# Calorimeters for Precision Timing Measurements in High Energy Physics

To cite this article: Adolf Bornheim *et al* 2015 *J. Phys.: Conf. Ser.* **587** 012057

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# Calorimeters for Precision Timing Measurements in High Energy Physics

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**Abstract.** Current and future high energy physics particle colliders are capable to provide instantaneous luminosities of 1034 cm-2s-1 and above. The high center of mass energy, the large number of simultaneous collision of beam particles in the experiments and the very high repetition rates of the collision events pose huge challenges. They result in extremely high particle fluxes, causing very high occupancies in the particle physics detectors operating at these machines. To reconstruct the physics events, the detectors have to make as much information as possible available on the final state particles. We discuss how timing information with a precision of around 10 ps and below can aid the reconstruction of the physics events under such challenging conditions. High energy photons play a crucial role in this context. About one third of the particle flux originating from high energy hadron collisions is detected as photons, stemming from the decays of neutral mesons. In addition, many key physics signatures under study are identified by high energy photons in the final state. They pose a particular challenge in that they can only be detected once they convert in the detector material. The particular challenge in measuring the time of arrival of a high energy photon lies in the stochastic component of the distance to the initial conversion and the size of the electromagnetic shower. They extend spatially over distances which propagation times of the initial photon and the subsequent electromagnetic shower which are large compared to the desired precision. We present studies and measurements from test beams and a cosmic muon test stand for calorimeter based timing measurements to explore the ultimate timing precision achievable for high energy photons of 10 GeV and above. We put particular focus on techniques to measure the timing with a precision of about 10 ps in association with the energy of the photon. For calorimeters utilizing scintillating materials and light guiding components, the propagation speed of the scintillation light in the calorimeter is important. We present studies and measurements of the propagation speed on a range of detector geometries. Finally, possible applications of precision timing in future high energy physics experiments are discussed.

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1.  Introduction

Current and future high energy physics particle colliders are capable to provide instantaneous luminosities of $10^{34}$ cm$^{-2}$s$^{-1}$ and above. The high centre of mass energy, the large number of simultaneous collision of beam particles in the experiments and the very high repetition rates of the collision events pose huge challenges. They result in extremely high particle fluxes, causing very high occupancies in the particle physics detectors operating at these machines. To reconstruct the physics events, the detectors have to make as much information as possible available on the final state particles. Aside from the detailed spatial information of the final state particles as well as their momenta and energies one can make use of the relative time of arrival at a given location in the detector. The work presented in this document is inspired by the experimental conditions expected for the high luminosity upgrade of the Large Hadron Collider (HL-LHC) at CERN. At luminosities of $10^{34}$ cm$^{-2}$s$^{-1}$ and above at HL-LHC one expects 140 to 200 simultaneous proton-proton collisions at every bunch crossing. The proton bunches will cross every 25 ns inside the experiments. The luminous region inside the detector, the location where the protons collide, has a length of a few 10 cm. Due to the size of the proton bunches and the resulting time it takes them to pass through each other in the luminous region, the collisions are in addition spread out in time. For the LHC machine parameters as in the first LHC run in 2011 and 2012 this spread was about 200 ps. For HL-LHC this spread may increase as a consequence of an advanced beam optics of the interaction region (Fartouk). The multi-purpose detectors ALTAS and CMS are expected to undergo significant upgrades and modifications, the basic geometric layout and size will however remain unchanged. In this work we assume that a detector capable of measuring the time of arrival of a particle would be located at the outer perimeter of the tracking device or in the front part of the calorimeter, as for example in the electromagnetic part of the calorimeter. Under this assumption, the typical time of flight of a particle at the speed of light from the primary vertex of a proton-proton collision to the location of the precision timing device would be in the range of 4 ns to 11 ns in the case of the CMS detector. Finally, in this document we specifically study the possibility to measure the time of arrival of particles with scintillator based calorimeter. The size of the shower of electromagnetically interacting particles at high energies results in a typical time scale of order 1 ns over which the showering process evolves. In Figure 1 we summaries the relevant time scales discussed above.
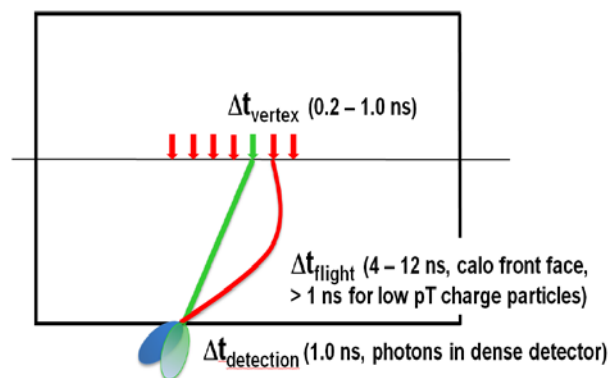


