Time reconstruction and performance of the CMS electromagnetic calorimeter

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CMS Collaboration

ABSTRACT: The resolution and the linearity of time measurements made with the CMS electromagnetic calorimeter are studied with samples of data from test beam electrons, cosmic rays, and beam-produced muons. The resulting time resolution measured by lead tungstate crystals is better than 100 ps for energy deposits larger than 10 GeV. Crystal-to-crystal synchronization with a precision of 500 ps is performed using muons produced with the first LHC beams in 2008.

KEYWORDS: Calorimeters; Large detector systems for particle and astroparticle physics

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1 Introduction

The primary goal of the Compact Muon Solenoid (CMS) experiment [1] is to explore particle physics at the TeV energy scale, exploiting the proton-proton collisions delivered by the Large Hadron Collider (LHC) at CERN [2]. The electromagnetic calorimeter (ECAL), which measures the energy of electrons and photons produced in LHC collisions, is located inside the bore of the solenoid magnet. It is a hermetic homogeneous calorimeter made of 75 848 lead tungstate ($PbWO_4$) scintillating crystals: 61 200 in the barrel (EB) and 7324 in each endcap (EE). The barrel has an inner radius of 129 cm, while the distance between the center of the interaction region and the endcap envelope is about 315 cm. Lead tungstate has a fast scintillation response and is resistant to radiation; it has a high density (8.3 g cm^{-3}), a short radiation length ($X_0 = 0.89$ cm), and a small Molière radius ($R_M = 2.0$ cm), features that allow a highly granular, compact detector to be built. Each individual crystal is a truncated pyramid, with a lateral size comparable to R_M and a length of 25.8 X_0 (24.7 X_0) for the barrel (endcaps). The scintillation decay time of the crystals is comparable to the LHC bunch crossing interval of 25 ns, and about 80% of the light is emitted in 25 ns. For the light detection, the crystals are equipped with avalanche photodiodes in the barrel and vacuum phototriodes in the endcaps.

The main purpose of the ECAL is the precise energy measurement, needed for many physics analyses. In the barrel region, the target energy resolution for unconverted photons with energies larger than 50 GeV is 0.5%. Tests illuminating 25% of all ECAL barrel crystals with 120 GeV electrons have demonstrated that this target resolution is achievable [3]. Searches for the Higgs boson particularly benefit from this performance: a Standard Model Higgs with a mass of 120 GeV can be observed by CMS in the two-photon decay channel with a 5σ significance with less than 10 fb^{-1} of integrated luminosity collected at 14 TeV center of mass energy [4, 5].

In addition to the energy measurement, the combination of the scintillation timescale of $PbWO_4$, the electronic pulse shaping, and the sampling rate allow excellent time resolution to be obtained with the ECAL. This is important in CMS in many respects. The better the precision of time measurement and synchronization, the larger the rejection of backgrounds with a broad time distribution. Such backgrounds are cosmic rays, beam halo muons, electronic noise, and out-of-time proton-proton interactions. Precise time measurement also makes it possible to identify particles predicted by different models beyond the Standard Model. Slow heavy charged R-hadrons [6], which travel through the calorimeter and interact before decaying, and photons from the decay of long-lived new particles reach the calorimeter out-of-time with respect to particles travelling at the speed of light from the interaction point. As an example, to identify neutralinos decaying into photons with decay lengths comparable to the ECAL radial size, a time measurement resolution better than 1 ns is necessary. To achieve these goals the time measurement performance both at low energy (1 GeV or less) and high energy (several tens of GeV for showering photons) becomes relevant. In addition, amplitude reconstruction of ECAL energy deposits benefits greatly if all ECAL channels are synchronized within 1 ns [7]. Previous experiments have shown that it is possible to measure time with electromagnetic calorimeters with a resolution better than 1 ns [8].

In section 2, the algorithm used to extract the time from the digitized ECAL signal is presented. In section 3, the uncertainties in the time measurement and the time resolution extracted using electrons from a test beam are detailed. In section 4, the synchronization of ECAL crystals in preparation for the first LHC collisions is discussed, and the time inter-calibration obtained using muons from the first LHC beam events is presented. Finally, section 5 shows results on the ECAL time resolution and linearity, obtained using cosmic ray muons after the insertion of the ECAL into its final position in CMS.

The scope of this paper is limited to the timing extracted for single crystals. For electromagnetic showers that spread over several crystals, the time measurement can be averaged, thus improving the resolution.

2 Time extraction with ECAL crystals

The front-end electronics of the ECAL amplifies and shapes the signal from the photodetectors [9]. Figure 1(a) shows the time structure of the signal pulse measured after amplification (solid line). The amplitude of the pulse, A, is shown as a function of the time difference $T - T_{\mathrm{max}}$, where T_{max} is defined as the time when the pulse reaches its maximum value, A_{max}. The pulse shape is defined by the analog part of the front-end electronics. For a given electronic channel, the same pulse shape is obtained, to a very good approximation, for all types of particles and for all momenta. The pulse is then digitized at 40 MHz by a 12-bit voltage-sampling analog-to-digital converter on the front-end, providing a discrete set of amplitude measurements. These samples are stored in a buffer until a Level-1 trigger is received. At that time the ten consecutive samples corresponding to the selected event are transmitted to the off-detector electronics for insertion into the CMS data stream. In this paper, ECAL time reconstruction is defined as the measurement of T_{max} using the ten available samples of pulse amplitude. For each ECAL channel, the amplitudes of these samples depend on three factors: the value of A_{max}; the relative position of T_{max} between time samples, which will be referred to as a “T_{max} phase”; and the pulse shape itself.

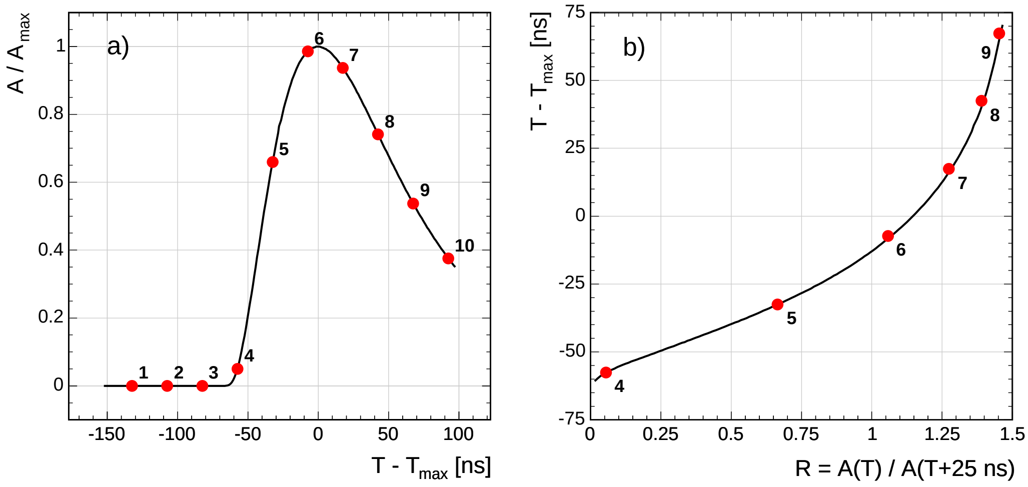

Figure 1. (a) Typical pulse shape measured in the ECAL, as a function of the difference between the time (T) of the ADC sample and the time ($T_{\rm max}$) of the maximum of the pulse. The dots indicate ten discrete samples of the pulse, from a single event, with pedestal subtracted and normalized to the maximum amplitude. The solid line is the average pulse shape, as measured with a beam of electrons triggered asynchronously with respect to the digitizer clock phase. (b) Pulse shape representation using the time difference $T - T_{\rm max}$ as a function of the ratio of the amplitudes in two consecutive samples (R).

An alternative representation of the pulse shape is provided by a ratio variable, defined as $R(T) = A(T)/A(T+25\ \mathrm{ns})$. Figure 1(b) shows the measured pulse shape using the variable $T - T_{\rm max}$, as a function of $R(T)$. In view of the universal character of the pulse shape, this representation is independent of $A_{\rm max}$. It can be described well with a simple polynomial parameterization. The corresponding parameters have been determined in an electron test beam (see section 3) for a representative set of EB and EE crystals, and are subsequently used for the full ECAL.

Each pair of consecutive samples gives a measurement of the ratio $R_i = A_i/A_{i+1}$, from which an estimate of $T_{\rm max,i}$ can be extracted, with $T_{\rm max,i} = T_i - T(R_i)$. Here T_i is the time when the sample i was taken and $T(R_i)$ is the time corresponding to the amplitude ratio R_i, as given by the parameterization corresponding to figure 1(b). The uncertainty on each $T_{\rm max,i}$ measurement, σ_i, is the product of the derivative of the $T(R)$ function and the uncertainty on the value of R_i. The latter has three independent contributions, which are added in quadrature. The first contribution is due to noise fluctuations in each sample. The second contribution is due to the uncertainty on the estimation of the pedestal value subtracted from the measured amplitudes [7]. The last contribution is due to truncation during 12-bit digitization.

The number of available ratios depends on the absolute timing of a pulse with respect to the trigger. Ratios corresponding to large derivatives of the $T(R)$ function and to very small amplitudes are not used. Pulses from particles arriving in-time with the LHC bunch crossing typically have 4 or 5 available ratios. The time of the pulse maximum, $T_{\rm max}$, and its error are then evaluated from the weighted average of the estimated $T_{\rm max,i}$:

$$T_{\rm max} = \frac{\sum_i \frac{T_{\rm max,i}}{\sigma_i^2}}{\sum_i \frac{1}{\sigma_i^2}} \quad ; \quad \frac{1}{\sigma_T^2} = \sum_i \frac{1}{\sigma_i^2} \quad . \tag{2.1}$$

The values of $T_{\mathrm{max,i}}$ and their errors σ_i are combined as if they were uncorrelated. Adjacent R_i ratios, however, share a common amplitude measurement value, and are thus anti-correlated. Monte Carlo studies show that the uncertainty estimated using eq. (2.1) is, on average, about 20% too large because of the anti-correlation, and that the averaging of individual time measurements results in a bias of about 10% of the statistical uncertainty of T_{max}, which is negligible. The different R_i ratios are also correlated because there are correlations in the noise contributions to the samples (see figure 3 of ref. [7]). This has no impact on the average and a very small effect on the estimated uncertainty of T_{max}, corresponding to $< 10\%$ of the statistical uncertainty.

3 Time measurement resolution

The time resolution can be expressed as the sum in quadrature of three terms accounting for different sources of uncertainty, and may be parameterized as follows:

$$\sigma^2(t) = \left(\frac{N\sigma_n}{A}\right)^2 + \left(\frac{S}{\sqrt{A}}\right)^2 + C^2 \quad . \tag{3.1}$$

Here A is the measured amplitude, σ_n is related to the noise level in individual samples, and N, S, and C represent the noise, stochastic, and constant term coefficients, respectively. The noise term contains the three uncertainties mentioned above, in the discussion of the uncertainty on $T_{\mathrm{max,i}}$. Monte Carlo simulation studies give $N = 33$ ns, when the electronic noise in the barrel and endcaps is $\sigma_n \sim 42$ MeV and $\sigma_n \sim 140$ MeV, respectively. The stochastic term comes from fluctuations in photon collection times, associated with the finite time of scintillation emission. It is estimated to be negligible and it is not considered in this study. The constant term has several contributions: effects correlated with the point of shower initiation within the crystal and systematic effects in the time extraction, such as those due to small differences in pulse shapes for different channels.

