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. For CLIC and FCC, high-precision time stamping will be essential for background rejection and pile-up mitigation. For the ILC initiative, timing layers can help dealing with overlap of particle flow objects in high-granular calorimeters. From physics point of view, timing layers can be used for detection of long-lived particles and identification of Standard Model particles. At this moment, conceptional design reports for these future experiments did not fully explore the benefits of the time of flight (TOF) measurements with tens-of-picosecond resolutions.

In this paper we will explore the benefits of the timing layers for Standard Model (SM) measurements of particles and jets, as well as investigate the capabilities of timing layers for identification of heavy stable particles which may be produced beyond the Standard Model (BSM).

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

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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 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 In the following, the first timing layer (closest to the interaction point) will be called TL1, while the second timing layer after the electromagnetic calorimeter will be called TL2.

There are several reasons why the second timing layer (TL2) can be useful:

- It can be used to measure the time of flight between TL2 and TL1, which can be used for identification of stable massive particles without known production vertex. This is especially important since the current detectors do not have acceptance for models where the production vertex of the stable heavy particles is close to the surface of the electromagnetic calorimeter. The distance between TL2 and TL1 is typically 0.2-0.4 m (depending on the design of the electromagnetic calorimeter).

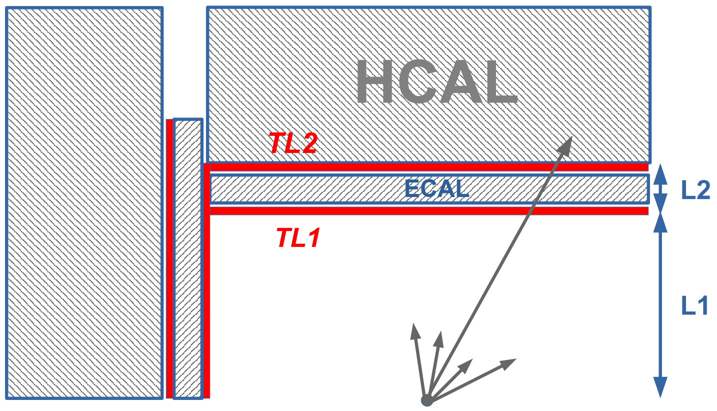


Figure 1: An example of positions of the thin timing layers for a generic detector. The thin timing layers will enclose the electromagnetic calorimeter, allow a reliable reconstruction of the mip signals with a timing resolution of the order of 10 ps.

This distance is not significant since a particle traveling with the speed of light can travel between TL1 and TL1 within ~ 1 ns. As we will discuss later, this distance is sufficient for heavy particle identification for a 10-20 ps detector.

- It be useful in cases when a long lived particle (neutral or charged) is produced without precise knowledge of the primary vertex (0,0,0) due to the beam (or pileup) smearing.
- It allows to correlate the hits with the first layer, and thus provides directionality of the hits. This feature can be useful to match the hits with the calorimeter cells and to deal with back-scatter hits arriving (typically at later time) from the hadronic calorimeter.
- It provides the redundancy for TOF measurements.

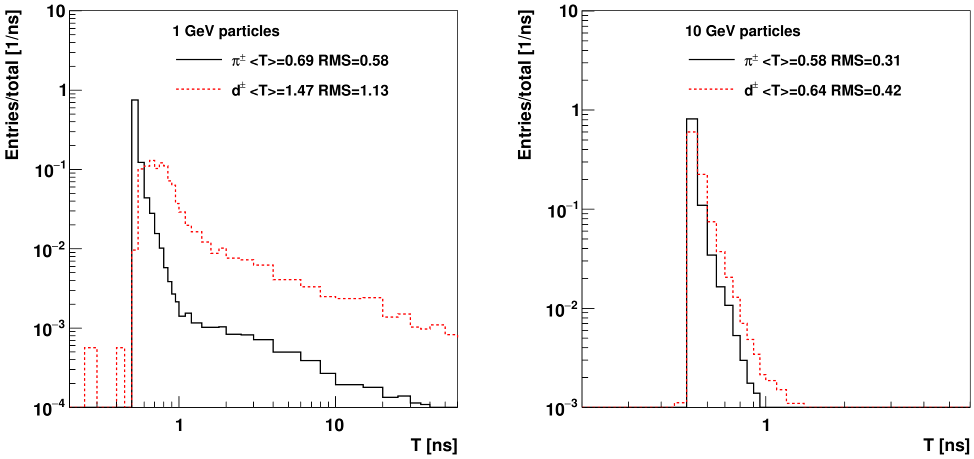
The second layer of the timing detector can be justified if the recorded time difference for hits in the electromagnetic showers is not significantly different from that expected from a particle traveling with the speed of light. In oder to verify this, we used a full Geant4 (version 10.3) [6] simulation 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. The distance between the centers of the last and first ECAL layer is about 240 mm.

