

# Physics potential of timing layers for future detectors

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## Abstract

The physics potential of timing layers with a few tens of pico-second resolution for calorimeters of future detectors used in particle-collision experiments is explored. The presented studies show how such layers can be used for identification of separate particles, as well as illustrate the benefit of using such detectors for detection of new event signatures beyond the Standard Model.

*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 reduce background events. For CLIC and FCC, high-precision time stamping of calorimeter energy deposits will be essential for background rejection (i.e. fake energy deposits) and pile-up mitigation. Precise timing information can be used to improve reconstruction of particle flow objects by reducing overlap of energy showers in high-granular calorimeters.

From the 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 future experiments did not fully explore the benefits of the time of flight (TOF) measurements with tens-of-picosecond resolutions for calorimeters.

In this paper we will investigate the benefits of the timing layers with the resolution in the range 10 ps – 1 ns for Standard Model (SM) measurements of particles. The resolution of 1 ns is quite standard for the existing and planned calorimeters, and is only used as a benchmark for comparisons with more challenging 10 – 20 ps resolution devices. In addition, we investigate the capabilities of timing layers for identification of heavy stable particles which may be produced beyond the Standard Model (BSM).

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30 We hope such studies can help shape the requirements for future calorimeters, which  
31 were already outlined in the CPAD report [5] that emphasizes the need to develop fast  
32 timing for calorimeter measurements.

## 33 2. Proposal

34 A generic design of hadronic (electromagnetic) calorimeters for future particle colli-  
35 sion experiments (HE-LHC, FCC, CLIC, ILC etc.) is based on two main characteristics:  
36 (1) high-granularity calorimeters with cells ranged from  $3 \times 3 \text{ mm}^2$  (for ECAL) to  $5 \times 5$   
37  $\text{cm}^2$  (for HCAL) in sizes. (2) timing with a nanosecond precision that improves back-  
38 ground rejection, vertex association, and detection of new particles. According to the  
39 CPAD report [5], a development of “picosecond time resolution” for future calorimeters  
40 is one of the critical needs. Presently, high-granularity calorimeters (with  $\sim 1$  millions  
41 channels) with tens of picoseconds resolution represent a significant challenge due the  
42 large cost.

43 As a part of the HL-LHC upgrade program, CMS and ATLAS experiments are  
44 designing high-precision timing detectors with the time resolution of about 30 ps. They  
45 are based on silicon sensors that add an extra “dimension to event reconstruction.  
46 Such timing capabilities are not fully explored for future detectors beyond the HL-LHC  
47 upgrade. High-precision timing will be beneficial for new physics searches and b-tagging  
48 for all post-LHC experiments. For CLIC and FCC, high-precision time stamping will  
49 be essential for background rejection and pile-up mitigation.

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

57 In this paper we will investigate physics advantages of installing timing layers in the  
58 front of calorimeters of the post-LHC experiments. Typically, thin detectors on front of  
59 calorimeters are called “preshower”, and they have been installed for the ZEUS, CDF  
60 and ATLAS experiments. The design goal of such detectors is to count the number  
61 of charged particles in order to correct for energy losses. The timing information of  
62 “mips” (minimumionising particles) is not used for particle identifications, nor precise  
63 timing. Unlike the standard pre-shower detector, we propose not only count mips,  
64 but also reconstruct high-precision timing and the position. This timing detector will  
65 have a similar granularity as the proposed high-granularity electromagnetic calorime-  
66 ters themselves, but will have the sensor technology and the readout which are best  
67 suited for time stamping of mip signals (not necessarily for energy reconstruction). Our  
68 proposal is to enclose the EM detectors with two timing layers, one - before the first  
69 EM layer, and the second is after the last EM layer (but before the HCAL). The two  
70 layers of the timing detector allow a robust identification of time by correlating the  
71 position and timestamps of the particle passing through the ECAL.