To study the pulse shape and determine the intrinsic time resolution of the ECAL detector, electrons from a test beam are used. Several fully equipped barrel and endcap sectors were exposed to electrons at the H2 and H4 test beam facilities at CERN, prior to their installation into the CMS detector [3]. The beam lines delivered electrons with energies between 15 GeV and 250 GeV. In the test beam, sectors were mounted on a rotating table that allowed the beam to be directed onto each crystal of the supermodule. The 2-D profile of the electron beam was almost Gaussian, with a spread comparable to the crystal size. As a consequence, in a single run, electrons hit the crystal in different positions and the fraction of energy deposited by an electron in a given crystal varied from event to event.

The time resolution is extracted from the distribution of the time difference between adjacent crystals that share the same electromagnetic shower and measure similar energies. This approach is less sensitive to the constant term C, since effects due to synchronization do not affect the spread but only the average of the time difference. As electrons enter the crystal from the front face and there is the requirement of depositing a similar energy in both crystals, the uncertainty due to the variation of the point of shower initiation is also negligible. In addition, the $T - T_{\mathrm{max}}$ vs. R polynomial parameterization is determined individually for every crystal to avoid systematic effects due to pulse shape parameterization. The distribution of the time difference is well described by a

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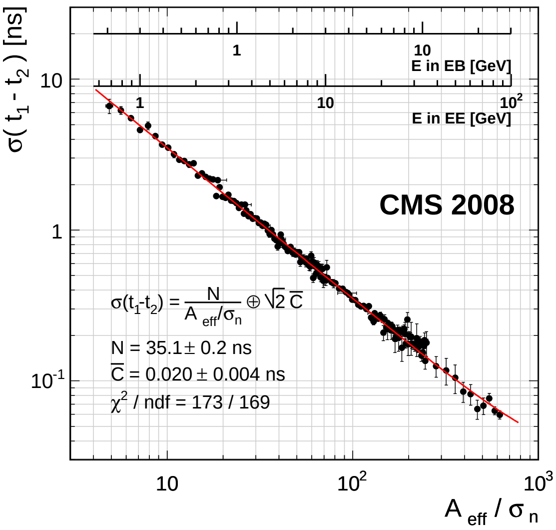

Figure 2. Gaussian width of the time difference between two neighboring crystals as a function of the variable $A_{\mathrm{eff}}/\sigma_n$, for test beam electrons with energies between 15 and 300 GeV. The equivalent single-crystal energy scales for barrel and endcaps are overlaid on the plot.

Gaussian function with negligible tails for all amplitudes. The spread is defined as the sigma of the Gaussian fit to the distribution and is parameterized, following eq. (3.1), as

$$\sigma^2(t_1 - t_2) = \left(\frac{N\sigma_n}{A_{\mathrm{eff}}}\right)^2 + 2\overline{C}^2 \tag{3.2}$$

where $A_{\mathrm{eff}} = A_1 A_2 / \sqrt{A_1^2 + A_2^2}$, with $t_{1,2}$ and $A_{1,2}$ corresponding to the times and amplitudes measured in the two crystals, and $\overline{C}$ being the residual contribution from the constant terms. The extracted width is presented in figure 2 as a function of the variable $A_{\mathrm{eff}}/\sigma_n$. The fitted noise term corresponds to $N = (35.1 \pm 0.2)$ ns. $\overline{C}$ is very small, $\overline{C} = (20 \pm 4)$ ps. For values of $A_{\mathrm{eff}}/\sigma_n$ greater than 400, $\sigma(t)$ is less than 100 ps, demonstrating that, with a carefully calibrated and synchronized detector, it is possible to reach a time resolution better than 100 ps for large energy deposits ($E >$10–20 GeV in the barrel). As a crosscheck, the stochastic component was left free in the fit and found to be $S < 7.9$ ns MeV$^{\frac{1}{2}}$ (90% C.L.), confirming that this term is negligible.

4 Synchronization between crystals

For each individual ECAL channel, the signals generated by particles originating from the interaction point (IP) are registered with approximately the same value of T_{max}, because their flight times to the crystal do not change (up to small differences related to the precise position of the IP). Because the time of flight varies across the ECAL by a few nanoseconds and there are different intrinsic delays among channels, a crystal-to-crystal synchronization of the ECAL must be performed.

The ECAL front-end electronics allows adjustment of T_{max} for groups of 5×5 channels in steps of 1.04 ns. The determination of values for these adjustments is called hardware synchronization. To take full advantage of the high precision of the ECAL time reconstruction, the value of T_{max}

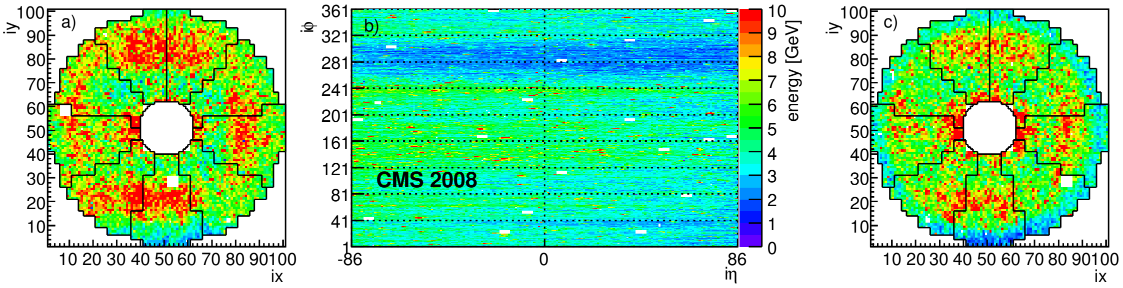

Figure 3. ECAL average energy deposit per crystal for a typical "beam splash" event with muons coming from the "minus" side. (a) Occupancy of the "minus" endcap, where *ix* and *iy* indicate the indices of the crystals in the horizontal (x) and vertical (y) coordinates, respectively. (b) Occupancy of the barrel, where $i\eta$ and $i\phi$ indicate the indices of the crystals in the η and ϕ coordinates. (c) Occupancy of the "plus" endcap. The white regions correspond to channels masked in the readout. They represent a small fraction of the total number of channels, smaller than 1% in that specific run. Many of these channels have been recovered subsequently.

corresponding to particles coming from the IP must be determined for each ECAL channel with an accuracy exceeding the typical time resolution. These additional corrections, called software synchronizations, can be extracted offline with physics collision events. Minimum bias events, which have a typical energy scale of 500 MeV/channel, can be used for this purpose. With the trigger menus planned for early data taking, they will yield about 1000 events/channel/day. A synchronization precision on the order of 100 ps is estimated to be achievable using data from a single day of running at the start of the LHC.

Beam-produced muons, collected by CMS with the first beams circulating in the LHC in September 2008, are used to synchronize the detector. The beams were dumped on collimators located approximately 150 m upstream of CMS, producing so-called "beam splash" events. The proton bunch length along the direction of propagation was about 6 cm, corresponding to about 200 ps spread in time. The resulting pions and kaons decayed into a very large number of muons, moving horizontally along the beam direction, corresponding to the z axis, at close to the speed of light. The arrival time of these muons at each crystal depends on the crystal position, and can be precisely predicted. In figure 3 the ECAL energy deposits in each crystal for a typical "beam splash" event are shown. Several muons cross each crystal, resulting in energy deposits between 2 and 10 GeV. It may be noted that almost every crystal registered a significant energy.

As stated above, it is important to synchronize the calorimeter such that particles travelling from the interaction region appear in-time. Since muons from "beam splash" events travel as a plane wave and do not come from the interaction region, a correction using the predicted time of flight is applied. In order to compare times obtained from different events, the average times in the barrel and each endcap are used as references. It should be noted that, because of the time of flight of muons, the "T_{max} phase" depends on the position of the crystal and muon direction. Crystals with the same pseudorapidity η, forming a ring in ϕ, have a common "T_{max} phase".

Two independent samples of "beam splash" events are used to synchronize ECAL channels: about 20 events containing a large number of muons travelling in the negative direction of the z axis ("minus" beam, moving clockwise in the LHC) and about 35 events with muons travelling in the

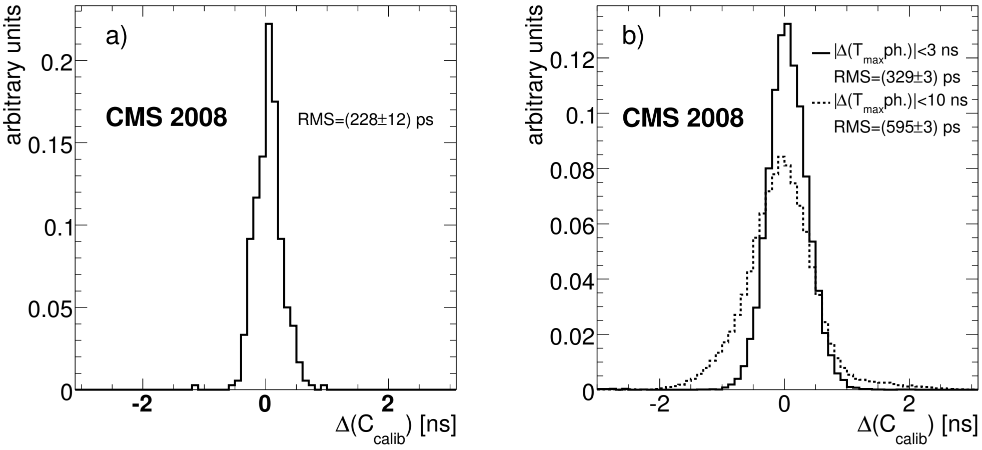

Figure 4. Distributions of the differences between the calibration coefficients obtained using muons from the "plus" beam and muons from the "minus" beam for (a) 360 barrel channels in which muons arrived at the same time delay with respect to the trigger, and (b) two different samples of barrel crystals, for which the difference between the mean measured absolute times (t) is in the range 3 to 10 ns (see text). The histograms are normalized to have unit area in each case.

opposite direction ("plus" beam). For every individual channel, an average of time measurements weighted by their uncertainties is calculated, resulting in the time intercalibration coefficient. This procedure is applied separately for "plus" and "minus" beam events. Comparison of the "plus" and "minus" calibrations yields an estimate of the statistical and systematic uncertainties of the calibration and time reconstruction algorithms, while the sum of the two samples is used to extract the intercalibration coefficients.

Figure 4(a) shows the difference between "plus" and "minus" calibrations for the 360 barrel channels in which muons arrived at the same time delay with respect to the trigger in both "plus" and "minus" runs. These channels, forming a ring in ϕ, have the unique property of sharing the same "$T_{\max}$ phase" for both "plus" and "minus" muons. Thus channels in this ring experience conditions similar to those in normal LHC operation i.e. the energy deposits are synchronous. The Gaussian spread of the distribution is about 230 ps, which is in good agreement with the expected statistical uncertainty. Summing the event samples from both "plus" and "minus" beams results in a synchronization of ECAL channels with a statistical uncertainty of about 85 ps in the barrel and 105 ps in the endcaps.

