# Precision timing for collider-experiment-based calorimetry

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#### ABSTRACT

In this White Paper for the 2021 Snowmass process, we discuss aspects of precision timing within electromagnetic and hadronic calorimeter systems for highenergy physics collider experiments. Areas of applications include particle identification, event and object reconstruction, and pileup mitigation. Two different system options are considered, namely cell-level timing capabilities covering the full detector volume, and dedicated timing layers integrated in calorimeter systems. A selection of technologies for the different approaches is also discussed.

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# 1 Introduction

Electromagnetic (ECAL) and hadronic (HCAL) calorimeters are central elements of detectors for high-energy physics (HEP). While their primary purpose is the measurement of the energy of charged and neutral particles and overall event energy, they are also important systems for overall event reconstruction, particle identification and triggering. The physics goals and the experimental conditions at future colliders require technical advances in calorimeter technology to fully exploit the physics potential of these facilities. For future  $e^+e^-$  colliders, so-called Higgs Factories, the overall precision of event reconstruction is the main focus, while future hadron colliders at energies and luminosities significantly beyond the HL-LHC impose new challenges in terms of the experimental environment. The detector requirements for future facilities are given in various reports dedicated to  $e^+e^-$  colliders, such as the Compact Linear Collider (CLIC) [1], the International Linear Collider (ILC) [2], the FCC-ee [3] and Circular Electron Positron Collider (CEPC) [4], and pp colliders, such as FCC-hh [5] and SppC [6].

The usage of timing information in calorimeter systems has significant potential for further improvements, both in terms of the technology and in terms of reconstruction techniques exploiting this information.

This paper explores the benefits of precise timing information for calorimetry, and discusses different possible implementations ranging from timing layers with extreme time resolution, timing in larger elements, and volume timing in highly granular calorimeter with moderate time resolution in each cell. We expect this discussion can help shaping the requirements for future calorimeters, which were already outlined in the CPAD report [7] that emphasized the need to develop fast calorimetric readouts.

### 2 Event and object reconstruction

The event reconstruction can benefit from the calorimeter timing capacities at several hierarchical levels: timing in cells, in highly granular calorimeters, helps shower reconstruction and energy corrections, timing of individual showers improves particle identification and objects reconstruction, and object timing allows event pile-up mitigation and characterization.

### 2.1 Particle identification

Timing capabilities of the calorimeter systems of collider detectors open up new possibilities in event and object reconstruction. The concrete possibilities depend on the achieved time resolution and on the technological implementation. Figure 1 shows an overview of time-offlight (TOF) at a typical distance for the barrel region calorimeters, for a range of particle masses, and energies ranging from  $\sim 1$  GeV up to several TeV. For timing resolution at the 10 ps level, pions can be resolved up to  $\sim 3$  GeV, K-mesons to about 10 GeV, and neutrons and hyperons to several tens of GeV. Heavier nuclei and hypothetical stable BSM particles with be resolved to a high precision at this timing level.

The energy range below 100 GeV, shown in Figure 1, is typical for final-state particle produced in  $e^+e^-$  colliders. For future hadron colliders, such as FCC-pp, average particle energies will require order-of-magnitude better timing precision than for  $e^+e^-$  colliders, i.e. to the picosecond level.

With a timing resolution on the order of 10 - 20 ps for charged hadrons, TOF can be used to identify particles which are heavier than pions. Such a resolution can either be obtained by dedicated timing layers integrated in the electromagnetic calorimeter achieving the required resolution for minimum-ionizing particles, or by a corresponding resolution for hadronic showers provided by the overall calorimeter system.

In order to estimate the separation power between different mass hypotheses as a function of the distance between the interaction point and the first layer of the ECAL (or a timing layer to be considered later), one calculate the mass and momentum for which one can achieve a separation significance higher than  $3\sigma$  (or p-value < 0.3%). If there are two particles with mass m and a reference (fixed) mass  $m_F$ , respectively, the  $3\sigma$  separation can be achieved for this condition [8, 9].