72 In this paper we will explore this idea using semi-analytical approach and Monte  
73 Carlo simulations. A schematic representation of the positions of the timing layers for

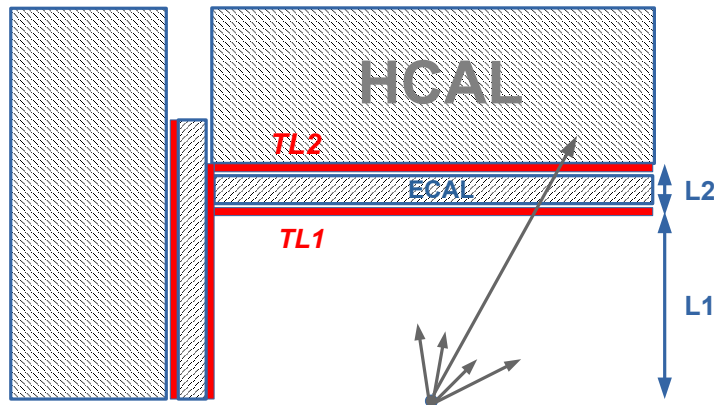


Figure 1: An example of positions of the thin timing layers for a generic detector. The thin timing layers will enclose the electromagnetic calorimeter, allow a reliable reconstruction of the mip signals with a timing resolution of the order of 10 ps.

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 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), and it is not immediately obvious that such small distance can be used for physics measurements. A particle traveling with the speed of light can cross the distance between TL1 and TL1 within  $\sim 1$  ns. As we will discuss later, this distance is sufficient for heavy particle identification for 10 – 20 ps detectors.

- Two layers are useful in the 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 which are typically arriving from the hadronic calorimeter at later time.

- 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 order 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 cells with the transverse size of  $2 \times 2$  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 ( $\pi^\pm$ ) was created with 1 and 10 GeV momentum. The pseudorapidity for all pions was  $\eta = 0$  (central region). The particles were reconstructed in the ECAL calorimeter, and the time difference  $\Delta T = T_{\text{last}} - T_{\text{first}}$  of the hits between the last and first ECAL layers was calculated. Only hits that arrive first were considered since electronics typically register fastest hits (while slower hits can be saved in pipeline buffers).

Figure 2 shows the time distribution of first arriving hits 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 ECAL layers. Therefore, the hits registered by TL1 and TL2 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.

To check the latter point, Figure 2 shows the hit distribution for (anti)deutrons, denoted as  $d^\pm$ . The distributions are significantly different from the  $\pi^\pm$  case. 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 of 0.7 ns 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 deuterons 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 deuteron particles can also be identified for a

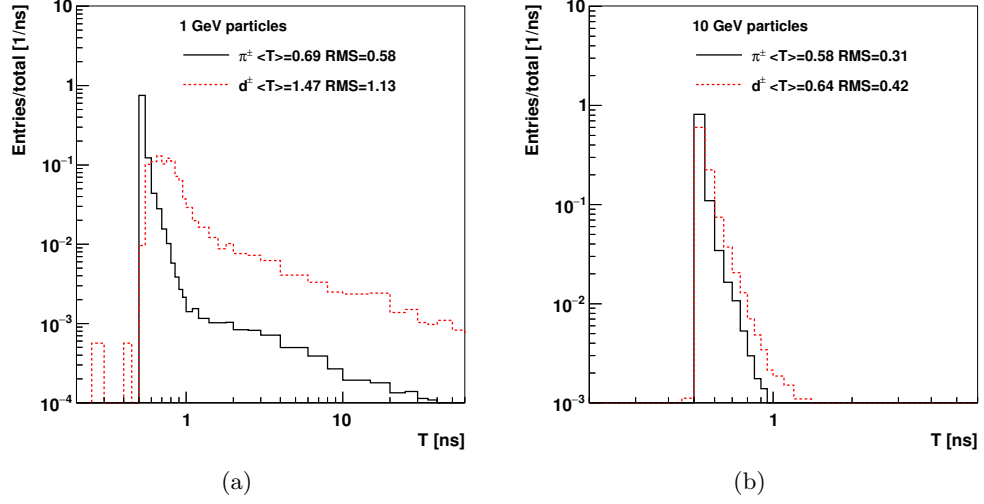


Figure 2: The difference between time of hits between the last and first layer of ECAL for single pions and deuterons with the transverse momentum 1 and 10 GeV. Only first (fastest) hits were considered to calculate the difference in TOF.