Figure 1 : The time of arrival of a high momentum particle created in a high energy proton collider such as the LHC can be decomposed in three major contributions. The creation time and location varies with respect to the nominal time and location ($\Delta t_{vertex}$). The time of flight from the vertex location to the location of the timing measurement may be referred to as the actual time of flight. The characteristic time of the detection process depends on the specific technology choice for the timing measurement

The reason that we focus on electromagnetically interacting particles is that the event reconstruction in the LHC detectors combines the information from tracking devices and calorimeter devices in a very

sophisticated fashion. One can assume that the association of any charged particle to its origin in the collision region can be accomplished by the tracking system. Any calorimeter cluster originating from a charged hadron can be associated to an extrapolated track as well and hence to its origin in the collision region. Photons however, as the will not leave tracks, cannot be associated to their production vertex easily. This is where a very precise timing would benefit the event reconstruction tremendously if a precision of a few 10 ps, corresponding to a few mm resolution at the vertex location, can be achieved. To be utilized effectively it seems mandatory that the timing measurement is very closely linked to the energy measurement, ideally based on the same active detector element. It is in this context that we study the possibility to measure the time of arrival of electromagnetic particles with a calorimetric device.

2.    Precision Timing Measurements with Scintillating Crystals

The study we present here is using scintillation crystals as an active medium to detect the high energy particles. This choice is driven by the potential use case of a precision timing detector for the Phase II upgrade of the LHC experiments. For this, the measurement of the time of arrival of high energy photons with energies of 1 GeV and above is of particular importance.

In Figure 2 we illustrate the major contributions to the precision of the timing measurement with a monolithic, large scintillating crystal. Upon entering the crystal the photon will need to convert and start showering to induce scintillation light in the crystal. This time span between entering the crystal and the first occurrence of scintillation light we refer to as $t_C$. The scintillation process may be described by two time constants, the rise time of the scintillation light and its typical decay constant. The rise time of the scintillation light signal from LYSO crystals has been measured to on the order of 75 ps [2]. The result was limited by the experimental setup of the respective measurement. The decay time constant for LYSO is on the order of 40 ns. For high energy particles in the multi GeV range the shower even for electromagnetic particles will extend over several centimetres. This process will take on the order of a nanosecond. With our current experimental setup we cannot de-convolute the time structure of the scintillation process and the propagation of the shower through the crystal. We denote the related characteristic time constant with $t_S$.

The scintillation light produced needs to be detected. Typically this is done with one or several photo detectors attached to the scintillator. The time $t_T$ it takes the scintillation photons to travel through the crystal may vary substantially due to the isotropic angular distribution of the scintillation light and the possible internal reflection of the light inside the crystal before eventually reaching the photo detector. Finally, the photo detector and its readout system have characteristic time constants $t_P$ and $t_D$ which will affect the precision of the measurement as well.
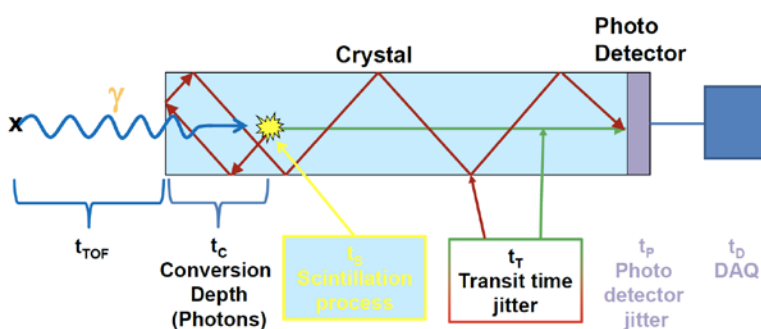
Figure 2 : Time difference between the two MCP photo sensors at the end of a 10 cm long LYSO crystal as measured in the transverse setup. The beam was hitting the crystal about 3cm from one end of the crystal. The time is extracted with a fit to the entire pulse shape. An electron beam was used for this measurement. The electrons were

In this study we focus on studying the effects of the shower development, scintillation light emission and light propagation inside the crystal with their characteristic time constants $t_S$ and $t_T$. The contribution of the photo detectors and the readout system, $t_P$ and $t_D$, was studied independently and

reported at this conference [3]. In this reference the precision with which the time of flight can be measured with two reference detectors is better than 20 ps. In all results presented here which invoke the MCP based reference detector measurement we did not unfold its contribution to the final result. In the initial studies presented here we focus on measurements which allow to quantify the contribution of the showering process in the crystals, the scintillation light emission and the light propagation inside the crystal. These contributions will dependent on the type of scintillator used, its size and its surface properties. Future experiments will be carried out to study all these factors in detail.