Figure 4(b) shows a distribution similar to that in figure 4(a), except that muons in these channels need not arrive at the same time in both "plus" and "minus" splashes. This has the effect of including many more crystals in the selection and introduces sensitivity to any "$T_{\max}$ phase"-dependent effects. The solid line represents the distribution of channels fulfilling the requirement that the difference in "$T_{\max}$ phase" between "plus" and "minus" muons is within a 3 ns time range, which includes about 43% of the barrel channels. The dotted line is the distribution conditioned by requiring a "$T_{\max}$ phase" difference of less than 10 ns, selecting about 70% of the barrel channels. The widths of these distributions are (329 ± 3) ps and (595 ± 3) ps, respectively, both of which are significantly larger than the expected statistical uncertainty, indicating the presence of systematic effects correlated with the uncertainties in the pulse shape. The time reconstruction method assumes the same pulse shape for all ECAL channels, but the real pulse shapes slightly differ from channel to channel (see figure 10 of ref. [7]). Detailed Monte Carlo simulation studies and measurements with electrons from a test beam show that these differences in shape pose no problem for in-time signals, while out-of-time signals are reconstructed with a systematic uncertainty ranging from tens to hundreds of picoseconds. The effect is proportional to the size of the range in "T_{max} phase". The results shown in figure 4(b) confirm these studies. In LHC collisions, the time range will not have a wide spread since events will be synchronous and the accumulated bias in the time reconstruction will be minimal. Thus the systematic error on the synchronization is expected to be negligible when using collision events.

It can be concluded that the overall uncertainty in the determination of the synchronization coefficients, which is the quadratic sum of the statistical and systematic uncertainties, is about 300–600 ps. This is the time resolution expected at the start-up of the LHC, when these synchronization coefficients will be used.

5 Resolution and linearity checks using cosmic ray muons

The resolution and the linearity of time measurements are determined with a sample of cosmic ray muons collected during summer 2008, when the ECAL was already inserted into its final position in CMS. Samples used for this analysis were taken from runs without magnetic field. Muon tracks are reconstructed in the muon system and, where possible, in the inner tracker. Muons typically deposit energy in several ECAL crystals, which are then grouped to form clusters. The purity of the sample is increased by requiring the extrapolated muon track to point towards the barycenter of the ECAL cluster. This is done by requiring that the distance between the calorimeter deposit and the position of entrance of the muon track in the η-ϕ plane is consistent with zero within the experimental resolution [10]. The selection is restricted to the barrel region, resulting in a sample of about 2×10^5 muons. The associated clusters correspond to muons that lose energy in the calorimeter by ionization, with very little background contamination. The synchronization constants obtained from "beam splash" events are then applied.

The approach to extract the resolution is similar to that described in section 3, but in this case the crystal with the maximum amplitude is compared with the other crystals in the cluster. Since different pairs of crystals are used, covering the entire barrel, a constant term comparable to the systematic uncertainty of the synchronization is expected.

The results on the resolution are presented in figure 5(a). The noise term is found to be $N = (31.5 \pm 0.7)$ ns and is very similar to that obtained from test beam data. The constant term is measured to be $C = (380 \pm 10)$ ps, which is consistent with the expected systematic uncertainty from "beam splash" synchronization.

The same sample of cosmic ray muons is used to test the linearity of the time measurement. For muons which traverse the ECAL barrel from top to bottom, the times of respective clusters are taken to be the times of the crystals with the largest amplitudes. The difference in time between the two crystals is then compared with the corresponding time of flight of a relativistic muon travelling over the distance between the two crystals. The crystals are ordered depending on their vertical position, assuming that all muons are coming from the top of the detector. The distance

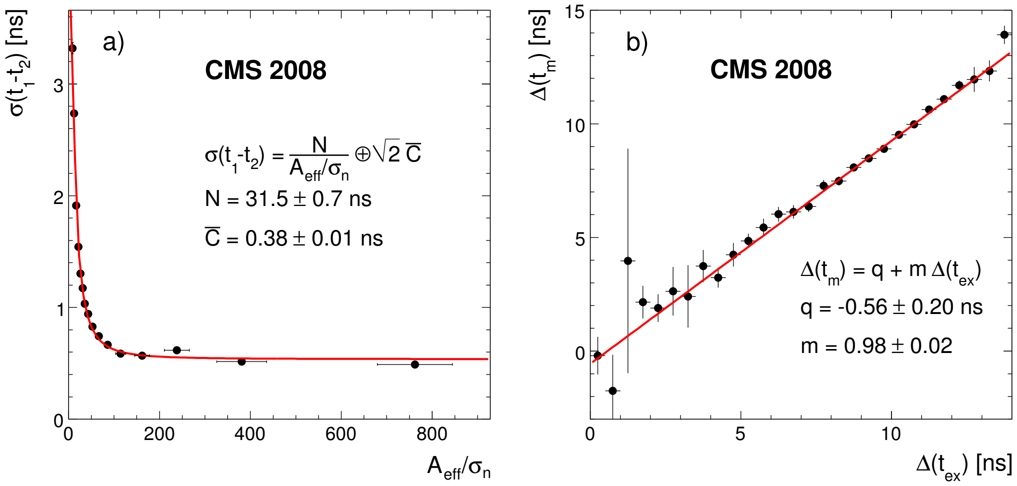

Figure 5. (a) Spread of the time difference between crystals of the same cluster, as a function of the variable $A_{\text{eff}} = A_1A_2/\sqrt{A_1^2+A_2^2}$, for cosmic ray muons. (b) Measured time difference between top and bottom muon clusters, $\Delta(t_m)$, as a function of the expected difference corresponding to the time of flight of a relativistic muon, $\Delta(t_{ex})$.

is calculated taking into account the fact that, on average, cosmic ray muons enter crystals at the center of the lateral edge. The time of flight ranges from about 0 ns, which corresponds to muons almost tangential to the ECAL surface, to about 14 ns. In figure 5(b) the correlation between expected and measured times is shown. The distribution is fitted with a straight line, resulting in a slope (m) compatible with unity. The offset (q) is compatible with zero within the systematic uncertainty on the synchronization, which is of the order of 300–600 ps, as discussed in section 4.

6 Conclusions

The resolution and the linearity of the time measurement of the CMS electromagnetic calorimeter have been investigated with samples of data from test beam electrons, cosmic rays, and “beam splash” events. Results obtained with test beam electrons show that the resolution for electromagnetic showers, which can be reached with a perfect time alignment, is better than 100 ps for large energies (more than 10–20 GeV in the barrel). At lower energies, the noise term limits the resolution. As an example, 1 GeV energy deposits in the ECAL barrel have a time resolution of 1.5 ns. The noise term measurement has been confirmed using cosmic ray muon events with the ECAL detector fully equipped and inserted in CMS. The linearity of the time measurement has been verified using cosmic ray muons that travel across the ECAL barrel, by comparing the measured time difference between the top and the bottom parts of the detector with the expected muon time of flight.

“Beam splash” events have been used to synchronize all ECAL crystals with a precision of ∼500 ps. The corresponding set of synchronization coefficients will be used at LHC start-up. The synchronization will be much improved once collision data are available.

In summary, in addition to measuring the energy of electromagnetic particles with high resolution, the CMS ECAL also provides precise timing information, which will be important for additional background rejection and discoveries of new physics with time-sensitive signatures.

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The CMS collaboration

Yerevan Physics Institute, Yerevan, Armenia
S. Chatrchyan, V. Khachatryan, A.M. Sirunyan

Institut für Hochenergiephysik der OeAW, Wien, Austria
W. Adam, B. Arnold, H. Bergauer, T. Bergauer, M. Dragicevic, M. Eichberger, J. Erö, M. Friedl, R. Frühwirth, V.M. Ghete, J. Hammer[1], S. Hänsel, M. Hoch, N. Hörmann, J. Hrubec, M. Jeitler, G. Kasieczka, K. Kastner, M. Krammer, D. Liko, I. Magrans de Abril, I. Mikulec, F. Mittermayr, B. Neuherz, M. Oberegger, M. Padrta, M. Pernicka, H. Rohringer, S. Schmid, R. Schöfbeck, T. Schreiner, R. Stark, H. Steininger, J. Strauss, A. Taurok, F. Teischinger, T. Themel, D. Uhl, P. Wagner, W. Waltenberger, G. Walzel, E. Widl, C.-E. Wulz

National Centre for Particle and High Energy Physics, Minsk, Belarus
V. Chekhovsky, O. Dvornikov, I. Emeliantchik, A. Litomin, V. Makarenko, I. Marfin, V. Mossolov, N. Shumeiko, A. Solin, R. Stefanovitch, J. Suarez Gonzalez, A. Tikhonov

Research Institute for Nuclear Problems, Minsk, Belarus
A. Fedorov, A. Karneyeu, M. Korzhik, V. Panov, R. Zuyeuski

Research Institute of Applied Physical Problems, Minsk, Belarus
P. Kuchinsky

Universiteit Antwerpen, Antwerpen, Belgium
W. Beaumont, L. Benucci, M. Cardaci, E.A. De Wolf, E. Delmeire, D. Druzhkin, M. Hashemi, X. Janssen, T. Maes, L. Mucibello, S. Ochesanu, R. Rougny, M. Selvaggi, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel

Vrije Universiteit Brussel, Brussel, Belgium
V. Adler, S. Beauceron, S. Blyweert, J. D'Hondt, S. De Weirdt, O. Devroede, J. Heyninck, A. Kalogeropoulos, J. Maes, M. Maes, M.U. Mozer, S. Tavernier, W. Van Doninck[1], P. Van Mulders, I. Villella

Université Libre de Bruxelles, Bruxelles, Belgium
O. Bouhali, E.C. Chabert, O. Charaf, B. Clerbaux, G. De Lentdecker, V. Dero, S. Elgammal, A.P.R. Gay, G.H. Hammad, P.E. Marage, S. Rugovac, C. Vander Velde, P. Vanlaer, J. Wickens

Ghent University, Ghent, Belgium
M. Grunewald, B. Klein, A. Marinov, D. Ryckbosch, F. Thyssen, M. Tytgat, L. Vanelderen, P. Verwilligen

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
S. Basegmez, G. Bruno, J. Caudron, C. Delaere, P. Demin, D. Favart, A. Giammanco, G. Grégoire, V. Lemaitre, O. Militaru, S. Ovyn, K. Piotrzkowski[1], L. Quertenmont, N. Schul

Université de Mons, Mons, Belgium
N. Beliy, E. Daubie

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
G.A. Alves, M.E. Pol, M.H.G. Souza

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
W. Carvalho, D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, L. Mundim, V. Oguri, A. Santoro, S.M. Silva Do Amaral, A. Sznajder

Instituto de Fisica Teorica, Universidade Estadual Paulista, Sao Paulo, Brazil
T.R. Fernandez Perez Tomei, M.A. Ferreira Dias, E. M. Gregores[2], S.F. Novaes