138 momentum larger than 1 GeV. In the following, we will abstract from the full simula-  
 139 tions and calculate the kinematic regions where identification of heavy stable particles  
 140 is possible.

### 141 3. Timing layers for single particles

142 Now let us discuss the kinematic regions for the TOF measurements in relation to  
 143 either SM particles or BSM particles. Instead of the full Geant4 simulations, we will  
 144 use a semi-analytic approach.

145 For an estimation of the separation power between different mass hypotheses, we  
 146 will calculate the mass and momentum for which one can achieve separation significance  
 147 higher than  $3\sigma$  (or  $p\text{-val} < 0.03$ ). If there are two particles with a mass  $m$  and a reference  
 148 (fixed) mass  $m_F$ , the  $3\sigma$  separation can be achieved for this condition [8]:

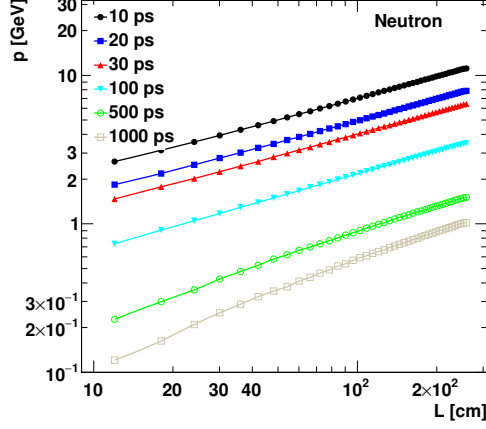
$$\frac{L}{c\sigma_{\text{TOF}}} \left| \sqrt{1 + \frac{m^2}{p^2}} - \sqrt{1 + \frac{m_F^2}{p^2}} \right| > 3 \quad (1)$$

149 where  $p$  is the momentum of a particle with a mass  $m$ ,  $L$  is the length of the particle's  
 150 trajectory, and  $\sigma_{\text{TOF}}$  is the resolution of the timing layer that measures the TOF.

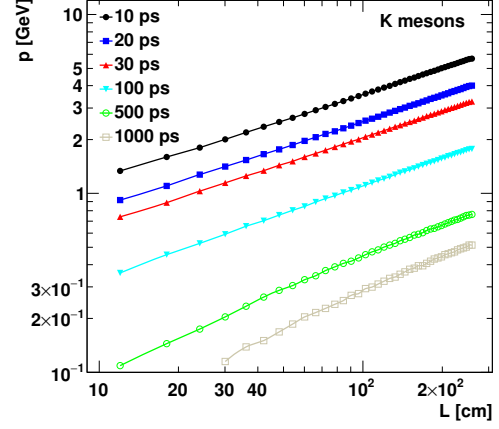
151 Figure 3 shows the  $3\sigma$  separation from the pion mass hypothesis ( $m_F = m_\pi$ ) using  
 152 the same procedure as discussed in [8]. The calculations are performed for several  
 153 options for the resolution of the timing layer, from 10 ps to 1 ns, as a function of  
 154 the travel length  $L$  and the momenta. For a 20 ps detector and for a typical travel  
 155 distance of  $L \sim 0.2$  m from the interaction point to the electromagnetic calorimeter,  
 156 neutrons (and protons) can be separated from the pion hypothesis up to 7 GeV. The  
 157 separation of  $K$ -mesons can be performed up to 3 GeV. This momentum range should  
 158 be sufficient for a reliable particle identification in a wide momentum range for many  
 159 physics studies focused on single-particle reconstruction. This can also be used for jets  
 160 that are dominated by this momentum range of separate particles. For a detector with  
 161 1 ns, the separation can only be possible up to 300 – 500 MeV. This is below than  
 162 a typical minimum transverse momentum of 0.5 – 1 GeV for particles considered for  
 163 high-energy proton colliders. Therefore, a timing layer with 1 ns resolution cannot  
 164 effectively be used for particle identification in such experiments.

