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Detection of high energy muons with sub-20 ps timing resolution using L(Y)SO crystals and SiPM readout

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ABSTRACT

Precise timing capability will be a key aspect of particle detectors at future high energy colliders, as the time information can help in the reconstruction of physics events at the high collision rate expected there. Other than being used in detectors for PET, fast scintillating crystals coupled to compact Silicon Photomultipliers (SiPMs) constitute a versatile system that can be exploited to realize an ad-hoc timing device to be hosted in a larger high energy physics detector. In this paper, we present the timing performance of LYSO:Ce and LSO:Ce codoped 0.4% Ca crystals coupled to SiPMs, as measured with 150 GeV muons at the CERN SPS H2 extraction line. Small crystals, with lengths ranging from 5 mm up to 30 mm and transverse size of $2 \times 2\ \text{mm}^2$ or $3 \times 3\ \text{mm}^2$, were exposed to a 150 GeV muon beam. SiPMs from two different companies (*Hamamatsu* and *FBK*) were used to detect the light produced in the crystals. The best coincidence time resolution value of (14.5 ± 0.5)ps, corresponding to a single-detector time resolution of about 10 ps, is demonstrated for 5 mm long LSO:Ce,Ca crystals coupled to *FBK* SiPMs, when time walk corrections are applied.

1. Introduction

The high track density and event pile-up expected at future high luminosity particle colliders pose serious challenges for physics event reconstruction and analysis. For energy measurements, one important source of degradation is represented by the contamination of neutral particles originating from secondary vertexes. A precise timing of both calorimeter deposits and vertexes can aid in the reconstruction, allowing the rejection of spurious energy deposits that are not consistent with the primary vertex time. It can be estimated [1] that the level of needed timing resolution is of about 20–30 ps σ[1].

Scintillating LSO and LYSO crystals coupled to Silicon Photomultiplier devices (SiPM) are known to constitute an efficient configuration for the detection of the two 511 keV photons originating from the radioactive tracer in positron emission tomography (PET). In this field too, precise timing is a valuable information to allow so-called time-of-flight PET and improve the image signal-to-noise ratio [2,3]. Recent R&D activity in this field has demonstrated the capability of reaching sub-100 ps FWHM CTR values with LSO:Ce crystals codoped with Ca and coupled to optimized SiPM detectors [4].

In this work, we profit from advancements of this technology in the medical imaging field transferred to high energy physics (HEP), since inorganic crystals coupled to SiPMs can offer a versatile solution to have a precise timing of calorimetric deposits or to detect charged tracks with high efficiency and reconstruct the associated vertex time. The timing performance of LYSO and LSO crystals was studied with a 150 GeV muon beam produced with the SPS proton accelerator along the H2 extraction line at CERN. In Section 2 the experimental setup is described, results are presented in Section 3 and discussed in Section 4.

2. Experimental setup

Two different sets of crystals were considered in the study: LYSO:Ce crystals, produced by *Crystal Photonics, Inc.* with dimensions $3 \times 3 \times l\ \text{mm}^3$ (l=5, 10, 20, and 30 mm) and LSO:Ce codoped 0.4%Ca crystals produced by *Agile Technologies, Inc.* with dimension $2 \times 2 \times 5\text{mm}^3$ (see Fig. 1 left). Two crystals for each type and length were wrapped with Teflon and glued to SiPMs using Meltmount (refractive index n=1.68). For LYSO:Ce crystals, the TSV MPPC devices from *Hamamatsu* were used, having a surface of $3 \times 3\ \text{mm}^2$ and a SPAD size of $50 \times 50\ \mu\text{m}^2$, whereas for LSO:Ce,Ca crystals, the NUV-HD SiPMs from *FBK* were used [5],

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[1] Unless specified otherwise, timing resolution values throughout this paper are expressed in terms of σ.

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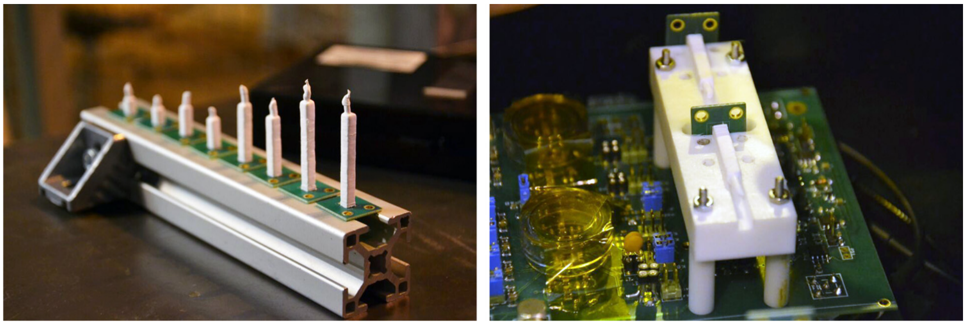

Fig. 1. Teflon-wrapped LYSO crystal pairs of different lengths (5, 10, 20, and 30 mm), each glued to a SiPM (left). Photo of a couple of crystals hosted in the holder (right).

with a surface of $4 \times 4\,\text{mm}^2$ and a SPAD size of $25 \times 25\,\mu\text{m}^2$. *Hamamatsu* and *FBK* SiPMs were operated at a bias voltage of 67.7 V and 38.0 V, respectively (64 V and 26 V breakdown voltage at 15 °C).

Couples of same-length and same-type crystals were hosted in a Teflon support that kept the crystals aligned along their main axis (see Fig. 1 right).

To attain the best possible energy and time resolution, a board was specifically designed [6] to readout each SiPM through independent channels for energy and time information reconstruction. The energy information was obtained from an instrumentation amplifier, whereas the timing information was derived from the leading edge discrimination delivered by the NINO chip (for more information about NINO, see [7]). A NINO threshold of 520 mV, corresponding to approximatively 4 times the amplitude of a single photoelectron, was used. Due to a different geometry of the two types of SiPMs, *Hamamatsu* SiPMs were connected to the board via ~5 cm long cables, while *FBK* SiPMs were directly plugged into it. The board was designed to readout two SiPMs independently, and two such boards were available, thus allowing two pairs of crystals to be tested on beam simultaneously.

The setup was housed in a dark box and exposed to a muon beam so that muons entered the crystal volume from the side opposite to the SiPM. The dark box we used was lacking a temperature stabilization system. The effect of the high temperatures during the beam test will be discussed in Section 4. In Fig. 2, the final setup with the electronic boards for SiPM biasing and signal readout, and the crystal supports mounted on top can be seen.

The amplifier analog signal, as well as the NINO digital output, were digitized at 5 GS/s using a CAEN V1742 module. The amplitude of each crystal was reconstructed as the maximum of the analog pulse, whereas the time was computed at the 50% of the NINO output amplitude and extracted from a linear fit of the signal leading edge. Examples of the acquired pulses can be seen in Fig. 3.

To estimate the intrinsic time resolution of our setup, the output of one SiPM was split and sent to two independent NINO input channels. The reconstructed time difference between the two NINO output signals yielded an intrinsic $\sigma_{\text{CTR}} = 7$ ps, as obtained from a Gaussian fit of the resulting distribution.

3. Results

A typical observed energy distribution is shown in Fig. 4 for a 5 mm LSO crystal. The peak generated by muons traversing the entire crystal length is clearly visible, with smaller values

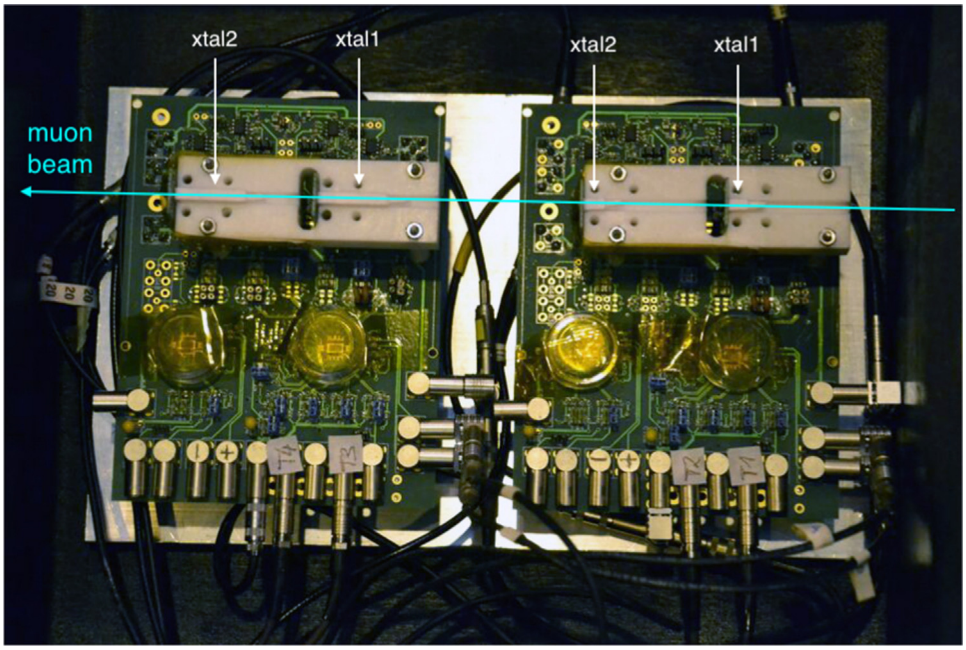

Fig. 2. Photo of the final setup: electronics boards providing bias to the SiPMs and hosting the amplifiers for energy reconstruction and the NINO chips for time reconstruction. The crystal holders are visible as well. The muon beam direction is marked on the picture.

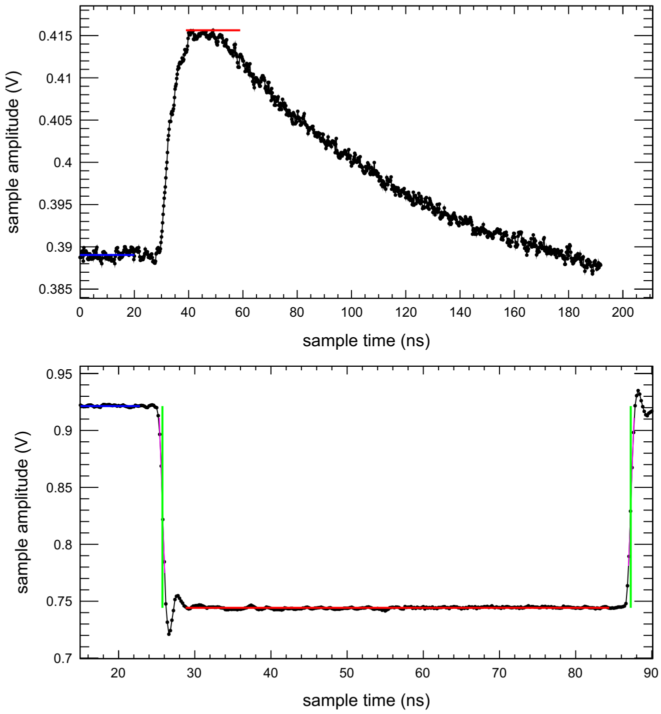

Fig. 3. Digitized pulses from the amplifier (top) and NINO (bottom) for energy and time reconstruction, respectively.

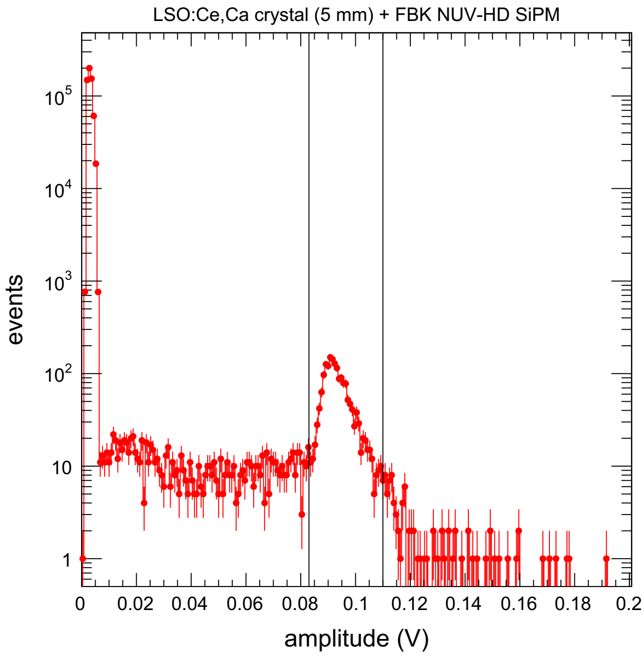

Fig. 4. Distribution of the reconstructed signal amplitude as seen by the SiPM coupled to a 5 mm long LSO crystal. The peak corresponding to muons traversing the entire crystal length is visible(>0.08 V) as well as the noise peak (<0.01 V). The continuum in between are events where muons only marginally traversed the crystal. Events contained between the two vertical lines are selected for the analysis.

corresponding to events where muons traveled a shorter length inside the crystal due to crystal-beam axis misalignment and/or beam divergence. By means of a GEANT4 simulation, we estimated the average energy deposit of 150 GeV muons in LYSO and LSO crystals to be 1.06 and 1.08 MeV per traversed mm, respectively.

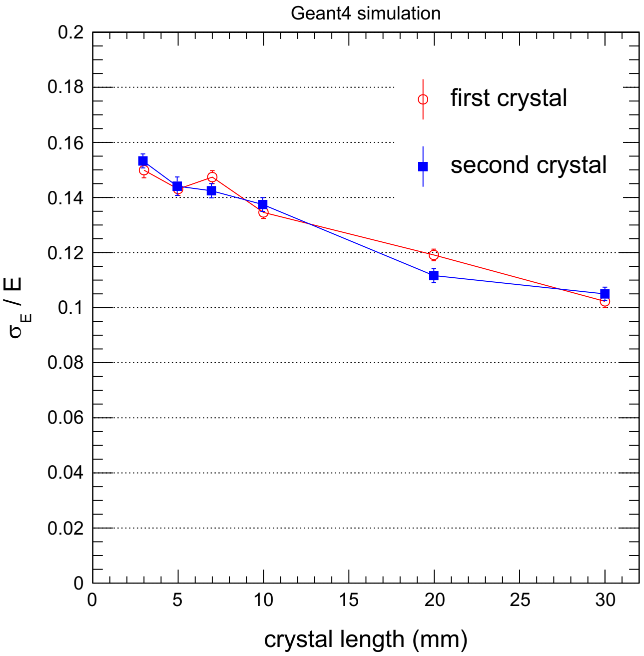

Fig. 5. Relative spread of energy deposited by 150 GeV muons in LSO crystals as a function of the crystal length, as predicted by a GEANT4 simulation.

This value is comparable to the expected energy deposit of a minimum ionizing particle (mip) in the crystals, since radiative photons escape detection in the small crystal volume. Due to Landau fluctuations in the energy release process, the spread of the mean value is non negligible and varies between 10% and 15%, as visible in Fig. 5.

The distribution of the difference of the time reconstructed in the two crystals of each pair, in formulae $\Delta t = t_{xtal2} - t_{xtal1}$, was studied selecting events in the muon peak in both crystals simultaneously. The distribution was modeled with a Gaussian function whose σ parameter was taken as an estimate of the CTR. Given the significant spread of the energy deposited by muons, a dependence of Δt on the measured amplitudes in the two crystals is expected, as a result of the time walk effect from the NINO leading edge discrimination. This dependence was studied by plotting the average Δt as a function of the amplitudes of the two crystals, as shown in Fig. 6. The profiles were parametrized with a logarithmic function, and an event-based correction of the CTR was extracted: for each crystal, the fit function value at the measured amplitude was added to the CTR.

The full set of results are summarized in Table 1 and presented in Fig. 7 for LYSO:Ce crystals+*Hamamatsu* devices and Fig. 8 for LSO:Ce,Ca crystals+*FBK* devices. In the plots, red empty points correspond to the uncorrected Δt distributions. Blue solid squares show the resulting distribution after time walk corrections are applied. In general, a considerable improvement with respect to the raw distribution is observed.

4. Discussion

Uncorrected CTR values for LYSO crystals and *Hamamatsu* SiPMs range between ~43 and ~33 ps, exhibiting an improving trend with crystal length. This can be explained by the spread in the muon energy deposit, as shown in Fig. 5, combined with the larger number of scintillation photons produced in long crystals, which is beneficial for timing measurements. Corrected CTR

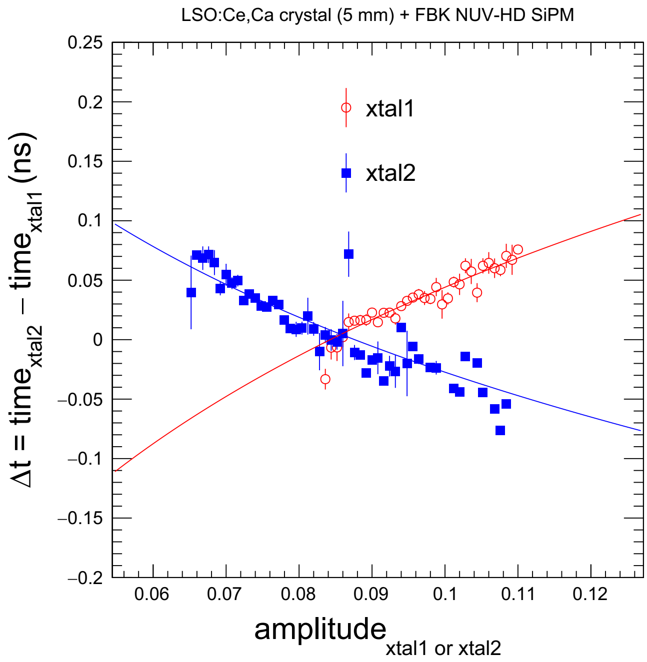

Fig. 6. Average measured time difference $\Delta t = t_{xtal2} - t_{xtal1}$ as a function of the amplitude of the first (xtal1, red empty points) or second (xtal2, blue solid squares) crystal in the pair. A logarithmic fit is superimposed. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Uncorrected (2nd column) and time walk-corrected (3rd column) CTR values and corrected, single-detector time resolution values (4th column) for the different sets of crystals. CTR values correspond to the σ of the Gaussian fit function, whereas single-detector values are computed as CTR/$\sqrt{2}$, assuming an equal contribution of both crystals. Uncertainties are statistical only.

Crystal	Uncorrected CTR values	Time walk-corrected CTR values	Time walk-corrected single TR values
5 mm LYSO:Ce	(43.2 ± 0.8) ps	(27.5 ± 0.5) ps	(19.4 ± 0.4) ps
10 mm LYSO:Ce	(35.0 ± 0.6) ps	(25.1 ± 0.4) ps	(17.7 ± 0.3) ps
20 mm LYSO:Ce	(33.8 ± 0.6) ps	(27.4 ± 0.4) ps	(19.4 ± 0.3) ps
30 mm LYSO:Ce	(32.9 ± 0.5) ps	(28.7 ± 0.8) ps	(20.3 ± 0.6) ps
5 mm LSO: Ce,Ca	(26.9 ± 0.6) ps	(14.5 ± 0.5) ps	(10.3 ± 0.4) ps

values, on the other hand, are essentially independent of the crystal length and flatten around a value of ~27 ps. Simple considerations on light propagation inside the crystal can account for this. As we use a signal leading edge discrimination, our time estimate is mostly determined by the first photons reaching the photodetector. This means that, with a large enough photon yield, only the photons produced in the last part of the crystal close to the photodetector contribute to timing, while those generated further upstream reach the photodetector at too delayed times to effectively contribute to it. Considering that the muon and the optical photons take 3.3 ps/mm and 6.1 ps/mm, respectively, to travel inside the crystal (L(Y)SO index of refraction is ~1.8), our measured time resolution of ~27 ps sets an effective crystal length of $\lesssim$10 mm, as longer crystals cannot bring any further advantage to timing measurements.[2] In addition to this, cables were used in the LYSO+*Hamamatsu* SiPMs configuration to connect the SiPMs to the readout board. This might have caused a degradation of the result because of the additional impedance of the cables together with electronic noise generating an uncorrelated time pickup jitter. Tests performed in laboratory with 511 keVγ events from β^+ decays confirm that the usage of cables as opposed to direct plugging of the SiPMs into the board introduces a significant extra smearing to the CTR. In these tests, a degradation of ~16 ps was measured, although with a large uncertainty. The actual size of this effect in the beam test condition is difficult to estimate, but likely to be non-negligible.

With 5 mm LSO:Ce,Ca crystals and *FBK* SiPMs, lower CTR values of ~27 and 14.5 ps are measured in the uncorrected and time walk-corrected case, respectively. The reasons for better results in this configuration are multiple. First of all, the usage of calcium as a co-dopant in addition to cerium in LSO crystals improves the timing response of the crystal thanks to a shorter decay time (~30 ns vs. ~40 ns for LYSO:Ce [8]). Moreover, the performances of the *FBK* SiPMs coupled to LSO crystals are superior to those of *Hamamatsu* SiPMs we used for LYSO crystals. As a matter of fact, the former exhibit better photon collection efficiency due to the absence of an optical window on top of the SiPM and a better single photon time resolution [4]. Finally, SiPMs in this configuration were directly plugged into the readout board, as opposed to the LYSO configuration, which prevented degradation of the performance due to pick-up noise.

For both configurations, the high temperature registered in the experimental box during the data taking – around 29 °C – and the absence of a temperature-stabilized environment to host our setup might have negatively influenced the overall system performance due to a higher dark count rate.

5. Conclusions

In a HEP experiment, the technology described in this paper could be used to precisely measure the time of charged tracks or calorimetric deposits. Thanks to the large number of scintillation photons produced, the system proved to be 100% efficient to the passage of particles through the crystal volume. Moreover, only one detector is involved in the measurement of a particle's time, and therefore the timing performance of a single detector is the relevant parameter. In the reasonable assumption of an equal contribution of the two crystals in the pair, the time resolution of a single crystal coupled to a SiPM is equal to CTR/$\sqrt{2}$. In the last column of Table 1 the single-detector time resolution values computed from the measured CTR are reported. As can be seen, all the tested configurations allow 20 ps or better time resolution, thus meeting the requirements for future high luminosity colliders. The best setup made by LSO:Ce,Ca crystals and *FBK* SiPMs allows as low as 10 ps time resolution to be obtained. This value is comparable to the results obtained by a similar setup (a $3 \times 3 \times 30$ mm^3 quartz Cherenkov radiator coupled to a *Hamamatsu* SiPM) which measured 14.5 ps single-detector time resolution at a beam test with 120 GeV protons [9].

It should be further noticed that our best timing results can be achieved with only 5 to 10 mm long crystals, which is likely an advantage in view of the integration of a timing layer in a compact HEP detector. Further studies towards the design of a full-scale crystal-based timing detector are therefore worth pursuing.

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[2] In this calculation, only photons directly traveling to the photodetector are considered.

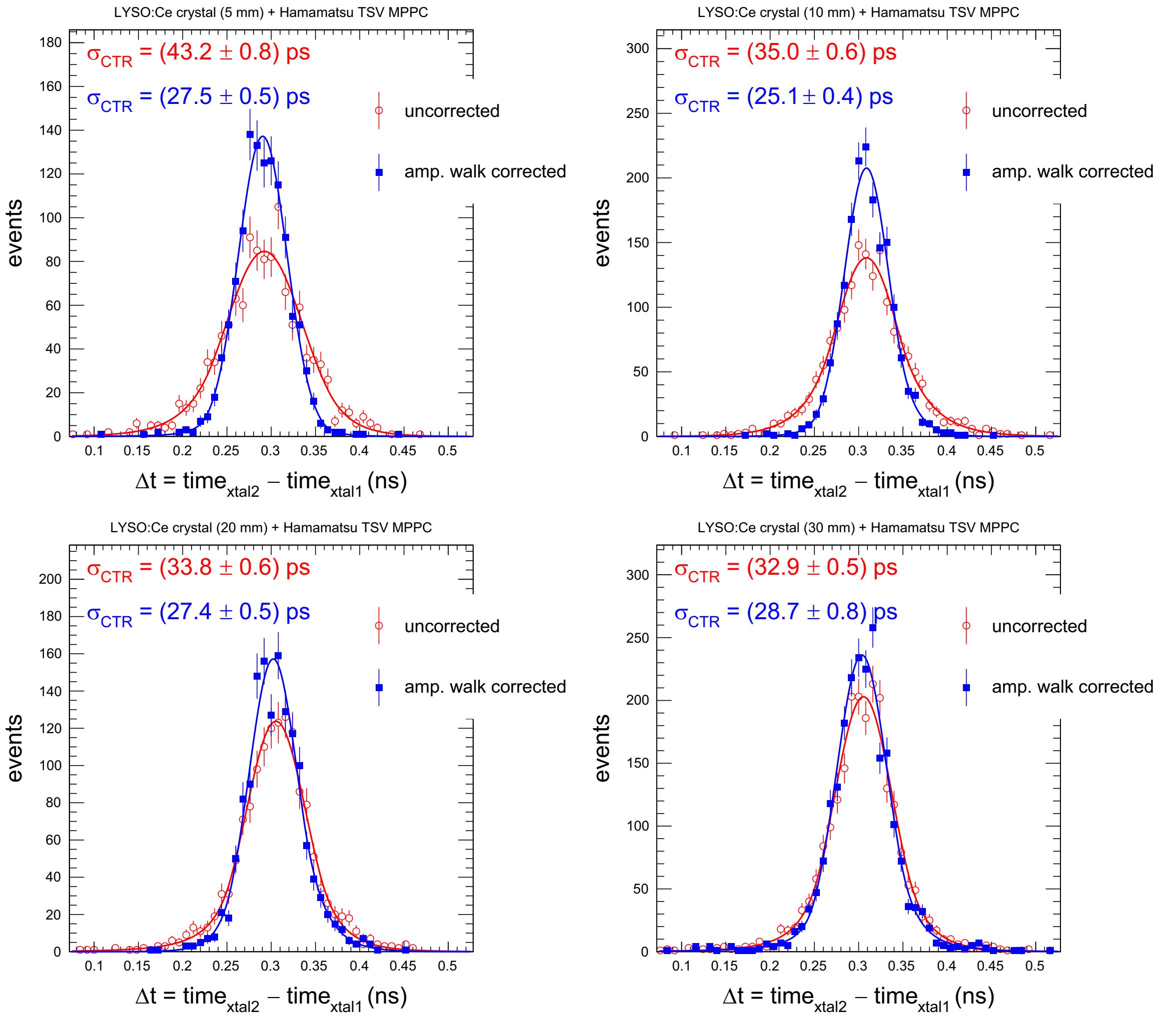

Fig. 7. Distribution of Δt observed for 5, 10, 20 and 30 mm long LYSO:Ce crystals coupled to *Hamamatsu* TSV MPPC devices. Red empty points and blue solid squares correspond to the uncorrected and time walk-corrected distributions, respectively. The CTR values as extracted from a Gaussian fit to the data are superimposed. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

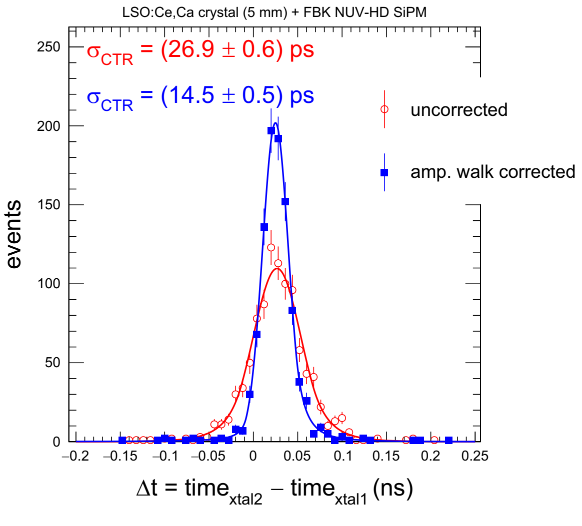

Fig. 8. Distribution of Δt observed for 5 mm long LSO:Ce,Ca crystals coupled to *FBK* SiPMs. Red empty points and blue solid squares correspond to the uncorrected and time walk-corrected distributions, respectively. The CTR values as extracted from a Gaussian fit to the data are superimposed. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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