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria
K. Abadjiev[1], T. Anguelov, J. Damgov, N. Darmenov[1], L. Dimitrov, V. Genchev[1], P. Iaydjiev, S. Piperov, S. Stoykova, G. Sultanov, R. Trayanov, I. Vankov

University of Sofia, Sofia, Bulgaria
A. Dimitrov, M. Dyulendarova, V. Kozhuharov, L. Litov, E. Marinova, M. Mateev, B. Pavlov, P. Petkov, Z. Toteva[1]

Institute of High Energy Physics, Beijing, China
G.M. Chen, H.S. Chen, W. Guan, C.H. Jiang, D. Liang, B. Liu, X. Meng, J. Tao, J. Wang, Z. Wang, Z. Xue, Z. Zhang

State Key Lab. of Nucl. Phys. and Tech., Peking University, Beijing, China
Y. Ban, J. Cai, Y. Ge, S. Guo, Z. Hu, Y. Mao, S.J. Qian, H. Teng, B. Zhu

Universidad de Los Andes, Bogota, Colombia
C. Avila, M. Baquero Ruiz, C.A. Carrillo Montoya, A. Gomez, B. Gomez Moreno, A.A. Ocampo Rios, A.F. Osorio Oliveros, D. Reyes Romero, J.C. Sanabria

Technical University of Split, Split, Croatia
N. Godinovic, K. Lelas, R. Plestina, D. Polic, I. Puljak

University of Split, Split, Croatia
Z. Antunovic, M. Dzelalija

Institute Rudjer Boskovic, Zagreb, Croatia
V. Brigljevic, S. Duric, K. Kadija, S. Morovic

University of Cyprus, Nicosia, Cyprus
R. Fereos, M. Galanti, J. Mousa, A. Papadakis, F. Ptochos, P.A. Razis, D. Tsiakkouri, Z. Zinonos

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
A. Hektor, M. Kadastik, K. Kannike, M. Müntel, M. Raidal, L. Rebane

Helsinki Institute of Physics, Helsinki, Finland
E. Anttila, S. Czellar, J. Härkönen, A. Heikkinen, V. Karimäki, R. Kinnunen, J. Klem, M.J. Kortelainen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, P. Luukka, T. Mäenpää, J. Nysten, E. Tuominen, J. Tuominiemi, D. Ungaro, L. Wendland

Lappeenranta University of Technology, Lappeenranta, Finland
K. Banzuzi, A. Korpela, T. Tuuva

Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France
P. Nedelec, D. Sillou

DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France
M. Besancon, R. Chipaux, M. Dejardin, D. Denegri, J. Descamps, B. Fabbro, J.L. Faure, F. Ferri, S. Ganjour, F.X. Gentit, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, M.C. Lemaire, E. Locci, J. Malcles, M. Marionneau, L. Millischer, J. Rander, A. Rosowsky, D. Rousseau, M. Titov, P. Verrecchia

Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
S. Baffioni, L. Bianchini, M. Bluj[3], P. Busson, C. Charlot, L. Dobrzynski, R. Granier de Cassagnac, M. Haguenauer, P. Miné, P. Paganini, Y. Sirois, C. Thiebaux, A. Zabi

Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France
J.-L. Agram[4], A. Besson, D. Bloch, D. Bodin, J.-M. Brom, E. Conte[4], F. Drouhin[4], J.-C. Fontaine[4], D. Gelé, U. Goerlach, L. Gross, P. Juillot, A.-C. Le Bihan, Y. Patois, J. Speck, P. Van Hove

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France
C. Baty, M. Bedjidian, J. Blaha, G. Boudoul, H. Brun, N. Chanon, R. Chierici, D. Contardo, P. Depasse, T. Dupasquier, H. El Mamouni, F. Fassi[5], J. Fay, S. Gascon, B. Ille, T. Kurca, T. Le Grand, M. Lethuillier, N. Lumb, L. Mirabito, S. Perries, M. Vander Donckt, P. Verdier

E. Andronikashvili Institute of Physics, Academy of Science, Tbilisi, Georgia
N. Djaoshvili, N. Roinishvili, V. Roinishvili

Institute of High Energy Physics and Informatization, Tbilisi State University, Tbilisi, Georgia
N. Amaglobeli

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
R. Adolphi, G. Anagnostou, R. Brauer, W. Braunschweig, M. Edelhoff, H. Esser, L. Feld, W. Karpinski, A. Khomich, K. Klein, N. Mohr, A. Ostaptchouk, D. Pandoulas, G. Pierschel, F. Raupach, S. Schael, A. Schultz von Dratzig, G. Schwering, D. Sprenger, M. Thomas, M. Weber, B. Wittmer, M. Wlochal

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
O. Actis, G. Altenhöfer, W. Bender, P. Biallass, M. Erdmann, G. Fetchenhauer[1], J. Frangenheim, T. Hebbeker, G. Hilgers, A. Hinzmann, K. Hoepfner, C. Hof, M. Kirsch, T. Klimkovich, P. Kreuzer[1], D. Lanske[†], M. Merschmeyer, A. Meyer, B. Philipps, H. Pieta, H. Reithler, S.A. Schmitz, L. Sonnenschein, M. Sowa, J. Steggemann, H. Szczesny, D. Teyssier, C. Zeidler

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
M. Bontenackels, M. Davids, M. Duda, G. Flügge, H. Geenen, M. Giffels, W. Haj Ahmad, T. Hermanns, D. Heydhausen, S. Kalinin, T. Kress, A. Linn, A. Nowack, L. Perchalla, M. Poettgens, O. Pooth, P. Sauerland, A. Stahl, D. Tornier, M.H. Zoeller

Deutsches Elektronen-Synchrotron, Hamburg, Germany
M. Aldaya Martin, U. Behrens, K. Borras, A. Campbell, E. Castro, D. Dammann, G. Eckerlin, A. Flossdorf, G. Flucke, A. Geiser, D. Hatton, J. Hauk, H. Jung, M. Kasemann, I. Katkov, C. Kleinwort, H. Kluge, A. Knutsson, E. Kuznetsova, W. Lange, W. Lohmann, R. Mankel[1],

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M. Marienfeld, A.B. Meyer, S. Miglioranzi, J. Mnich, M. Ohlerich, J. Olzem, A. Parenti, C. Rosemann, R. Schmidt, T. Schoerner-Sadenius, D. Volyanskyy, C. Wissing, W.D. Zeuner[1]

University of Hamburg, Hamburg, Germany

C. Autermann, F. Bechtel, J. Draeger, D. Eckstein, U. Gebbert, K. Kaschube, G. Kaussen, R. Klanner, B. Mura, S. Naumann-Emme, F. Nowak, U. Pein, C. Sander, P. Schleper, T. Schum, H. Stadie, G. Steinbrück, J. Thomsen, R. Wolf

Institut für Experimentelle Kernphysik, Karlsruhe, Germany

J. Bauer, P. Blüm, V. Buege, A. Cakir, T. Chwalek, W. De Boer, A. Dierlamm, G. Dirkes, M. Feindt, U. Felzmann, M. Frey, A. Furgeri, J. Gruschke, C. Hackstein, F. Hartmann[1], S. Heier, M. Heinrich, H. Held, D. Hirschbuehl, K.H. Hoffmann, S. Honc, C. Jung, T. Kuhr, T. Liamsuwan, D. Martschei, S. Mueller, Th. Müller, M.B. Neuland, M. Niegel, O. Oberst, A. Oehler, J. Ott, T. Peiffer, D. Piparo, G. Quast, K. Rabbertz, F. Ratnikov, N. Ratnikova, M. Renz, C. Saout[1], G. Sartisohn, A. Scheurer, P. Schieferdecker, F.-P. Schilling, G. Schott, H.J. Simonis, F.M. Stober, P. Sturm, D. Troendle, A. Trunov, W. Wagner, J. Wagner-Kuhr, M. Zeise, V. Zhukov[6], E.B. Ziebarth

Institute of Nuclear Physics "Demokritos", Aghia Paraskevi, Greece

G. Daskalakis, T. Geralis, K. Karafasoulis, A. Kyriakis, D. Loukas, A. Markou, C. Markou, C. Mavrommatis, E. Petrakou, A. Zachariadou

University of Athens, Athens, Greece

L. Gouskos, P. Katsas, A. Panagiotou[1]

University of Ioánnina, Ioánnina, Greece

I. Evangelou, P. Kokkas, N. Manthos, I. Papadopoulos, V. Patras, F.A. Triantis

KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary

G. Bencze[1], L. Boldizsar, G. Debreczeni, C. Hajdu[1], S. Hernath, P. Hidas, D. Horvath[7], K. Krajczar, A. Laszlo, G. Patay, F. Sikler, N. Toth, G. Vesztergombi

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

N. Beni, G. Christian, J. Imrek, J. Molnar, D. Novak, J. Palinkas, G. Szekely, Z. Szillasi[1], K. Tokesi, V. Veszpremi

University of Debrecen, Debrecen, Hungary

A. Kapusi, G. Marian, P. Raics, Z. Szabo, Z.L. Trocsanyi, B. Ujvari, G. Zilizi

Panjab University, Chandigarh, India

S. Bansal, H.S. Bawa, S.B. Beri, V. Bhatnagar, M. Jindal, M. Kaur, R. Kaur, J.M. Kohli, M.Z. Mehta, N. Nishu, L.K. Saini, A. Sharma, A. Singh, J.B. Singh, S.P. Singh

University of Delhi, Delhi, India

S. Ahuja, S. Arora, S. Bhattacharya[8], S. Chauhan, B.C. Choudhary, P. Gupta, S. Jain, S. Jain, M. Jha, A. Kumar, K. Ranjan, R.K. Shivpuri, A.K. Srivastava

Bhabha Atomic Research Centre, Mumbai, India

R.K. Choudhury, D. Dutta, S. Kailas, S.K. Kataria, A.K. Mohanty, L.M. Pant, P. Shukla, A. Topkar

Tata Institute of Fundamental Research - EHEP, Mumbai, India

T. Aziz, M. Guchait[9], A. Gurtu, M. Maity[10], D. Majumder, G. Majumder, K. Mazumdar, A. Nayak, A. Saha, K. Sudhakar

Tata Institute of Fundamental Research - HECR, Mumbai, India
S. Banerjee, S. Dugad, N.K. Mondal

Institute for Studies in Theoretical Physics & Mathematics (IPM), Tehran, Iran
H. Arfaei, H. Bakhshiansohi, A. Fahim, A. Jafari, M. Mohammadi Najafabadi, A. Moshaii, S. Paktinat Mehdiabadi, S. Rouhani, B. Safarzadeh, M. Zeinali

University College Dublin, Dublin, Ireland
M. Felcini

INFN Sezione di Bari [a], Università di Bari [b], Politecnico di Bari [c], Bari, Italy
M. Abbrescia[a,b], L. Barbone[a], F. Chiumarulo[a], A. Clemente[a], A. Colaleo[a], D. Creanza[a,c], G. Cuscela[a], N. De Filippis[a], M. De Palma[a,b], G. De Robertis[a], G. Donvito[a], F. Fedele[a], L. Fiore[a], M. Franco[a], G. Iaselli[a,c], N. Lacalamita[a], F. Loddo[a], L. Lusito[a,b], G. Maggi[a,c], M. Maggi[a], N. Manna[a,b], B. Marangelli[a,b], S. My[a,c], S. Natali[a,b], S. Nuzzo[a,b], G. Papagni[a], S. Piccolomo[a], G.A. Pierro[a], C. Pinto[a], A. Pompili[a,b], G. Pugliese[a,c], R. Rajan[a], A. Ranieri[a], F. Romano[a,c], G. Roselli[a,b], G. Selvaggi[a,b], Y. Shinde[a], L. Silvestris[a], S. Tupputi[a,b], G. Zito[a]