To verify that the time differences between last and first layer of ECAL is close to the time required for a particle that travels with the speed of light, and can be neglected for the timing layers that have a timing resolution of the order of 1 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 $\Delta T = T_{\mathrm{last}} - T_{\mathrm{first}}$ 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 ns, as expected for the distance of about 20 cm between the centers of the last and first layers. Therefore, hits will be simultaneous for the standard 1 ns resolution, i.e. well correlated in time and are identified as a single crossing particle. If a resolution of the timing layer will be of the order of 10 – 20 ps, a physics measurement of TOF would be possible.

Figure 2 also shows the hit distribution for (anti)deutrons, denoted as $d^{\pm}$. The distribution are significantly different from $\pi^{\pm}$. On average, 1 GeV (anti)deutrons should be measured with the time delay of 0.7 – 1.4 ns between the last and first layers. The value 0.7 was estimated from the mean position of the Landau distribution used to fit the $d^{\pm}$ curve presented in Figure 2(a), while 1.4 ns was obtained for the mean of this distribution. Even for the most conservative 0.7 ns value, there is an indication that 1 GeV deutrons can be separated from pions that have 0.5 ns time difference. Such a separation can be observed when using a tens-of-picosecond detector. For 10 GeV particles presented in Figure 2(b), separation between $d^{\pm}$ and $\pi^{\pm}$ cannot be observed.

In summary, we have illustrated that a typical difference between TL2 and TL1 (which is approximated by the difference between the last and first layer of the electromagnetic calorimeter) is sufficient for particle identification using the TOF. As an example, a $d^{\pm}$ can be identified and separated from pions for the momentum less than 1 GeV. This means that heavier than deutron particles can also be identified for a momentum larger than 1 GeV. In the following, we will abstract from the full simulations and calculate the kinematic regions where identification of heavy stable particles is possible.



(a) (b)

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

Now let us discuss the kinematic regions for the TOF measurements in relation to either SM particles or BSM particles.

For an estimation of the separation power between different mass hypotheses, we will calculate the mass and momentum for which one can achieve separation significance higher than 3σ (or p-val< 0.03) If we have two particles with masses m and a reference (fixed) mass m_F, the 3σ separation can be achieved assuming this condition [8]:

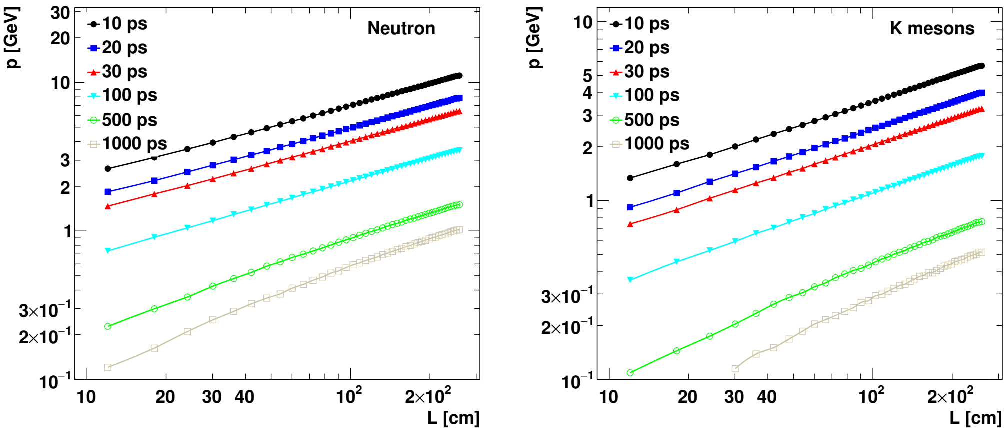
$$\frac{L}{c\sigma_{\text{TOF}}}\left|\sqrt{1+\frac{m^2}{p^2}}-\sqrt{1+\frac{m_F^2}{p^2}}\right|>3 \tag{1}$$

where p is the momenta of particles, L is the length of the particle trajectory, and σ_{TOF} is the resolution of the timing layer that measures the TOF.