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

179 Figure 4 shows the particle identification power for different choices of the timing  
 180 layer resolution and the distance  $L = L_1$  to the first timing layer (see Fig. 1). For  
 181  $L = L_1 = 2$  m, one can see that a stable heavy particle with a mass of 100 GeV can

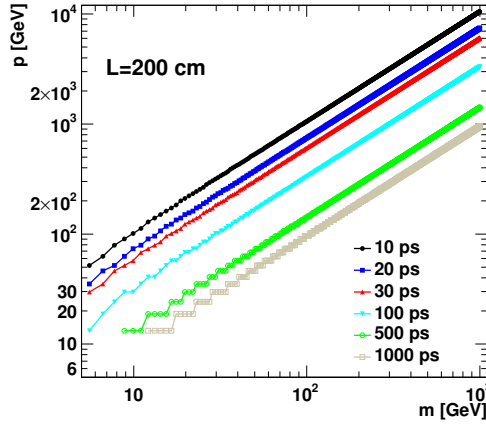


(a) Neutrons

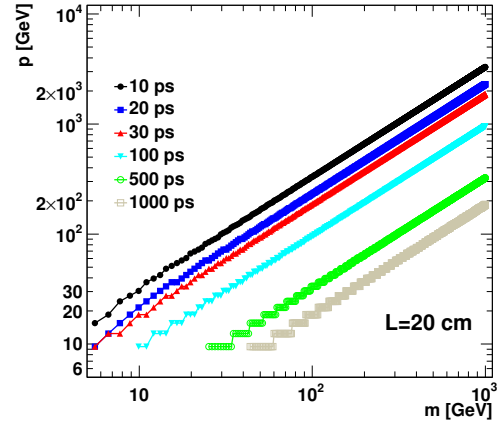


(b)  $K$ -mesons

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



(a) for  $L = 2$  m



(b) for  $L = 0.2$  m

Figure 4: The  $3\sigma$  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 TL1, 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.

be reconstructed up to 400 GeV assuming a 20 ps timing layer, but only up to 50 GeV using the standard 1 ns readout for time measurement.

In the case when TOF is measured between the two layers, TL1 and TL2, assuming a successful spacial match of the hits, the knowledge of the interaction vertex is not required. This type of measurements can be beneficial for neutral particles in collisions with large pile-up (multiple number of vertexes). 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 stable particle with a mass of 100 GeV, the identification is possible up to 100 GeV in momentum. The standard calorimeter with 1 ns resolution can perform the identification up to 20 GeV.

#### 4. Showcase for the Dark QCD model

The arguments discussed before can be illustrated using a concrete physics scenario for BSM models. In particular, we will consider the dark QCD model [9, 10] which predicts “emerging” jets that are created in the decays of new long-lived neutral particles (dark hadrons), produced in a parton-shower process by dark QCD. The process includes two mediators with masses  $Mx$ , each of which decays to a Standard Model quark and a dark quark. The final-state signature consists of four high transverse momentum jets, two of which are from two from dark quarks. These two “emerging” jets contain many displaced vertices arising from the decays of the dark pions produced in the dark parton shower.

Recently searches for such emerging jets have been performed [11] by the CMS Collaboration. The emerging jet contains multiple displaced vertices and multiple tracks with large impact parameters. Assuming that the mass of the dark pion is 5 GeV, the signal acceptance using this approach does not exceed 40% at large masses of the mediators (see Figure 4 of [11]). Dark pion decay length defines the distance from the interaction point where a jet emerges. The emerging jet contains multiple displaced vertices, which are reconstructed using a tracker [11].

