Physics potential of timing layers for future detectors

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Abstract

Keywords:

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1. Introduction

Future experiments, such as CLIC [1], International Linear Collider (ILC) [2], high-energy LHC (HE-LHC), future circular *pp* colliders of the European initiative, FCC-hh [3] and the Chinese initiative, SppC [4] will require high precision measurements of particle and jets at large transverse momenta. The usage of timing information for such experiments can provide additional information that can be used to improve particle and jet reconstruction, as well as to deal with background events. At this moment, conceptional design reports for these experiments did not fully explore the benefits of the time of flight (TOF) measurements with tens-of-picosecond resolutions.

2. Proposal

A generic design of hadronic (electromagnetic) calorimeters for future particle collision experiments (HE-LHC, FCC, CLIC, ILC etc.) is based on two main characteristics: (1) high-granularity calorimeters with cells ranged from 3×3 mm^2 (for ECAL) to 5×5 cm^2 (for HCAL) in sizes. (2) timing with nanosecond precision that improves background rejection, vertex association, and detection of new particles. According to the CPAD report [5], a development of picosecond time resolution for future calorimeters is one of the critical needs. Presently. high-granularity calorimeters (with ¿1 millions channels) with tens of picoseconds resolution represent a significant challenge due the large cost.

As a part of the HL-LHC upgrade program, CMS and ATLAS experiments are designing high-precision timing detectors with the time resolution of about 30 ps. They are based on silicon sensors that add an extra “dimension to event reconstruction. Such timing capabilities are not fully explored for future detectors beyond the HL-LHC

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upgrade. High-precision timing will be beneficial for new physics searches and b-tagging for all post-LHC experiments. For CLIC and FCC, high-precision time stamping will be essential for background rejection and pile-up mitigation.

Currently, the baseline designs of the high-granularity ECAL and HCAL of the CLIC/FCC detectors have not been optimized for precision timing in the range of a few tens of picoseconds. The latter is considered as an expensive option for many mullions of channels of these high-granularity detectors. This opens an opportunity to investigate a cost-effective timing layer (with the time resolution of smaller than 30 ps) for the post-LHC detectors. This layer will be installed on front of high-granularity calorimeters, covering both the forward and barrel regions.

In this paper we will investigate physics advantages for timing layers in the front of calorimeters of the post-LHC experiments. Typically, thin detectors on front of calorimeters are called "preshower". The design goal of such detectors is to count the number of charged particles in oder to correct for energy loses. The timing information of "mips" (minimumionising particles) is not used for particle identifications. Unlike the standard pre-shower detector, we propose not only count mips, but also reconstruct high-precision timing and the position. This timing detector will have a similar granularity as the proposed high-granularity EM calorimeters themselves, but will have a sensor technology and readout which is best suited for mip time stamping (not necessarily for energy reconstruction). Our proposal is to enclose the EM detectors with two timing layers, one - before the first EM layer, and the second is after the last EM layer (but before the HCAL). The two layers of the timing detector allows a robust identification of time by correlating the position and timestamps of the particle passing through the ECAL.

In this paper we will explore this idea using full Monte Carlo simulations. A schematic representation of the positions of the timing layers for a generic detector geometry is shown in Fig. 1

The second layer of the timing detector can be justified if fluctuations of hits times are smaller than the resolution of the timing layers. In oder to verify this, we used a full Geant4 (version 10.3) [6] simulation of the SiFCC detector [7] that allows to use the information on hits from the ECAL. The ECAL is built from a highly segmented silicon-tungsten with the transverse cell size of 2×2 cm. The ECAL has 30 layers built from tungsten pads with silicon readout, corresponding to 35 X_0. The first 20 layers use tungsten of 3 mm thickness. The last ten layers use tungsten layers of twice the thickness, and thus have half the sampling fraction.

To verify that the time differences between last and first layer of ECAL is sufficiently small, and can be neglected for the timing layers that have a timing resolution of the order of 10 ns, a sample of single pions was created with 1 and 10 GeV momenta. The particles were reconstructed in the ECAL calorimeter, and the time difference $\Delta T = T_{\rm last} - T_{\rm first}$ of the hits between the last and first ECAL layers was calculated. Only hits that arrive first were considered. Figure 2 shows the time distribution for 1 and 10 GeV pions. It can be seen that the peak positions of the distributions are smaller than 1 ps, as expected for the distance of about 20 cm between the last and first layers[1]. More importantly, the RMS of these distributions are significantly smaller