INFN Sezione di Bologna [a], Universita di Bologna [b], Bologna, Italy
G. Abbiendi[a], W. Bacchi[a,b], A.C. Benvenuti[a], M. Boldini[a], D. Bonacorsi[a], S. Braibant-Giacomelli[a,b], V.D. Cafaro[a], S.S. Caiazza[a], P. Capiluppi[a,b], A. Castro[a,b], F.R. Cavallo[a], G. Codispoti[a,b], M. Cuffiani[a,b], I. D'Antone[a], G.M. Dallavalle[a,1], F. Fabbri[a], A. Fanfani[a,b], D. Fasanella[a], P. Giacomelli[a], V. Giordano[a], M. Giunta[a,1], C. Grandi[a], M. Guerzoni[a], S. Marcellini[a], G. Masetti[a,b], A. Montanari[a], F.L. Navarria[a,b], F. Odorici[a], G. Pellegrini[a], A. Perrotta[a], A.M. Rossi[a,b], T. Rovelli[a,b], G. Siroli[a,b], G. Torromeo[a], R. Travaglini[a,b]

INFN Sezione di Catania [a], Universita di Catania [b], Catania, Italy
S. Albergo[a,b], S. Costa[a,b], R. Potenza[a,b], A. Tricomi[a,b], C. Tuve[a]

INFN Sezione di Firenze [a], Universita di Firenze [b], Firenze, Italy
G. Barbagli[a], G. Broccolo[a,b], V. Ciulli[a,b], C. Civinini[a], R. D'Alessandro[a,b], E. Focardi[a,b], S. Frosali[a,b], E. Gallo[a], C. Genta[a,b], G. Landi[a,b], P. Lenzi[a,b,1], M. Meschini[a], S. Paoletti[a], G. Sguazzoni[a], A. Tropiano[a]

INFN Laboratori Nazionali di Frascati, Frascati, Italy
L. Benussi, M. Bertani, S. Bianco, S. Colafranceschi[11], D. Colonna[11], F. Fabbri, M. Giardoni, L. Passamonti, D. Piccolo, D. Pierluigi, B. Ponzio, A. Russo

INFN Sezione di Genova, Genova, Italy
P. Fabbricatore, R. Musenich

INFN Sezione di Milano-Biccoca [a], Universita di Milano-Bicocca [b], Milano, Italy
A. Benaglia[a], M. Calloni[a], G.B. Cerati[a,b,1], P. D'Angelo[a], F. De Guio[a], F.M. Farina[a], A. Ghezzi[a], P. Govoni[a,b], M. Malberti[a,b,1], S. Malvezzi[a], A. Martelli[a], D. Menasce[a], V. Miccio[a,b], L. Moroni[a], P. Negri[a,b], M. Paganoni[a,b], D. Pedrini[a], A. Pullia[a,b], S. Ragazzi[a,b], N. Redaelli[a], S. Sala[a], R. Salerno[a,b], T. Tabarelli de Fatis[a,b], V. Tancini[a,b], S. Taroni[a,b]

INFN Sezione di Napoli [a], Universita di Napoli "Federico II" [b], Napoli, Italy
S. Buontempo[a], N. Cavallo[a], A. Cimmino[a,b,1], M. De Gruttola[a,b,1], F. Fabozzi[a,12], A.O.M. Iorio[a], L. Lista[a], D. Lomidze[a], P. Noli[a,b], P. Paolucci[a], C. Sciacca[a,b]

INFN Sezione di Padova [a], Università di Padova [b], Padova, Italy

P. Azzi[a,1], N. Bacchetta[a], L. Barcellan[a], P. Bellan[a,b,1], M. Bellato[a], M. Benettoni[a], M. Biasotto[a,13], D. Bisello[a,b], E. Borsato[a,b], A. Branca[a], R. Carlin[a,b], L. Castellani[a], P. Checchia[a], E. Conti[a], F. Dal Corso[a], M. De Mattia[a,b], T. Dorigo[a], U. Dosselli[a], F. Fanzago[a], F. Gasparini[a,b], U. Gasparini[a,b], P. Giubilato[a,b], F. Gonella[a], A. Gresele[a,14], M. Gulmini[a,13], A. Kaminskiy[a,b], S. Lacaprara[a,13], I. Lazzizzera[a,14], M. Margoni[a,b], G. Maron[a,13], S. Mattiazzo[a,b], M. Mazzucato[a], M. Meneghelli[a], A.T. Meneguzzo[a,b], M. Michelotto[a], F. Montecassiano[a], M. Nespolo[a], M. Passaseo[a], M. Pegoraro[a], L. Perrozzi[a], N. Pozzobon[a,b], P. Ronchese[a,b], F. Simonetto[a,b], N. Toniolo[a], E. Torassa[a], M. Tosi[a,b], A. Triossi[a], S. Vanini[a,b], S. Ventura[a], P. Zotto[a,b], G. Zumerle[a,b]

INFN Sezione di Pavia [a], Universita di Pavia [b], Pavia, Italy

P. Baesso[a,b], U. Berzano[a], S. Bricola[a], M.M. Necchi[a,b], D. Pagano[a,b], S.P. Ratti[a,b], C. Riccardi[a,b], P. Torre[a,b], A. Vicini[a], P. Vitulo[a,b], C. Viviani[a,b]

INFN Sezione di Perugia [a], Universita di Perugia [b], Perugia, Italy

D. Aisa[a], S. Aisa[a], E. Babucci[a], M. Biasini[a,b], G.M. Bilei[a], B. Caponeri[a,b], B. Checcucci[a], N. Dinu[a], L. Fanò[a], L. Farnesini[a], P. Lariccia[a,b], A. Lucaroni[a,b], G. Mantovani[a,b], A. Nappi[a,b], A. Piluso[a], V. Postolache[a], A. Santocchia[a,b], L. Servoli[a], D. Tonoiu[a], A. Vedaee[a], R. Volpe[a,b]

INFN Sezione di Pisa [a], Universita di Pisa [b], Scuola Normale Superiore di Pisa [c], Pisa, Italy

P. Azzurri[a,c], G. Bagliesi[a], J. Bernardini[a,b], L. Berretta[a], T. Boccali[a], A. Bocci[a,c], L. Borrello[a,c], F. Bosi[a], F. Calzolari[a], R. Castaldi[a], R. Dell'Orso[a], F. Fiori[a,b], L. Foà[a,c], S. Gennai[a,c], A. Giassi[a], A. Kraan[a], F. Ligabue[a,c], T. Lomtadze[a], F. Mariani[a], L. Martini[a], M. Massa[a], A. Messineo[a,b], A. Moggi[a], F. Palla[a], F. Palmonari[a], G. Petragnani[a], G. Petrucciani[a,c], F. Raffaelli[a], S. Sarkar[a], G. Segneri[a], A.T. Serban[a], P. Spagnolo[a,1], R. Tenchini[a,1], S. Tolaini[a], G. Tonelli[a,b,1], A. Venturi[a], P.G. Verdini[a]

INFN Sezione di Roma [a], Universita di Roma "La Sapienza" [b], Roma, Italy

S. Baccaro[a,15], L. Barone[a,b], A. Bartoloni[a], F. Cavallari[a,1], I. Dafinei[a], D. Del Re[a,b], E. Di Marco[a,b], M. Diemoz[a], D. Franci[a,b], E. Longo[a,b], G. Organtini[a,b], A. Palma[a,b], F. Pandolfi[a,b], R. Paramatti[a,1], F. Pellegrino[a], S. Rahatlou[a,b], C. Rovelli[a]

INFN Sezione di Torino [a], Università di Torino [b], Università del Piemonte Orientale (Novara) [c], Torino, Italy

G. Alampi[a], N. Amapane[a,b], R. Arcidiacono[a,b], S. Argiro[a,b], M. Arneodo[a,c], C. Biino[a], M.A. Borgia[a,b], C. Botta[a,b], N. Cartiglia[a], R. Castello[a,b], G. Cerminara[a,b], M. Costa[a,b], D. Dattola[a], G. Dellacasa[a], N. Demaria[a], G. Dughera[a], F. Dumitrache[a], A. Graziano[a,b], C. Mariotti[a], M. Marone[a,b], S. Maselli[a], E. Migliore[a,b], G. Mila[a,b], V. Monaco[a,b], M. Musich[a,b], M. Nervo[a,b], M.M. Obertino[a,c], S. Oggero[a,b], R. Panero[a], N. Pastrone[a], M. Pelliccioni[a,b], A. Romero[a,b], M. Ruspa[a,c], R. Sacchi[a,b], A. Solano[a,b], A. Staiano[a], P.P. Trapani[a,b,1], D. Trocino[a,b], A. Vilela Pereira[a,b], L. Visca[a,b], A. Zampieri[a]

INFN Sezione di Trieste [a], Universita di Trieste [b], Trieste, Italy

F. Ambroglini[a,b], S. Belforte[a], F. Cossutti[a], G. Della Ricca[a,b], B. Gobbo[a], A. Penzo[a]

Kyungpook National University, Daegu, Korea

S. Chang, J. Chung, D.H. Kim, G.N. Kim, D.J. Kong, H. Park, D.C. Son

Wonkwang University, Iksan, Korea
S.Y. Bahk

Chonnam National University, Kwangju, Korea
S. Song

Konkuk University, Seoul, Korea
S.Y. Jung

Korea University, Seoul, Korea
B. Hong, H. Kim, J.H. Kim, K.S. Lee, D.H. Moon, S.K. Park, H.B. Rhee, K.S. Sim

Seoul National University, Seoul, Korea
J. Kim

University of Seoul, Seoul, Korea
M. Choi, G. Hahn, I.C. Park

Sungkyunkwan University, Suwon, Korea
S. Choi, Y. Choi, J. Goh, H. Jeong, T.J. Kim, J. Lee, S. Lee

Vilnius University, Vilnius, Lithuania
M. Janulis, D. Martisiute, P. Petrov, T. Sabonis

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
H. Castilla Valdez[1], A. Sánchez Hernández

Universidad Iberoamericana, Mexico City, Mexico
S. Carrillo Moreno

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico
A. Morelos Pineda

University of Auckland, Auckland, New Zealand
P. Allfrey, R.N.C. Gray, D. Krofcheck

University of Canterbury, Christchurch, New Zealand
N. Bernardino Rodrigues, P.H. Butler, T. Signal, J.C. Williams

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
M. Ahmad, I. Ahmed, W. Ahmed, M.I. Asghar, M.I.M. Awan, H.R. Hoorani, I. Hussain, W.A. Khan, T. Khurshid, S. Muhammad, S. Qazi, H. Shahzad