Alternatively, emerging jets can be reconstructed using calorimeters with high-resolution time measurements. This method is expected to have advantage for dark pions with a large decay length, i.e. in the situation when the tracker cannot be efficient in reconstructing tracks. It was also pointed out [10] that the emerging jets may have significant fraction of neutral particles and the reconstruction using charged tracks can have a low acceptance.

To estimate the performance of the timing layers in reconstructing emerging jets, we will use the same Monte Carlo settings as for Ref. [11]: The  $pp$  collision event samples are generated with the “hidden valley” model framework in PYTHIA 8.2 assuming the centre-of-mass energy of 13 TeV, a fixed mass of 5 GeV for the dark pions. The samples were created after changing the decay distance  $c\tau$  of the dark pions. The mass  $Mx$  of the mediator was also varied.

To calculate the acceptance, will use the formalism based on Eq. 1, where  $L = c\tau$ , and  $m$  is the mass of the dark pion, i.e.  $L$  can be considered as a travel distance. After the dark pion creates a SM jet, we assume that such jets travel to the surface of the timing layer with the same speed for all values of  $m$ . For the timing layers, the signature of emerging jets is time delays compared to the other SM jets. The



production vertex cannot be observed by the timing layers if such jets emerges before TL1<sup>1</sup>. After events being generated, the weighted average of the decay distances of all particles that originate from the dark pions, using the particle momentum as the weight, were calculated. This decay distance is used to approximate the decay length, without using a jet reconstruction. The calculation for the  $3\sigma$  separation assumed  $m_F = m_\alpha \simeq 3.73$  GeV although such a choice can be rather arbitrary. This value of  $m_F$  is used to give a conservative estimate of the arrival time of the SM jets. (One can argue that the SM jets mainly consist of light-flavour hadrons and photons, therefore,  $m_F$  is significantly lower).

The acceptance of reconstruction of the emerging jets events was calculated by counting the number of events that pass the Eq. 1 condition with the parameters as discussed before, divided by the total number of entries without this requirement. Figure 5 shows the acceptance as a function of the mediator mass  $Mx$  and the decay distance of the dark pions. This figure can directly be compared to the similar acceptance figure for the method based on tracks [11]. The acceptance based on the TOF is significantly larger for low  $Mx$  and large  $c\tau$  of the pions, compared to a similar acceptance distribution based on tracking information. The acceptance is larger for the timing layers smaller than 100 ns, than for the standard 1 ns calorimeter resolution.

Now we will be interested in the acceptance of the reconstruction of dark pions as a function of their mass and their lifetime, but assuming a fixed mass  $Mx$  for the mediator. This time we will consider the HE-LHC environment with  $pp$  collisions at the centre-of-mass energy of 27 TeV. The Monte Carlo settings for the signal model were similar to those discussed in [11], but then were further tuned [12] to obtain samples which were most suitable for the detector performance studies. The mass of the mediator was set to 10 TeV, while the mass of the dark pion was varied in the range between 5 and 1000 GeV. The dark pion proper decay length,  $c\tau$ , was varied between 1 mm and 1000 mm (independent of its mass). Other parameters were also appropriately modified to allow a sufficient phase space for the dark meson production. The mass of the dark pion is assumed to be one half the mass of the dark quark. The mass of the dark  $\rho$  is four times of the dark pion mass. The width of the mediator particle is assumed to be small as compared to the detector mass resolution.