Figure 2 shows the  $3\sigma$  separation from the pion mass hypothesis  $(m_F = m_\pi)$  using the procedure discussed in [8, 9] for several values of resolution of the timing layer, ranging from 10 ps to 1 ns. The lines are shown as a function of the distance L from the interaction point and momentum p. For a 20 ps detector and a typical travel distance  $L \sim 1.5 - 2$  m from the production vertex to the ECAL, neutrons and protons can be separated from the



Figure 1: Time-of-flight for a range of energies and particle or ion masses, for a location typical of a barrel-region calorimeter, 2.5 m from the interaction point.

pion hypothesis up to  $p \approx 7$  GeV.

According to these studies, separation of kaons from pions can be performed up to 3 GeV. This momentum range should be sufficient for a reliable particle identification in a momentum range adequate for some physics studies focused on single-particle reconstruction (such as B-meson physics). This can also be used for jets that are dominated by particles in this momentum range.

#### 2.2 Identification of long-lived particles

Searches for new physics beyond the Standard Model (BSM) often predict the existence of long-lived particles (LLPs) that can give rise to many distinct signatures in calorimeters. High-granular calorimeters with precise timing provide the shower direction and timing information with unprecedented precision, enabling us to view them as "tracks" (see [10]) for a recent review). Calorimeters with tens-of-picosecond timing lead to significant benefits for reconstruction of heavy LLPs. For example, timing layers (or calorimeter cells) with 20 ps resolution lead to almost 100% acceptance for large values of dark-pion decay length ( $c\tau$ ) and dark-meson masses [9]. This result is difficult to achieve using track-only measurements since only a few outer tracking layers can be used for LLPs reconstruction. In addition, it has been pointed out [11, 12] that the emerging jets from the "dark" QCD models may have a significant fraction of neutral particles that can be measured most efficiently by



Figure 2: The  $3\sigma$  separation from the pion-mass hypothesis for (a) neutrons and (b) kaons as a function of the length of the particle's trajectory L and the momentum p. The lines show extrapolated results between the calculations indicated by the symbols. Reproduced from [9].

calorimeter systems.

#### 2.3 Shower reconstruction and PFA

Highly granular calorimeters together with Particle Flow Algorithms (PFAs) [13, 14] are a widely adopted concept for future collider detectors. With such algorithms, individual final state particles are reconstructed using an optimal combination of tracking and calorimeter information. The overall performance of such algorithms depends on the capability to associate showers in the calorimeters to tracked particles, and on the energy resolution of the calorimeters. Studies have demonstrated that software compensation using the spatial information of the energy density to improve the hadronic energy resolution in the HCAL also significantly improves PFA performance, with contributions both from the improved reconstruction of neutral particles, and a better track-cluster association [15].

Since hadronic showers show a complex time structure, with late components connected to neutron-induced processes, timing on the cell level can have benefits for the spatial reconstruction of hadronic showers. The neutron-driven part of the shower is more diffuse and extended in space than the electromagnetic and relativistic hadronic parts of the shower. A time resolution on the order of a few 100 ps to 1 ns results in a sharper definition of the core part of the shower, and thus potentially in a better separation of different particles in the calorimeter, and improved track-cluster assignment in PFA. A time resolution corresponding



Figure 3: Simulated events of the HGCAL before and after a cut on the time of the particles (from [16]).

to the cell separation times the speed of light, on the order of a few 10 ps or better  $^1$ , may provide additional benefits for pattern recognition, allowing to follow the full space-time evolution of the shower.

First, an early cut on the timing of the cells, along the direction of propagation, displays the "skeleton" of the hadronic showers. Reducing the number of cells in the early stage of the reconstruction dramatically reduces the combinatorial cost of the particle flow algorithms.

The reconstruction of the time-of-flight of a particle at the front face of the calorimeter from the impacted cells is far from simple. It must take into account the correction of the propagation of the components of the shower, which not is linear (e.g. in a magnetic field) and depends on the shower's nature, electromagnetic or hadronic. Then, the precision of the cell time roughly scales as the inverse of the signal-to-noise ratio: many cells might bring valuable timing information. As for the measure of the energy, electromagnetic showers are expected to have a better defined time-of-flight than hadronic ones. Some preliminary studies hint at 10 ps to 50 ps precision for below 30 GeV photons, using 1 ns resolution

<sup>&</sup>lt;sup>1</sup>In a given calorimeter layer, cell centers will be separated by their size. Propagation time between layers will involve the interlayer distance. Charge or photon collection inside a uniform cell can also limit the achievable intrinsic (without position correction) resolution to the cell size/2



Figure 4: Simulated single-hadron energy resolution for a highly granular SiPM-on-tile calorimeter closely modelled on the CALICE AHCAL [17] with local software compensation using energy density alone, as well as timing with 1 ns resolution and with a perfect time resolution (corresponding to a few 100 ps, in practice). Figure taken from [18].

for at mip level, 3 times more for hadronic showers. This might be improved by having a higher precision in the first layers of the ECAL. Finally, the performances will depend on precise propagation of the signal in the sensors and the associated electronics scheme and the possible corrections. Those need to be properly defined and simulated before drawing conclusions.