### 3.  Experimental Setup

In this document we report on measurements using cosmic muons, performed at Caltech Lauritsen Laboratory, and test beam measurements performed at the Fermi National Laboratory (Fermilab) M-test beam facility using high energy electrons of 4, 8 and 16 GeV as well as protons of 120 GeV.

For our test beam measurements we used commercially available multichannel plate photo multiplier tubes (MCP PMT or just MCP) from Photek 240 and Hamamatsu R3809U. In the test beam setup the MCP were read out with a wave form digitizer with an analogue bandwidth of 700 MHz and a sampling rate of 5 GS/s (DRS4). For the cosmic measurements at Caltech we used an Agilent MSO9404A oscilloscope with an analogue bandwidth of 4 GHz and up to 20 GS/s. As a photo detector for the cosmic setup we used Philips XP2020 photo multipliers. A picture of the experimental setup as used in the Fermilab test beam is shown in Figure 3.

To extract the time of arrival information of a high energy particle from the scintillation light pulses we explored various methods, such as a constant fraction fit on the rising edge of the pulses as well as a fit of a parameterized fit function to the entire pulse. For this again we explored a range of functional forms. Results from a fit to the full pulse shape shown in this document are done with an exponentially modified Gaussian. At the precision we have tested so far we did not find a significant difference among the methods we tested. The observed rise time of the scintillation light signal as measured with the MCP and DRS4 is on the order of 1 ns. We did not find any significant dependency on the particle type inducing the signal, the size of the crystal used or the distance between the shower and the photo sensor. The signal line shape of the reference detector pulse is well described with a Gaussian. The observed sigma of the Gaussian line shape is about 0.5 ns. The details of the scintillation light pulse shape will be studied further in forthcoming measurement campaigns.
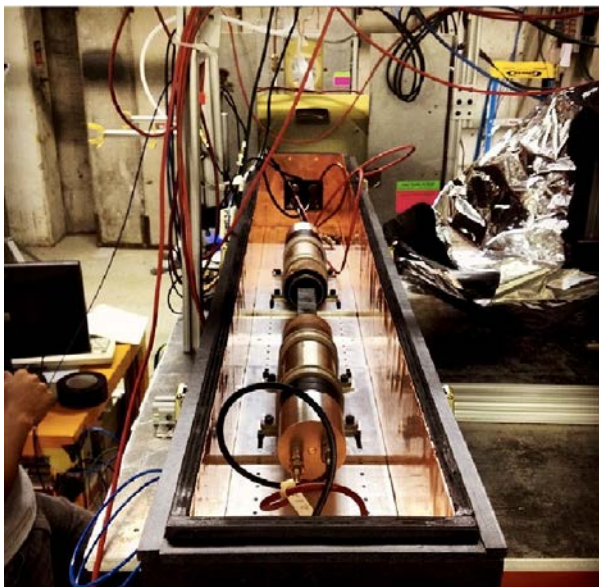


Figure 3 : Experimental setup for the test beam measurements. Inside a light tight box, shielded against environmental noise, a LYSO crystal with photo detectors mounted on both ends is installed. The setup shown is the one used for the Fermilab test beam. The setup for the cosmic test is largely identical. Depending on the configuration reference and trigger counter were installed. The different configurations are described schematically in the following figures.

In Figure 4 we show the conceptual setup of the cosmic ray test bench. The goal for measurements with this setup was to explore the effective propagation speed of the scintillation light inside in a solid LYSO crystal and to explore if there is any dependency on the pulse shape if the location and shape of the shower inside the crystal is varied. To achieve this, we spatially constrained the location at which scintillation light is created by cosmic muons passing through the crystal with two scintillation counters. The scintillation light will then propagate from where it was created through the crystal and be detected at both ends with a photo detector. By scanning along the axis of the crystal we extract the average propagation speed. We also used this setup to do initial studies of the pulse shape and test different time extraction methods.
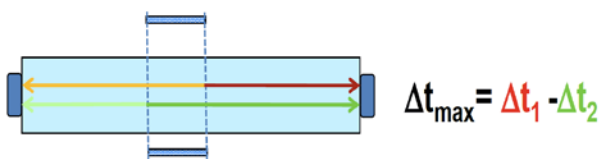


Figure 4 : Time difference between the two MCP photo sensors at the end of a 10 cm long LYSO crystal as measured in the transverse setup. The beam was hitting the crystal about 3cm from one end of the crystal. The time is extracted with a fit to the entire pulse shape. An electron beam was used for this measurement.