As before, the acceptance of reconstruction of the emerging jets by measuring the timing information was calculated by counting the number of events that pass the Eq. 1 condition with the parameters as discussed before, divided by the total number of entries without this requirement. Figure 6 shows the efficiency as a function of  $c\tau$  and the mass of the dark pion. It can be seen that a detector with the standard 1 ns resolution does not have acceptance for the dark meson measurements. The acceptance is significantly larger for the timing layers that have a resolution smaller than 100 ns. The acceptance is small for low  $c\tau$  or small masses, which is the expected feature of the timing measurement. The timing layers with 20 ps have have 100% acceptance for large values of  $c\tau$  and dark-meson masses. The efficiency as a function of the particle velocity for 20 ps and 1 ns timing layer resolutions is shown in the Appendix A.

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<sup>1</sup>It is possible that if such jets are created in the area between TL1 and TL2, such signatures can also be detected, but we will not consider this case.

269        Note that these results are relatively general since they are independent of the posi-  
270        tion of the timing layers, and other details relevant to the geometry of the calorimeter.

## 271    **5. Summary**

272        This paper discusses the benefits of the timing layers positioned in front of the  
273        hadronic calorimeters. Using the full Geant4 simulations and a semi-analytic approach,  
274        the figures of merits for identification of single particles using timing layers with res-  
275        olutions of 10 ps – 1 ns were calculated. It was illustrated how such layers can be  
276        used for single particle identification and identification of heavy long-lived particles in  
277        the context of the dark QCD model. It was shown that the timing layers lead to a  
278        significant benefit for reconstruction of heavy long-lived particles in region of  $c\tau$  and  
279        momentum where track measurements have low reconstruction acceptance.