Along the same lines, highly granular time information of hadronic showers can also be used in software compensation techniques as an additional dimension, with the potential for further improvement of the energy resolution. Simulation studies performed in the context of the CALICE SiPM-on-tile analog hadron calorimeter show that a cell-by-cell time resolution on the ns level for MIP-equivalent energy depositions results in an increase of the improvement of the energy resolution by 10% to 15% compared to a purely energydensity-based local method [18]. The gain provided by timing can be approximately doubled with significant better time resolution, as illustrated in Figure 4. The study also illustrates the significant degree of correlation between energy-density-based and time-based shower observables, limiting the additional gain provided by timing. Both are sensitive to the share of shower activity between electromagnetic and hadronic and hadronic components. The local energy density is primarily sensitive to the electromagnetic fraction, while late shower components accessible via timing provide sensitivity to neutron-induced processes, and thus track hadronic shower activity.



Figure 5: Hit distribution versus the distance from the shower axis and time for all hits (left) and with the hits without those originating from neutrons (right), simulated for the RPC-based CALICE SDHCAL.

Measurement of timing along tracks in the calorimeters can also provide the beta and dE/dx of long travelling particle inside the shower, helping their identification, hence energy reconstruction, or correction of their leakage.

More complex reconstruction algorithms can potentially make even better use of the multi-dimensional information provided by highly granular calorimeters with timing. First promising results have been achieved with convolutional and graph neural networks, with a performance increasing with time resolution [19].

The sensitivity to different parts of the shower also strongly depends on the type of active medium. While in particular organic scintillators with their large hydrogen content are sensitive to MeV-scale neutrons, gaseous detectors, such as RPCs, Micromegas or GEMs, provide significantly less sensitivity to neutrons, resulting in less sensitivity to the widerspread neutron component of hadronic showers. Timing on the sub-ns level further helps to increase the separation of close-by showers. This is illustrated with simulations performed in the context of the RPC-based highly granular CALICE semi-digital hadron calorimeter (SDHCAL) [20] in Figure 5. The figure shows the hit distribution versus the distance from the shower axis and the time of all hits (left) and the hits without those originating from neutrons (right). The neutron-induced hits introduce fluctuations on the event-byevent basis that deteriorate the resolution of the energy reconstruction. They also increase, by their geometrical distribution, the confusion between two nearby showers and decrease thereby the possibility to separate them. With sub-ns-level time resolution, as provided by RPCs with a single gas gap, late hits originating primarily from neutrons can be included in a first step of the shower reconstruction. In subsequent steps, the time and geometrical information of these hits can then be used for an improved assignment to the correct shower. In addition, techniques for energy reconstruction as the one outlined above for scintillatorbased calorimeters, are also applicable here.

Beyond single shower reconstruction, the efficient separation of particle showers in higher-density environments is important for PFA. In the absence of time information, the separation between two hadrons impinging on the SDHCAL with a distance less than 10 cm decreases significantly, reaching only 60% at a separation distance of 5 cm. The connection of hits belonging to the same shower is based on their position in the different reconstruction algorithms. Close-by hits in space are associated to each other and then assigned to the same shower even if they occur at two different times. Comparable behaviour is also observed for other detection media.

Significant further improvement is expected with a time resolution that is better than the one imposed by the causality relation linking two neighboring hits. This requires a time resolution comparable to the granularity of the calorimeter, multiplied by the speed of light, corresponding to a few 10 to 100 ps. Different technologies exist that are in principle capable of delivering such a performance on the cell level, as briefly outlined in Section 4.2.