For measurements with high energy particles in the Fermilab test beam we used two different configurations. In Figure 5 we show what we refer to as perpendicular setup. The beam is triggered with two wire chambers which allow to spatially constrain the location where the beam particles hit the crystal. A MCP is used as a reference counter and the crystal is read out by two MPC as in the cosmic setup. The goal using this setup was to understand if the spatially much larger showers induced by electromagnetic particles compared to the energy deposition pattern of a muon would influence the pulse shape or the differential time distribution.
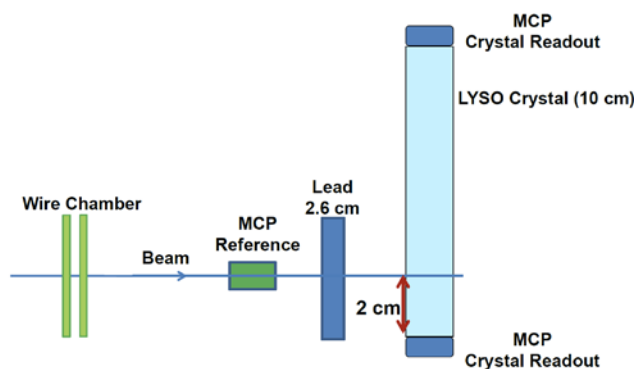


Figure 5 : Transverse setup for the test beam measurements. The LYSO crystal was equipped with two MCP photo detectors of both ends. The beam particles were triggered with two wire chambers, defining an area of about 1.6 cm x 1.6 cm. A third MCP detector was used as a reference counter in front of the crystal setup. A lead sheet with a thickness of 2.6 cm was used for some runs to have the particles create a shower before the crystal.

In Figure 6 we show what we refer to as the longitudinal setup. Here, the crystal is aligned along the axis of the incoming particle beam. The particles have to trespass a reference MCP and the MCP on one side of the crystal readout. We refer to the photo sensor closer to the reference counter as the near side counter, the one on the other side of the crystal as the far side counter. A key difference with this setup is that the two photo sensors are not symmetric with the respect to the location of the shower in the crystal any more. The shower of electromagnetic particles will develop closer to the near side sensor and then propagate through the crystal away from the near side and towards the far side detector. As the scintillation light created in any given location inside the shower has to propagate to the photo sensor, the effective time of arrival at the photo sensor – a convolution of the shower evolution time pattern and the light propagation time pattern – will be different for the far side and the near side.
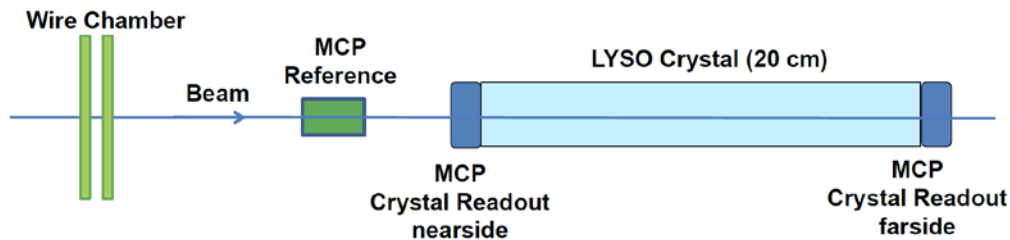
Figure 6 : The longitudinal setup for the test beam measurements. The LYSO crystal was equipped with two MCP photo detectors of both ends. The beam particles were triggered with two wire chambers, defining an area of about 1.6 cm x 1.6 cm. A third MCP detector was used as a reference counter in front of the crystal setup.

In this section we present initial results which reveal the importance of the contributions from the shower evolution and the scintillation light propagation to the measurement of the time of arrival. The results presented in this report are the first ones of a series of such measurements which we plan to carry out.

4.1 Results from the cosmic test setup.

A key result from the cosmic setup is the measurement of the propagation speed of the average scintillation light inside a large, monolithic LYSO crystal. Our cosmic setup was not equipped with a precise reference detector which defines the arrival of the particle inside the crystal. Instead we determine the propagation speed of the light by defining the distance the scintillation light had to propagate through the crystal. Using a setup in which we read out the crystal on two sides we eliminate the trigger jitter. As shown in Figure 7, we measure the propagation speed to be approximately 11 cm/ns or about one third the speed of light. Given the refractive index of LYSO of about 1.82 we conclude that there is a significant effect of the fact that the isotropic emitted scintillation photons do not reach the photo detector on the shortest possible path.

