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

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.

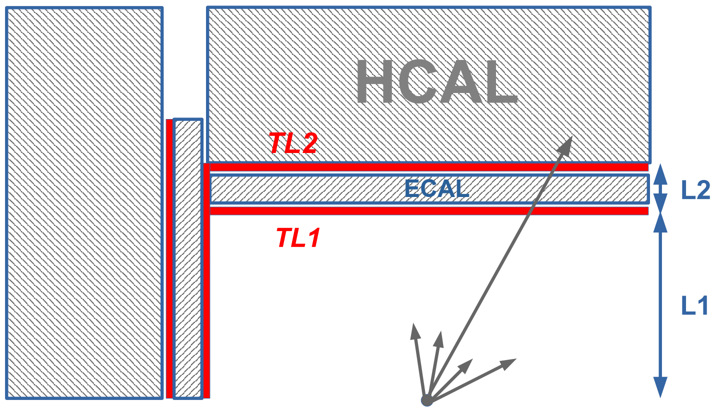


Figure 1: An example of positions of the thin timing layers for a generic detector. The thin timing layers will enclose the electromagnetic calorimeter, allow a reliable reconstruction of the mip signals with a timing resolution of the order of 10 ps.

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 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 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.

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

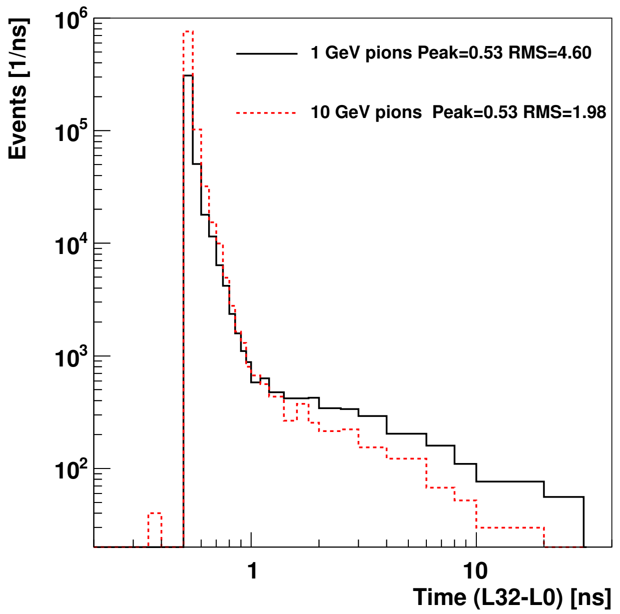


Figure 2: The difference between time of hits between the last and first layer of ECAL for single pions with the transverse momentum 1 and 10 GeV. Only first (fastest) hits were considered

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, 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]:

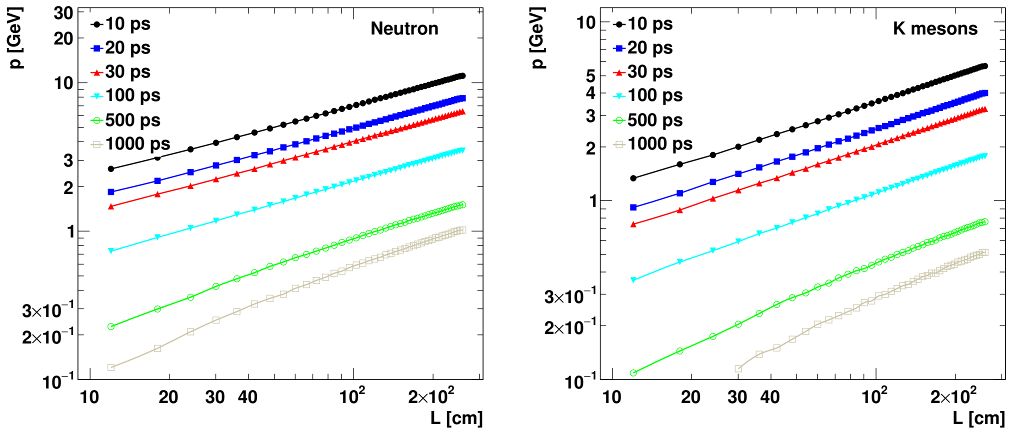
$$\frac{L}{c\sigma_{\mathrm{TOF}}}\left|\sqrt{1+\frac{m^2}{p^2}}-\sqrt{1+\frac{m_F^2}{p^2}}\right|>3 \tag{1}$$

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 two 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



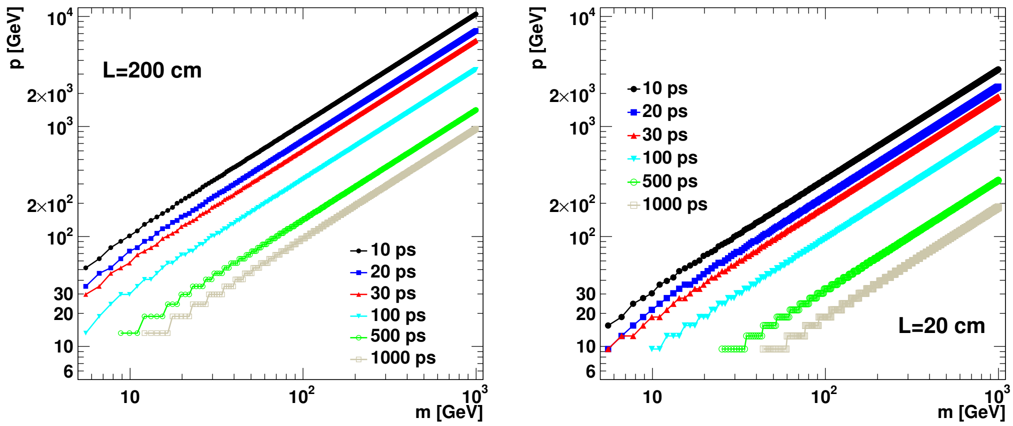
(a) Neutrons

(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.

be reconstructed up to 400 GeV assuming a 20 ns timing layer, but only up to 50 GeV using the standard 1 ns calorimeter.

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, TL_1 and TL_2, assuming a successful spacial match of the hits. The identification power in the case when $L = L_2 = 0.2$ 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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