### 2.4 Longitudinal shower reconstruction for fiber sampling calorimeters

The time information can also be used to reconstruct shower shape for longitudinally unsegmented fiber sampling calorimeters like the dual-readout calorimeter [21], where optical fibers are inserted longitudinally then attached to photodetectors such as SiPM at the rear end. As the energy deposit closer to the readout requires a much shorter propagation time than the more distant one, the difference between the speed of incident high-energy particles and that of emitted photons inside optical fibers provides us a tool to estimate energy density shape along the longitudinal axis.

The timing distribution can be interpreted as the energy density shape by deconvoluting exponentiating components from detected signals, which can be caused by the response of photodetectors to the unit pulse and the scintillation decay. We measured the depth of a shower maximum and the length of a shower, defined as a distance between the furthest two points exceeding 10% of energy density at the peak, in an event after applying the signal processing. Figure 6 shows the correlation between the reconstructed and MC truth shower depth and length for 20 GeV electrons and pions events using GEANT4 simulation assuming a 100 ps sampling rate, without rescaling interpreted time observables.

A significant difference in the shower length between electrons and pions well describes a feature of event-by-event fluctuation of hadronic showers, illustrating that the timing is utterly useful for particle identification. Moreover, a certain correlation between the reconstructed and MC truth observables demonstrates the possibility of using longitudinal shower shapes even for the longitudinally unsegmented calorimeters by exploiting time observables.



Figure 6: Correlation between the reconstructed and MC truth shower depth (a) and length (b) for 20 GeV electrons (lined contour) and pions (filled contour) in the dual-readout fiber sampling calorimeter [21] using the timing distribution of detected photons in GEANT4 simulation.



Figure 7: The Receiver Operator Characteristic (ROC) curves for Z' mass of 5 TeV (left) and 40 TeV (right), obtained using the following variables: (i)  $\Delta R$  between the leading- $p_T$ and the trailing- $p_T$  particles (black), and (ii) adding the information of  $\Delta R$  between the leading- $p_T$  and trailing-T particles (red). The ROC obtained using the tracker-information only is also shown for comparison (green). All the physical variables, including  $\Delta R$  and the ranking in  $p_T$  and T, are obtained from the reconstruction-level information.

#### 2.5 Jet substructure reconstruction

Another area where high-precision timing is potentially important is the reconstruction of jet substructure for resolving highly-boosted objects. Some theoretical ideas with the support of truth-level Monte Carlo simulations indicate that a boosted object tagger incorporating timing information can be complementary to traditional taggers, and may help discriminating signals against background events [22]. In the context of the Snowmass 21 study, there was an attempt to understand the time structure of jets using a full Geant4 simulation [23] of a generic future detector [24, 25] for a 100 TeV proton-proton collider.

In these studies, a hypothetical heavy Z' gauge boson, postulated in extensions of the standard model, is simulated with the masses of 5, 10, 20, and 40 TeV. The Z' bosons are forced to decay to two light-flavor jets  $q\bar{q}$  to model the background and to WW pairs where the W bosons decay hadronically to model the boosted W boson "signals". It was explored how the background rejection can be achieved by including the timing information, in addition to the measurement of particle transverse momenta.

Particles and calorimeter hits of jets from Z' were ranked by their transverse momenta  $p_T$  and by their TOF. Then the signal to background separation was calculated for: (i) exploiting only the  $p_T$  of the trailing- $p_T$  particles, (ii) adding the TOF of the trailing-T (slowest) particles at the truth-level, and (iii) adding the measured TOF of the trailing-T particles.

Figure 7 shows the the Receiver Operator Characteristic (ROC) curves for Z' mass at 5 TeV (left) and 40 TeV (right), obtained using the following variables at the reconstruction level: (i)  $\Delta R$  between the leading- $p_T$  and the trailing- $p_T$  particles (black), and (ii) adding the information of  $\Delta R$  between the leading- $p_T$  and trailing-T particles (red). The results show that the timing information does improve the background rejection for highly-boosted jets from Z' mass above 20 TeV. Below this this, no significant improvements have been seen. However, more studies in this direction will require to confirm this observation.

#### 2.6 Pileup mitigation

In high-energy proton collisions, the biggest challenges in detector design arise from a large number of pile-up events (interactions per beam crossing). For the FCC-hh machine, about O(1000) effective pileup events are expected. For low momentum particles, a 2D vertexing with an extreme timing resolution 5–10 ps per track is essential [26]. For example, 90% assigned tracks in the central region can be achieved with 5–10 ps timing cuts [5], that will keep the effective pile-up below one per bunch crossing within the central region. A calorimeter with a tens-of picosecond resolution should bring additional improvements using both charged and neutral particles.