As can be seen in Figure 3 the observed relation of the mean time difference and the location of the scintillation light creation is linear. We did not observe any change in rise time or the pulse shapes if the distance of the source of the scintillation light to the photo detector is varied.
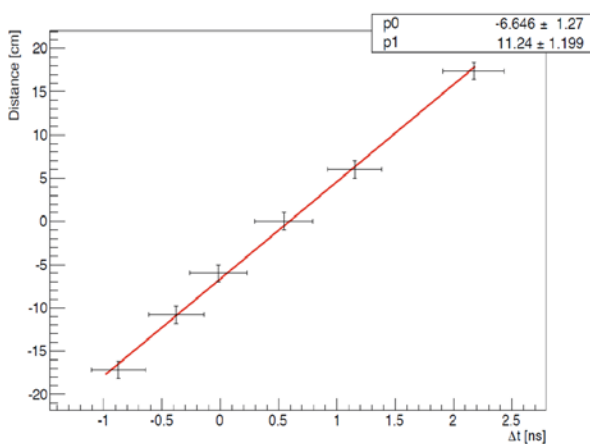


Figure 7 : Relative time difference measured between the two ends of long LYSO crystal. Two XP2020 photo multiplier was used as a photo detector, a high bandwidth oscilloscope as a data acquisition system. The scintillation signals were induced by cosmic muons traversing the crystal transversely in a small area defined with a plastic scintillator trigger counter. The time difference shown is the mean value of a large number of events recorded. From six measurements performed at different locations along the long axis of the crystal we deduce the average propagation speed of the scintillation light to be about 11 cm/ns inside the LYSO crystal.

The uncertainty of the $\Delta t$ measurement is dominated by the size of the trigger counters which define the spatial precision with which the location of the scintillation light creation is defined. For cosmic

muons we assume the energy deposit in the crystal to be uniform along the path of muon through the crystal and predominantly close to it. We have tested two different trigger counter sizes, with a width of approximately 3 cm and 1 cm. The spread of the measured time difference is 300 ps and 160 ps respectively. This dependency clearly reflects that the difference of the time measurement on the two ends of the crystal is very sensitive to the location where the scintillation light is created.

4.2. Results from the perpendicular test beam setup.

The perpendicular test beam setup allows testing the impact of the spatially much wider shower from an electromagnetically interacting particle. In Figure 8 we show the result of the time difference as measured with the perpendicular setup. We measure 120 ps differential time resolution. The size of the trigger counter is approximately 1.6 cm, slightly larger than the 1 cm wide counter used for the cosmic measurement in which we measured 160 ps differential time resolution. As can be seen from Figure 5 a lead sheet was placed in the beam before the crystal. This ensures that the shower is fully developed inside the LYSO crystal. Again we observe a further reduction of the spread in the measured time differential. With a Molière radius of about 1.2 cm (CHECK ME) the width of the shower is of similar width as the width of the trigger counter. We conclude that the dense nature of electromagnetic showers and the large number of scintillation photons created out weights the statistical nature of the showering process and we do not observe an increase in the measured differential time difference.
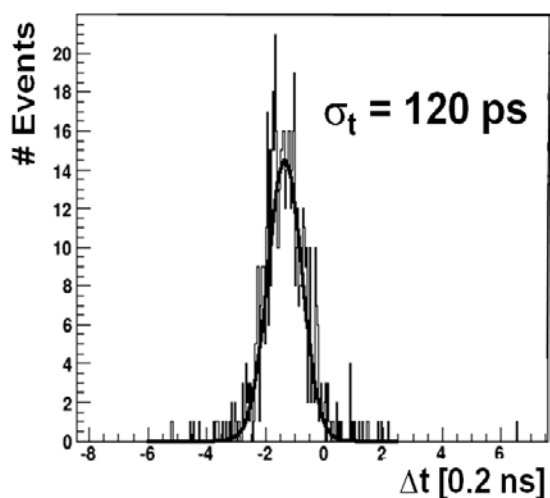


Figure 8 : Time difference between the two MCP photo sensors at the end of a 10 cm long LYSO crystal as measured in the transverse setup. The beam was hitting the crystal about 3cm from one end of the crystal. The time is extracted with a fit to the entire pulse shape. An electron beam was used for this measurement. The electrons were passing through a lead plate with 2.6 cm before hitting the crystal. We measure a time differential between the two ends of the crystal of 120 ps.

