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COMMISSIONING OF THE CMS EXPERIMENT WITH COSMIC RAYS

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Performance study of the CMS barrel resistive plate chambers with cosmic rays

CMS Collaboration

ABSTRACT: In October and November 2008, the CMS collaboration conducted a programme of cosmic ray data taking, which has recorded about 270 million events. The Resistive Plate Chamber system, which is part of the CMS muon detection system, was successfully operated in the full barrel. More than 98% of the channels were operational during the exercise with typical detection efficiency of 90%. In this paper, the performance of the detector during these dedicated runs is reported.

KEYWORDS: Large detector systems for particle and astroparticle physics; Trigger detetectors

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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 collisions between protons delivered by the Large Hadron Collider (LHC) [2]. The Resistive Plate Chamber (RPC) system [3] is part of the muon detection system and is used for triggering purposes. RPCs have been chosen because of their good time resolution (about 2 ns) and high granularity, which permit a fast and efficient triggering of muons over large areas.

During October-November 2008, the CMS Collaboration conducted a month-long data-taking exercise known as the Cosmic Run At Four Tesla (CRAFT), with the goal of commissioning the experiment for extended operation [4]. With all installed detector systems participating, CMS recorded 270 million cosmic-ray-triggered events with the solenoid at a central flux density of 3.8 T.

The muon system is composed of a central barrel (in the pseudo-rapidity window $|\eta| < 1.04$) and two closing endcaps ($1.04 < |\eta| < 2.4$). The RPCs participated in the CRAFT data taking with the full barrel and half of the endcaps in operation. Part of the endcaps was not operational because the readout electronics was not yet available.

For the RPC system, the CRAFT 2008 exercise has permitted the check of the full data taking chain, from the detector up to the data acquisition boards, and the confirmation of the detector

performance established during the quality control phase [5], also in presence of the CMS magnetic field. The exercise was also a useful benchmark to complete the commissioning of the endcap part of the RPC system.

This paper is focused on the barrel RPC system performance. Sections 2 and 3 describe the RPC system layout, and the operation and monitoring procedures during the CRAFT exercise, respectively. In section 4, the readout electronics is presented and the synchronization procedure is described. Section 5 deals with the barrel RPC performance, in terms of cluster size, position resolution and detection efficiency.

2 RPC system layout

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter. The silicon pixel and strip tracker, the crystal electromagnetic calorimeter (ECAL) and the brass-scintillator hadronic calorimeter (HCAL) are located within the solenoidal field volume. Muons are measured in gas ionization detectors embedded in the steel return yoke. CMS uses a right-handed coordinate system, with the origin at the nominal collision point, the x-axis pointing to the centre of the LHC, the y-axis pointing up (perpendicular to the LHC plane), and the z-axis along the anticlockwise-beam direction. The polar angle, θ, is measured from the positive z-axis, the azimuthal angle, ϕ, is measured in the x-y plane.

The RPC detectors are employed in CMS as a dedicated trigger system in both the barrel and in the endcap regions. They complement the muon tracking system: drift tubes (DT) [6] in the barrel and cathode strip chambers (CSC) [7] in the endcaps.

From the geometrical point of view, the muon system is divided into five wheels in the barrel and three disks in each endcap. Each barrel wheel is divided in 12 sectors, covering the full azimuthal dimension (see figure 1). Each sector consists of four layers of DTs and six layers of RPCs, with a total of 480 RPC stations of average area of 12 m^2. The two innermost DT layers are sandwiched between RPC layers ($RB1_{in}$ and $RB1_{out}$ for the innermost DT layer, $RB2_{in}$ and $RB2_{out}$ for the second one). The third and fourth DT layers are complemented with a single RPC layer, placed on their inner side (RB3 and RB4). A detailed description of the muon system geometry can be found in ref. [1].

Each barrel RPC station is mechanically composed of two or three adjacent RPC units, called "rolls", making a total of 1020 rolls for the barrel RPC system. Figure 2 shows a schematic layout of a RPC station composed by two rolls. The CMS RPC rolls are double RPC units, where each unit is composed of two bakelite electrodes, each 2 mm thick, and a 2 mm wide gas gap. Readout strips, which are oriented along the beam direction, are placed between the two RPC units, with an independent electronic channel for each strip. The total readout system of the barrel RPC detector consists of 68 136 channels.

The strip location defines a point in the local reference frame of the RPC with a precision given by the strip width, ranging from 2.3 cm, for the innermost $RB1_{in}$ layer, to 4.1 cm, for the RB4 layer (see table 1). The strip signals are discriminated and shaped into 100 ns digital pulses by front-end boards with programmable discriminator thresholds.

The RPC detectors, which work in saturated avalanche mode, use a three-component, non-flammable gas mixture composed of 96.2% $C_2H_2F_4$ (R134a), 3.5% isobutane (C_4H_{10}) and 0.3%