Figure 8: Two examples of the potential of coherent microwave Cherenkov timing, based on results from the ACE collaboration [30]. Left: Data from a 2018 beam test of electron showers with a single element, scaled to a full-timing layer with liquid argon cooling. This estimate assumes a pre-shower timing layer with  $\sim 3.5X_0$  upstream of it. Right: Timing of heavy ions, via coherent Cherenkov from their Z. Coherence in this case is significantly higher since nuclear charge is complete unresolved at microwave frequencies.

### 2.7 The picosecond/sub-picosecond frontier.

A timing resolution of 10 ps has been used as a benchmark above, based on recent advances in ultra-fast silicon detectors (UFSD), which have recently achieved a timing precision of 16 ps [27], demonstrated through combining signals from a three-element detector ensemble. These devices, with use low-gain avalanche detectors tailored specifically to improve their timing characteristics, are plausible candidates to achieve 10 ps in the near future. The one difficult challenge currently facing these devices is their loss of gain at high radiation fluences; recent work has shown substantial gain damage at neutron equivalent fluences of  $\sim 10^{15}$  neq/cm<sup>2</sup> [28], more than an order of magnitude below the exposure expected at the HL-LHC or the Future Circular Hadron Collider [29]. Thus the challenges at the timing frontier are two-fold: to push the time resolution down to the 10 ps level and below, and at the same time to develop radiation-hard devices and systems as colliders push into regions of radiation fluences that are far above current levels.

One new technology under development with a view toward the FCC is coherent microwave Cherenkov detection, which has now demonstrated  $\sim 2-3$  ps timing of electromagnetic showers using dielectric-loaded rectangular wave-guide elements [31]. While the UFSD described above may achieve 10 ps timing for a tracking detector, no other technology has achieved picosecond timing for showers, which are the natural domain of calorimeters. Microwave signals, multi-GHz bandwidth and center frequencies, have rise times an order of magnitude faster than solid-state detectors. They have very high dynamic range,  $> 10^4$ ,

and inherent radiation hardness. The current drawback of this method is the relatively high least-count energy, several tens of GeV, due to the fundamental limits of thermal noise, but for colliders at 100 TeV center-of-momentum energy, this limitation may have much less importance, as the mean momentum of jets and collision products shifts to much higher energies and to the forward direction [30].

Estimates based on recent beam test data indicate that  $\leq 1$  picosecond timing is achievable for both electromagnetic and hadronic showers over a large range of the collision products at the FCC-hh [30]. Figure 8, adapted from reference [30], shows an example of timing precision using this emerging methodology. On the left, data from a 2018 beam test of electromagnetic showers in a single dielectric-loaded wave-guide element is scaled to a fully optimized multi-element timing layer, showing a transition to timing precision of several picoseconds in the 10-100 GeV range, and drops to the subpicosecond regime above 100 GeV. On the right in Fig. 8, simulation results for heavy ions timing using this technique are shown. In this case, the coherence of the microwave emission is significantly higher because the nuclear charge is completely unresolved at microwave frequencies, and thus showering of the ion is not required to detect and time it, even to sub-picosecond levels for the heavier ions.

## 3 System options

When considering technology for timing detection, one should take into account several factors, such as the physics potential and the price for instrumentation.

Below we will discuss several possible options.

#### 3.1 Volume timing

Under "volume timing" we understand timing information to be collected by all active calorimeter cells. The implementation in a highly granular calorimeter enables a full fivedimensional reconstruction of shower activity in the detector, with corresponding benefits for pattern recognition, spatial shower reconstruction and separation and energy measurement as outlined above. From a physics perspective, this technology represents the best possible choice since all information from readout cells can be included in physics analysis. At the same time, the very large number of channels in such designs may require compromises on the timing resolution for cost or technology reasons. Besides, good "classical" calorimetric and timing performances might be contradictory: a good energy resolution implies the collection of a large signal, hence cell volumes, while the timing might be limited by the fluctuations linked to the volumes needed (see [32] for the case of silicon sensors). A possible solution might lay in the development of fully digital calorimetry: some work has started (CALICE SDHCAL, ALICE FOCAL) but will still require significant efforts on the technology.