We note that the photo detectors and the photo detector readout were different in the perpendicular setup in the test beam compared to the cosmic setup. We used a full pulse shape fit to extract the time from the test beam data while we used a constant ratio fit for the cosmic data. Further we note that with the mean propagation speed measured for the scintillation light of 11 cm/ns the width of the 1.6 cm trigger counter in the test beam setup corresponds to a time difference of approximately 145 ps. We conclude that a significant portion of the observed differential dime difference can be attributed to the geometric spread of the mean shower position, as defined by the size of the trigger counter. Within the precision of or pulse shape sampling we did not observe any significant difference in the mean pulse shapes from the MCP detectors on the two sides of the crystals, even though the beam was not impinging in the middle between the two sensors. From this we conclude that the pulse shape does not depend on the average propagation distance of the scintillation photon inside the crystal. We conclude further that the observed differential time difference for the dual side readout in the cosmic setup as well as in the test beam setup is dominated by the geometric spread in the mean shower position, as defined by the size of the trigger counter. The photo sensor and data acquisition characteristics do not seem to impact the result.

We extracted the time of flight from the perpendicular setup as shown in Figure 9. Shown is the time difference between the reference MCP and the signal on one side of the crystal as detected by the MCP. For this result we use the constant fraction fit to the leading edge of the signal. We measure a resolution of about 60 ps. We do not observe any significant difference between measurements performed with and without an additional lead sheet in front of the crystal. This suggests that enhancing the shower activity in the crystal does not change the measured time resolution. We conclude from this that we are not sensitive to the photo statistics. The resolution we measure is better than the differential time resolution between the two sides of the crystal as shown in Figure 8. One difference is that for the time of flight measurements we use an MCP as a reference while the measurement in Figure 8 compares the two signals extracted from the crystal. Future measurements will be optimized to reduce the impact of the spatial uncertainties of the shower location contributing to the 120 ps measured as in Figure 8. The perpendicular setup will be optimized to better understand the contribution of charged shower particles hitting the MCP detectors. We know from our reference MCP detectors that direct hits of the MCP with particles allows to measure the time of arrival with a precision of around 15 ps. While this would allow a precise measurement of charged particles it is not applicable to photons which is the main target of our study as detailed in the introduction.
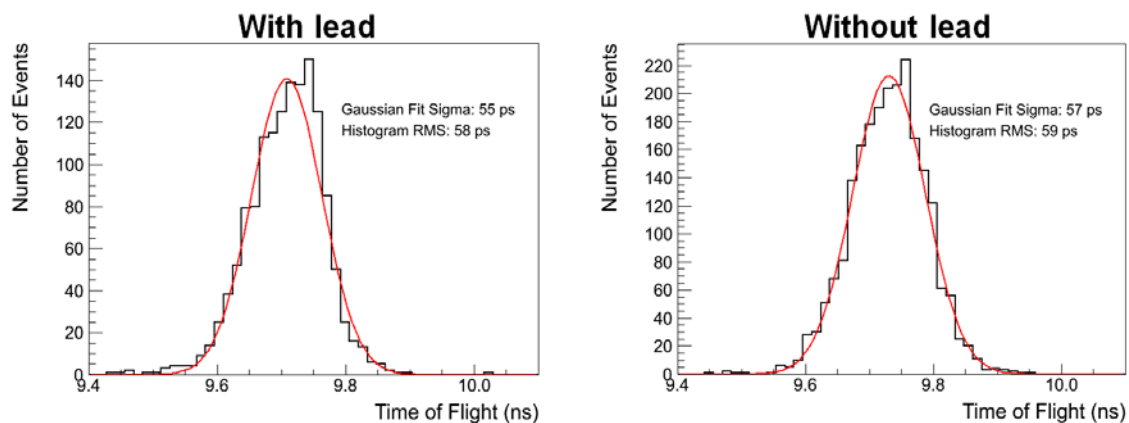


Figure 9 : Time of flight results for the perpendicular setup. The results show the time difference between the reference MCP and the signal extracted from the MCP attached to the crystal. The absolute time difference scale is arbitrary. We observe a resolution of about 60 ps. We perform the measurement with and without an additional lead sheet in the beam in front of the crystal. We do not see any significant change in the time resolution.

### 4.3. Results from the longitudinal setup

An important difference for the longitudinal setup is that there is no geometric effect due to the size of the trigger counter. However the shower development inside the crystal may fluctuate on an event by even basis. For the time measurement the shower depth is of importance. If a given shower develops deeper inside the crystal it will take longer for the shower reaching the point of maximal intensity and the mean path length of the scintillation light propagating to the near side photo detector will be longer. The inverse holds for the far side photo sensor. We recall that the mean speed of the scintillation light propagation inside the crystal is significantly less than the speed of light. As the shower development inside the crystal propagates with the speed of light the mean depth of the shower also impacts the time of arrival as measured at the far side detector. This effect is visualised in Figure 9 from a GEANT simulation of a single, 16 cm long LYSO crystal. The near and far side crystal face