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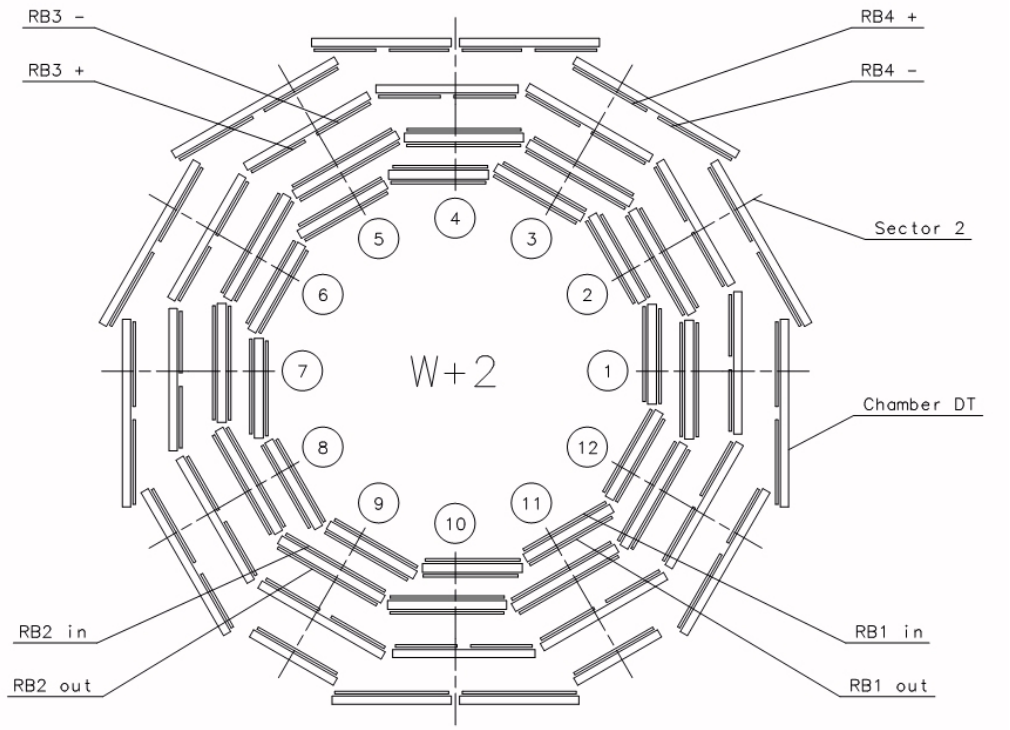

Figure 1. Transverse view of the muon system layout in the barrel region, showing the positions of the DT and RPC stations.

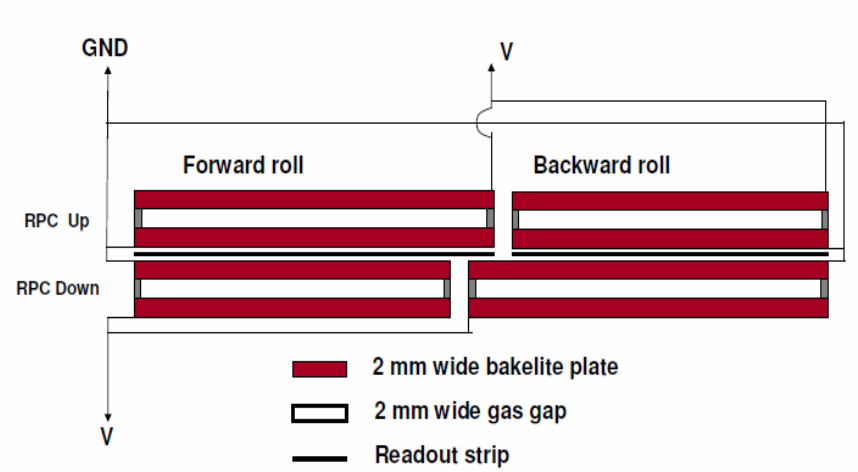

Figure 2. Schematic layout of a RPC station composed of two rolls.

SF_6. Water vapour is added to obtain a mixture with a relative humidity of 40–50%, in order to maintain a constant bakelite resistivity and, thus, avoid a degradation of RPC performance under high background conditions. The large volume of the total RPC system (18 m^3) and the use of a rather expensive gas mixture impose the use of a gas recirculation system. This system consists of

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Table 1. Strip pitch and average cluster size, counted as the number of strips, for pointing track segments, with operating voltage of 9.2 kV.

RPC layer	strip pitch (cm)	average cluster size
$RB1_{in}$	2.3	1.52
$RB1_{out}$	2.5	1.46
$RB2_{in}$	2.8	1.41
$RB2_{out}$	3.0	1.38
RB3	3.5	1.31
RB4	4.1	1.25

the following modules: the primary supply, the mixer, the humidifier, the closed-loop circulators, the gas distributors to the chambers, the purifiers, and the pump. The purifier system is made of a set of filters designed to remove contaminants from the gas mixture. The system operates with a fraction of fresh gas mixture in the range from 10% to 2%. This is the first time that such a large RPC system is operated with a closed loop gas system.

3 Detector operation and monitoring

The effective working voltage, V_{eff}, relevant for the charge avalanche production inside the RPC, depends on environmental parameters such as gas temperature (T) and pressure (P), according to eq. (3.1) [8]

$$V_{\text{eff}} = V \times \frac{P_0}{P} \times \frac{T}{T_0} \quad , \tag{3.1}$$

where V_{eff} is the effective voltage, V is the applied power voltage, and $P_0 = 1010$ mbar and $T_0 = 293$ K are the reference pressure and temperature, respectively. Only the effective voltage is relevant when comparing detector performance in different sites and run conditions.

The CMS RPCs have been extensively tested at the production sites and their physics performance was studied [3, 5]. During 2006, a small fraction of the RPC system was calibrated and operated [9]. In both cases, it was found that 95% of the maximum plateau efficiency is reached at an effective voltage of 9.6 kV, corresponding to an average applied voltage of 9.2 kV for the pressure conditions in the CMS cavern.

For the CRAFT 2008 exercise, the operating voltage was set to 9.2 kV and the electronic thresholds of the readout system were set to 230 mV, corresponding to an induced charge of 180 fC. These operating conditions are conservative and do not permit the detector to reach its maximum efficiency. This approach was chosen to maintain low noise levels and safe operating conditions, since this was the first time that the full system was operated. Following extensive past studies [10], the working conditions were maintained within strict ranges: temperature lower than 24 °C, humidity in the range 40–50% and fraction of O_2 below 300 ppm.

These parameters were monitored and controlled by the Detector Control System (DCS) [11]. Their values were stored in a database and used, offline, to study the system stability.