An alternative option is to integrate high-precision timing in several dedicated calorime-

ter cells separated by some distance in the transverse (to the beam) direction, providing timing only for a subset of all detector cells. This may enable more aggressive time resolution goals in a fraction of the overall detector volume while still respecting cost and technology constraints. If such cells are located in the first (last) layers of the ECAL, this option will be similar to the "timing" layer choice to be discussed below.

#### 3.2 Timing layers

Building a full-scale calorimeter system with the primary sensing elements with a tens-ofpicosecond resolution for all cells can be challenging. As a possible alternative, dedicated detectors can be installed on the front of the ECAL. An LYSO+SiPM timing layer aiming at 30 ps timing resolution is currently under construction by the CMS experiment for the HL-LHC [33]. The potential for such timing layers (TLs) was studied in the context of future collider experiments for example in [9].

A similar idea is discussed for the Segmented Crystal Electromagnetic Precision Calorimeter (SCEPCal) [34] with dual readout. The proposed detector consists of two thin layers with the capability of measuring single MIPs with a time resolution of about 20 ps. Each layer is made of inorganic scintillator square fibers close to each other.

The usage of detectors with timing capabilities on the front of the ECAL is not new. Unlike the calorimeter "volume" systems, the timing detectors can be optimized for precise time measurements using different types of technologies. Such detectors can also be optimized for granularity, and ultimately, for the price per channel. One new study conducted during Snowmass21 was focused on the verification of the usage of several timing layers, one before the ECAL, and the second layer - after the ECAL. The second timing layer can be used to measure the TOF between TL2 and TL1 in the identification of stable massive particles without a known production vertex, correlate the hits with the first layer, and thus provide directionality of the hits. Finally, it can be used for redundancy for the calculation of TOF. A schematic view of two timing layers for a generic detector is shown in Fig 9. It was verified that a typical time difference between TL2 and TL1 (which is approximated by the difference between the last and first ECAL layer) is sufficient [9] for identification of low-mass particles below the GeV-scale in momentum assuming the tens-of picosecond resolution of both timing layers.

### 4 Possible technologies

In this section we will consider several possible technology choices for the implementation of precision timing in calorimeters with resolutions in the range of a few tens of picosecond. We divided such technologies into two categories to be discussed below.



Figure 9: Example positions of timing layers (TLs) for a generic detector. The timing detectors enclose the electromagnetic calorimeter, allowing a reliable calculation of the MIP signals with a timing resolution of the order of 10 ps.

### 4.1 Technologies for timing layers

Here we will discuss possible technologies that can be used for precision time stamping of charged particles entering electromagnetic calorimeters (or the hadronic calorimeters in the case of the designs with several timing layers discussed in Sect 3.2). In addition to the excellent time resolution, small radiation lengths, small thickness and radiation tolerance are the main technology requirements for timing layers. Space for the cooling, readout and other services that are required for the timing layers can be allocated in the front and the back of the ECAL/HCAL sections.

- Low-Gain Avalanche Detectors (LGADs) developed for High Luminosity LHC experiments have demonstrated precise time resolution of about 30 ps. The position resolution of 1 mm is sufficient for most physics cases for calorimeter measurements.
- Ultra-fast silicon monolithic sensors with integrated electronic readout using the CMOS technology, in an effort to achieve 20-10 picosecond timing resolution. They are also expected to significantly reduce costs while maintaining radiation hardness. An example of this sensor, Depleted Monolithic Active Pixel Sensor (DMAPS), is discussed in [35]
- Micro-channel plate (MCP) detectors enable the detection of single ionizing particles to a precision of a few ps [36, 37]. For example, Micro-Channel-Plate Photomultiplier Tubes (MCP-PMT), R3809U-50, by Hamamatsu, indicate a time resolution better than 10 ps [37].
- A two-stage Micromegas detector coupled to a Cherenkov radiator equipped with a photocathode can lead to timing resolution for charged particles significantly below 100 ps [38].
- Sampling calorimeters based on a Lutetium-yttrium oxyorthosilicate (LYSO) crystals were demonstrated to have a time resolution in the range of a few tens of picosecond [39]. Such scintillating crystals coupled to a SiPM represents a flexible option that

has been proposed for the Segmented Crystal Electromagnetic Precision Calorimeter [34].