are at -8 cm and +8 cm respectively. A 100 GeV photon enters the crystal from the minus side. We show the mean arrival time of the scintillation and the Cherenkov photons on the near and far side of the crystal as a function of the location of the first conversion of the impinging photon inside the crystal. We see that the photon arrive later on the near side surface if the conversion happens deeper inside the crystal and earlier at the far side surface of the crystal. The effect is more pronounced on the near side crystal surface since the distance between the shower maximum and the crystal surface is smaller and the dispersion in the photon path is smaller. For the scintillation light we observe a delay of about 100 ps per 1 cm additional depth for the first conversion. This matches approximately the 11cm/ns we observed for the propagation speed of the scintillation light inside a long LYSO crystal.
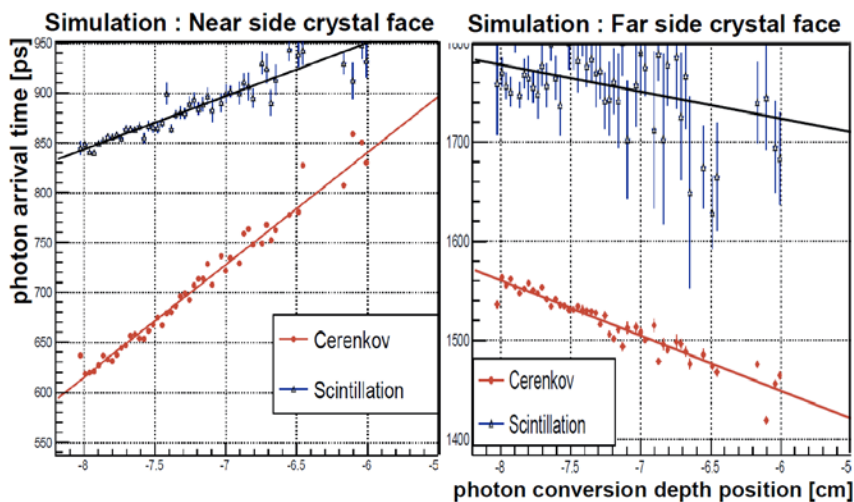


Figure 10 : Simulation of the mean arrival time of the scintillation light from a 100 GeV photon shower in a LYSO crystal. The way axis shows the depth of the first conversion of the photon. The crystal starts at -8 cm on the scale shown. One sees that the conversion depth is correlated with the mean arrival of the scintillation photons at the crystal face.

With the longitudinal test beam setup the goal was to explore if the expected differences with respect to the perpendicular setup can be reproduced. In Figure 11 we show the time difference between the near side and the far side photo detector in the longitudinal setup mounted on a 20 cm long LYSO crystal. We observe a differential time resolution of about 30 ps. As expected we see a further reduction of the differential time resolution compared to the corresponding measurement with cosmic muons and from the perpendicular setup. We attribute this to the fact that the geometric variation of the location of the shower relative to the photo sensor is reduced to the fluctuations of the shower depth. As these fluctuations are typically on the scale of one radiation length the resulting uncertainty is small.
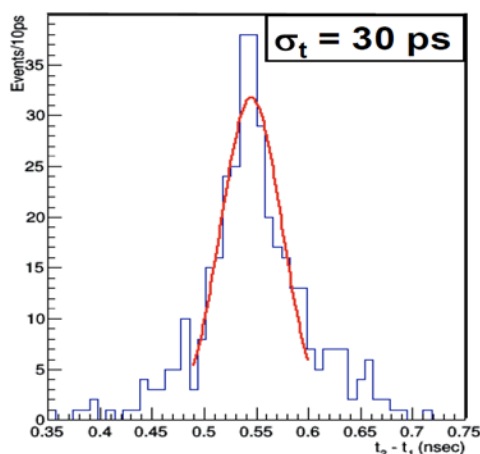


Figure 11 : Time difference between the two MCP photo sensors at the end of a 20 cm long LYSO crystal as measured in the longitudinal setup. The lateral size of the crystal is 2.5 cm x 2.5 cm. The beam was hitting the crystal approximately in the centre. The time is extracted with a constant fraction fit to the rising edge of the pulse shape. An electron beam was used for this measurement. In this setup the time difference between the two sides is not affected by geometric effects due the variations of the impact point. We measure 30 ps differential resolution. We observe some non-gaussian tails in this distribution which we attribute to particles showering before the near side MCP.

If indeed the shower depth is contributing to the measured resolution one would expect to find a correlation as shown in the simulation results in Figure 10. In our initial studies we found indeed indications for such a correlation. We are carrying out further measurements to study in more detail if this observation can indeed be solely explained by the effective path length of scintillation light propagating through the crystal.