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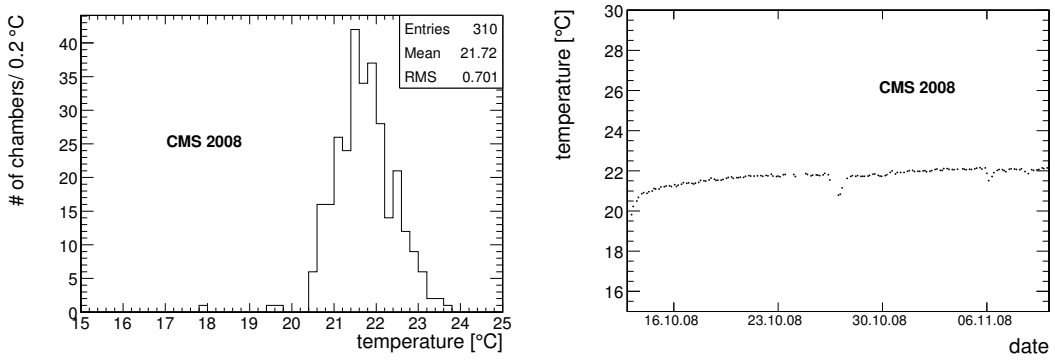

Figure 3. RPC temperature, as measured by the probes installed inside the stations. Left side: distribution of RPC temperature taken at the end of the CRAFT period and averaged over one full day of data taking. Right side: Average RPC temperature as a function of time. Each point represents the temperature averaged over 4 hours and over all barrel stations. The increase and the variations of the temperature are triggered by the start of the CMS electronics.

3.1 Temperature

Out of the 480 RPC stations, 310 are equipped with a temperature probe installed inside the mechanical frame. Figure 3 shows in the left plot the temperature distribution of those barrel stations at the end of the CRAFT period (averaged over one day) and on the right plot its average vs. time. The system temperature was maintained below 24 °C during the full CRAFT period, in order to guarantee proper RPC operation. Clear variations are observed when the electronics of CMS is switched on or off. The steep increase seen at the start of the CRAFT exercise, when all the detectors were fully operating, is a consequence of the non optimized cooling of the system. A special effort was dedicated to increase the cooling circuit capability after the end of the CRAFT exercise. The temperature of the input cooling water has been reduced by one degree in order to guarantee a constant stable temperature lower than 24 °C, as confirmed in 2009, during long cosmic rays data taking periods.

3.2 Currents

The currents drawn by the RPCs, I, are strongly affected by variations of the environmental conditions. A sudden current increase could also indicate a malfunctioning of the detector. Therefore, a careful and continuous monitoring of the currents is performed. Each RPC station is powered by a separate high voltage supply. The current drawn in each RPC station is read out and stored through the DCS. Figure 4 shows in the left plot the I distribution at an operating voltage of 9.2 kV, for the 480 barrel stations, at the end of the CRAFT period. Only for 11 stations the value of I is larger than 3 μA. During the CRAFT exercise, ten units out of 2040 were disconnected because of problems with the high voltage connections, leaving the corresponding rolls working in single gap mode. Figure 4 right plot shows that the average current drawn by the stations was around 1 μA and stable in time. No correlation is observed between the mean current values and the temperature variations, in the operating range.

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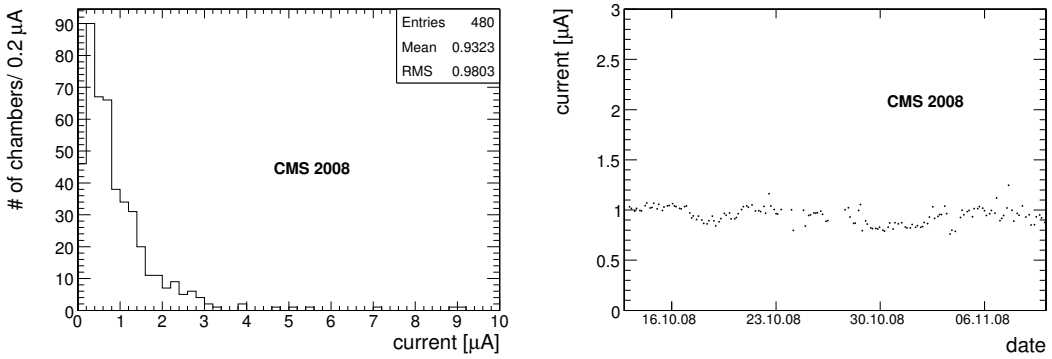

Figure 4. Distribution of the current drawn by the RPCs. Left plot shows the average over one full day of data taking at the end of the CRAFT period. The plot has no overflow. Right plot: average current as a function of time. Each point is the average current over 4 hours and over all barrel stations. The operating voltage is 9.2 kV.

3.3 Counting rates

The RPC noise rate is carefully monitored, since abnormal values in some parts of the detector can result in high fake muon trigger rates. At the beginning of each run, dedicated calibration data were taken and analysed to identify and mask noisy readout channels with rates above 100 Hz/cm^2. This value was chosen because it corresponds to the limit that the trigger system can sustain. The total number of masked and dead channels was stable during the CRAFT period, at about 1% of the total number of channels in both cases.

The average noise per second and per cm^2 is computed for each roll by adding the contributions from all non-masked channels. The distribution of the number of rolls as a function of the average noise is shown in figure 5, for one specific run. Only 3% of the rolls have an average noise rate greater than 1 Hz/cm^2.

Although the average noise rate is very low, a problem related to events with correlated noise on several layers has been detected few times per day affecting about 10^{-3} of the total data taking time during the CRAFT exercise. A special effort has been made to understand the sensitivity of the RPCs to external noise sources. The detector grounding has been improved where possible, and further studies are in progress. Preliminary analyses have demonstrated that the fake trigger rate is reduced by two orders of magnitude when the LHC trigger algorithm is used instead of the dedicated cosmic ray trigger employed during the CRAFT exercise. The LHC trigger algorithm requires more stringent constraints on the incoming muon direction and is less sensitive to the detector noise.

3.4 Gas monitoring

The mixture composition and its quality are monitored by two independent devices. The Gas Quality Monitor [12, 13] performs chemical analyses (mainly gas chromatography, pH and fluoride monitoring). The Gas Gain Monitor [14], is based on the monitoring of the performance of three sets of 50 $\times$ 50 cm^2 single gap RPCs, each supplied with a different gas mixture (fresh gas, and gas from the recirculating system, before and after the purifiers).

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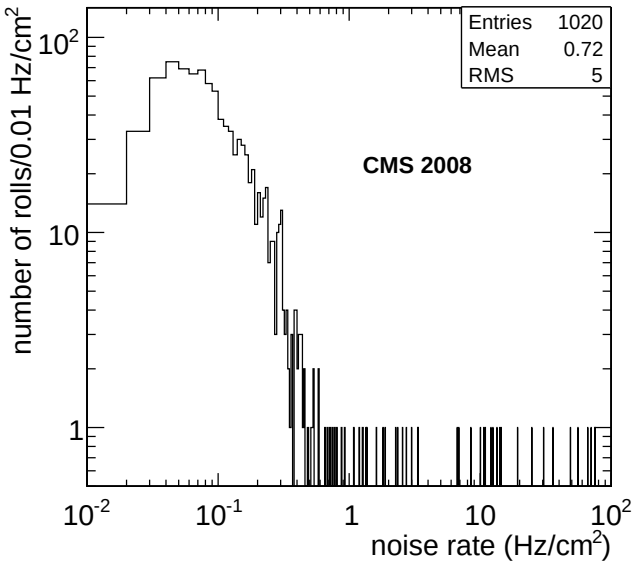

Figure 5. Example distribution of the number of rolls as a function of the average noise in the roll, for a given data taking run. Channels exceeding 100 Hz/cm^2 are masked and do not contribute to the average noise. The operating voltage is 9.2 kV.

During the CRAFT exercise, the gas system was operated continuously with a fraction of 8% of fresh mix. The lifetime of the purifiers before regeneration was about 36 hours between regenerations of first stage purifier, to remove water from gas mixture humidity, and one week between regenerations of second stage purifier, to remove air contamination. The full system was running smoothly during the operation. The downtime due to gas system stops was less than 1%.

4 Synchronization of RPC data

Muon signals detected by the RPC chambers and transmitted by the readout electronics must arrive in dedicated electronic boards at a specified time, in order to correctly contribute to the trigger decisions. In addition, RPC data sent to the CMS Data Acquisition system (DAQ) and RPC trigger information must be associated to the right LHC bunch crossing (BX: 25 ns time interval).

The different steps of data transmission in the RPC system are described in detail in ref. [15]. After pulse discrimination in the front end boards, the data are transmitted asynchronously to the Link Boards situated on the CMS detector, where zero-suppression is performed. The data are then sent through optical fibres to the CMS counting room, in the underground cavern, where RPC muon trigger objects are identified, as part of the CMS Level-1 trigger system, and sent to the Global Muon Trigger. In parallel, the data are sent to the CMS DAQ system. To ensure integration with CMS, the RPC readout and trigger systems work in synchronous mode using the CMS Timing, Trigger and Control (TTC) system [16].

The TTC signals (including clock and reference bunch crossing identification) are distributed to the Link Boards, where the signals from the detector are synchronized with the LHC clock. The data are assigned to the proper bunch crossing according to a time window determined by the length

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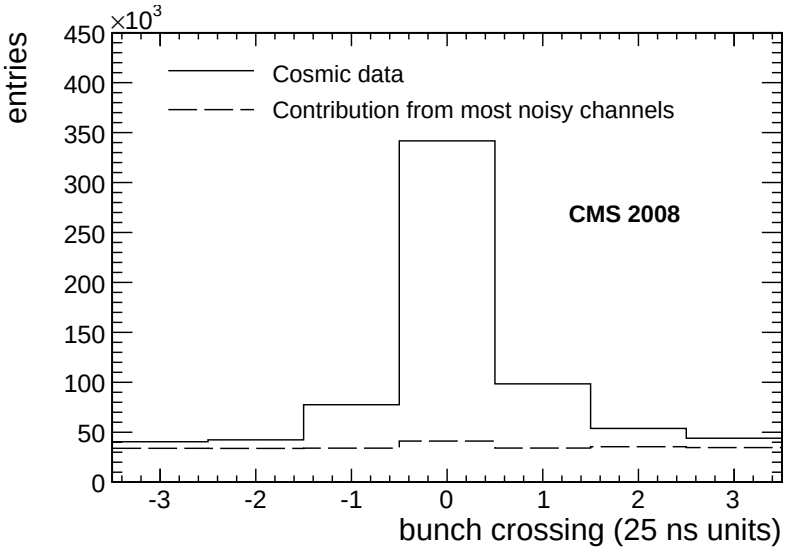

Figure 6. Typical time distribution (in bunch crossing units of 25 ns) of the data coming from individual RPCs with respect to the RPC global trigger time. The dashed line shows the background caused by the 10 over 1020 Link Boards connected to the most noisy channels.

of the TTC fibres, the muon time of flight, and the signal propagation and transmission times along the strips, cables and electronics.

The RPC readout [17] is designed to send data from up to 8 consecutive bunch crossings (BXs) to the DAQ system: the trigger BX plus 3 pre- and 4 post-trigger BXs. During the CRAFT exercise, only 7 BXs were transmitted to the DAQ ($\pm$3 BXs around the triggered event).

The timing setups of the system are different for the LHC beam mode and for the cosmic ray runs. In beam mode the synchronization is driven by beam collisions, which are fixed in phase with respect to the LHC clock, while in the cosmic mode this phase is arbitrary: cosmic rays arrive randomly with respect to the LHC clock. The synchronizations of the upper and lower parts of the detector differ significantly in the two modes, due to the asymmetric phi distribution of the cosmic rays.