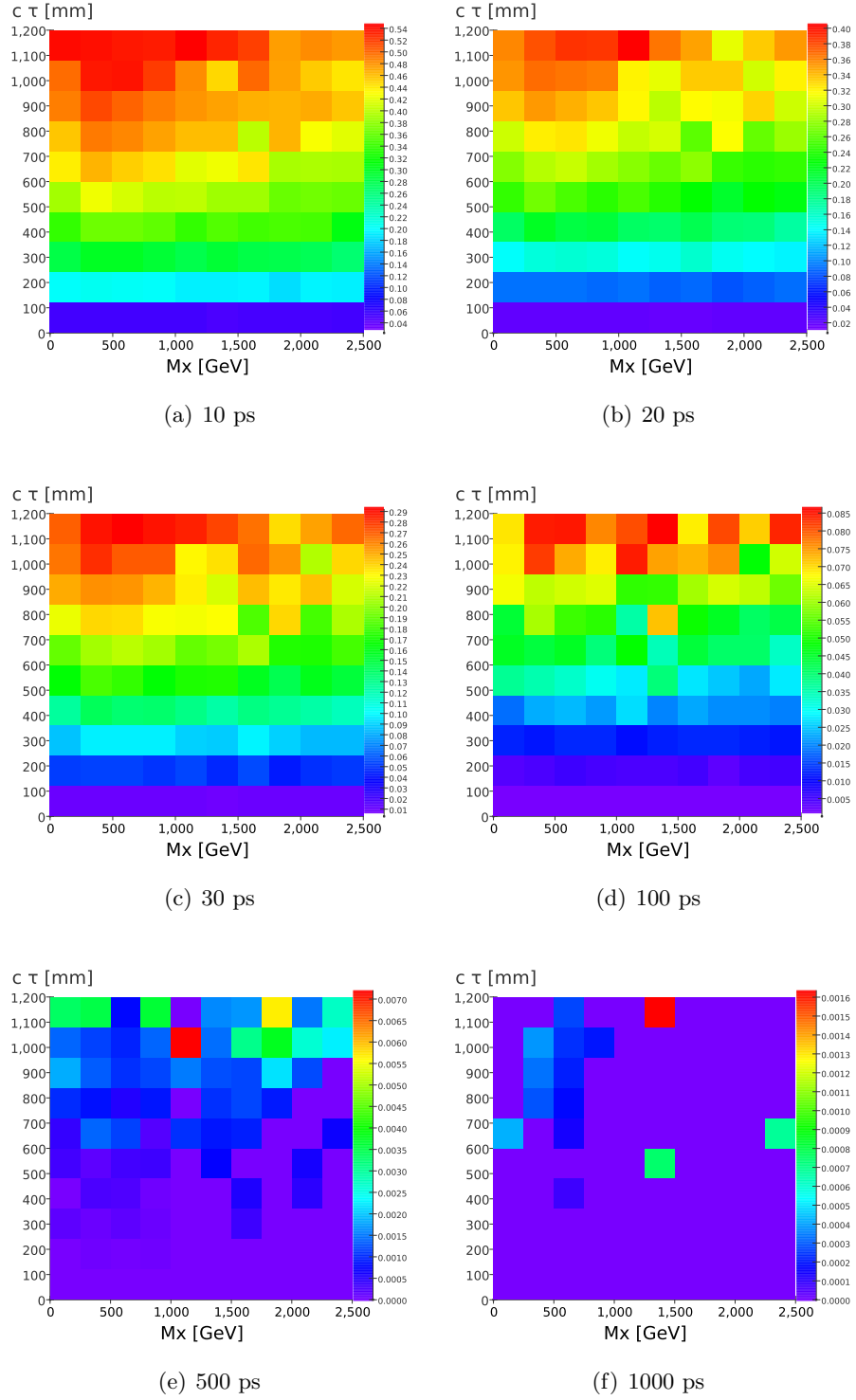


Figure 5: The acceptance for the reconstruction of emerging jets using the timing layers with different timing resolutions as a function of the mediator mass  $Mx$  and the  $c\tau$  of the dark pions with the mass 5 GeV. The Pythia8 simulations are performed for the  $pp$  collisions at  $\sqrt{s} = 13$  TeV.