- Deep diffused avalanche photodiodes which were demonstrated [40] to achieve the time resolution of about 40 ps.
- Coherent microwave Cherenkov detectors, as noted in section 2.7 above, have demonstrated  $\leq 3$  ps timing of energetic electromagnetic showers [31]. Coupled electromagnetic + GEANT4 models of the process indicate that 0.3 1 ps timing of electromagnetic and hadronic showers is already achievable for typical FCC-hh energies [30].

### 4.2 Technologies for volume timing

The technology for the "volume" timing should take into account the fact that the same active material should be used for the energy and timing measurements. This list encapsulates the technologies that can be most appropriate for calorimeter cells where both the time-of-arrival and energy of the particle are measured in the same active detector element.

- Silicon tiles in different implementations. Achieving a few 10 ps for single particles requires sensors with intrinsic gain, such as LGADs, while precise timing for high-amplitude signals is also possible with conventional sensors. One example of such an application is the CMS HGCAL, where the timing information from many individual cells is used for a precise overall determination of the time of physics objects [41].
- Plastic scintillator tiles or strips with SiPM readout. SiPMs are intrinsically capable of a few 10 ps level resolution, a key factor is the scintillator response and the light collection, and the light yield, which drives the stochastic aspect of the time resolution. For the CALICE SiPM-on-Tile analog hadron calorimeter, sub-ns time resolution is achieved for minimum-ionizing particles on the cell level [42]. Ongoing studies show that this resolution is driven by the number of detected photons, which can be increased by increased sensor size, and the emission characteristics and light collection effects in the scintillator.
- Resistive plate chambers, in particular multi-gap RPCs provide a high time resolution and can be used to efficiently cover large active areas for digital and semi-digital hadronic calorimeters. Detectors with four gas gaps with less than 300  $\mu$ m each can provide sub-100 ps time resolution, which can be exploited on the system level with suitable electronics (see, for example, [43]). A small prototype based on 4-gap RPCs and PETIROC ASICs is currently in development in the framework of the SDHCAL project within CALICE, with a larger prototype, referred to as T-SDHCAL, as a longer-term perspective in case of adequate funding.
- Highly granular crystal-based detectors, using a highly segmented readout based on small scintillating crystals or other high-density scintillating materials. As for plastic-scintillator-based highly-granular sampling calorimeters key factors for the time resolution are the time characteristics of the scintillation emission and the light yield.

The higher density of crystals and the correspondingly larger energy loss can, with a suitably fast scintillator, result in faster timing than for common plastic scintillators in otherwise similar geometries.

One example are ultrafast heavy crystals with sub-nanosecond decay time, which would help to break the ps timing barrier for precision timing. Inorganic scintillators with core valence transition features with its energy gap between the valence band and the uppermost core band less than the fundamental bandgap, allowing an ultra-fast decay time. Decay time of 0.5 nanosecond is observed for barium fluoride (BaF<sub>2</sub>) crystals. Ultrafast crystals with mass production capability are discussed in [44].

• Digital Silicon PhotoMultipliers (dSiPM), based on arrays of digitally combined and managed Single Photon Avalanche Diodes (SPAD), might provide better than 20 ps time resolution for single mips [45, 46]. With 3D integration, they might have consumption and integration compatible with large calorimeters.

Common to all volume timing technologies is the need for electronics that support the required time resolution while also satisfying the constraints on power consumption associated with highly integrated systems with extreme channel counts. R&D in this area is critical for the further development of these calorimeter concepts.

# 5 Conclusion

High-precision timing is emerging as a key capability of calorimeter systems at future highenergy-physics collider experiments, expanding capabilities for particle identification, energy measurement, shower reconstruction and particle-flow event reconstruction, as well as pileup mitigation and background rejection. Two different conceptual approaches exist, with dedicated timing layers providing high-precision measurements within calorimeter systems at selected longitudinal positions, and volume timing delivering uniform, often somewhat less aggressive, time resolution for all detector cells in the calorimeter. A wide range of technologies is being explored in this context, ranging from silicon-based sensors to organic and inorganic scintillators coupled to different types of photon sensors and gaseous detectors. Calorimeters with such capabilities, providing time resolutions in the range of a few tens of picoseconds are expected to be an important step towards accurate reconstruction of events at future colliders.

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