Figure 3 shows the 3σ separation from the pion mass hypothesis ($m_F = m_\pi$) 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.

Having discussed a rather obvious case of identification of neutrons (or protons) and the K-mesons from the pion hypothesis, let us turn to the BSM searches for heavy particles. The most abundant SM background for light BSM particles from primary interactions are protons and neutrons. Other stable particles, that can be produced mainly in detector material (or from the interaction in the beam pipe) and detected by calorimeter are deutrons and α particles (composed from two protons and two neutrons). Although the rate of α particles sh be low since such particles can easy be stopped by detector material, it is not impossible that residual rate may still represent background for BSM searches that have a lower production rate. Therefore, we will choose $m_F = m_\alpha \simeq 3.73$ GeV for Eq. 1 and evaluate the 3σ separation for a wide range of masses and momentum. For most future experiments the distance between the interaction point and the first layer of the electromagnetic calorimeter is $L = 1.5 - 2.5$ m. For a representative purpose, we will use $L = 2$ m and consider 0.2 m for the separation distance between the TL2 and TL1 timing layers.

Figure 4 shows the particle identification power for different choices of the timing layer resolution and the distance $L = L_1$ to the first timing layer (see Fig. 1). For $L = L_1 = 2$ m, one can be see that a stable heavy particle with a mass of 100 GeV can be reconstructed up to 400 GeV assuming a 20 ns timing layer, but only up to 50 GeV using the standard 1 ns calorimeter.

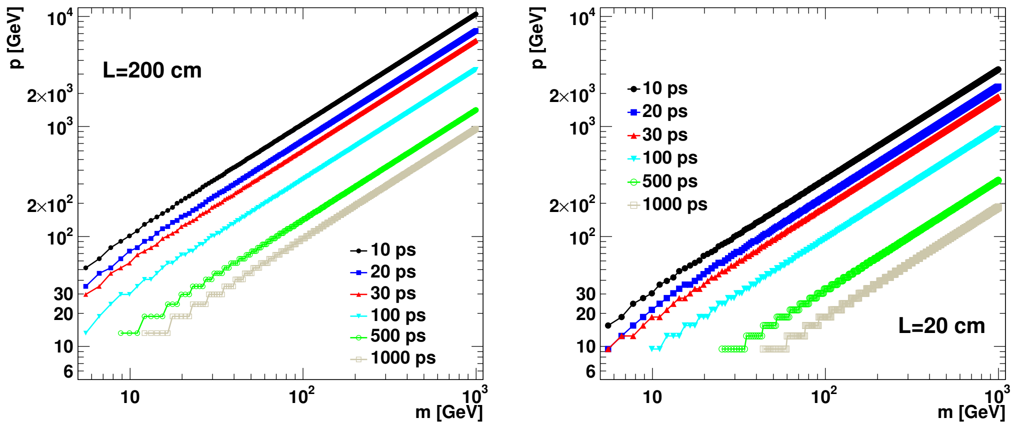


(a) Neutrons (b) K-mesons

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

One can also consider a measurement that does not involve a priory knowledge of the vertex, thus can be better designed for neutral particles in collisions with large pile-up (multiple number of vertexes). In the case the TOF is measured between the two layers, TL1 and TL2, assuming a successful spacial match of the hits.

The identification power in the case when the distance between TL2 and TL1 is 0.2 m is shown in Figure 4(b). For a 100 GeV stable particle, the identification is possible up to about 100 GeV. The standard calorimeter with 1 ns resolution can perform the identification up to 20 GeV.



(a) for $L = 2$ m

(b) for $L = 0.2$ m

Figure 4: The 3σ identification for heavy particles assuming timing layers with different resolutions for TOF, and using $L = 2$ m and $L = 0.2$ m. The first value is a typical distance from the vertex to the first layer (TL_1), while the second value is the typical distance between two timing layers enclosing an electromagnetic calorimeter, assuming a typical calorimeter based on the silicon technology.

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