Institute of Experimental Physics, Warsaw, Poland
M. Cwiok, R. Dabrowski, W. Dominik, K. Doroba, M. Konecki, J. Krolikowski, K. Pozniak[16], R. Romaniuk, W. Zabolotny[16], P. Zych

Soltan Institute for Nuclear Studies, Warsaw, Poland
T. Frueboes, R. Gokieli, L. Goscilo, M. Górski, M. Kazana, K. Nawrocki, M. Szleper, G. Wrochna, P. Zalewski

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
N. Almeida, L. Antunes Pedro, P. Bargassa, A. David, P. Faccioli, P.G. Ferreira Parracho, M. Freitas Ferreira, M. Gallinaro, M. Guerra Jordao, P. Martins, G. Mini, P. Musella, J. Pela, L. Raposo, P.Q. Ribeiro, S. Sampaio, J. Seixas, J. Silva, P. Silva, D. Soares, M. Sousa, J. Varela, H.K. Wöhri

Joint Institute for Nuclear Research, Dubna, Russia

I. Altsybeev, I. Belotelov, P. Bunin, Y. Ershov, I. Filozova, M. Finger, M. Finger Jr., A. Golunov, I. Golutvin, N. Gorbounov, V. Kalagin, A. Kamenev, V. Karjavin, V. Konoplyanikov, V. Korenkov, G. Kozlov, A. Kurenkov, A. Lanev, A. Makankin, V.V. Mitsyn, P. Moisenz, E. Nikonov, D. Oleynik, V. Palichik, V. Perelygin, A. Petrosyan, R. Semenov, S. Shmatov, V. Smirnov, D. Smolin, E. Tikhonenko, S. Vasil'ev, A. Vishnevskiy, A. Volodko, A. Zarubin, V. Zhiltsov

Petersburg Nuclear Physics Institute, Gatchina (St Petersburg), Russia

N. Bondar, L. Chtchipounov, A. Denisov, Y. Gavrikov, G. Gavrilov, V. Golovtsov, Y. Ivanov, V. Kim, V. Kozlov, P. Levchenko, G. Obrant, E. Orishchin, A. Petrunin, Y. Shcheglov, A. Shchetkovskiy, V. Sknar, I. Smirnov, V. Sulimov, V. Tarakanov, L. Uvarov, S. Vavilov, G. Velichko, S. Volkov, A. Vorobyev

Institute for Nuclear Research, Moscow, Russia

Yu. Andreev, A. Anisimov, P. Antipov, A. Dermenev, S. Gninenko, N. Golubev, M. Kirsanov, N. Krasnikov, V. Matveev, A. Pashenkov, V.E. Postoev, A. Solovey, A. Solovey, A. Toropin, S. Troitsky

Institute for Theoretical and Experimental Physics, Moscow, Russia

A. Baud, V. Epshteyn, V. Gavrilov, N. Ilina, V. Kaftanov[†], V. Kolosov, M. Kossov[1], A. Krokhotin, S. Kuleshov, A. Oulianov, G. Safronov, S. Semenov, I. Shreyber, V. Stolin, E. Vlasov, A. Zhokin

Moscow State University, Moscow, Russia

E. Boos, M. Dubinin[17], L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, S. Petrushanko, L. Sarycheva, V. Savrin, A. Snigirev, I. Vardanyan

P.N. Lebedev Physical Institute, Moscow, Russia

I. Dremin, M. Kirakosyan, N. Konovalova, S.V. Rusakov, A. Vinogradov

State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia

S. Akimenko, A. Artamonov, I. Azhgirey, S. Bitioukov, V. Burtovoy, V. Grishin[1], V. Kachanov, D. Konstantinov, V. Krychkine, A. Levine, I. Lobov, V. Lukanin, Y. Mel'nik, V. Petrov, R. Ryutin, S. Slabospitsky, A. Sobol, A. Sytine, L. Tourtchanovitch, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

Vinca Institute of Nuclear Sciences, Belgrade, Serbia

P. Adzic, M. Djordjevic, D. Jovanovic[18], D. Krpic[18], D. Maletic, J. Puzovic[18], N. Smiljkovic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain

M. Aguilar-Benitez, J. Alberdi, J. Alcaraz Maestre, P. Arce, J.M. Barcala, C. Battilana, C. Burgos Lazaro, J. Caballero Bejar, E. Calvo, M. Cardenas Montes, M. Cepeda, M. Cerrada, M. Chamizo Llatas, F. Clemente, N. Colino, M. Daniel, B. De La Cruz, A. Delgado Peris, C. Diez Pardos, C. Fernandez Bedoya, J.P. Fernández Ramos, A. Ferrando, J. Flix, M.C. Fouz, P. Garcia-Abia, A.C. Garcia-Bonilla, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, J. Marin, G. Merino, J. Molina, A. Molinero, J.J. Navarrete, J.C. Oller, J. Puerta Pelayo, L. Romero, J. Santaolalla, C. Villanueva Munoz, C. Willmott, C. Yuste

Universidad Autónoma de Madrid, Madrid, Spain
C. Albajar, M. Blanco Otano, J.F. de Trocóniz, A. Garcia Raboso, J.O. Lopez Berengueres

Universidad de Oviedo, Oviedo, Spain
J. Cuevas, J. Fernandez Menendez, I. Gonzalez Caballero, L. Lloret Iglesias, H. Naves Sordo, J.M. Vizan Garcia

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
I.J. Cabrillo, A. Calderon, S.H. Chuang, I. Diaz Merino, C. Diez Gonzalez, J. Duarte Campderros, M. Fernandez, G. Gomez, J. Gonzalez Sanchez, R. Gonzalez Suarez, C. Jorda, P. Lobelle Pardo, A. Lopez Virto, J. Marco, R. Marco, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, T. Rodrigo, A. Ruiz Jimeno, L. Scodellaro, M. Sobron Sanudo, I. Vila, R. Vilar Cortabitarte

CERN, European Organization for Nuclear Research, Geneva, Switzerland
D. Abbaneo, E. Albert, M. Alidra, S. Ashby, E. Auffray, J. Baechler, P. Baillon, A.H. Ball, S.L. Bally, D. Barney, F. Beaudette[19], R. Bellan, D. Benedetti, G. Benelli, C. Bernet, P. Bloch, S. Bolognesi, M. Bona, J. Bos, N. Bourgeois, T. Bourrel, H. Breuker, K. Bunkowski, D. Campi, T. Camporesi, E. Cano, A. Cattai, J.P. Chatelain, M. Chauvey, T. Christiansen, J.A. Coarasa Perez, A. Conde Garcia, R. Covarelli, B. Curé, A. De Roeck, V. Delachenal, D. Deyrail, S. Di Vincenzo[20], S. Dos Santos, T. Dupont, L.M. Edera, A. Elliott-Peisert, M. Eppard, M. Favre, N. Frank, W. Funk, A. Gaddi, M. Gastal, M. Gateau, H. Gerwig, D. Gigi, K. Gill, D. Giordano, J.P. Girod, F. Glege, R. Gomez-Reino Garrido, R. Goudard, S. Gowdy, R. Guida, L. Guiducci, J. Gutleber, M. Hansen, C. Hartl, J. Harvey, B. Hegner, H.F. Hoffmann, A. Holzner, A. Honma, M. Huhtinen, V. Innocente, P. Janot, G. Le Godec, P. Lecoq, C. Leonidopoulos, R. Loos, C. Lourenço, A. Lyonnet, A. Macpherson, N. Magini, J.D. Maillefaud, G. Maire, T. Mäki, L. Malgeri, M. Mannelli, L. Masetti, F. Meijers, P. Meridiani, S. Mersi, E. Meschi, A. Meynet Cordonnier, R. Moser, M. Mulders, J. Mulon, M. Noy, A. Oh, G. Olesen, A. Onnela, T. Orimoto, L. Orsini, E. Perez, G. Perinic, J.F. Pernot, P. Petagna, P. Petiot, A. Petrilli, A. Pfeiffer, M. Pierini, M. Pimiä, R. Pintus, B. Pirollet, H. Postema, A. Racz, S. Ravat, S.B. Rew, J. Rodrigues Antunes, G. Rolandi[21], M. Rovere, V. Ryjov, H. Sakulin, D. Samyn, H. Sauce, C. Schäfer, W.D. Schlatter, M. Schröder, C. Schwick, A. Sciaba, I. Segoni, A. Sharma, N. Siegrist, P. Siegrist, N. Sinanis, T. Sobrier, P. Sphicas[22], D. Spiga, M. Spiropulu[17], F. Stöckli, P. Traczyk, P. Tropea, J. Troska, A. Tsirou, L. Veillet, G.I. Veres, M. Voutilainen, P. Wertelaers, M. Zanetti

Paul Scherrer Institut, Villigen, Switzerland
W. Bertl, K. Deiters, W. Erdmann, K. Gabathuler, R. Horisberger, Q. Ingram, H.C. Kaestli, S. König, D. Kotlinski, U. Langenegger, F. Meier, D. Renker, T. Rohe, J. Sibille[23], A. Starodumov[24]

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland
B. Betev, L. Caminada[25], Z. Chen, S. Cittolin, D.R. Da Silva Di Calafiori, S. Dambach[25], G. Dissertori, M. Dittmar, C. Eggel[25], J. Eugster, G. Faber, K. Freudenreich, C. Grab, A. Hervé, W. Hintz, P. Lecomte, P.D. Luckey, W. Lustermann, C. Marchica[25], P. Milenovic[26], F. Moortgat, A. Nardulli, F. Nessi-Tedaldi, L. Pape, F. Pauss, T. Punz, A. Rizzi, F.J. Ronga, L. Sala, A.K. Sanchez, M.-C. Sawley, V. Sordini, B. Stieger, L. Tauscher[†], A. Thea, K. Theofilatos, D. Treille, P. Trüb[25], M. Weber, L. Wehrli, J. Weng, S. Zelepoukine[27]

Universität Zürich, Zurich, Switzerland
C. Amsler, V. Chiochia, S. De Visscher, C. Regenfus, P. Robmann, T. Rommerskirchen, A. Schmidt, D. Tsirigkas, L. Wilke

National Central University, Chung-Li, Taiwan
Y.H. Chang, E.A. Chen, W.T. Chen, A. Go, C.M. Kuo, S.W. Li, W. Lin

National Taiwan University (NTU), Taipei, Taiwan
P. Bartalini, P. Chang, Y. Chao, K.F. Chen, W.-S. Hou, Y. Hsiung, Y.J. Lei, S.W. Lin, R.-S. Lu, J. Schümann, J.G. Shiu, Y.M. Tzeng, K. Ueno, Y. Velikzhanin, C.C. Wang, M. Wang

Cukurova University, Adana, Turkey
A. Adiguzel, A. Ayhan, A. Azman Gokce, M.N. Bakirci, S. Cerci, I. Dumanoglu, E. Eskut, S. Girgis, E. Gurpinar, I. Hos, T. Karaman, T. Karaman, A. Kayis Topaksu, P. Kurt, G. Önengüt, G. Önengüt Gökbulut, K. Ozdemir, S. Ozturk, A. Polatöz, K. Sogut[28], B. Tali, H. Topakli, D. Uzun, L.N. Vergili, M. Vergili