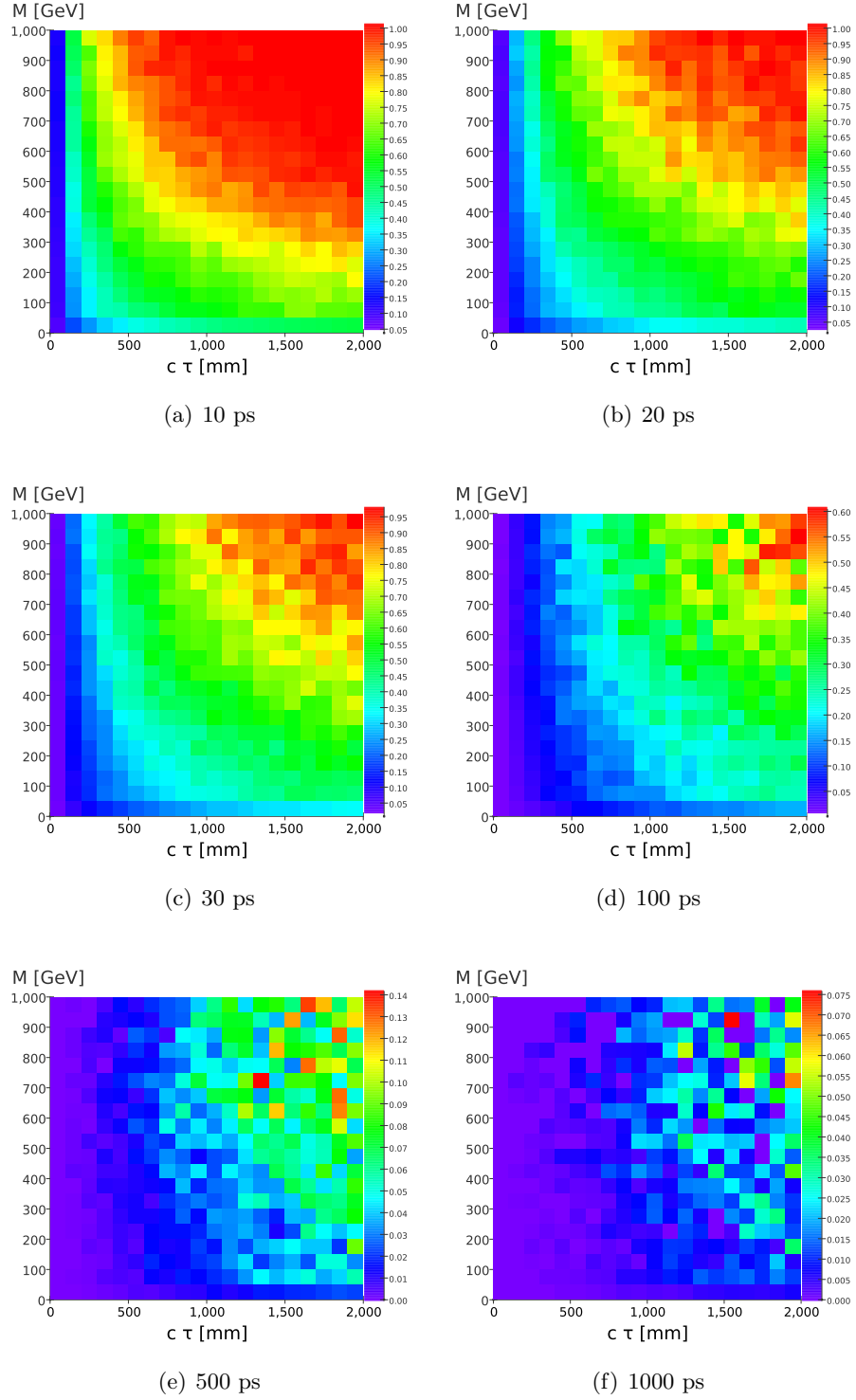


Figure 6: The acceptance for the reconstruction of emerging jets using the timing layers with different timing resolutions as a function of the mass of the dark pions and their  $c\tau$ . The mediator mass was fixed to 10 TeV. The Pythia8 simulations are performed for the  $pp$  collisions at  $\sqrt{s} = 27$  TeV.

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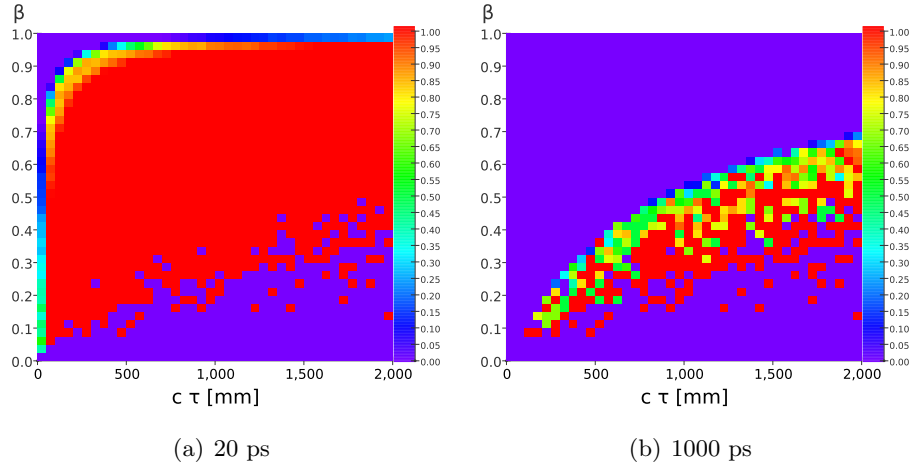


Figure A.7: The efficiency for the reconstruction of emerging jets using the timing layers with different timing resolutions. The plot shows the efficiency as a function of  $c\tau$  and the particle velocity  $\beta$

## 311 Appendices

### 312 Appendix A. Appendix

313 Figure A.7 shows the reconstruction efficiency as a function of  $c\tau$  and the particle  
 314 velocity  $\beta = |p|/E$ , for the two extreme cases of the timing layers.