5.  Test with a small LYSO plate

A key feature of LYSO is its high light yield. This makes a sampling calorimeter with LYSO as active medium a feasible design. Even with a sampling fraction of around 0.1 and a readout of the LYSO plates via fibers the effective light yield for high energy showers is still be large enough to achieve an acceptable stochastic term in the energy resolution. The CMS collaboration at LHC is currently studying the feasibility of a sampling calorimeter with LYSO as active medium and tungsten as absorber. The results we presented above indicate that the achievable time resolution for high energy particles in a large LYSO crystal is significantly impacted by the optical transit time jitter. Shower fluctuations and photo statistics on the other hand are less relevant for multi-GeV electromagnetic showers. An important question is if this will remain true is the shower is sampled with a fraction of 0.1 and the light is guided from the active medium via fiber to the photo sensor. We carried out an initial test with a LYSO plate of 14 mm x 14 mm size and 1.5 mm thickness. Stacked with tungsten absorber plates of approximately 2.5 mm thickness the effective Molière radius of the Shashlik configuration is 14 mm. This is the current design baseline for the CMS ECAL Shashlik prototype. As shown in Figure 12 we read out a single such LYSO plate by bringing one of the sides of the plate into contact with the MCP window. We then exposed the LYSO plate to electron and proton beams.
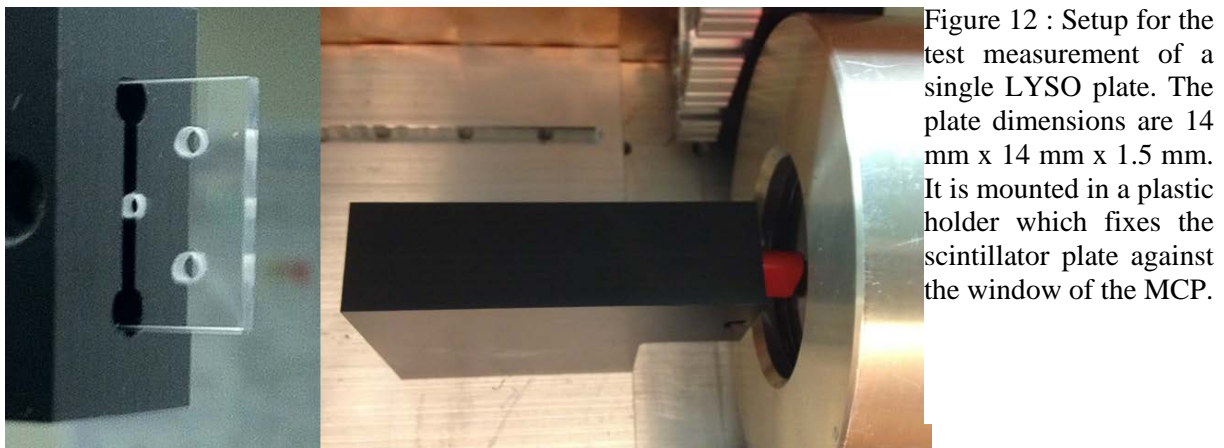


Figure 12 : Setup for the test measurement of a single LYSO plate. The plate dimensions are 14 mm x 14 mm x 1.5 mm. It is mounted in a plastic holder which fixes the scintillator plate against the window of the MCP.

Results from the initial tests suggest that the rise time observed on the pulses from the LYSO plate is not significantly different from the one observed on larger LYSO crystals. We were able to extract time resolutions on the order of 50 ps with respect to the reference MCP detector. With our initial setup it was not possible to control the shower position on the LYSO plate very well. Also, the signal from the MCP may have contributions from shower particles hitting the sensor directly. Future tests with a refined setup will allow to disentangle the contribution of the signal from direct hits and from scintillation light. We also plan to test the time response of individual LYSO plates inside a full Shashlik configuration as well as the time response of a full Shashlik cell where the light is extracted from the LYSO/tungsten stack via wavelength shifting fibers.

6.  Summary

We perform measurements on the timing properties of scintillation light from high energy electromagnetic showers in LYSO scintillating crystals of various sizes. For our measurements we use commercially available Photek and Hamamatsu multichannel plate photo multipliers, read out with DRS4 sampling digitizer. We found that the rise time observed on LYSO samples of different size, for particles of different type and energy does not vary significantly within the precision of our measurements. We measure the average propagation speed of scintillation light to be around 11 cm/ns inside a large monolithic LYSO crystal of 20 cm length. Differential time resolution measurements on a large LYSO crystal, read out by two identical photo sensors, suggest that the scintillation light propagation inside the crystal is a very significant contribution to the measured time of arrival extracted from the scintillation light. Time of arrival measurements with high energy electrons 4 GeV, 8 GeV and 16 GeV suggest that time resolutions of a few 10 ps can be achieved.

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