked to a trackster in HGCAL, are not considered in this plot. Neutral candidates have been excluded as well. Those in blue are TICL Candidates coming from the primary vertex interaction, while in red there are the TICL Candidates produced from pileup interactions, with kinematics following the expected physical distribution of a Minimum Bias event. [6]

Combination with MTD time

The time assignment to the final candidates given in input to Particle Flow, the TICL Candidates, is performed by combining the track time at the vertex from MTD and the trackster time with a weighted average if both are available. The track time is obtained by propagating the time of the MTD cluster along the track path and using a mass hypothesis (pion, kaon, or proton) for the speed. This hypothesis is the one that yielded the best fit for the vertex time during the primary vertices reconstruction. For the trackster in HGCAL, if a track has been linked its path is used to propagate the local HGCAL time to the point of closest approach to the beam spot, otherwise, the propagation is performed in a straight line to the origin. The propagation speed in this case is the one computed by MTD if available, the speed of light otherwise.

Figure 4 shows the distribution of the difference between the reconstructed TICLCandidate time and the simulated time for charged candidates only. A sample of charged pions uniformly sampled in the $10 < p_T < 20$ GeV and $1.7 < \eta < 2.7$ ranges is used and the combination between the HGCAL and MTD time is enabled.

Those in blue are TICL Candidates coming from the primary vertex interaction, while in red there are the TICL Candidates produced from pileup interactions. Their kinematics follows the expected physical distribution of a Minimum Bias event.

4 Conclusion

This work presents the integration of timing information from the High Granularity Calorimeter (HGCAL) into the CMS event reconstruction. Timing data is assigned to each reconstructed object at every step of TICL, to improve the accuracy of particle identification and reconstruction. In track-to-trackster linking, timing information from both tracks and tracksters is used to reduce pileup contamination by distinguishing signals from different interactions. The combination of timing data from HGCAL with MTD enables for the first time a time-aware global event description within CMS, facilitating better discrimination of overlapping events and becoming an important tool to improve pileup mitigation in HL-LHC collisions. Further studies will address the incorporation of time information in trackster-to-trackster linking to reduce as much as possible the pileup contamination also at this stage of the reconstruction.

These advancements will be used as a foundation for similar studies on future collider detectors, where leveraging timing information will be crucial for achieving high-precision measurements in increasingly challenging conditions.

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