In order to optimize the data synchronization, initial delays were estimated, based on the length of cables and fibres. The bottom-central part of the detector was chosen as a reference, and delays of data from other parts of the detector were fine-tuned to optimize the data alignment in time. The same timing was kept for the full CRAFT period. As an illustration of the RPC synchronization during the CRAFT exercise, figure 6 presents a typical example of the time distribution of the data coming from individual RPCs. The time is counted with respect to the bunch crossing assigned by the RPC Level-1 global trigger logic, based on the coincidence of at least 3 chambers along a muon trajectory. The peak in the central bin corresponds to data which are synchronous with the RPC Level-1 trigger. The spread to the two neighbouring bins is caused mainly by the arbitrary choice of the synchronization phase, relevant only for cosmic ray runs. The spread over the other bins is due to the non-perfect synchronization of contributing triggers, and to a background caused by Link Boards connected to the most noisy electronic channels.

In view of the good quality of the present data, much better synchronization is expected for LHC runs.

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5 Detector performance

The performance of the RPC system has been studied by making use of the local DT hit reconstruction [6]. The three innermost DT layers are able to locally reconstruct three dimensional muon track segments with up to eight hits in the $r\phi$ plane and up to four hits in the rz plane. The outermost DT layer provides a segment in the $r\phi$ plane.

The extrapolation of a DT track segment onto an RPC plane allows the study of the local RPC performance, by searching for RPC channels over threshold in a small region around the impact point. Previous studies [9] have shown that a range of $\pm$ 2 strips between the extrapolated impact point and the closest firing strip is adequate.

In addition, the CRAFT exercise led to the identification of 15 swapped readout cables out of a total of 4720, and a few cases of RPC to DT misalignments at the level of more than 1 cm.

In the following sub-sections the results on cluster size, position resolution and detection efficiency are reported for the whole barrel system. The RPC cluster size and the position resolution are studied separately for layers with different strip pitches. No special selection is applied to the DT track segments used for the extrapolation, except for the requirement that no other segment is reconstructed in the DT station. This condition is imposed to reject multiple muon events and other possible ambiguous topologies. Moreover, only pointing segments in the $r\phi$ plane have been used in these analyses. A pointing track segment in the $r\phi$ plane is defined as a segment within an angle of $\pm$ 20 degrees around the normal to the RPC layer, in the plane perpendicular to the strip direction. All the figures have been produced by analysing a run of about 2 million events, representative of the full CRAFT period.

5.1 Cluster size

A cluster is defined as a consecutive set of strips, each of them collecting an induced charge above the discrimination threshold of 180 fC. The number of strips in the cluster is called the cluster size.

The cluster size depends on the RPC strip pitch, on the impact point position with respect to the strip, and on the track crossing angle. Figure 7 shows the cluster size distribution for the $\mathrm{RB1}_{\mathrm{in}}$ layers, for pointing muons. The different strip pitches and the average cluster sizes are given for all layers in table 1. The fractions of events having cluster sizes corresponding to 1, 2, 3 or more than 3 strips are shown for different layers in figure 8.

The number of firing strips for a crossing muon is a function of the local impact point position with respect to the RPC strip. The distribution in figure 9 shows the deviation, Δ, measured in strip pitch units, between the impact point and the cluster centre for the $\mathrm{RB1}_{\mathrm{in}}$ layer, in a local reference frame. In this local frame the fired strip is between 0 and 1 for events with cluster size of 1, the two fired strips are between -1 and 1 for events with cluster size of 2, and the three fired strips are between -1 and 2 for events with cluster size of 3. The three distributions, normalized to the same area, are overlayed. Events with cluster size of 1 are more frequent for tracks crossing the RPC layer close to the middle of a strip, while the fraction of events with a cluster size of 2 increases for muons close to the edge between two adjacent strips.

In addition, the cluster size depends on the muon incident angle with respect to the RPC surface, in the plane orthogonal to the strip direction. This is visible in figure 10, which presents the dependence of the average cluster size on the absolute value of the tangent of the angle α, defined as

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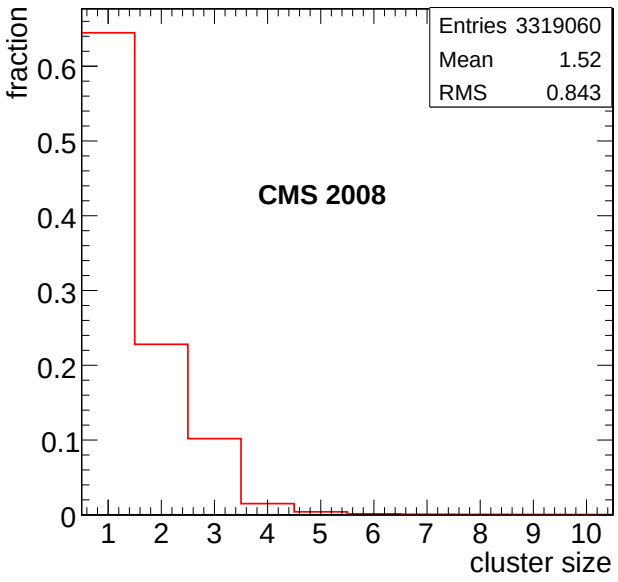

Figure 7. Normalized distribution of the cluster size for the $RB1_{in}$ layer, for pointing track segments.

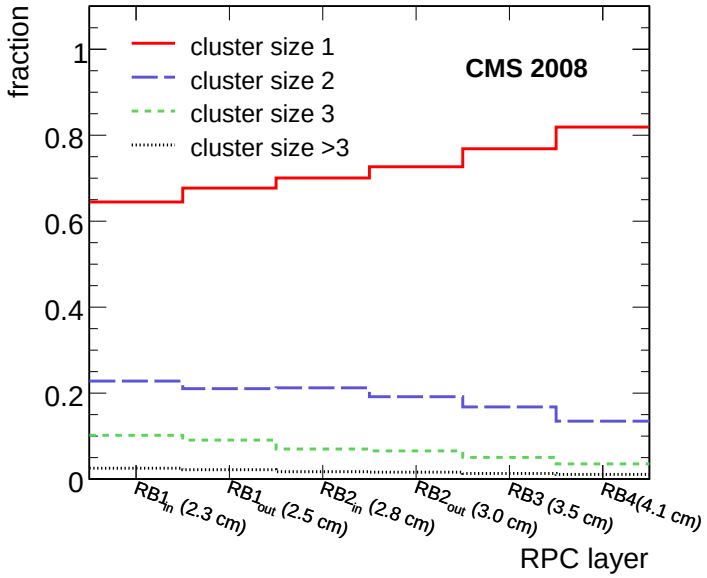

Figure 8. Relative population of reconstructed clusters with size equal to 1, 2, 3 and more than 3 strips, for each RPC layer.

the angle between the muon direction and the normal to the RPC surface in the plane perpendicular to the strip direction, for the $RB1_{in}$ layer. This dependence is due both to the increased path length in the crossed gas gap and to the RPC double gap structure where two independent avalanches develop in the two gas gaps, 6 mm apart, which may induce signals on different strips, increasing the cluster size.

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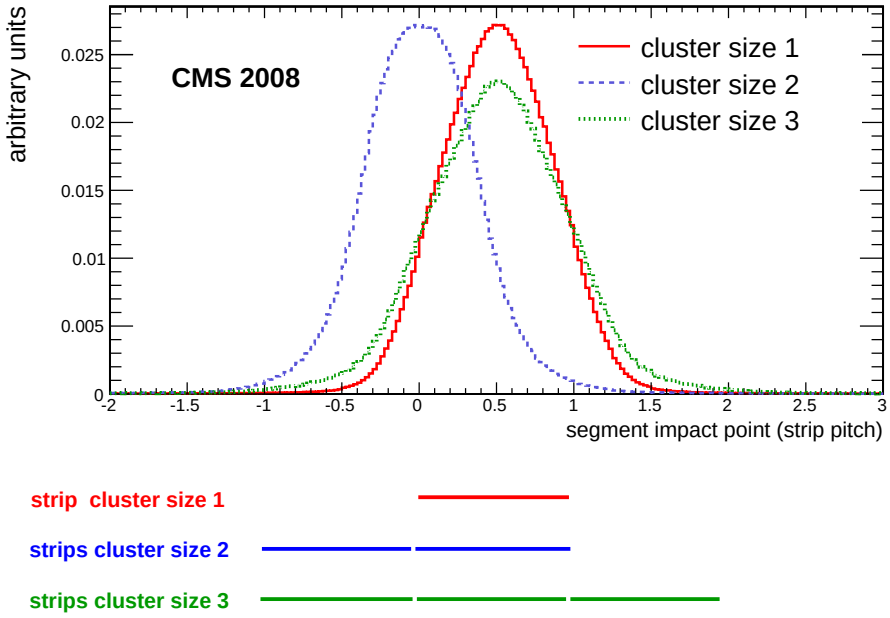

Figure 9. Distribution of the track impact point for the $RB1_{in}$ layer in a local reference frame, for events with cluster size of 1, 2 and 3, in units of strip pitch. The local frame, described by the drawing under the plot, is defined in such a way that the fired strip is between 0 and 1 for events with cluster size of 1, the two fired strips are between -1 and 1 for events with cluster size of 2, and the three fired strips are between -1 and 2 for events with cluster size of 3. The three distributions are normalized to the same unit area.

It should be noted that, because of the bending of muon trajectories due to the magnetic field, low momentum muons coming from the interaction point, during LHC runs, may cross the RPC detectors with relatively large angles. Cosmic muons are very useful to study these topologies since they cross the detector at all possible angles, depending on the sector.

5.2 Position resolution

The centre of a cluster provides a measurement of the position of the muon track crossing point, in the $r\phi$ plane. In order to study the RPC position resolution, the cluster centre is compared to the extrapolated point of the DT segment onto the RPC layer. The distribution of the off-set between the position of the track crossing point onto the surface separating the two gaps and the cluster centre, named residual, is computed for every roll, providing an estimate of the relative DT and RPC alignment.

Figure 11 presents the distribution of the mean value of the residuals for all barrel rolls. The relative alignment is of a few millimetres, but two cases of a few centimetres have also been observed (not visible on the plot scale). The mean values extracted from the residual distributions have been used to correct the data offline, in order to improve the position resolution.

Figure 12 shows the residual distribution in cm for the $RB1_{in}$ layer, after having applied the alignment corrections, for events with cluster size lower than four.

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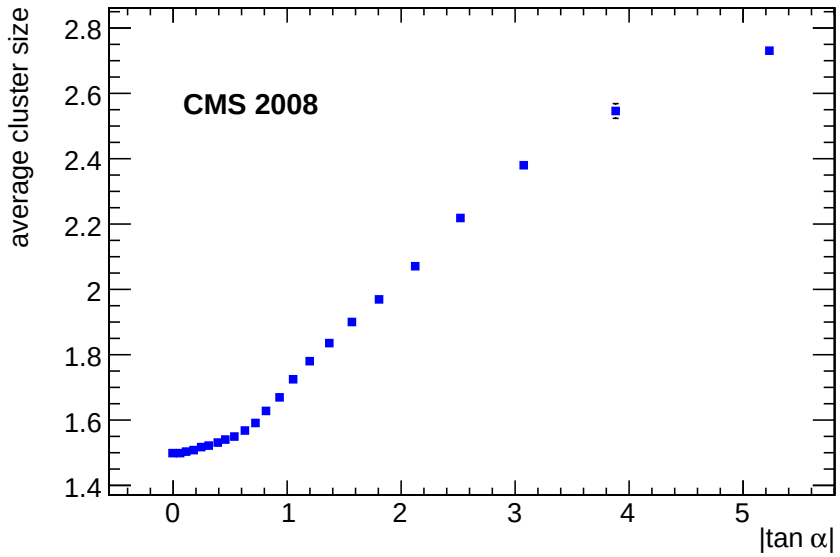

Figure 10. Average cluster size as a function of the absolute value of the tangent of the angle α, defined as the angle between the track direction and the normal to the RPC surface in the plane perpendicular to the strip direction, for the $RB1_{in}$ layer and with an operating voltage of 9.2 kV.

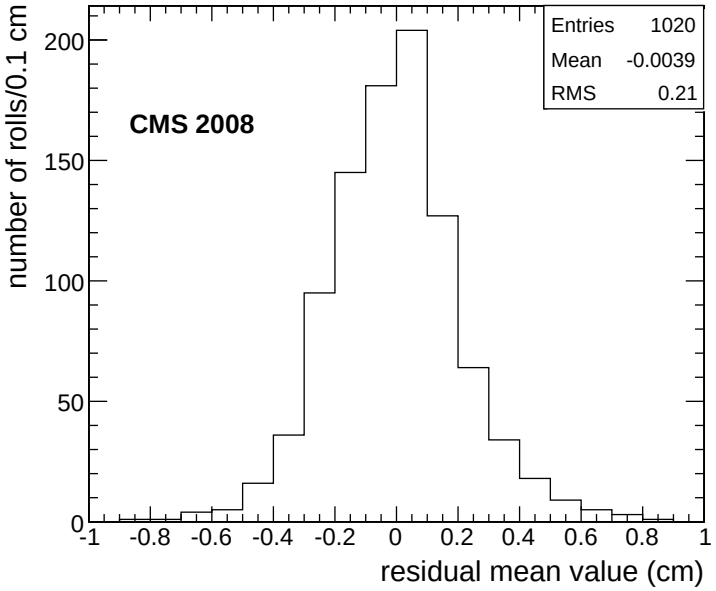

Figure 11. Normalized distribution of the mean value of the residuals in cm, for all the RPC rolls. Two entries are out of the range.

The analysis of the RPC residuals has been performed for all layers, corresponding to different strip pitches as reported in table 1, and for events with different cluster sizes. The RMS values of the residual distribution are presented in figure 13, as a function of the layer, for different cluster sizes. The trend reflects the variation of the strip pitch and the geometry of the different RPC layers.

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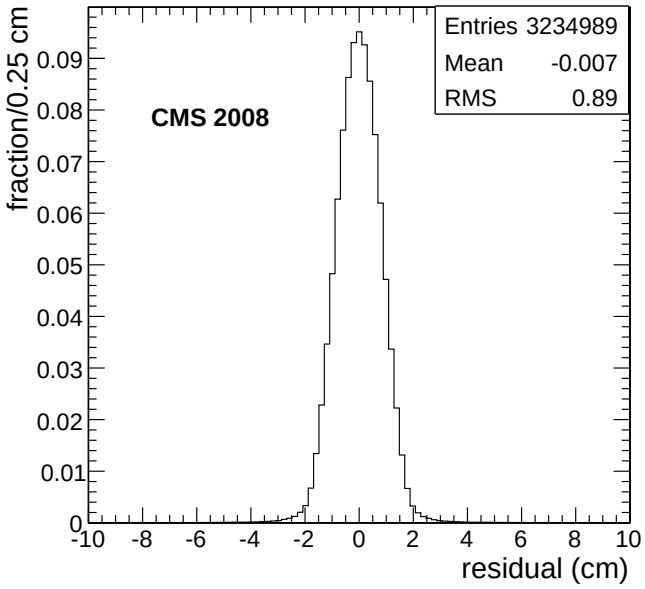

Figure 12. Normalized distribution of the residuals in cm, for the $RB1_{in}$ layer (events with cluster size larger than three are not included).

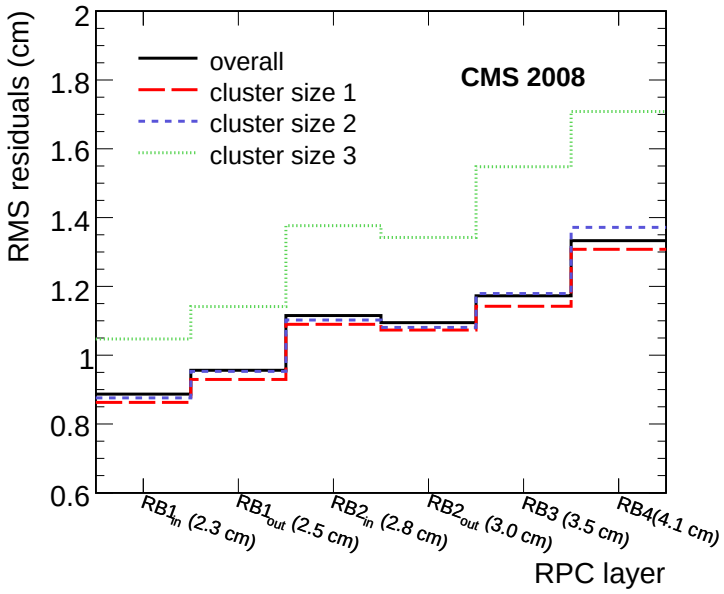

Figure 13. RMS of the distributions of the residuals, for the different layers (corresponding to different strip pitches) and for different cluster sizes.

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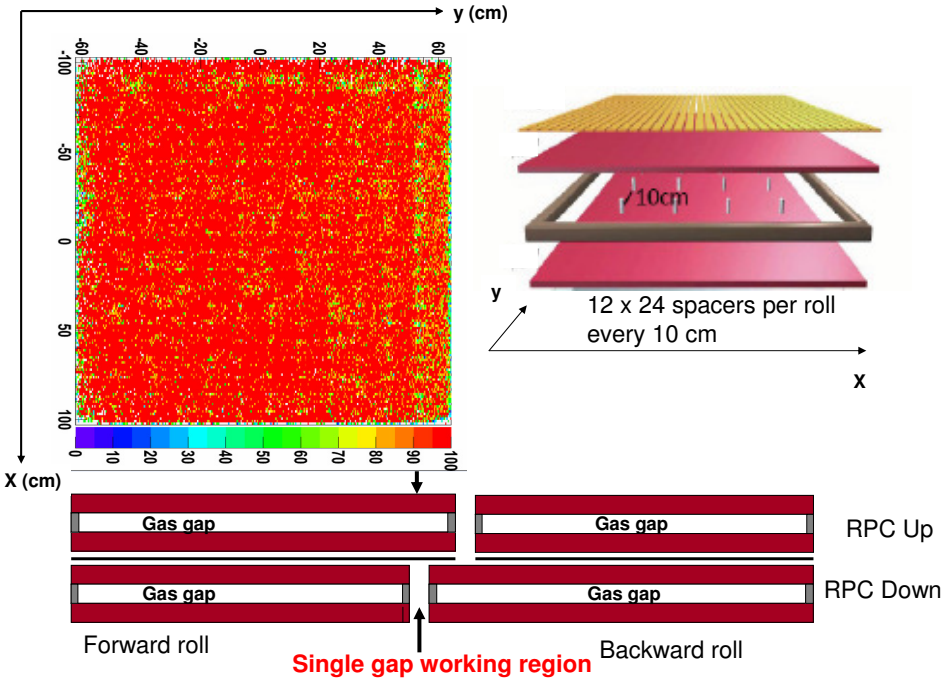

Figure 14. Efficiency of an $RB1_{in}$ roll as a function of the x and y coordinates (as defined in the figure) of the extrapolated track impact point. The lower efficiency spots are due to the dead regions induced by spacers on a 10×10 cm^2 grid. An efficiency reduction is also visible for the y coordinate at about 55 cm, where only a single gap is present.

5.3 Detection efficiency

The most important parameter defining the RPC performance is the detection efficiency. The DT segment extrapolation, presented at the beginning of section 5, is used to estimate the RPC efficiency, for a full roll.

For each DT track segment extrapolated onto the RPC surface, a roll is considered efficient if at least one RPC strip is over threshold within $\pm$ 2 strips from the extrapolated impact point. Figure 14 shows the efficiency vs. the local impact point on the RPC surface. The pattern due to the spacers placed on a 10×10 cm^2 grid is clearly visible. Moreover, a reduction of the overall efficiency is visible in the y coordinate (as defined in the figure) at about 55 cm, where only one gap is present.

The roll efficiency distribution is shown in figure 15 for a typical run, taken at the operating voltage of 9.2 kV. The peak of the distribution is about 90 %, while the tail at lower efficiency values is due to now known swapped cables, chambers working in single gap mode and chambers with synchronization problems.

After the end of the CRAFT exercise many improvements have been obtained and the operating conditions have been optimized. In 2009 the efficiency distribution was around 95% at 9.4 kV.

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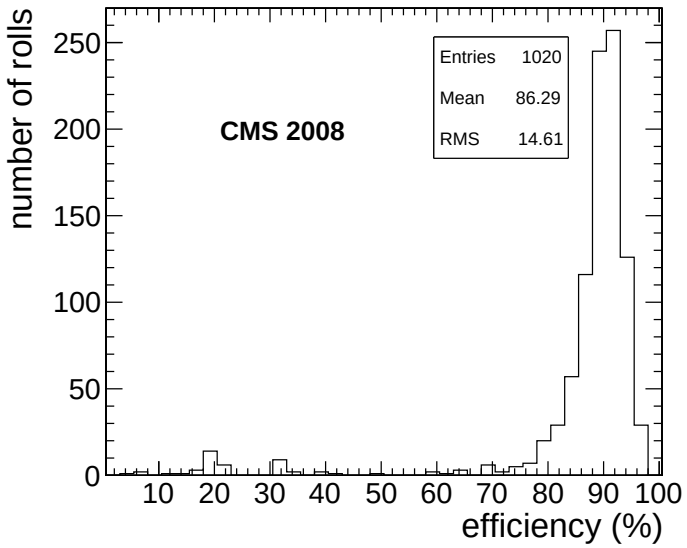

Figure 15. Efficiency distribution for barrel rolls, at an operating voltage of 9.2 kV. The tail at lower efficiency values is due to now known swapped cables, chambers working in single gap mode and chambers with synchronization problems.

6 Conclusions

Data collected during the CRAFT 2008 period have been very useful for detector commissioning. About 98 % of the electronic channels were operational during the exercise. Hardware problems such as swapped cables and electronic failures have been identified and fixed. The relative position of each RPC station with respect to the DT chambers has been measured in the $r\phi$ direction, and the position resolution of the RPC system has been determined. Software tools to monitor the system performance have been developed and tuned during the running period. The performance of the barrel system has been measured from data. The results show a good stability of the detector and an efficiency around 90 % at the operating voltage of 9.2 kV. Many improvements have been made after the CRAFT 2008 exercise. The temperature of the input cooling water has been reduced by one degree. Hardware failures have been fixed, the working voltage and the electronic threshold have been optimized, and the synchronization of the RPC barrel signals has been improved. Although more systematic studies are still in progress, the RPC barrel system is ready for LHC beam collisions.

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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

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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

2010 JINST 5 T03017

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

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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]

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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

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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

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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

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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]

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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

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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

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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

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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

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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

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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

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