Middle East Technical University, Physics Department, Ankara, Turkey
I.V. Akin, T. Aliev, S. Bilmis, M. Deniz, H. Gamsizkan, A.M. Guler, K. Öcalan, M. Serin, R. Sever, U.E. Surat, M. Zeyrek

Bogaziçi University, Department of Physics, Istanbul, Turkey
M. Deliomeroglu, D. Demir[29], E. Gülmez, A. Halu, B. Isildak, M. Kaya[30], O. Kaya[30], S. Ozkorucuklu[31], N. Sonmez[32]

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine
L. Levchuk, S. Lukyanenko, D. Soroka, S. Zub

University of Bristol, Bristol, United Kingdom
F. Bostock, J.J. Brooke, T.L. Cheng, D. Cussans, R. Frazier, J. Goldstein, N. Grant, M. Hansen, G.P. Heath, H.F. Heath, C. Hill, B. Huckvale, J. Jackson, C.K. Mackay, S. Metson, D.M. Newbold[33], K. Nirunpong, V.J. Smith, J. Velthuis, R. Walton

Rutherford Appleton Laboratory, Didcot, United Kingdom
K.W. Bell, C. Brew, R.M. Brown, B. Camanzi, D.J.A. Cockerill, J.A. Coughlan, N.I. Geddes, K. Harder, S. Harper, B.W. Kennedy, P. Murray, C.H. Shepherd-Themistocleous, I.R. Tomalin, J.H. Williams[†], W.J. Womersley, S.D. Worm

Imperial College, University of London, London, United Kingdom
R. Bainbridge, G. Ball, J. Ballin, R. Beuselinck, O. Buchmuller, D. Colling, N. Cripps, G. Davies, M. Della Negra, C. Foudas, J. Fulcher, D. Futyan, G. Hall, J. Hays, G. Iles, G. Karapostoli, B.C. MacEvoy, A.-M. Magnan, J. Marrouche, J. Nash, A. Nikitenko[24], A. Papageorgiou, M. Pesaresi, K. Petridis, M. Pioppi[34], D.M. Raymond, N. Rompotis, A. Rose, M.J. Ryan, C. Seez, P. Sharp, G. Sidiropoulos[1], M. Stettler, M. Stoye, M. Takahashi, A. Tapper, C. Timlin, S. Tourneur, M. Vazquez Acosta, T. Virdee[1], S. Wakefield, D. Wardrope, T. Whyntie, M. Wingham

Brunel University, Uxbridge, United Kingdom
J.E. Cole, I. Goitom, P.R. Hobson, A. Khan, P. Kyberd, D. Leslie, C. Munro, I.D. Reid, C. Siamitros, R. Taylor, L. Teodorescu, I. Yaselli

Boston University, Boston, U.S.A.
T. Bose, M. Carleton, E. Hazen, A.H. Heering, A. Heister, J. St. John, P. Lawson, D. Lazic, D. Osborne, J. Rohlf, L. Sulak, S. Wu

Brown University, Providence, U.S.A.
J. Andrea, A. Avetisyan, S. Bhattacharya, J.P. Chou, D. Cutts, S. Esen, G. Kukartsev, G. Landsberg, M. Narain, D. Nguyen, T. Speer, K.V. Tsang

University of California, Davis, Davis, U.S.A.
R. Breedon, M. Calderon De La Barca Sanchez, M. Case, D. Cebra, M. Chertok, J. Conway, P.T. Cox, J. Dolen, R. Erbacher, E. Friis, W. Ko, A. Kopecky, R. Lander, A. Lister, H. Liu, S. Maruyama, T. Miceli, M. Nikolic, D. Pellett, J. Robles, M. Searle, J. Smith, M. Squires, J. Stilley, M. Tripathi, R. Vasquez Sierra, C. Veelken

University of California, Los Angeles, Los Angeles, U.S.A.
V. Andreev, K. Arisaka, D. Cline, R. Cousins, S. Erhan[1], J. Hauser, M. Ignatenko, C. Jarvis, J. Mumford, C. Plager, G. Rakness, P. Schlein[†], J. Tucker, V. Valuev, R. Wallny, X. Yang

University of California, Riverside, Riverside, U.S.A.
J. Babb, M. Bose, A. Chandra, R. Clare, J.A. Ellison, J.W. Gary, G. Hanson, G.Y. Jeng, S.C. Kao, F. Liu, H. Liu, A. Luthra, H. Nguyen, G. Pasztor[35], A. Satpathy, B.C. Shen[†], R. Stringer, J. Sturdy, V. Sytnik, R. Wilken, S. Wimpenny

University of California, San Diego, La Jolla, U.S.A.
J.G. Branson, E. Dusinberre, D. Evans, F. Golf, R. Kelley, M. Lebourgeois, J. Letts, E. Lipeles, B. Mangano, J. Muelmenstaedt, M. Norman, S. Padhi, A. Petrucci, H. Pi, M. Pieri, R. Ranieri, M. Sani, V. Sharma, S. Simon, F. Würthwein, A. Yagil

University of California, Santa Barbara, Santa Barbara, U.S.A.
C. Campagnari, M. D'Alfonso, T. Danielson, J. Garberson, J. Incandela, C. Justus, P. Kalavase, S.A. Koay, D. Kovalskyi, V. Krutelyov, J. Lamb, S. Lowette, V. Pavlunin, F. Rebassoo, J. Ribnik, J. Richman, R. Rossin, D. Stuart, W. To, J.R. Vlimant, M. Witherell

California Institute of Technology, Pasadena, U.S.A.
A. Apresyan, A. Bornheim, J. Bunn, M. Chiorboli, M. Gataullin, D. Kcira, V. Litvine, Y. Ma, H.B. Newman, C. Rogan, V. Timciuc, J. Veverka, R. Wilkinson, Y. Yang, L. Zhang, K. Zhu, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, U.S.A.
B. Akgun, R. Carroll, T. Ferguson, D.W. Jang, S.Y. Jun, M. Paulini, J. Russ, N. Terentyev, H. Vogel, I. Vorobiev

University of Colorado at Boulder, Boulder, U.S.A.
J.P. Cumalat, M.E. Dinardo, B.R. Drell, W.T. Ford, B. Heyburn, E. Luiggi Lopez, U. Nauenberg, K. Stenson, K. Ulmer, S.R. Wagner, S.L. Zang

Cornell University, Ithaca, U.S.A.
L. Agostino, J. Alexander, F. Blekman, D. Cassel, A. Chatterjee, S. Das, L.K. Gibbons, B. Heltsley, W. Hopkins, A. Khukhunaishvili, B. Kreis, V. Kuznetsov, J.R. Patterson, D. Puigh, A. Ryd, X. Shi, S. Stroiney, W. Sun, W.D. Teo, J. Thom, J. Vaughan, Y. Weng, P. Wittich

Fairfield University, Fairfield, U.S.A.
C.P. Beetz, G. Cirino, C. Sanzeni, D. Winn

Fermi National Accelerator Laboratory, Batavia, U.S.A.
S. Abdullin, M.A. Afaq[1], M. Albrow, B. Ananthan, G. Apollinari, M. Atac, W. Badgett, L. Bagby, J.A. Bakken, B. Baldin, S. Banerjee, K. Banicz, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, K. Biery, M. Binkley, I. Bloch, F. Borcherding, A.M. Brett, K. Burkett, J.N. Butler, V. Chetluru, H.W.K. Cheung, F. Chlebana, I. Churin, S. Cihangir, M. Crawford, W. Dagenhart, M. Demarteau, G. Derylo, D. Dykstra, D.P. Eartly, J.E. Elias, V.D. Elvira, D. Evans, L. Feng, M. Fischler, I. Fisk, S. Foulkes, J. Freeman, P. Gartung, E. Gottschalk, T. Grassi, D. Green, Y. Guo, O. Gutsche, A. Hahn, J. Hanlon, R.M. Harris, B. Holzman, J. Howell, D. Hufnagel, E. James, H. Jensen, M. Johnson, C.D. Jones, U. Joshi, E. Juska, J. Kaiser, B. Klima, S. Kossiakov, K. Kousouris, S. Kwan, C.M. Lei, P. Limon, J.A. Lopez Perez, S. Los, L. Lueking, G. Lukhanin, S. Lusin[1], J. Lykken, K. Maeshima, J.M. Marraffino, D. Mason, P. McBride, T. Miao, K. Mishra, S. Moccia, R. Mommsen, S. Mrenna, A.S. Muhammad, C. Newman-Holmes, C. Noeding, V. O'Dell, O. Prokofyev, R. Rivera, C.H. Rivetta, A. Ronzhin, P. Rossman, S. Ryu, V. Sekhri, E. Sexton-Kennedy, I. Sfiligoi, S. Sharma, T.M. Shaw, D. Shpakov, E. Skup, R.P. Smith[†], A. Soha, W.J. Spalding, L. Spiegel, I. Suzuki, P. Tan, W. Tanenbaum, S. Tkaczyk[1], R. Trentadue[1], L. Uplegger, E.W. Vaandering, R. Vidal, J. Whitmore, E. Wicklund, W. Wu, J. Yarba, F. Yumiceva, J.C. Yun

University of Florida, Gainesville, U.S.A.
D. Acosta, P. Avery, V. Barashko, D. Bourilkov, M. Chen, G.P. Di Giovanni, D. Dobur, A. Drozdetskiy, R.D. Field, Y. Fu, I.K. Furic, J. Gartner, D. Holmes, B. Kim, S. Klimenko, J. Konigsberg, A. Korytov, K. Kotov, A. Kropivnitskaya, T. Kypreos, A. Madorsky, K. Matchev, G. Mitselmakher, Y. Pakhotin, J. Piedra Gomez, C. Prescott, V. Rapsevicius, R. Remington, M. Schmitt, B. Scurlock, D. Wang, J. Yelton

Florida International University, Miami, U.S.A.
C. Ceron, V. Gaultney, L. Kramer, L.M. Lebolo, S. Linn, P. Markowitz, G. Martinez, J.L. Rodriguez

Florida State University, Tallahassee, U.S.A.
T. Adams, A. Askew, H. Baer, M. Bertoldi, J. Chen, W.G.D. Dharmaratna, S.V. Gleyzer, J. Haas, S. Hagopian, V. Hagopian, M. Jenkins, K.F. Johnson, E. Prettner, H. Prosper, S. Sekmen

Florida Institute of Technology, Melbourne, U.S.A.
M.M. Baarmand, S. Guragain, M. Hohlmann, H. Kalakhety, H. Mermerkaya, R. Ralich, I. Vodopiyanov

University of Illinois at Chicago (UIC), Chicago, U.S.A.
B. Abelev, M.R. Adams, I.M. Anghel, L. Apanasevich, V.E. Bazterra, R.R. Betts, J. Callner, M.A. Castro, R. Cavanaugh, C. Dragoiu, E.J. Garcia-Solis, C.E. Gerber, D.J. Hofman, S. Khalatian, C. Mironov, E. Shabalina, A. Smoron, N. Varelas