[1]The precision with which the simulations were performed are about 0.2-0.3 ns

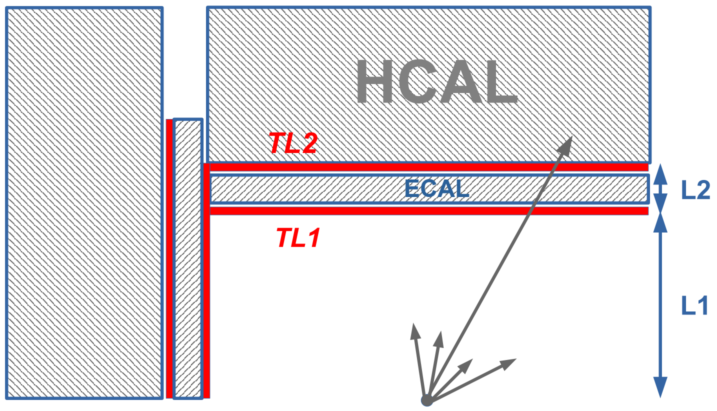


Figure 1: An example of positions of the thin timing layers for a generic detector. The thin timing layers will enclose the electromagnetic calorimeter, allow a reliable reconstruction of the mip signals with a timing resolution of the order of 10 ps.

than the 10 ns. Therefore, for the timing layers that have a resolution of the order of 10-20 ns, a single particle crossing the two layers will be seen a single simultaneous hit, thus such hits can be well correlated in time and identified as a single crossing particle.

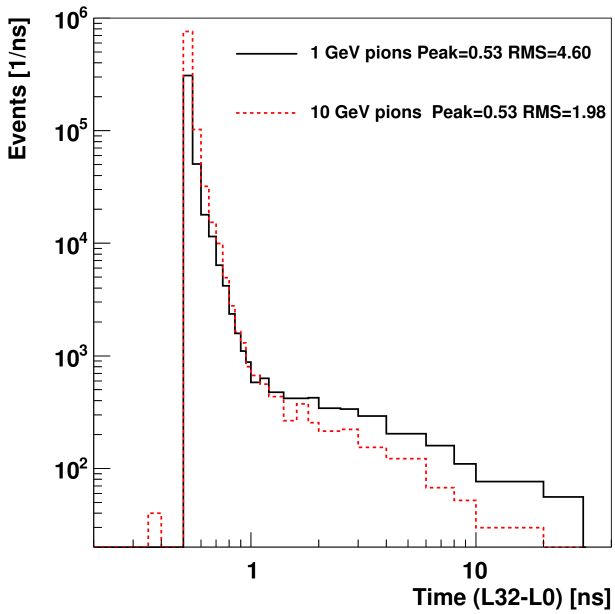


Figure 2: The difference between time of hits between the last and first layer of ECAL for single pions with the transverse momentum 1 and 10 GeV. Only first (fastest) hits were considered

3. Timing layers for single particles

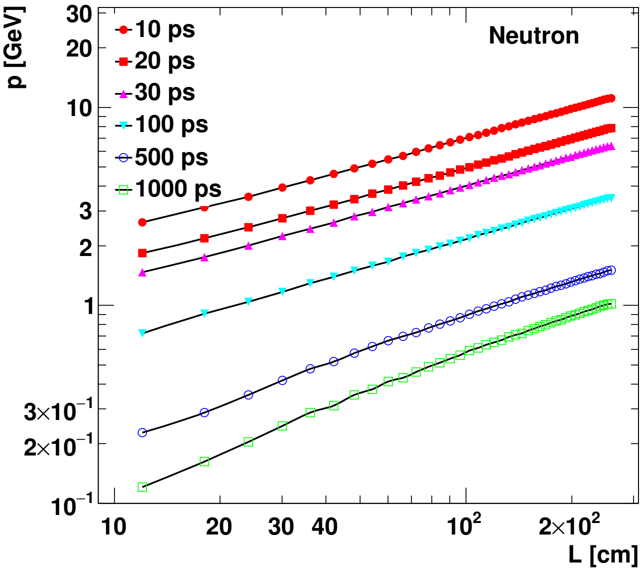
Before considering the full Geant4 simulation, let us discuss the benefit of the TOF information for identification of separate particles. Fig. 3 shows the 3σ separation from the pion mass hypothesis using the same procedure as discussed in [8]. The calculations are performed for several options for the resolution of the timing layer, from 10 ps to 1 ns, as a function of the travel length L and the momenta. For a 20 ps detector and for a typical travel distance of $L \sim 0.2$ m from the interaction point to the electromagnetic calorimeter, neutrons (and protons) can be separated from the pion hypothesis up to 7 GeV. The separation of $K-$mesons can be performed up to 3 GeV. This momentum range should be sufficient for reliable particle identification in a wide range of physics studies, especially if such identification is used for jets that are dominated by this momentum range of separate particles. For a detector with 1 ns, the separation can only be possible up to 300 – 500 MeV. This is below than a typical minimum transverse momentum of 0.5 – 1 GeV for particles considered for high-energy proton colliders . Therefore, a timing layer with 1 ns resolution cannot effectively be used for particle identification in such experiments.

4. Timing layers for FCC and jets

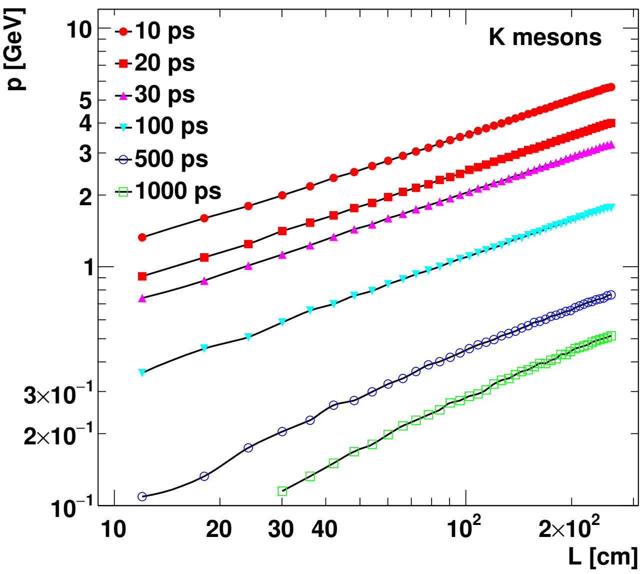
In the previous sections, the capability of the timing among the various resolutions of the detector used on distinguishing the different kinds of single particle that has the different mass, momentum as well as the length of going through the detector is well-investigated as the excellent variable within the three sigma hypothesis. The next necessary step is to employ the timing, which is the potential method of discriminating the different number of the subjets in a large radius jet as well, into tackling the intractable dilemma that has been being concerned about on the highly-boosted circumstances resulting in the particles of the jet are too close to each other, and the truth number of the subjet could be misestimated, along with impacting on the analysis in the future dramatically.

The simplified-cases simulating the pileup-free conditions with the already-known processes are involved in these studies under the environment of a very-high-energy collider will be explored as the benchmark of the timing applied in the future. The same processes of Z'→qq(Background), Z'→WW(Signal) with 5, 10, 20 and 40TeV center-of-mass energy(C.M.) as the ones exploited in our second paper, are taken into account as the targets of doing the researches on the same matter with the timing implemented.

In terms of digging out the potential of the timing, several studies have been done trying on a couple of variables to see whether the timing can give us another degree of information helping on having the improvement on the issue in addition to the P_T that we could obtain directly from the detector . The ΔR, which is the common variable that has been being used in the collider as acquiring the angle between two particles/-jets, is found to be the possible one that can take advantage of using the timing to analyze the structure of the jets more evidently. Also, the ideal cases of separating the different particles with the help of the timing are also premeditated.



(a) Neutrons



(b) K-mesons

Figure 3: The 3σ separation from the pion mass for neutrons and K-mesons as a function of the distance and the momenta.

The two sets of the collections of the data including both of the generator level(truth-level) and the reconstruction level(reco-level) are utilized in the studies for the purpose of corresponding between each other as the benchmark of the parameters that are found beneficial. At the first place, the definition of many terms applied in the studies will be well-defined as a favor of proceeding smoothly. The second one is to make use of the truth-level information of the four momenta for each particle to figure out the anticipation of the timing being capable of helping on the issue at best ideally. Last but not least, the well-established cases illustrated by using the reco-level information of the non-smearing four momenta and the fastest-response timing[2] from each cell of the calorimeter will be given as the true cases we could expect in our life when the time of the timing-capable detector installed in the collider with the very high C.M. energy comes.

4.1. The definitions of the terms introduced in the following studies

In case for avoiding being confused by the terms applied in these studies, pre-defining for those terms is essential.

4.1.1. The timing used in the truth-level cases

At the first place, the definition of the timing should be obtained as our benchmark to do these studies when dealing with the truth-level information. The standard formula of the timing is as follows for each particle:

$$Timing = \frac{L(\eta)}{V(V_x, V_y, V_z)} \tag{1}$$

Basically, it is the normal formula of the time of flight(TOF), depending on the different η, leading to the different distances L between collision point and HCAL barrel, along with the three-dimensional velocities V of the particles.

But, since the effect of the magnetic field is taken into account, the timing applied in this paper is the modified one with only considering the Z direction of the distance and velocity, and then we can get more precise value of the timing by the truth of the Z-direction trace of the particle isn't changed by the magnetic field. The formula used in this paper is as follows:

$$Timing = \frac{L_z}{V(V_z)} \tag{2}$$

After applying this formula on all particles, and the timing can be obtained without the bending effect coming from the magnetic field.

[2] As a matter of fact that the detector can response to the first-arrival particle barely in one event, the timing observed from the reco-level can merely be treated as the part of the jet but not the whole one. Oppositely, the particles of the four momenta from a jet can be explicitly known from the information of the truth-level, the timing of each particle should be well-calculated with the formula of the timing listed in the following sections as the ideal cases.