The University of Iowa, Iowa City, U.S.A.
U. Akgun, E.A. Albayrak, A.S. Ayan, B. Bilki, R. Briggs, K. Cankocak[36], K. Chung, W. Clarida, P. Debbins, F. Duru, F.D. Ingram, C.K. Lae, E. McCliment, J.-P. Merlo, A. Mestvirishvili, M.J. Miller, A. Moeller, J. Nachtman, C.R. Newsom, E. Norbeck, J. Olson, Y. Onel, F. Ozok, J. Parsons, I. Schmidt, S. Sen, J. Wetzel, T. Yetkin, K. Yi

Johns Hopkins University, Baltimore, U.S.A.
B.A. Barnett, B. Blumenfeld, A. Bonato, C.Y. Chien, D. Fehling, G. Giurgiu, A.V. Gritsan, Z.J. Guo, P. Maksimovic, S. Rappoccio, M. Swartz, N.V. Tran, Y. Zhang

The University of Kansas, Lawrence, U.S.A.
P. Baringer, A. Bean, O. Grachov, M. Murray, V. Radicci, S. Sanders, J.S. Wood, V. Zhukova

Kansas State University, Manhattan, U.S.A.
D. Bandurin, T. Bolton, K. Kaadze, A. Liu, Y. Maravin, D. Onoprienko, I. Svintradze, Z. Wan

Lawrence Livermore National Laboratory, Livermore, U.S.A.
J. Gronberg, J. Hollar, D. Lange, D. Wright

University of Maryland, College Park, U.S.A.
D. Baden, R. Bard, M. Boutemeur, S.C. Eno, D. Ferencek, N.J. Hadley, R.G. Kellogg, M. Kirn, S. Kunori, K. Rossato, P. Rumerio, F. Santanastasio, A. Skuja, J. Temple, M.B. Tonjes, S.C. Tonwar, T. Toole, E. Twedt

Massachusetts Institute of Technology, Cambridge, U.S.A.
B. Alver, G. Bauer, J. Bendavid, W. Busza, E. Butz, I.A. Cali, M. Chan, D. D'Enterria, P. Everaerts, G. Gomez Ceballos, K.A. Hahn, P. Harris, S. Jaditz, Y. Kim, M. Klute, Y.-J. Lee, W. Li, C. Loizides, T. Ma, M. Miller, S. Nahn, C. Paus, C. Roland, G. Roland, M. Rudolph, G. Stephans, K. Sumorok, K. Sung, S. Vaurynovich, E.A. Wenger, B. Wyslouch, S. Xie, Y. Yilmaz, A.S. Yoon

University of Minnesota, Minneapolis, U.S.A.
D. Bailleux, S.I. Cooper, P. Cushman, B. Dahmes, A. De Benedetti, A. Dolgopolov, P.R. Dudero, R. Egeland, G. Franzoni, J. Haupt, A. Inyakin[37], K. Klapoetke, Y. Kubota, J. Mans, N. Mirman, D. Petyt, V. Rekovic, R. Rusack, M. Schroeder, A. Singovsky, J. Zhang

University of Mississippi, University, U.S.A.
L.M. Cremaldi, R. Godang, R. Kroeger, L. Perera, R. Rahmat, D.A. Sanders, P. Sonnek, D. Summers

University of Nebraska-Lincoln, Lincoln, U.S.A.
K. Bloom, B. Bockelman, S. Bose, J. Butt, D.R. Claes, A. Dominguez, M. Eads, J. Keller, T. Kelly, I. Kravchenko, J. Lazo-Flores, C. Lundstedt, H. Malbouisson, S. Malik, G.R. Snow

State University of New York at Buffalo, Buffalo, U.S.A.
U. Baur, I. Iashvili, A. Kharchilava, A. Kumar, K. Smith, M. Strang

Northeastern University, Boston, U.S.A.
G. Alverson, E. Barberis, O. Boeriu, G. Eulisse, G. Govi, T. McCauley, Y. Musienko[38], S. Muzaffar, I. Osborne, T. Paul, S. Reucroft, J. Swain, L. Taylor, L. Tuura

Northwestern University, Evanston, U.S.A.
A. Anastassov, B. Gobbi, A. Kubik, R.A. Ofierzynski, A. Pozdnyakov, M. Schmitt, S. Stoynev, M. Velasco, S. Won

University of Notre Dame, Notre Dame, U.S.A.
L. Antonelli, D. Berry, M. Hildreth, C. Jessop, D.J. Karmgard, T. Kolberg, K. Lannon, S. Lynch, N. Marinelli, D.M. Morse, R. Ruchti, J. Slaunwhite, J. Warchol, M. Wayne

The Ohio State University, Columbus, U.S.A.
B. Bylsma, L.S. Durkin, J. Gilmore[39], J. Gu, P. Killewald, T.Y. Ling, G. Williams

Princeton University, Princeton, U.S.A.
N. Adam, E. Berry, P. Elmer, A. Garmash, D. Gerbaudo, V. Halyo, A. Hunt, J. Jones, E. Laird, D. Marlow, T. Medvedeva, M. Mooney, J. Olsen, P. Piroué, D. Stickland, C. Tully, J.S. Werner, T. Wildish, Z. Xie, A. Zuranski

University of Puerto Rico, Mayaguez, U.S.A.
J.G. Acosta, M. Bonnett Del Alamo, X.T. Huang, A. Lopez, H. Mendez, S. Oliveros, J.E. Ramirez Vargas, N. Santacruz, A. Zatzerklyany

Purdue University, West Lafayette, U.S.A.
E. Alagoz, E. Antillon, V.E. Barnes, G. Bolla, D. Bortoletto, A. Everett, A.F. Garfinkel, Z. Gecse, L. Gutay, N. Ippolito, M. Jones, O. Koybasi, A.T. Laasanen, N. Leonardo, C. Liu, V. Maroussov, P. Merkel, D.H. Miller, N. Neumeister, A. Sedov, I. Shipsey, H.D. Yoo, Y. Zheng

Purdue University Calumet, Hammond, U.S.A.
P. Jindal, N. Parashar

Rice University, Houston, U.S.A.
V. Cuplov, K.M. Ecklund, F.J.M. Geurts, J.H. Liu, D. Maronde, M. Matveev, B.P. Padley, R. Redjimi, J. Roberts, L. Sabbatini, A. Tumanov

University of Rochester, Rochester, U.S.A.
B. Betchart, A. Bodek, H. Budd, Y.S. Chung, P. de Barbaro, R. Demina, H. Flacher, Y. Gotra, A. Harel, S. Korjenevski, D.C. Miner, D. Orbaker, G. Petrillo, D. Vishnevskiy, M. Zielinski

The Rockefeller University, New York, U.S.A.
A. Bhatti, L. Demortier, K. Goulianos, K. Hatakeyama, G. Lungu, C. Mesropian, M. Yan

Rutgers, the State University of New Jersey, Piscataway, U.S.A.
O. Atramentov, E. Bartz, Y. Gershtein, E. Halkiadakis, D. Hits, A. Lath, K. Rose, S. Schnetzer, S. Somalwar, R. Stone, S. Thomas, T.L. Watts

University of Tennessee, Knoxville, U.S.A.
G. Cerizza, M. Hollingsworth, S. Spanier, Z.C. Yang, A. York

Texas A&M University, College Station, U.S.A.
J. Asaadi, A. Aurisano, R. Eusebi, A. Golyash, A. Gurrola, T. Kamon, C.N. Nguyen, J. Pivarski, A. Safonov, S. Sengupta, D. Toback, M. Weinberger

Texas Tech University, Lubbock, U.S.A.
N. Akchurin, L. Berntzon, K. Gumus, C. Jeong, H. Kim, S.W. Lee, S. Popescu, Y. Roh, A. Sill, I. Volobouev, E. Washington, R. Wigmans, E. Yazgan

Vanderbilt University, Nashville, U.S.A.
D. Engh, C. Florez, W. Johns, S. Pathak, P. Sheldon

University of Virginia, Charlottesville, U.S.A.
D. Andelin, M.W. Arenton, M. Balazs, S. Boutle, M. Buehler, S. Conetti, B. Cox, R. Hirosky, A. Ledovskoy, C. Neu, D. Phillips II, M. Ronquest, R. Yohay

Wayne State University, Detroit, U.S.A.
S. Gollapinni, K. Gunthoti, R. Harr, P.E. Karchin, M. Mattson, A. Sakharov

University of Wisconsin, Madison, U.S.A.
M. Anderson, M. Bachtis, J.N. Bellinger, D. Carlsmith, I. Crotty[1], S. Dasu, S. Dutta, J. Efron, F. Feyzi, K. Flood, L. Gray, K.S. Grogg, M. Grothe, R. Hall-Wilton[1], M. Jaworski, P. Klabbers, J. Klukas, A. Lanaro, C. Lazaridis, J. Leonard, R. Loveless, M. Magrans de Abril, A. Mohapatra, G. Ott, G. Polese, D. Reeder, A. Savin, W.H. Smith, A. Sourkov[40], J. Swanson, M. Weinberg, D. Wenman, M. Wensveen, A. White

†: Deceased
1: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
2: Also at Universidade Federal do ABC, Santo Andre, Brazil
3: Also at Soltan Institute for Nuclear Studies, Warsaw, Poland
4: Also at Université de Haute-Alsace, Mulhouse, France
5: Also at Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules (IN2P3), Villeurbanne, France
6: Also at Moscow State University, Moscow, Russia
7: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
8: Also at University of California, San Diego, La Jolla, U.S.A.
9: Also at Tata Institute of Fundamental Research - HECR, Mumbai, India
10: Also at University of Visva-Bharati, Santiniketan, India
11: Also at Facolta' Ingegneria Universita' di Roma "La Sapienza", Roma, Italy
12: Also at Università della Basilicata, Potenza, Italy
13: Also at Laboratori Nazionali di Legnaro dell' INFN, Legnaro, Italy
14: Also at Università di Trento, Trento, Italy
15: Also at ENEA - Casaccia Research Center, S. Maria di Galeria, Italy
16: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
17: Also at California Institute of Technology, Pasadena, U.S.A.
18: Also at Faculty of Physics of University of Belgrade, Belgrade, Serbia
19: Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
20: Also at Alstom Contracting, Geneve, Switzerland
21: Also at Scuola Normale e Sezione dell' INFN, Pisa, Italy
22: Also at University of Athens, Athens, Greece
23: Also at The University of Kansas, Lawrence, U.S.A.
24: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
25: Also at Paul Scherrer Institut, Villigen, Switzerland
26: Also at Vinca Institute of Nuclear Sciences, Belgrade, Serbia
27: Also at University of Wisconsin, Madison, U.S.A.
28: Also at Mersin University, Mersin, Turkey
29: Also at Izmir Institute of Technology, Izmir, Turkey
30: Also at Kafkas University, Kars, Turkey
31: Also at Suleyman Demirel University, Isparta, Turkey
32: Also at Ege University, Izmir, Turkey

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33: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
34: Also at INFN Sezione di Perugia; Universita di Perugia, Perugia, Italy
35: Also at KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary
36: Also at Istanbul Technical University, Istanbul, Turkey
37: Also at University of Minnesota, Minneapolis, U.S.A.
38: Also at Institute for Nuclear Research, Moscow, Russia
39: Also at Texas A&M University, College Station, U.S.A.
40: Also at State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia