



Search for dark matter and large extra dimensions in monojet events in pp collisions at $\sqrt{s} = 7$ TeV

The CMS Collaboration*

Abstract

A search has been made for events containing an energetic jet and an imbalance in transverse momentum using a data sample of pp collisions at a center-of-mass energy of 7 TeV. This signature is common to both dark matter and extra dimensions models. The data were collected by the CMS detector at the LHC and correspond to an integrated luminosity of 5.0 fb^{-1} . The number of observed events is consistent with the standard model expectation. Constraints on the dark matter-nucleon scattering cross sections are determined for both spin-independent and spin-dependent interaction models. For the spin-independent model, these are the most constraining limits for a dark matter particle with mass below $3.5 \text{ GeV}/c^2$, a region unexplored by direct detection experiments. For the spin-dependent model, these are the most stringent constraints over the $0.1\text{--}200 \text{ GeV}/c^2$ mass range. The constraints on the Arkani-Hamed, Dimopoulos, and Dvali model parameter M_D determined as a function of the number of extra dimensions are also an improvement over the previous results.

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1 Introduction

A search for new physics has been made based on events containing a jet and an imbalance in transverse momentum (E_T^{miss}) in a data sample corresponding to an integrated luminosity of 5.0 fb^{-1} . The data were collected with the Compact Muon Solenoid (CMS) detector in pp collisions provided by the Large Hadron Collider (LHC) at a center-of-mass energy of 7 TeV. This search is sensitive to beyond the standard model particles that do not interact in the CMS detector and whose presence can thus only be inferred by the observation of E_T^{miss} . The signature has been proposed as a discovery signal for many new physics scenarios. In this paper, we use this signature to constrain the pair production of dark matter particles [1, 2] and large extra dimensions in the framework of the model proposed by Arkani-Hamed, Dimopoulos, and Dvali (ADD) [3–7]. The primary backgrounds to this signature arise from the production of Z+jet and W+jet events.

Dark matter (DM) is required to accommodate numerous astrophysical measurements, such as the rotational speed of galaxies and gravitational lensing [8–10]. One of the best candidates for dark matter is a stable weakly interacting massive particle. These particles may be pair-produced at the LHC provided their mass is less than half the parton center-of-mass energy, $\sqrt{\hat{s}}$. When accompanied by a jet from initial state radiation (ISR), DM events will have the signature of a jet plus missing transverse momentum. The interaction between the dark matter particle (χ) and standard model (SM) particles can be assumed to be mediated by a heavy particle such that it can be treated as a contact interaction, characterized by a scale $\Lambda = M/\sqrt{g_\chi g_q}$ where M is the mass of the mediator, g_χ and g_q are its coupling to χ and to quarks, respectively [2]. In this paper, results for the vector and axial-vector interactions between χ and quarks are presented, assuming χ is a Dirac fermion. The vector interaction can be related to spin-independent DM-nucleon whereas axial-vector interaction can be converted to spin-dependent DM-nucleon interactions. The results are not greatly altered if the DM particle is a Majorana fermion, although the vector interactions are not present in this case [2].

Results from previous collider searches in the monojet plus E_T^{miss} channel [11, 12] have been used to set limits on the dark matter-nucleon scattering cross section ($\sigma_{\chi N}$) [2, 13]. Limits on $\sigma_{\chi N}$ have also been determined by the CMS Collaboration in the monophoton plus E_T^{miss} channel [14], and by the CDF Collaboration in the monojet channel [15]. Dark matter particle production results from colliders can be compared with results from searches for dark matter-nucleon scattering (direct detection) [16–22] and from searches for dark matter annihilation (indirect detection) [23, 24]. Indirect detection experiments assume that the DM particle is a Majorana fermion.

The ADD model accommodates the large difference between the electroweak and Planck scales by introducing a number δ of extra spatial dimensions, which in the simplest scenario are compactified over a multidimensional torus of common radius R . In this framework, the SM particles and gauge interactions are confined to the ordinary $3 + 1$ space-time dimensions, whereas gravity is free to propagate through the entire multidimensional space. The strength of the gravitational force in $3 + 1$ dimensions is effectively diluted. The fundamental scale M_D of this $4 + \delta$ -dimensional theory is related to the apparent four-dimensional Planck scale M_{Pl} according to $M_{\text{Pl}}^2 \approx M_D^{\delta+2} R^\delta$. The production of gravitons is expected to be greatly enhanced by the increased phase space available in the extra dimensions. Once produced, the graviton escapes undetected into extra dimensions and its presence must be inferred from E_T^{miss} . Searches for large extra dimensions in monojet or monophoton channels were performed previously [11, 12, 25–31], and no evidence of new physics was observed. The current lower limits on M_D range from $3.67 \text{ TeV}/c^2$ for $\delta = 2$ to $2.25 \text{ TeV}/c^2$ for $\delta = 6$ [11].

This paper is organized as follows. Section 2 contains a brief description of the CMS detector and event reconstruction, and this is followed by a description of signal and SM event simulation in Section 3. In Section 4 we present the event selection. The determination of dominant backgrounds from data is described in Section 5 and the results are given in Section 6. The conclusions are summarized in Section 7.

2 The CMS detector and event reconstruction

CMS uses a right-handed coordinate system in which the z axis points in the anticlockwise beam direction, the x axis points towards the center of the LHC ring, and the y axis points up, perpendicular to the plane of the LHC ring. The azimuthal angle ϕ is measured in the x - y plane, and the polar angle θ is measured with respect to the z axis. A particle with energy E and momentum \vec{p} is characterized by transverse momentum $p_T = |\vec{p}| \sin \theta$, and pseudorapidity $\eta = -\ln[\tan(\theta/2)]$.

The CMS superconducting solenoid, 12.5 m long with an internal diameter of 6 m, provides a uniform magnetic field of 3.8 T. The inner tracking system is composed of a pixel detector with three barrel layers at radii between 4.4 and 10.2 cm and a silicon strip tracker with 10 barrel detection layers extending outwards to a radius of 1.1 m. This system is complemented by two endcaps, extending the acceptance up to $|\eta| = 2.5$. The momentum resolution for reconstructed tracks in the central region is about 1% at $p_T = 100$ GeV/ c . The calorimeters inside the magnet coil consist of a lead tungstate crystal electromagnetic calorimeter (ECAL) and a brass-scintillator hadron calorimeter (HCAL) with coverage up to $|\eta| = 3$. The quartz/steel forward hadron calorimeters extend the calorimetry coverage up to $|\eta| = 5$. The HCAL has an energy resolution of about 10% at 100 GeV for charged pions. Muons are measured up to $|\eta| < 2.4$ in gas-ionization detectors embedded in the flux-return yoke of the magnet. A full description of the CMS detector can be found in Ref. [32].

Particles in an event are individually identified using a particle-flow reconstruction [33]. This algorithm reconstructs each particle produced in a collision by combining information from the tracker, the calorimeters, and the muon system, and identifies them as either charged hadrons, neutral hadrons, photons, muons, or electrons. These particles are used as inputs to the anti- k_T algorithm [34] with a distance parameter of 0.5. Jet energies are corrected to particle level with p_T - and η -dependent correction factors. These corrections are derived from Monte Carlo (MC) simulation and, for data events, are supplemented by a correction, derived by measuring the p_T balance in dijet events from collision data [35]. The E_T^{miss} in this analysis is defined as the magnitude of the vector sum of the transverse momentum of all particles reconstructed in the event excluding muons. This definition allows the use of a control sample of $Z(\mu\mu)$ events for estimating the $Z(\nu\bar{\nu})$ background.

Muons are reconstructed by finding compatible track segments in the silicon tracker and the muon detectors [36] and are required to be within $|\eta| < 2.1$. Electron candidates are reconstructed starting from a cluster of energy deposits in the ECAL that is then matched to the energy associated with a track in the silicon tracker. Electron candidates are required to have $|\eta| < 1.44$ or $1.56 < |\eta| < 2.5$ to avoid poorly instrumented regions. Muon and electron candidates are required to originate within 2 mm of the beam axis in the transverse plane. Muons (electrons) are also required to be spatially separated from jets by at least $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.3$, where $\Delta\eta$ and $\Delta\phi$ are differences between the muon (electron) and jet directions in pseudorapidity and azimuthal angle, respectively. A relative isolation parameter is defined as the sum of the p_T of the charged hadrons, neutral hadrons, and photon contributions computed in a cone of radius 0.3 around the lepton direction, divided by the lepton p_T . Lepton candidates

with relative isolation values below 0.2 are considered isolated.

3 Monte Carlo event generation

The DM signal samples, consisting of $\chi\bar{\chi}$ pairs associated with one parton, are produced using the leading order (LO) matrix element event generator MADGRAPH [37] interfaced with PYTHIA 6.42 [38] with tune Z2 [39] for parton showering and hadronization. Dark matter particles masses $M_\chi = 0.1, 1, 10, 200, 300, 400, 700,$ and $1000 \text{ GeV}/c^2$ are generated for both vector and axial-vector interactions. In addition, the p_T of the associated parton is required to be greater than $80 \text{ GeV}/c$. The parton showering program generates partons in a phase space that overlaps with the phase space of the partons generated by the matrix element calculator. Double-counting by the matrix element calculation and parton showering is resolved by using the MLM matching prescription [40], as implemented in [37]. The CTEQ 6L1 [41] parton distribution functions (PDF) are used.

The events for the ADD model are generated with PYTHIA 8.130 [42, 43], using tune 4C [44] and the CTEQ 6.6M [41] PDFs. This model is an effective theory and holds only for energies well below M_D . For a parton center-of-mass energy $\sqrt{\hat{s}} > M_D$, the simulated cross sections of the graviton are suppressed by a factor M_D^4/\hat{s}^2 [43]. Because the $\sqrt{\hat{s}}$ values for the data are smaller than the current limits on M_D , the results are not affected by this suppression. The next-to-leading-order (NLO) QCD corrections to direct graviton production in the ADD model are sizable and depend on the p_T of the recoiling parton [45]. As a simplifying assumption, we use K -factors ($\sigma_{\text{NLO}}/\sigma_{\text{LO}}$) corresponding to a fixed graviton p_T of several hundred GeV/c ; the values are 1.5 for $\delta = 2, 3$ and 1.4 for $\delta = 4, 5,$ and 6 .

The Z+jets, W+jets, $t\bar{t}$, and single-top event samples are produced using MADGRAPH interfaced with PYTHIA 6.42, using tune Z2 and the CTEQ 6L1 PDFs. They are normalized to NLO cross sections [46]. The QCD multijet sample is generated with PYTHIA 6.42, using tune Z2 and CTEQ 6L1 PDFs and PYTHIA LO cross sections are used. All the generated signal and background events are passed through a GEANT4 [47] simulation of the CMS detector.

4 Event selection

The data used in this analysis were recorded by a trigger that required an event to have a jet with $p_T > 80 \text{ GeV}/c$ and $E_T^{\text{miss}} > 80$ or $95 \text{ GeV}/c$ as measured online by the trigger system. The threshold of 80 (95) GeV/c was used to collect 4.2 (0.87) fb^{-1} of data.

Events are required to have at least one primary vertex [48] reconstructed within a $\pm 24 \text{ cm}$ window along the beam axis around the detector center, and a transverse distance from the beam axis of less than 2 cm . Signals in the calorimeter that are not associated with pp interactions are identified based either on energy sharing between neighboring channels or timing requirements and are excluded from further reconstruction [49].

To suppress the remaining instrumental and beam-related backgrounds, events are rejected if less than 20% of the energy of the highest p_T jet is carried by charged hadrons or more than 70% of this energy is carried by either neutral hadrons or photons. Events are also rejected if more than 70% of the p_T of the second highest p_T jet is carried by neutral hadrons. Such spurious jets primarily arise from instrumental noise, where the energy deposition is limited to one sub-detector. Jets resulting from energy deposition by beam halo or cosmic-ray muons do not have associated tracks and are also rejected by these selections. All events passing these selection requirements and with $E_T^{\text{miss}} > 500 \text{ GeV}/c$ were visually inspected and found to be

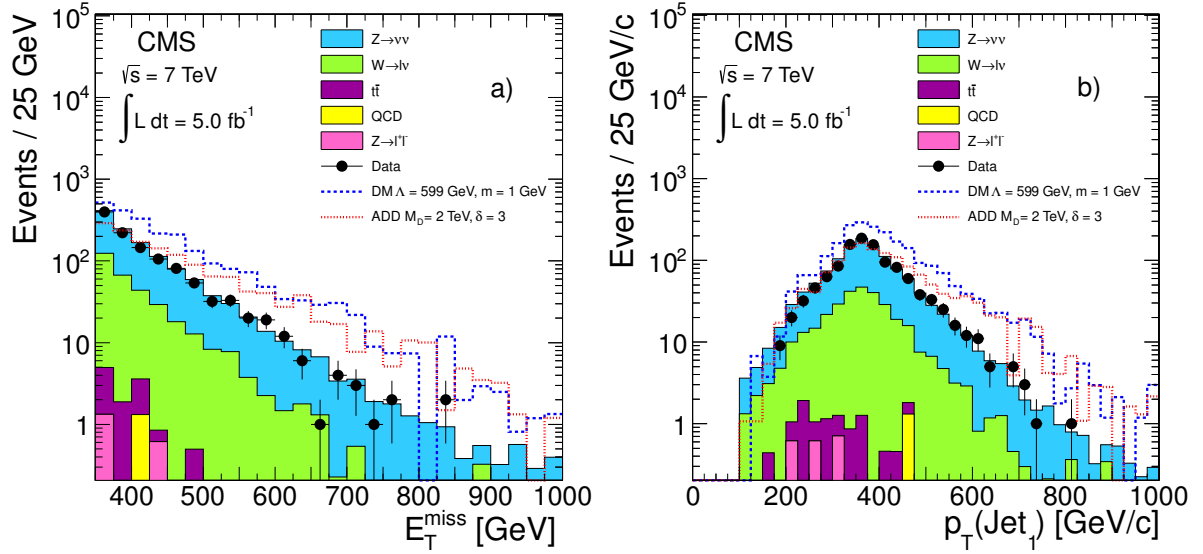


Figure 1: The distribution of (a) E_T^{miss} and (b) $p_T(j_1)$ for data (black full points with error bars) and simulation (histograms) for $E_T^{\text{miss}} > 350$ GeV/c after the full event selection criteria are applied. The $Z(\nu\nu)$ +jets and W +jets backgrounds are normalized to their estimates from data. An example of a dark matter signal (for axial-vector couplings and $M_\chi = 1$ GeV/ c^2) is shown as a dashed blue histogram and an ADD signal (with $M_D = 2$ TeV, $\delta = 3$) is shown as a dotted red histogram.

consistent with pp collision events. The application of these data cleanup requirements would reject approximately 2% of the dark matter signal and 3% of the ADD signal.

The signal sample is selected by requiring $E_T^{\text{miss}} > 200$ GeV/c and the jet with the highest transverse momentum (j_1) to have $p_T(j_1) > 110$ GeV/c and $|\eta(j_1)| < 2.4$. The triggers used to collect these data are fully efficient for events passing these selection cuts. Events with more than two jets with p_T above 30 GeV/c are discarded. As signal events typically contain jets from initial- or final-state radiation, a second jet (j_2) is allowed, provided $\Delta\phi(j_1, j_2) < 2.5$ rad. This angular requirement suppresses QCD dijet events. To reduce background from Z and W production and top-quark decays, events with isolated muons or electrons with $p_T > 10$ GeV/c are rejected. Events with an isolated track with $p_T > 10$ GeV/c are also removed as they come primarily from τ -lepton decays. A track is considered isolated if the scalar sum of the transverse momentum of all tracks with $p_T > 1$ GeV/c in the annulus of $0.02 < \Delta R < 0.3$ around its direction is less than 1% of its p_T . Table 1 lists the numbers of data and SM background events at each step of the analysis. Efficiencies for representative dark matter and ADD models relative to the event yield passing $E_T^{\text{miss}} > 200$ GeV/c selection are also shown. The dominant background is $Z(\nu\bar{\nu})$ +jets and the next largest source of background is W +jets. The event yields for $E_T^{\text{miss}} > 250, 300, 350,$ and 400 GeV/c are also shown. A study of the E_T^{miss} requirement using the signal samples showed that $E_T^{\text{miss}} > 350$ GeV/c is the optimal value for both the dark matter and ADD models searches.

The E_T^{miss} and $p_T(j_1)$ distributions are shown in Fig. 1, where the $Z(\nu\bar{\nu})$ +jets and W +jets backgrounds are normalized to the rate determined from data (Section 5) and other backgrounds are normalized to the integrated luminosity.

Table 1: Event yields at different stages of the event selection for (a) various SM processes from simulation, (b) sum of all SM processes, and the data, corresponding to an integrated luminosity of 5.0 fb^{-1} . Only statistical uncertainties are shown, which in most cases are smaller than the associated systematic uncertainties. Lepton removal eliminates events with isolated electrons, muons, or tracks with $p_T > 10 \text{ GeV}/c$. Efficiencies for representative dark matter and ADD models relative to the event yield passing $E_T^{\text{miss}} > 200 \text{ GeV}/c$ selection are also given.

| Requirement | (a) | | | | | | (b) | | | |
|---|---------------------------|-------------------------------------|------------------------|---------------------------|---------------|---------------------------|-----------------------|--------------------|--|--|
| | $Z(\nu\nu)$ +jets | $W(e\nu, \mu\nu, \tau\nu)$ +jets | $Z(\ell\ell)$ +jets | tt | Single t | QCD Multijet | Total Simulated SM | Data | DM (%) $M_\chi = 1 \text{ GeV}/c^2$ | ADD (%) $M_D = 2 \text{ TeV}/c^2, \delta = 3$ |
| $E_T^{\text{miss}} > 200 \text{ GeV}/c$ | $(324 \pm 1) \times 10^2$ | $(591 \pm 1) \times 10^2$ | 5255 ± 47 | $(133 \pm 1) \times 10^2$ | 1165 ± 7 | $(160 \pm 1) \times 10^2$ | 1273×10^2 | 1045×10^2 | 100.0 | 100.0 |
| $p_T(j_1) > 110 \text{ GeV}/c$ | $(302 \pm 1) \times 10^2$ | $(557 \pm 1) \times 10^2$ | 4908 ± 45 | $(119 \pm 1) \times 10^2$ | 1035 ± 6 | $(158 \pm 1) \times 10^2$ | 1195×10^2 | 1007×10^2 | 95.2 ± 0.71 | 92.8 ± 1.03 |
| $N_{\text{jet}}(p_T > 30 \text{ GeV}/c) \leq 2$ | $(227 \pm 1) \times 10^2$ | $(397 \pm 1) \times 10^2$ | 3453 ± 38 | 1587 ± 20 | 274 ± 3 | 5296 ± 14 | 730×10^2 | 624×10^2 | 69.8 ± 0.60 | 61.5 ± 0.84 |
| $\Delta\phi(j_1, j_2) < 2.5$ | $(211 \pm 1) \times 10^2$ | $(354 \pm 1) \times 10^2$ | 3139 ± 36 | 1344 ± 19 | 237 ± 3 | 62 ± 5 | 613×10^2 | 54×10^2 | 66.8 ± 0.59 | 58.0 ± 0.81 |
| Lepton Removal | $(198 \pm 1) \times 10^2$ | $(97 \pm 1) \times 10^2$ | 81 ± 6 | 214 ± 7 | 35 ± 1 | 2 ± 1 | 298×10^2 | 24×10^2 | 63.7 ± 0.58 | 54.8 ± 0.79 |
| $E_T^{\text{miss}} > 250 \text{ GeV}/c$ | 7306 ± 23 | 2951 ± 19 | 22 ± 3 | 70 ± 4 | 10 ± 0.5 | 2 ± 1 | 3932 | 2774 | 18.9 ± 0.31 | 19.9 ± 0.48 |
| $E_T^{\text{miss}} > 300 \text{ GeV}/c$ | 2932 ± 14 | 967 ± 11 | 6 ± 1.7 | 23 ± 2 | 3 ± 0.2 | 1 ± 0.7 | 1683 | 1142 | 10.8 ± 0.24 | 12.5 ± 0.38 |
| $E_T^{\text{miss}} > 350 \text{ GeV}/c$ | 1308 ± 9 | 362 ± 7 | 2 ± 0.9 | 9 ± 1.6 | 1 ± 0.2 | 1 ± 0.7 | 782 | 522 | 6.4 ± 0.18 | 7.9 ± 0.30 |
| $E_T^{\text{miss}} > 400 \text{ GeV}/c$ | 628 ± 7 | 148 ± 4 | 1 ± 0.4 | 3 ± 0.8 | 0.4 ± 0.1 | 1 ± 0.7 | | | | |

5 Background estimate from data

Table 1 shows that the SM backgrounds remaining after the full event selection are dominated by the following processes: Z+jets with the Z boson decaying into a pair of neutrinos and W+jets with the W boson decaying leptonically. These backgrounds are estimated from data utilizing a control sample of μ +jet events, where $Z(\mu\mu)$ events are used to estimate the $Z(\nu\nu)$ background and $W(\mu\nu)$ events are used to estimate the remaining W+jets background. The control sample is derived from the same set of triggers as those used to collect the signal sample by applying the full event selection criteria except for the vetoes on electrons, muons, and isolated tracks. One or more isolated muons with $p_T > 20 \text{ GeV}/c$ and $|\eta| < 2.1$ are required.

A sample of $Z(\mu\mu)$ events is selected by requiring two isolated muons with opposite-sign charges and a dimuon invariant mass between 60 and 120 GeV/c^2 . The observed yield is 111 events, which should be compared with a mean expected yield of 136 ± 8 events, where the uncertainty is only statistical. The dimuon invariant mass distributions, both for the data control sample and for the simulation, are shown in Fig. 2.

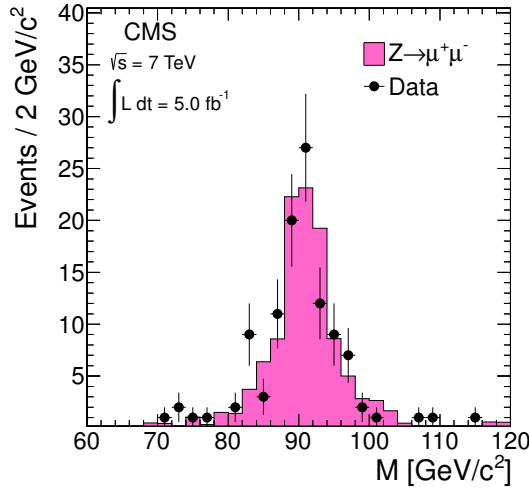


Figure 2: The dimuon invariant mass distribution in the dimuon control sample in data (black full points with error bars) and simulation (histogram) for $60 < M_{\mu\mu} < 120 \text{ GeV}/c^2$. The MC prediction has been normalized to the data yields. There is no significant non-Z background.

The production of a Z boson in association with jets and its subsequent decay into neutrinos has characteristics that are similar to those in the production of Z+jets where the Z decays to muons. Thus by treating the pair of muons as a pair of neutrinos, the topology of the $Z(\nu\bar{\nu})$ process is reproduced. The number of $Z(\nu\bar{\nu})$ events can then be predicted using:

$$N(Z(\nu\bar{\nu})) = \frac{N^{\text{obs}} - N^{\text{bgd}}}{A \times \epsilon} \cdot R \left(\frac{Z(\nu\bar{\nu})}{Z(\mu\mu)} \right) \quad (1)$$

where N^{obs} is the number of dimuon events observed, N^{bgd} is the estimated number of background events contributing to the dimuon sample, A is the geometric and kinematic acceptance of the detector and the Z mass window, ϵ is the selection efficiency for the event, and R is the ratio of branching fractions for the Z decay to a pair of neutrinos and to a pair of muons.

The acceptance A is defined as the fraction of all simulated events that pass all signal selection requirements except muon and track veto and have two muons with $p_T > 20 \text{ GeV}/c$ and

$|\eta| < 2.1$ and with an invariant mass within the Z mass window. The selection efficiency ϵ is defined as the fraction of the events passing acceptance cuts that have two reconstructed muons with $p_T > 20 \text{ GeV}/c$ and $|\eta| < 2.1$ and with an invariant mass within the Z mass window. This efficiency is estimated from simulation. The muon selection efficiency, both in the data and the simulation, is determined in the dimuon events with one of the muons passing tight selection criteria (tag) and with an invariant mass in the Z boson mass window. The efficiency of the second muon (probe), assumed to be a muon originating from the decay of the Z boson after background subtraction, is determined for the selection requirements used in this analysis. Details of this “tag-and-probe” method can be found in Ref. [50]. The efficiencies in the data and the simulation are consistent. The stability of this agreement is measured by varying the muon kinematics and the largest difference between the efficiencies in the data and the simulation is assigned as the uncertainty on the muon selection. This translates into 2% systematic uncertainty on ϵ . The ratio of the branching fractions R is 5.942 ± 0.019 [51]. Some of the $Z(\nu\bar{\nu})$ +jets events would be rejected by the track isolation requirement, and the background is multiplied by a factor of 0.94 to account for this effect. The scaling factor is obtained from simulation.

The final prediction for the number of $Z(\nu\bar{\nu})$ events is 900 ± 94 for $E_T^{\text{miss}} > 350 \text{ GeV}/c$, where the uncertainty includes statistical and systematic contributions. The sources of this uncertainty are: (i) the statistical uncertainties on the number of $Z(\mu\mu)$ events in the data and simulation, (ii) uncertainties on the acceptance from PDF uncertainties, evaluated based on the PDF4LHC [52] recommendations, and (iii) the uncertainty in the selection efficiency ϵ as determined from the difference in measured efficiencies in data and MC simulation. Table 2 summarizes the systematic uncertainties.

Table 2: Sources of systematic uncertainty and their fractional contributions to the total uncertainty on the $Z(\nu\bar{\nu})$ background.

| Source of Uncertainty | Size (%) |
|---|----------|
| Size of control sample (N_{obs}) | 9.5 |
| Geometric and kinematic acceptance (A) | 3.7 |
| Muon selection efficiency (ϵ) | 2.1 |
| Track isolation selection efficiency | 3.6 |
| Ratio of branching fractions (R) | 0.3 |
| Total | 11.0 |

The second largest background arises from W +jets events that are not removed by the lepton veto cut. These events can come from events in which the lepton (electron or muon) is either not identified, not isolated, or out of the acceptance region, or events in which a τ decays hadronically. The events where the lepton is ‘lost’ are estimated from the $W(\mu\nu)$ +jets control sample.

A $W(\mu\nu)$ sample is selected by requiring an isolated muon with $p_T > 20 \text{ GeV}/c$ and $|\eta| < 2.1$ and the transverse mass M_T to be between 50 and $100 \text{ GeV}/c^2$. The transverse mass is defined as $M_T = \sqrt{2p_T^\mu E_T^{\text{miss}} (1 - \cos(\Delta\phi))}$, where p_T^μ is the transverse momentum of the muon and $\Delta\phi$ is the angle between the muon p_T and the E_T^{miss} vectors. The event yields obtained for the $W(\mu\nu)$ sample for $E_T^{\text{miss}} > 350 \text{ GeV}/c$ are shown in Table 3, along with the contributions from Z +jets, $t\bar{t}$, and single top-quark events predicted by the simulation. The observed yield of $W(\mu\nu)$ +jets candidates is 531 which can be compared with a mean expected yield of 615.4 ± 9.3 , where uncertainty is statistical only. Figure 3 shows the W transverse mass distribution for data and simulation in the $W(\mu\nu)$ control sample.

Table 3: Event yields for the $W(\mu\nu)$ from simulation including non- W backgrounds, and from the data control sample.

| W +jets | $t\bar{t}$ | Z +jets | Single t | All MC | Data |
|-----------|------------|-----------|------------|--------|------|
| 581.5 | 23.3 | 6.4 | 4.2 | 615.4 | 531 |

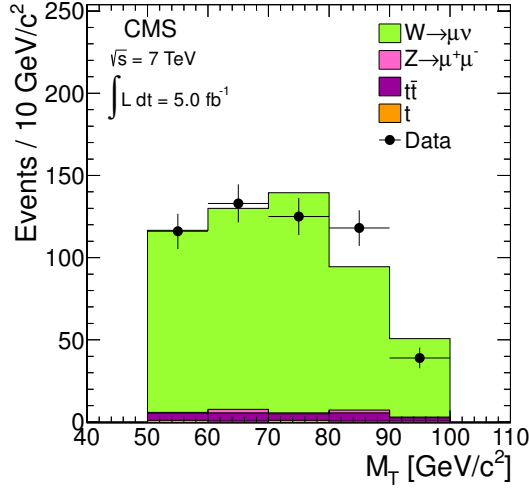


Figure 3: The transverse mass distribution M_T in the single muon data control sample and MC predictions for $W(\mu\nu)$, $t\bar{t}$, $Z(\mu\mu)$, and single top-quark production. The MC predictions have been normalized to the data yields. Data are dominated by $W(\mu\nu)$ events.

$W(\mu\nu)$ candidate events (N_{obs}), after subtracting non- W contamination (N_{bgd}), are corrected for the detector acceptance (A') and selection efficiency (ϵ') to obtain the total number of produced events $N_{\text{tot}} = (N_{\text{obs}} - N_{\text{bgd}}) / (A' \times \epsilon')$. This number is subsequently weighted by the inefficiency of the selection criteria used in the definition of the lepton veto to predict the number of events that are not rejected by the veto and thus remain in the signal sample.

The number of $W(\mu\nu)$ +jet events that are either out of the acceptance ($N_{\bar{A}}$) or are not identified or are not isolated ($N_{\bar{\epsilon}}$) can be written as:

$$N_{\bar{A}} = N_{\text{tot}} \times (1 - A) \quad (2)$$

$$N_{\bar{\epsilon}} = N_{\text{tot}} \times A \times (1 - \epsilon) \quad (3)$$

where A is the acceptance, and ϵ is the selection efficiency of the muon selection used in the lepton veto. The total background from events where the muon is 'lost' is then given by

$$N_{\text{lost}\mu} = N_{\bar{A}} + N_{\bar{\epsilon}}. \quad (4)$$

An estimate of the 'lost' electron background is similarly obtained from the $W(\mu\nu)$ +jets data sample, correcting for the muon acceptance and selection efficiency to obtain N_{tot} . The ratio of the generated $W(\mu\nu)$ and $W(e\nu)$ events passing the signal selection is taken from simulation and used to obtain N_{tot} for electrons. The same procedure is then applied to obtain the number of events where the electron is either not reconstructed or not isolated or out of the acceptance.

The detector acceptance for both muons and electrons is obtained from simulation. The selection efficiency is similarly obtained from simulation but with an assigned systematic uncer-

tainty to cover the largest difference in the efficiency measured in data and simulation with the tag-and-probe method.

There is a remaining component of the W +jets background from events where the W decays to a τ lepton and the τ decays hadronically, and this is estimated from simulation. This estimate is corrected using a normalization factor obtained from the ratio of $W(\mu\nu)$ events in data and simulation. The estimated W +jets background is corrected to account for the fraction of events that would be rejected by the track isolation veto. This correction factor is obtained from simulation and found to be 19%.

The total prediction for the number of W +jets events is 312 ± 35 for $E_T^{\text{miss}} > 350 \text{ GeV}/c$, where the uncertainty includes both statistical and systematic contributions. The sources of this uncertainty are: (i) the uncertainties on the number of single-muon events in the data and simulation samples, (ii) a conservative (100%) uncertainty on the non- W contamination obtained from simulation, (iii) uncertainties on the acceptance from PDFs, and (iv) the uncertainty in the selection efficiency ϵ as determined from the difference in measured efficiency between data and simulation. Table 4 summarizes the systematic uncertainties in the W +jets background.

Table 4: Sources of systematic uncertainty and their contribution to the total uncertainty on the W +jets background.

| Source of Uncertainty | Size (%) |
|--|----------|
| Size of control sample (N_{obs}) | 2.9 |
| Background (N_{bgd}) | 3.9 |
| Isolated track efficiency | 2.1 |
| Kinematic and geometrical acceptance (A) | 7.7 |
| Selection efficiency (ϵ) | 6.8 |
| Total | 11.6 |

Background contributions from QCD multijet events, $t\bar{t}$, and $Z(\ell\ell)$ +jets production are small and are obtained from the simulation. A 100% uncertainty is assigned to these background estimates.

6 Results

The total number of events observed is compared with the total number of estimated background events in Table 5, together with the breakdown of this background into separate subprocesses. Contribution from $Z(\nu\bar{\nu})$ +jets and W +jets processes are determined from the data. Contributions from $t\bar{t}$, $Z(\ell\ell)$, single t , and QCD multijet processes are determined from simulation and are assumed to have 100% uncertainty. The number of events observed is consistent with the number of events expected from SM backgrounds. Thus these data are used to set limits on the production of dark matter particles and to constrain the ADD model parameters. The CLs method [51, 53] is used for calculating the upper limits on the number of signal events, and systematic uncertainties are modeled by log-normal distributions.

The important uncertainties related to signal modeling are:

1. The jet energy scale uncertainty, estimated by shifting the four-vectors of the jets by an η - and p_T -dependent factor [54], yielding a variation of 8–11% (8–13%) for the dark matter (ADD) signal.

Table 5: SM background predictions compared with data passing the selection requirements for various E_T^{miss} thresholds, corresponding to integrated luminosity of 5.0 fb^{-1} . The uncertainties include both statistical and systematic terms. In the last two rows, expected and observed 95% confidence level upper limits on possible contributions from new physics passing the selection requirements are given.

| E_T^{miss} (GeV/c) \rightarrow | ≥ 250 | ≥ 300 | ≥ 350 | ≥ 400 |
|---|-----------------|-----------------|----------------|---------------|
| Process | Events | | | |
| Z($\nu\bar{\nu}$)+jets | 5106 ± 271 | 1908 ± 143 | 900 ± 94 | 433 ± 62 |
| W+jets | 2632 ± 237 | 816 ± 83 | 312 ± 35 | 135 ± 17 |
| t \bar{t} | 69.8 ± 69.8 | 22.6 ± 22.6 | 8.5 ± 8.5 | 3.0 ± 3.0 |
| Z($\ell\ell$)+jets | 22.3 ± 22.3 | 6.1 ± 6.1 | 2.0 ± 2.0 | 0.6 ± 0.6 |
| Single t | 10.2 ± 10.2 | 2.7 ± 2.7 | 1.1 ± 1.1 | 0.4 ± 0.4 |
| QCD Multijets | 2.2 ± 2.2 | 1.3 ± 1.3 | 1.3 ± 1.3 | 1.3 ± 1.3 |
| Total SM | 7842 ± 367 | 2757 ± 167 | 1225 ± 101 | 573 ± 65 |
| Data | 7584 | 2774 | 1142 | 522 |
| Expected upper limit non-SM | 779 | 325 | 200 | 118 |
| Observed upper limit non-SM | 600 | 368 | 158 | 95 |

2. The noise cleaning uncertainty, obtained by assigning the full effect of noise cleaning as systematic uncertainty, 2% (3%) for dark matter (ADD) signal.
3. PDF uncertainties evaluated using the PDF4LHC [52] prescription and resulting in a systematic uncertainty of 1–7% (1–4%) for the dark matter (ADD) signal.
4. The renormalization/factorization scale uncertainty, evaluated by varying the scale up and down by a factor of two, 5% for both dark matter and ADD signals.
5. ISR uncertainty, estimated by changing PYTHIA parameters, yielding a variation of 15% for both dark matter and ADD signals.
6. Uncertainty on the pileup simulation, 3% for both dark matter and ADD signals.
7. The limited statistics of the simulated sample yielding a variation of 2–5% (2–4%) on the dark matter (ADD) signal.

The total uncertainty on the signal for the DM (ADD) models for these sources of uncertainty is 20% (21%). In addition, a 2.2% uncertainty on the integrated luminosity measurement [55] is included.

For dark matter models, the observed limit on the cross section depends on the mass of the dark matter particle and the nature of its interaction with the SM particles. The limits on the effective contact interaction scale Λ as a function of M_χ can be translated into a limit on the dark matter-nucleon scattering cross section using the reduced mass of χ -nucleon system [2], which can be compared with the constraints from direct and indirect detection experiments. Figure 4 shows the 90% confidence level (CL) upper limits on the dark matter-nucleon scattering cross section as a function of the mass of dark matter particle for the spin-dependent and spin-independent models. Also shown are the results from the CMS Collaboration using the monophoton plus E_T^{miss} channel [14], p \bar{p} collider experiment CDF [15], direct detection experiments, COUPP [18], CoGeNT [17], Picasso [21], XENON100 [16], CDMS II [19, 20], and SIMPLE [22], and indirect detection experiments, IceCube [23] and Super-K [24]. Table 6 shows the 90% CL limits on

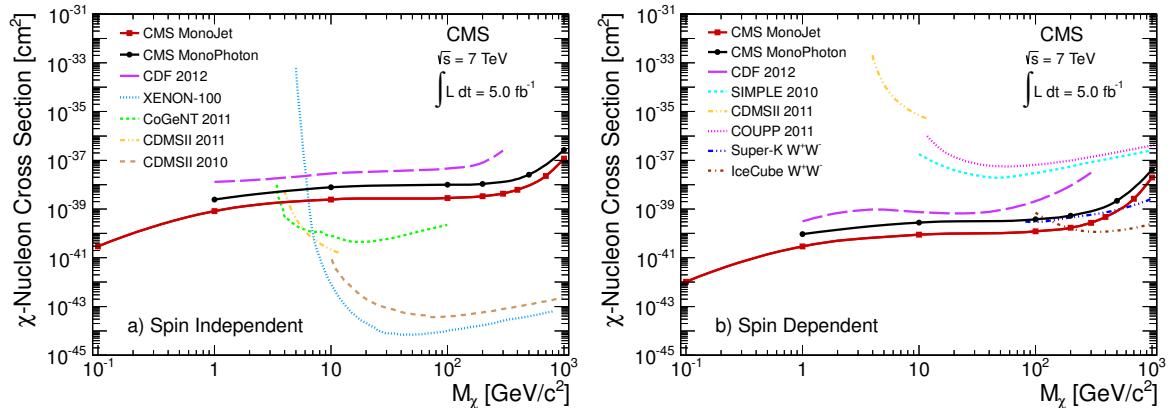


Figure 4: Comparison of the 90% CL upper limits on the dark matter-nucleon scattering cross section versus mass of dark matter particle for the (left) spin-independent and (right) spin-dependent models with results from CMS using monophoton signature [14], CDF [15], XENON100 [16], CoGeNT [17], COUPP[18], CDMS II [19, 20], Picasso [21], SIMPLE [22], IceCube [23], and Super-K [24] collaborations.

Table 6: Observed 90% CL limits on the dark matter-nucleon cross section and effective contact interaction scale Λ for the spin-dependent and spin-independent interactions.

| M_χ (GeV/ c^2) | Spin-dependent | | Spin-independent | |
|------------------------|-----------------|------------------------------|------------------|------------------------------|
| | Λ (GeV) | $\sigma_{\chi N}$ (cm 2) | Λ (GeV) | $\sigma_{\chi N}$ (cm 2) |
| 0.1 | 754 | 1.03×10^{-42} | 749 | 2.90×10^{-41} |
| 1 | 755 | 2.94×10^{-41} | 751 | 8.21×10^{-40} |
| 10 | 765 | 8.79×10^{-41} | 760 | 2.47×10^{-39} |
| 100 | 736 | 1.21×10^{-40} | 764 | 2.83×10^{-39} |
| 200 | 677 | 1.70×10^{-40} | 736 | 3.31×10^{-39} |
| 300 | 602 | 2.73×10^{-40} | 690 | 4.30×10^{-39} |
| 400 | 524 | 4.74×10^{-40} | 631 | 6.15×10^{-39} |
| 700 | 341 | 2.65×10^{-39} | 455 | 2.28×10^{-38} |
| 1000 | 206 | 1.98×10^{-38} | 302 | 1.18×10^{-37} |

Λ and the dark matter-nucleon cross section for the spin-dependent and spin-independent interactions.

Exclusion limits at 95% CL for the large extra dimension ADD model parameter M_D as a function of the number of extra dimensions are given in Table 7. A comparison of these results with results from previous searches is shown in Fig. 5. These limits are an improvement over the previous best limits, by $\sim 2 \text{ TeV}/c^2$ for $\delta = 2$ and $0.7 \text{ TeV}/c^2$ for $\delta = 6$.

7 Summary

A search has been performed for signatures of new physics yielding an excess of events in the monojet and E_T^{miss} channel. The results have been used to constrain the pair production of dark matter particles in models with a heavy mediator, and large extra dimensions in the context of the Arkani-Hamed, Dimopoulos, and Dvali model. The data sample corresponds to an integrated luminosity of 5.0 fb^{-1} and includes events containing a jet with transverse momentum above $110 \text{ GeV}/c$ and E_T^{miss} above $350 \text{ GeV}/c$. Many standard model processes also have

Table 7: Observed and expected 95% CL lower limits on the ADD model parameter M_D (in TeV/c^2) as a function of δ , with and without NLO K -factors applied.

| δ | LO | | NLO | |
|----------|------------------------------------|------------------------------------|------------------------------------|------------------------------------|
| | Exp. Limit (TeV/c^2) | Obs. Limit (TeV/c^2) | Exp. Limit (TeV/c^2) | Obs. Limit (TeV/c^2) |
| 2 | 3.81 | 4.08 | 4.20 | 4.54 |
| 3 | 3.06 | 3.24 | 3.32 | 3.51 |
| 4 | 2.69 | 2.81 | 2.84 | 2.98 |
| 5 | 2.44 | 2.52 | 2.59 | 2.71 |
| 6 | 2.28 | 2.38 | 2.40 | 2.51 |

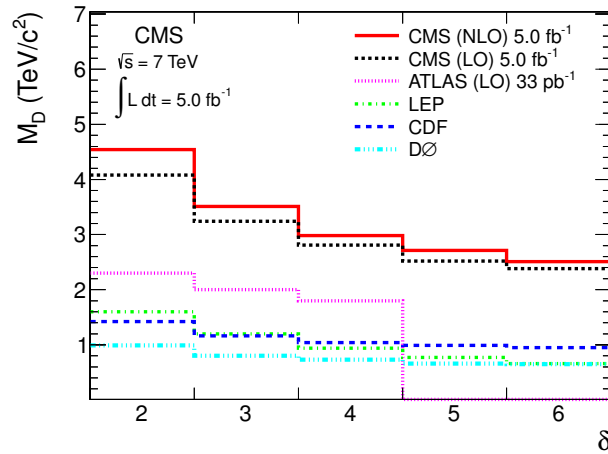


Figure 5: Comparison of lower limits on M_D versus the number of extra dimensions with ATLAS [12], LEP [25–28], CDF [29], and D0 [30].

the same signature. The QCD multijet contribution is reduced by several orders of magnitude to a negligible level using topological selections. The dominant backgrounds, $Z(\nu\bar{\nu})$ +jets and W +jets, are estimated from data samples enriched in $Z(\mu\mu)$ and $W(\mu\nu)$ events. The data are found to be in good agreement with the expected contributions from standard model processes.

A dark matter-nucleon scattering cross section in the framework of an effective theory is excluded above 1.03×10^{-42} (1.21×10^{-40}) cm^2 and 2.90×10^{-41} (2.83×10^{-39}) cm^2 for a dark matter particle with mass 0.1 (100) GeV/c^2 at the 90% CL for the spin-dependent and spin-independent models, respectively. For the spin-independent model, these are the best limits for dark matter particles with mass below $3.5 \text{ GeV}/c^2$, a region as yet unexplored by the direct detection experiments. For the spin-dependent model, these limits represent the most stringent constraints over the 0.1–200 GeV/c^2 mass range.

Values for the large extra dimensions ADD model parameter M_D smaller than 4.54, 3.51, 2.98, 2.71, and 2.51 TeV/c^2 are excluded for a number of extra dimensions $\delta = 2, 3, 4, 5$, and 6, respectively, representing a significant improvement (1 TeV/c^2) over the previous limits.

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A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia

S. Chatrchyan, V. Khachatryan, A.M. Sirunyan, A. Tumasyan

Institut für Hochenergiephysik der OeAW, Wien, Austria

W. Adam, E. Aguilo, T. Bergauer, M. Dragicevic, J. Erö, C. Fabjan¹, M. Friedl, R. Frühwirth¹, V.M. Ghete, J. Hammer, N. Hörmann, J. Hrubec, M. Jeitler¹, W. Kiesenhofer, V. Knünz, M. Krammer¹, I. Krätschmer, D. Liko, I. Mikulec, M. Pernicka[†], B. Rahbaran, C. Rohringer, H. Rohringer, R. Schöfbeck, J. Strauss, A. Taurok, W. Waltenberger, G. Walzel, E. Widl, C.-E. Wulz¹

National Centre for Particle and High Energy Physics, Minsk, Belarus

V. Mossolov, N. Shumeiko, J. Suarez Gonzalez

Universiteit Antwerpen, Antwerpen, Belgium

M. Bansal, S. Bansal, T. Cornelis, E.A. De Wolf, X. Janssen, S. Luyckx, L. Mucibello, S. Ochesanu, B. Roland, R. Rougny, M. Selvaggi, Z. Staykova, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel, A. Van Spillbeeck

Vrije Universiteit Brussel, Brussel, Belgium

F. Blekman, S. Blyweert, J. D'Hondt, R. Gonzalez Suarez, A. Kalogeropoulos, M. Maes, A. Olbrechts, W. Van Doninck, P. Van Mulders, G.P. Van Onsem, I. Villella

Université Libre de Bruxelles, Bruxelles, Belgium

B. Clerbaux, G. De Lentdecker, V. Dero, A.P.R. Gay, T. Hreus, A. Léonard, P.E. Marage, T. Reis, L. Thomas, G. Vander Marcken, C. Vander Velde, P. Vanlaer, J. Wang

Ghent University, Ghent, Belgium

V. Adler, K. Beernaert, A. Cimmino, S. Costantini, G. Garcia, M. Grunewald, B. Klein, J. Lellouch, A. Marinov, J. McCartin, A.A. Ocampo Rios, D. Ryckbosch, N. Strobbe, F. Thyssen, M. Tytgat, P. Verwilligen, S. Walsh, E. Yazgan, N. Zaganidis

Université Catholique de Louvain, Louvain-la-Neuve, Belgium

S. Basegmez, G. Bruno, R. Castello, L. Ceard, C. Delaere, T. du Pree, D. Favart, L. Forthomme, A. Giammanco², J. Hollar, V. Lemaître, J. Liao, O. Militaru, C. Nuttens, D. Pagano, A. Pin, K. Piotrkowski, N. Schul, J.M. Vizán Garcia

Université de Mons, Mons, Belgium

N. Belyi, T. Caebergs, E. Daubie, G.H. Hammad

Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil

G.A. Alves, M. Correa Martins Junior, D. De Jesus Damiao, T. Martins, M.E. Pol, M.H.G. Souza

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil

W.L. Aldá Júnior, W. Carvalho, A. Custódio, E.M. Da Costa, C. De Oliveira Martins, S. Fonseca De Souza, D. Matos Figueiredo, L. Mundim, H. Nogima, V. Oguri, W.L. Prado Da Silva, A. Santoro, L. Soares Jorge, A. Sznajder

Instituto de Física Teórica, Universidade Estadual Paulista, Sao Paulo, Brazil

T.S. Anjos³, C.A. Bernardes³, F.A. Dias⁴, T.R. Fernandez Perez Tomei, E. M. Gregores³, C. Lagana, F. Marinho, P.G. Mercadante³, S.F. Novaes, Sandra S. Padula

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria

V. Genchev⁵, P. Iaydjiev⁵, S. Piperov, M. Rodozov, S. Stoykova, G. Sultanov, V. Tcholakov, R. Trayanov, M. Vutova

University of Sofia, Sofia, Bulgaria

A. Dimitrov, R. Hadjiiska, V. Kozhuharov, L. Litov, B. Pavlov, P. Petkov

Institute of High Energy Physics, Beijing, China

J.G. Bian, G.M. Chen, H.S. Chen, C.H. Jiang, D. Liang, S. Liang, X. Meng, J. Tao, J. Wang, X. Wang, Z. Wang, H. Xiao, M. Xu, J. Zang, Z. Zhang

State Key Lab. of Nucl. Phys. and Tech., Peking University, Beijing, China

C. Asawatangtrakuldee, Y. Ban, S. Guo, Y. Guo, W. Li, S. Liu, Y. Mao, S.J. Qian, H. Teng, D. Wang, L. Zhang, B. Zhu, W. Zou

Universidad de Los Andes, Bogota, Colombia

C. Avila, J.P. Gomez, B. Gomez Moreno, A.F. Osorio Oliveros, J.C. Sanabria

Technical University of Split, Split, Croatia

N. Godinovic, D. Lelas, R. Plestina⁶, D. Polic, I. Puljak⁵

University of Split, Split, Croatia

Z. Antunovic, M. Kovac

Institute Rudjer Boskovic, Zagreb, Croatia

V. Brigljevic, S. Duric, K. Kadija, J. Luetic, S. Morovic

University of Cyprus, Nicosia, Cyprus

A. Attikis, M. Galanti, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis

Charles University, Prague, Czech Republic

M. Finger, M. Finger Jr.

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt

Y. Assran⁷, S. Elgammal⁸, A. Ellithi Kamel⁹, S. Khalil⁸, M.A. Mahmoud¹⁰, A. Radi^{11,12}

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

M. Kadastik, M. Müntel, M. Raidal, L. Rebane, A. Tiko

Department of Physics, University of Helsinki, Helsinki, Finland

P. Eerola, G. Fedi, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland

J. Härkönen, A. Heikkinen, V. Karimäki, R. Kinnunen, M.J. Kortelainen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, P. Luukka, T. Mäenpää, T. Peltola, E. Tuominen, J. Tuominiemi, E. Tuovinen, D. Ungaro, L. Wendland

Lappeenranta University of Technology, Lappeenranta, Finland

K. Banzuzi, A. Karjalainen, A. Korpela, T. Tuuva

DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France

M. Besancon, S. Choudhury, M. DeJardin, D. Denegri, B. Fabbro, J.L. Faure, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, E. Locci, J. Malcles, L. Millischer, A. Nayak, J. Rander, A. Rosowsky, I. Shreyber, M. Titov

Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France

S. Baffioni, F. Beaudette, L. Benhabib, L. Bianchini, M. Bluj¹³, C. Broutin, P. Busson, C. Charlot, N. Daci, T. Dahms, L. Dobrzynski, R. Granier de Cassagnac, M. Haguenaue, P. Miné, C. Mironov, I.N. Naranjo, M. Nguyen, C. Ochando, P. Paganini, D. Sabes, R. Salerno, Y. Sirois, C. Veelken, A. Zabi

Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France

J.-L. Agram¹⁴, J. Andrea, D. Bloch, D. Bodin, J.-M. Brom, M. Cardaci, E.C. Chabert, C. Collard, E. Conte¹⁴, F. Drouhin¹⁴, C. Ferro, J.-C. Fontaine¹⁴, D. Gelé, U. Goerlach, P. Juillot, A.-C. Le Bihan, P. Van Hove

Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules (IN2P3), Villeurbanne, France

F. Fassi, D. Mercier

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France

S. Beauceron, N. Beaupere, O. Bondu, G. Boudoul, J. Chasserat, R. Chierici⁵, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, T. Kurca, M. Lethuillier, L. Mirabito, S. Perries, V. Sordini, Y. Tschudi, P. Verdier, S. Viret

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

Z. Tsamalaidze¹⁵

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany

G. Anagnostou, S. Beranek, M. Edelhoff, L. Feld, N. Heracleous, O. Hindrichs, R. Jussen, K. Klein, J. Merz, A. Ostapchuk, A. Perieanu, F. Raupach, J. Sammet, S. Schael, D. Sprenger, H. Weber, B. Wittmer, V. Zhukov¹⁶

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany

M. Ata, J. Caudron, E. Dietz-Laursonn, D. Duchardt, M. Erdmann, R. Fischer, A. Güth, T. Hebbeker, C. Heidemann, K. Hoepfner, D. Klingebiel, P. Kreuzer, C. Magass, M. Merschmeyer, A. Meyer, M. Olschewski, P. Papacz, H. Pieta, H. Reithler, S.A. Schmitz, L. Sonnenschein, J. Steggemann, D. Teyssier, M. Weber

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany

M. Bontenackels, V. Cherepanov, Y. Erdogan, G. Flügge, H. Geenen, M. Geisler, W. Haj Ahmad, F. Hoehle, B. Kargoll, T. Kress, Y. Kuessel, A. Nowack, L. Perchalla, O. Pooth, P. Sauerland, A. Stahl

Deutsches Elektronen-Synchrotron, Hamburg, Germany

M. Aldaya Martin, J. Behr, W. Behrenhoff, U. Behrens, M. Bergholz¹⁷, A. Bethani, K. Borras, A. Burgmeier, A. Cakir, L. Calligaris, A. Campbell, E. Castro, F. Costanza, D. Dammann, C. Diez Pardos, G. Eckerlin, D. Eckstein, G. Flucke, A. Geiser, I. Glushkov, P. Gunnellini, S. Habib, J. Hauk, G. Hellwig, H. Jung, M. Kasemann, P. Katsas, C. Kleinwort, H. Kluge, A. Knutsson, M. Krämer, D. Krücker, E. Kuznetsova, W. Lange, W. Lohmann¹⁷, B. Lutz, R. Mankel, I. Marfin, M. Marienfeld, I.-A. Melzer-Pellmann, A.B. Meyer, J. Mnich, A. Mussgiller, S. Naumann-Emme, J. Olzem, H. Perrey, A. Petrukhin, D. Pitzl, A. Raspereza, P.M. Ribeiro Cipriano, C. Riedl, E. Ron, M. Rosin, J. Salfeld-Nebgen, R. Schmidt¹⁷, T. Schoerner-Sadenius, N. Sen, A. Spiridonov, M. Stein, R. Walsh, C. Wissing

University of Hamburg, Hamburg, Germany

C. Autermann, V. Blobel, J. Draeger, H. Enderle, J. Erfle, U. Gebbert, M. Görner, T. Hermanns, R.S. Höing, K. Kaschube, G. Kaussen, H. Kirschenmann, R. Klanner, J. Lange, B. Mura, F. Nowak, T. Peiffer, N. Pietsch, D. Rathjens, C. Sander, H. Schettler, P. Schleper, E. Schlieckau, A. Schmidt, M. Schröder, T. Schum, M. Seidel, V. Sola, H. Stadie, G. Steinbrück, J. Thomsen, L. Vanelderen

Institut für Experimentelle Kernphysik, Karlsruhe, Germany

C. Barth, J. Berger, C. Böser, T. Chwalek, W. De Boer, A. Descroix, A. Dierlamm, M. Feindt, M. Guthoff⁵, C. Hackstein, F. Hartmann, T. Hauth⁵, M. Heinrich, H. Held, K.H. Hoffmann, S. Honc, I. Katkov¹⁶, J.R. Komaragiri, P. Lobelle Pardo, D. Martschei, S. Mueller, Th. Müller, M. Niegel, A. Nürnberg, O. Oberst, A. Oehler, J. Ott, G. Quast, K. Rabbertz, F. Ratnikov, N. Ratnikova, S. Röcker, A. Scheurer, F.-P. Schilling, G. Schott, H.J. Simonis, F.M. Stober, D. Troendle, R. Ulrich, J. Wagner-Kuhr, S. Wayand, T. Weiler, M. Zeise

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

G. Daskalakis, T. Gerasis, S. Kesisoglou, A. Kyriakis, D. Loukas, I. Manolakos, A. Markou, C. Markou, C. Mavrommatis, E. Ntomari

University of Athens, Athens, Greece

L. Gouskos, T.J. Mertzimekis, A. Panagiotou, N. Saoulidou

University of Ioánnina, Ioánnina, Greece

I. Evangelou, C. Foudas, P. Kokkas, N. Manthos, I. Papadopoulos, V. Patras

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

G. Bencze, C. Hajdu, P. Hidas, D. Horvath¹⁸, F. Sikler, V. Veszpremi, G. Vesztergombi¹⁹

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

N. Beni, S. Czellar, J. Molnar, J. Palinkas, Z. Szillasi

University of Debrecen, Debrecen, Hungary

J. Karancsi, P. Raics, Z.L. Trocsanyi, B. Ujvari

Panjab University, Chandigarh, India

S.B. Beri, V. Bhatnagar, N. Dhingra, R. Gupta, M. Kaur, M.Z. Mehta, N. Nishu, L.K. Saini, A. Sharma, J. Singh

University of Delhi, Delhi, India

Ashok Kumar, Arun Kumar, S. Ahuja, A. Bhardwaj, B.C. Choudhary, S. Malhotra, M. Naimuddin, K. Ranjan, V. Sharma, R.K. Shivpuri

Saha Institute of Nuclear Physics, Kolkata, India

S. Banerjee, S. Bhattacharya, S. Dutta, B. Gomber, Sa. Jain, Sh. Jain, R. Khurana, S. Sarkar, M. Sharan

Bhabha Atomic Research Centre, Mumbai, India

A. Abdulsalam, R.K. Choudhury, D. Dutta, S. Kailas, V. Kumar, P. Mehta, A.K. Mohanty⁵, L.M. Pant, P. Shukla

Tata Institute of Fundamental Research - EHEP, Mumbai, India

T. Aziz, S. Ganguly, M. Guchait²⁰, M. Maity²¹, G. Majumder, K. Mazumdar, G.B. Mohanty, B. Parida, K. Sudhakar, N. Wickramage

Tata Institute of Fundamental Research - HECR, Mumbai, India

S. Banerjee, S. Dugad

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran

H. Arfaei, H. Bakhshiansohi²², S.M. Etesami²³, A. Fahim²², M. Hashemi, H. Hesari, A. Jafari²², M. Khakzad, M. Mohammadi Najafabadi, S. Paktinat Mehdiabadi, B. Safarzadeh²⁴, M. Zeinali²³

INFN Sezione di Bari ^a, Università di Bari ^b, Politecnico di Bari ^c, Bari, Italy

M. Abbrescia^{a,b}, L. Barbone^{a,b}, C. Calabria^{a,b,5}, S.S. Chhibra^{a,b}, A. Colaleo^a, D. Creanza^{a,c},

N. De Filippis^{a,c,5}, M. De Palma^{a,b}, L. Fiore^a, G. Iaselli^{a,c}, L. Lusito^{a,b}, G. Maggi^{a,c}, M. Maggi^a, B. Marangelli^{a,b}, S. My^{a,c}, S. Nuzzo^{a,b}, N. Pacifico^{a,b}, A. Pompili^{a,b}, G. Pugliese^{a,c}, G. Selvaggi^{a,b}, L. Silvestris^a, G. Singh^{a,b}, R. Venditti, G. Zito^a

INFN Sezione di Bologna ^a, Università di Bologna ^b, Bologna, Italy

G. Abbiendi^a, A.C. Benvenuti^a, D. Bonacorsi^{a,b}, S. Braibant-Giacomelli^{a,b}, L. Brigliadori^{a,b}, P. Capiluppi^{a,b}, A. Castro^{a,b}, F.R. Cavallo^a, M. Cuffiani^{a,b}, G.M. Dallavalle^a, F. Fabbri^a, A. Fanfani^{a,b}, D. Fasanella^{a,b,5}, P. Giacomelli^a, C. Grandi^a, L. Guiducci^{a,b}, S. Marcellini^a, G. Masetti^a, M. Meneghelli^{a,b,5}, A. Montanari^a, F.L. Navarria^{a,b}, F. Odorici^a, A. Perrotta^a, F. Primavera^{a,b}, A.M. Rossi^{a,b}, T. Rovelli^{a,b}, G. Siroli^{a,b}, R. Travaglini^{a,b}

INFN Sezione di Catania ^a, Università di Catania ^b, Catania, Italy

S. Albergo^{a,b}, G. Cappello^{a,b}, M. Chiorboli^{a,b}, S. Costa^{a,b}, R. Potenza^{a,b}, A. Tricomi^{a,b}, C. Tuve^{a,b}

INFN Sezione di Firenze ^a, Università di Firenze ^b, Firenze, Italy

G. Barbagli^a, V. Ciulli^{a,b}, C. Civinini^a, R. D'Alessandro^{a,b}, E. Focardi^{a,b}, S. Frosali^{a,b}, E. Gallo^a, S. Gonzi^{a,b}, M. Meschini^a, S. Paoletti^a, G. Sguazzoni^a, A. Tropiano^a

INFN Laboratori Nazionali di Frascati, Frascati, Italy

L. Benussi, S. Bianco, S. Colafranceschi²⁵, F. Fabbri, D. Piccolo

INFN Sezione di Genova, Genova, Italy

P. Fabbricatore, R. Musenich, S. Tosi

INFN Sezione di Milano-Bicocca ^a, Università di Milano-Bicocca ^b, Milano, Italy

A. Benaglia^{a,b,5}, F. De Guio^{a,b}, L. Di Matteo^{a,b,5}, S. Fiorendi^{a,b}, S. Gennai^{a,5}, A. Ghezzi^{a,b}, S. Malvezzi^a, R.A. Manzoni^{a,b}, A. Martelli^{a,b}, A. Massironi^{a,b,5}, D. Menasce^a, L. Moroni^a, M. Paganoni^{a,b}, D. Pedrini^a, S. Ragazzi^{a,b}, N. Redaelli^a, S. Sala^a, T. Tabarelli de Fatis^{a,b}

INFN Sezione di Napoli ^a, Università di Napoli "Federico II" ^b, Napoli, Italy

S. Buontempo^a, C.A. Carrillo Montoya^a, N. Cavallo^{a,26}, A. De Cosa^{a,b,5}, O. Dogangun^{a,b}, F. Fabozzi^{a,26}, A.O.M. Iorio^a, L. Lista^a, S. Meola^{a,27}, M. Merola^{a,b}, P. Paolucci^{a,5}

INFN Sezione di Padova ^a, Università di Padova ^b, Università di Trento (Trento) ^c, Padova, Italy

P. Azzi^a, N. Bacchetta^{a,5}, P. Bellan^{a,b}, D. Bisello^{a,b}, A. Branca^{a,5}, R. Carlin^{a,b}, P. Checchia^a, T. Dorigo^a, U. Dosselli^a, F. Gasparini^{a,b}, U. Gasparini^{a,b}, A. Gozzelino^a, K. Kanishchev^{a,c}, S. Lacaprara^a, I. Lazzizzera^{a,c}, M. Margoni^{a,b}, A.T. Meneguzzo^{a,b}, M. Nespolo^{a,5}, J. Pazzini, P. Ronchese^{a,b}, F. Simonetto^{a,b}, E. Torassa^a, S. Vanini^{a,b}, P. Zotto^{a,b}, G. Zumerle^{a,b}

INFN Sezione di Pavia ^a, Università di Pavia ^b, Pavia, Italy

M. Gabusi^{a,b}, S.P. Ratti^{a,b}, C. Riccardi^{a,b}, P. Torre^{a,b}, P. Vitulo^{a,b}

INFN Sezione di Perugia ^a, Università di Perugia ^b, Perugia, Italy

M. Biasini^{a,b}, G.M. Bilei^a, L. Fanò^{a,b}, P. Lariccia^{a,b}, A. Lucaroni^{a,b,5}, G. Mantovani^{a,b}, M. Menichelli^a, A. Nappi^{a,b†}, F. Romeo^{a,b}, A. Saha^a, A. Santocchia^{a,b}, A. Spiezia^{a,b}, S. Taroni^{a,b}

INFN Sezione di Pisa ^a, Università di Pisa ^b, Scuola Normale Superiore di Pisa ^c, Pisa, Italy

P. Azzurri^{a,c}, G. Bagliesi^a, T. Boccali^a, G. Broccolo^{a,c}, R. Castaldi^a, R.T. D'Agnolo^{a,c}, R. Dell'Orso^a, F. Fiori^{a,b,5}, L. Foà^{a,c}, A. Giassi^a, A. Kraan^a, F. Ligabue^{a,c}, T. Lomtadze^a, L. Martini^{a,28}, A. Messineo^{a,b}, F. Palla^a, A. Rizzi^{a,b}, A.T. Serban^{a,29}, P. Spagnolo^a, P. Squillacioti^{a,5}, R. Tenchini^a, G. Tonelli^{a,b,5}, A. Venturi^a, P.G. Verdini^a

INFN Sezione di Roma ^a, Università di Roma "La Sapienza" ^b, Roma, Italy

L. Barone^{a,b}, F. Cavallari^a, D. Del Re^{a,b}, M. Diemoz^a, C. Fanelli, M. Grassi^{a,b,5}, E. Longo^{a,b}

P. Meridiani^{a,5}, F. Micheli^{a,b}, S. Nourbakhsh^{a,b}, G. Organtini^{a,b}, R. Paramatti^a, S. Rahatlou^{a,b}, M. Sigamani^a, L. Soffi^{a,b}

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

N. Amapane^{a,b}, R. Arcidiacono^{a,c}, S. Argiro^{a,b}, M. Arneodo^{a,c}, C. Biino^a, N. Cartiglia^a, M. Costa^{a,b}, N. Demaria^a, C. Mariotti^{a,5}, S. Maselli^a, E. Migliore^{a,b}, V. Monaco^{a,b}, M. Musich^{a,5}, M.M. Obertino^{a,c}, N. Pastrone^a, M. Pelliccioni^a, A. Potenza^{a,b}, A. Romero^{a,b}, M. Ruspa^{a,c}, R. Sacchi^{a,b}, A. Solano^{a,b}, A. Staiano^a, A. Vilela Pereira^a

INFN Sezione di Trieste^a, Università di Trieste^b, Trieste, Italy

S. Belforte^a, V. Candelise^{a,b}, F. Cossutti^a, G. Della Ricca^{a,b}, B. Gobbo^a, M. Marone^{a,b,5}, D. Montanino^{a,b,5}, A. Penzo^a, A. Schizzi^{a,b}

Kangwon National University, Chunchon, Korea

S.G. Heo, T.Y. Kim, S.K. Nam

Kyungpook National University, Daegu, Korea

S. Chang, D.H. Kim, G.N. Kim, D.J. Kong, H. Park, S.R. Ro, D.C. Son, T. Son

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea

J.Y. Kim, Zero J. Kim, S. Song

Korea University, Seoul, Korea

S. Choi, D. Gyun, B. Hong, M. Jo, H. Kim, T.J. Kim, K.S. Lee, D.H. Moon, S.K. Park

University of Seoul, Seoul, Korea

M. Choi, J.H. Kim, C. Park, I.C. Park, S. Park, G. Ryu

Sungkyunkwan University, Suwon, Korea

Y. Cho, Y. Choi, Y.K. Choi, J. Goh, M.S. Kim, E. Kwon, B. Lee, J. Lee, S. Lee, H. Seo, I. Yu

Vilnius University, Vilnius, Lithuania

M.J. Bilinskas, I. Grigelionis, M. Janulis, A. Juodagalvis

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico

H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-de La Cruz, R. Lopez-Fernandez, R. Magaña Villalba, J. Martínez-Ortega, A. Sánchez-Hernández, L.M. Villasenor-Cendejas

Universidad Iberoamericana, Mexico City, Mexico

S. Carrillo Moreno, F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

H.A. Salazar Ibarguen

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico

E. Casimiro Linares, A. Morelos Pineda, M.A. Reyes-Santos

University of Auckland, Auckland, New Zealand

D. Krofcheck

University of Canterbury, Christchurch, New Zealand

A.J. Bell, P.H. Butler, R. Doesburg, S. Reucroft, H. Silverwood

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan

M. Ahmad, M.H. Ansari, M.I. Asghar, H.R. Hoorani, S. Khalid, W.A. Khan, T. Khurshid, S. Qazi, M.A. Shah, M. Shoaib

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland

G. Brona, K. Bunkowski, M. Cwiok, W. Dominik, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski

Soltan Institute for Nuclear Studies, Warsaw, Poland

H. Bialkowska, B. Boimska, T. Frueboes, R. Gokieli, M. Górski, M. Kazana, K. Nawrocki, K. Romanowska-Rybinska, M. Szleper, G. Wrochna, P. Zalewski

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal

N. Almeida, P. Bargassa, A. David, P. Faccioli, P.G. Ferreira Parracho, M. Gallinaro, J. Seixas, J. Varela, P. Vischia

Joint Institute for Nuclear Research, Dubna, Russia

I. Belotelov, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavin, G. Kozlov, A. Lanev, A. Malakhov, P. Moisenz, V. Palichik, V. Perelygin, S. Shmatov, V. Smirnov, A. Volodko, A. Zarubin

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

S. Evstyukhin, V. Golovtsov, Y. Ivanov, V. Kim, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev, An. Vorobyev

Institute for Nuclear Research, Moscow, Russia

Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, M. Kirsanov, N. Krasnikov, V. Matveev, A. Pashenkov, D. Tlisov, A. Toropin

Institute for Theoretical and Experimental Physics, Moscow, Russia

V. Epshteyn, M. Erofeeva, V. Gavrilo, M. Kossov, N. Lychkovskaya, V. Popov, G. Safronov, S. Semenov, V. Stolin, E. Vlasov, A. Zhokin

Moscow State University, Moscow, Russia

A. Belyaev, E. Boos, M. Dubinin⁴, L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, A. Markina, S. Obraztsov, M. Perfilov, S. Petrushanko, A. Popov, L. Sarycheva[†], V. Savrin, A. Snigirev

P.N. Lebedev Physical Institute, Moscow, Russia

V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, A. Leonidov, G. Mesyats, S.V. Rusakov, A. Vinogradov

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

I. Azhgirey, I. Bayshev, S. Bitioukov, V. Grishin⁵, V. Kachanov, D. Konstantinov, A. Korablev, V. Krychkin, V. Petrov, R. Ryutin, A. Sobol, L. Tourtchanovitch, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia

P. Adzic³⁰, M. Djordjevic, M. Ekmedzic, D. Krpic³⁰, J. Milosevic

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

M. Aguilar-Benitez, J. Alcaraz Maestre, P. Arce, C. Battilana, E. Calvo, M. Cerrada, M. Chamizo

Llatas, N. Colino, B. De La Cruz, A. Delgado Peris, D. Domínguez Vázquez, C. Fernandez Bedoya, J.P. Fernández Ramos, A. Ferrando, J. Flix, M.C. Fouz, P. Garcia-Abia, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, G. Merino, J. Puerta Pelayo, A. Quintario Olmeda, I. Redondo, L. Romero, J. Santaolalla, M.S. Soares, C. Willmott

Universidad Autónoma de Madrid, Madrid, Spain

C. Albajar, G. Codispoti, J.F. de Trocóniz

Universidad de Oviedo, Oviedo, Spain

H. Brun, J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, L. Lloret Iglesias, J. Piedra Gomez³¹

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain

J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, S.H. Chuang, J. Duarte Campderros, M. Felcini³², M. Fernandez, G. Gomez, J. Gonzalez Sanchez, A. Graziano, C. Jorda, A. Lopez Virto, J. Marco, R. Marco, C. Martinez Rivero, F. Matorras, F.J. Munoz Sanchez, T. Rodrigo, A.Y. Rodríguez-Marrero, A. Ruiz-Jimeno, L. Scodellaro, M. Sobron Sanudo, I. Vila, R. Vilar Cortabitarte

CERN, European Organization for Nuclear Research, Geneva, Switzerland

D. Abbaneo, E. Auffray, G. Auzinger, P. Baillon, A.H. Ball, D. Barney, J.F. Benitez, C. Bernet⁶, G. Bianchi, P. Bloch, A. Bocci, A. Bonato, C. Botta, H. Breuker, T. Camporesi, G. Cerminara, T. Christiansen, J.A. Coarasa Perez, D. D'Enterria, A. Dabrowski, A. De Roeck, S. Di Guida, M. Dobson, N. Dupont-Sagorin, A. Elliott-Peisert, B. Frisch, W. Funk, G. Georgiou, M. Giffels, D. Gigi, K. Gill, D. Giordano, M. Giunta, F. Glege, R. Gomez-Reino Garrido, P. Govoni, S. Gowdy, R. Guida, M. Hansen, P. Harris, C. Hartl, J. Harvey, B. Hegner, A. Hinzmann, V. Innocente, P. Janot, K. KAADZE, E. Karavakis, K. Kousouris, P. Lecoq, Y.-J. Lee, P. Lenzi, C. Lourenço, T. Mäki, M. Malberti, L. Malgeri, M. Mannelli, L. Masetti, F. Meijers, S. Mersi, E. Meschi, R. Moser, M.U. Mozer, M. Mulders, P. Musella, E. Nesvold, T. Orimoto, L. Orsini, E. Palencia Cortezon, E. Perez, L. Perrozzi, A. Petrilli, A. Pfeiffer, M. Pierini, M. Pimiä, D. Piparo, G. Polese, L. Quertenmont, A. Racz, W. Reece, J. Rodrigues Antunes, G. Rolandi³³, C. Rovelli³⁴, M. Rovere, H. Sakulin, F. Santanastasio, C. Schäfer, C. Schwick, I. Segoni, S. Sekmen, A. Sharma, P. Siegrist, P. Silva, M. Simon, P. Sphicas³⁵, D. Spiga, N. Srimanobhas³⁶, A. Tsiros, G.I. Veres¹⁹, J.R. Vlimant, H.K. Wöhri, S.D. Worm³⁷, W.D. Zeuner

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. Sibille³⁸

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland

L. Bäni, P. Bortignon, M.A. Buchmann, B. Casal, N. Chanon, A. Deisher, G. Dissertori, M. Dittmar, M. Donegà, M. Dünser, J. Eugster, K. Freudenreich, C. Grab, D. Hits, P. Lecomte, W. Lustermann, A.C. Marini, P. Martinez Ruiz del Arbol, N. Mohr, F. Moortgat, C. Nägeli³⁹, P. Nef, F. Nessi-Tedaldi, F. Pandolfi, L. Pape, F. Pauss, M. Peruzzi, F.J. Ronga, M. Rossini, L. Sala, A.K. Sanchez, A. Starodumov⁴⁰, B. Stieger, M. Takahashi, L. Tauscher[†], A. Thea, K. Theofilatos, D. Treille, C. Urscheler, R. Wallny, H.A. Weber, L. Wehrli

Universität Zürich, Zurich, Switzerland

C. Amsler, V. Chiochia, S. De Visscher, C. Favaro, M. Ivova Rikova, B. Millan Mejias, P. Otiougova, P. Robmann, H. Snoek, S. Tuppusti, M. Verzetti

National Central University, Chung-Li, Taiwan

Y.H. Chang, K.H. Chen, C.M. Kuo, S.W. Li, W. Lin, Z.K. Liu, Y.J. Lu, D. Mekterovic, A.P. Singh, R. Volpe, S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan

P. Bartalini, P. Chang, Y.H. Chang, Y.W. Chang, Y. Chao, K.F. Chen, C. Dietz, U. Grundler, W.-S. Hou, Y. Hsiung, K.Y. Kao, Y.J. Lei, R.-S. Lu, D. Majumder, E. Petrakou, X. Shi, J.G. Shiu, Y.M. Tzeng, X. Wan, M. Wang

Cukurova University, Adana, Turkey

A. Adiguzel, M.N. Bakirci⁴¹, S. Cerci⁴², C. Dozen, I. Dumanoglu, E. Eskut, S. Girgis, G. Gokbulut, E. Gurpinar, I. Hos, E.E. Kangal, T. Karaman, G. Karapinar⁴³, A. Kayis Topaksu, G. Onengut, K. Ozdemir, S. Ozturk⁴⁴, A. Polatoz, K. Sogut⁴⁵, D. Sunar Cerci⁴², B. Tali⁴², H. Topakli⁴¹, L.N. Vergili, M. Vergili

Middle East Technical University, Physics Department, Ankara, Turkey

I.V. Akin, T. Aliev, B. Bilin, S. Bilmis, M. Deniz, H. Gamsizkan, A.M. Guler, K. Ocalan, A. Ozpineci, M. Serin, R. Sever, U.E. Surat, M. Yalvac, E. Yildirim, M. Zeyrek

Bogazici University, Istanbul, Turkey

E. Gülmez, B. Isildak⁴⁶, M. Kaya⁴⁷, O. Kaya⁴⁷, S. Ozkorucuklu⁴⁸, N. Sonmez⁴⁹

Istanbul Technical University, Istanbul, Turkey

K. Cankocak

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine

L. Levchuk

University of Bristol, Bristol, United Kingdom

F. Bostock, J.J. Brooke, E. Clement, D. Cussans, H. Flacher, R. Frazier, J. Goldstein, M. Grimes, G.P. Heath, H.F. Heath, L. Kreczko, S. Metson, D.M. Newbold³⁷, K. Nirunpong, A. Poll, S. Senkin, V.J. Smith, T. Williams

Rutherford Appleton Laboratory, Didcot, United Kingdom

L. Basso⁵⁰, K.W. Bell, A. Belyaev⁵⁰, C. Brew, R.M. Brown, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, J. Jackson, B.W. Kennedy, E. Olaiya, D. Petyt, B.C. Radburn-Smith, C.H. Shepherd-Themistocleous, I.R. Tomalin, W.J. Womersley

Imperial College, London, United Kingdom

R. Bainbridge, G. Ball, R. Beuselinck, O. Buchmuller, D. Colling, N. Cripps, M. Cutajar, P. Dauncey, G. Davies, M. Della Negra, W. Ferguson, J. Fulcher, D. Futyan, A. Gilbert, A. Guneratne Bryer, G. Hall, Z. Hatherell, J. Hays, G. Iles, M. Jarvis, G. Karapostoli, L. Lyons, A.-M. Magnan, J. Marrouche, B. Mathias, R. Nandi, J. Nash, A. Nikitenko⁴⁰, A. Papageorgiou, J. Pela, M. Pesaresi, K. Petridis, M. Pioppi⁵¹, D.M. Raymond, S. Rogerson, A. Rose, M.J. Ryan, C. Seez, P. Sharp[†], A. Sparrow, M. Stoye, A. Tapper, M. Vazquez Acosta, T. Virdee, S. Wakefield, N. Wardle, T. Whyntie

Brunel University, Uxbridge, United Kingdom

M. Chadwick, J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, D. Leggat, D. Leslie, W. Martin, I.D. Reid, P. Symonds, L. Teodorescu, M. Turner

Baylor University, Waco, USA

K. Hatakeyama, H. Liu, T. Scarborough

The University of Alabama, Tuscaloosa, USA

O. Charaf, C. Henderson, P. Rumerio

Boston University, Boston, USA

A. Avetisyan, T. Bose, C. Fantasia, A. Heister, J. St. John, P. Lawson, D. Lazic, J. Rohlf, D. Sperka, L. Sulak

Brown University, Providence, USA

J. Alimena, S. Bhattacharya, D. Cutts, A. Ferapontov, U. Heintz, S. Jabeen, G. Kukartsev, E. Laird, G. Landsberg, M. Luk, M. Narain, D. Nguyen, M. Segala, T. Sinthuprasith, T. Speer, K.V. Tsang

University of California, Davis, Davis, USA

R. Breedon, G. Breto, M. Calderon De La Barca Sanchez, S. Chauhan, M. Chertok, J. Conway, R. Conway, P.T. Cox, J. Dolen, R. Erbacher, M. Gardner, R. Houtz, W. Ko, A. Kopecky, R. Lander, T. Miceli, D. Pellett, F. Ricci-tam, B. Rutherford, M. Searle, J. Smith, M. Squires, M. Tripathi, R. Vasquez Sierra

University of California, Los Angeles, Los Angeles, USA

V. Andreev, D. Cline, R. Cousins, J. Duris, S. Erhan, P. Everaerts, C. Farrell, J. Hauser, M. Ignatenko, C. Jarvis, C. Plager, G. Rakness, P. Schlein[†], P. Traczyk, V. Valuev, M. Weber

University of California, Riverside, Riverside, USA

J. Babb, R. Clare, M.E. Dinardo, J. Ellison, J.W. Gary, F. Giordano, G. Hanson, G.Y. Jeng⁵², H. Liu, O.R. Long, A. Luthra, H. Nguyen, S. Paramesvaran, J. Sturdy, S. Sumowidagdo, R. Wilken, S. Wimpenny

University of California, San Diego, La Jolla, USA

W. Andrews, J.G. Branson, G.B. Cerati, S. Cittolin, D. Evans, F. Golf, A. Holzner, R. Kelley, M. Lebourgeois, J. Letts, I. Macneill, B. Mangano, S. Padhi, C. Palmer, G. Petrucciani, M. Pieri, M. Sani, V. Sharma, S. Simon, E. Sudano, M. Tadel, Y. Tu, A. Vartak, S. Wasserbaech⁵³, F. Würthwein, A. Yagil, J. Yoo

University of California, Santa Barbara, Santa Barbara, USA

D. Barge, R. Bellan, C. Campagnari, M. D'Alfonso, T. Danielson, K. Flowers, P. Geffert, J. Incandela, C. Justus, P. Kalavase, S.A. Koay, D. Kovalskyi, V. Krutelyov, S. Lowette, N. Mccoll, V. Pavlunin, F. Rebassoo, J. Ribnik, J. Richman, R. Rossin, D. Stuart, W. To, C. West

California Institute of Technology, Pasadena, USA

A. Apresyan, A. Bornheim, Y. Chen, E. Di Marco, J. Duarte, M. Gataullin, Y. Ma, A. Mott, H.B. Newman, C. Rogan, M. Spiropulu, V. Timciuc, J. Veverka, R. Wilkinson, S. Xie, Y. Yang, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, USA

B. Akgun, V. Azzolini, A. Calamba, R. Carroll, T. Ferguson, Y. Iiyama, D.W. Jang, Y.F. Liu, M. Paulini, H. Vogel, I. Vorobiev

University of Colorado at Boulder, Boulder, USA

J.P. Cumalat, B.R. Drell, C.J. Edelmaier, W.T. Ford, A. Gaz, B. Heyburn, E. Luiggi Lopez, J.G. Smith, K. Stenson, K.A. Ulmer, S.R. Wagner

Cornell University, Ithaca, USA

J. Alexander, A. Chatterjee, N. Eggert, L.K. Gibbons, B. Heltsley, A. Khukhunaishvili, B. Kreis, N. Mirman, G. Nicolas Kaufman, J.R. Patterson, A. Ryd, E. Salvati, W. Sun, W.D. Teo, J. Thom, J. Thompson, J. Tucker, J. Vaughan, Y. Weng, L. Winstrom, P. Wittich

Fairfield University, Fairfield, USA

D. Winn

Fermi National Accelerator Laboratory, Batavia, USA

S. Abdullin, M. Albrow, J. Anderson, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, I. Bloch, K. Burkett, J.N. Butler, V. Chetluru, H.W.K. Cheung, F. Chlebana, V.D. Elvira, I. Fisk, J. Freeman, Y. Gao, D. Green, O. Gutsche, J. Hanlon, R.M. Harris, J. Hirschauer, B. Hooberman, S. Jindariani, M. Johnson, U. Joshi, B. Kilminster, B. Klima, S. Kunori, S. Kwan, C. Leonidopoulos, J. Linacre, D. Lincoln, R. Lipton, J. Lykken, K. Maeshima, J.M. Marraffino, S. Maruyama, D. Mason, P. McBride, K. Mishra, S. Mrenna, Y. Musienko⁵⁴, C. Newman-Holmes, V. O'Dell, O. Prokofyev, E. Sexton-Kennedy, S. Sharma, W.J. Spalding, L. Spiegel, P. Tan, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, R. Vidal, J. Whitmore, W. Wu, F. Yang, F. Yumiceva, J.C. Yun

University of Florida, Gainesville, USA

D. Acosta, P. Avery, D. Bourilkov, M. Chen, T. Cheng, S. Das, M. De Gruttola, G.P. Di Giovanni, D. Dobur, A. Drozdetskiy, R.D. Field, M. Fisher, Y. Fu, I.K. Furic, J. Gartner, J. Hugon, B. Kim, J. Konigsberg, A. Korytov, A. Kropivnitskaya, T. Kypreos, J.F. Low, K. Matchev, P. Milenovic⁵⁵, G. Mitselmakher, L. Muniz, R. Remington, A. Rinkevicius, P. Sellers, N. Skhirtladze, M. Snowball, J. Yelton, M. Zakaria

Florida International University, Miami, USA

V. Gaultney, S. Hewamanage, L.M. Lebolo, S. Linn, P. Markowitz, G. Martinez, J.L. Rodriguez

Florida State University, Tallahassee, USA

T. Adams, A. Askew, J. Bochenek, J. Chen, B. Diamond, S.V. Gleyzer, J. Haas, S. Hagopian, V. Hagopian, M. Jenkins, K.F. Johnson, H. Prosper, V. Veeraraghavan, M. Weinberg

Florida Institute of Technology, Melbourne, USA

M.M. Baarmand, B. Dorney, M. Hohlmann, H. Kalakhety, I. Vodopiyarov

University of Illinois at Chicago (UIC), Chicago, USA

M.R. Adams, I.M. Anghel, L. Apanasevich, Y. Bai, V.E. Bazterra, R.R. Betts, I. Bucinskaite, J. Callner, R. Cavanaugh, C. Dragoiu, O. Evdokimov, L. Gauthier, C.E. Gerber, D.J. Hofman, S. Khalatyan, F. Lacroix, M. Malek, C. O'Brien, C. Silkworth, D. Strom, N. Varelas

The University of Iowa, Iowa City, USA

U. Akgun, E.A. Albayrak, B. Bilki⁵⁶, W. Clarida, F. Duru, S. Griffiths, J.-P. Merlo, H. Mermerkaya⁵⁷, A. Mestvirishvili, A. Moeller, J. Nachtman, C.R. Newsom, E. Norbeck, Y. Onel, F. Ozok, S. Sen, E. Tiras, J. Wetzel, T. Yetkin, K. Yi

Johns Hopkins University, Baltimore, USA

B.A. Barnett, B. Blumenfeld, S. Bolognesi, D. Fehling, G. Giurgiu, A.V. Gritsan, Z.J. Guo, G. Hu, P. Maksimovic, S. Rappoccio, M. Swartz, A. Whitbeck

The University of Kansas, Lawrence, USA

P. Baringer, A. Bean, G. Benelli, O. Grachov, R.P. Kenny Iii, M. Murray, D. Noonan, S. Sanders, R. Stringer, G. Tinti, J.S. Wood, V. Zhukova

Kansas State University, Manhattan, USA

A.F. Barfuss, T. Bolton, I. Chakaberia, A. Ivanov, S. Khalil, M. Makouski, Y. Maravin, S. Shrestha, I. Svintradze

Lawrence Livermore National Laboratory, Livermore, USA

J. Gronberg, D. Lange, D. Wright

University of Maryland, College Park, USA

A. Baden, M. Boutemeur, B. Calvert, S.C. Eno, J.A. Gomez, N.J. Hadley, R.G. Kellogg, M. Kirn,

T. Kolberg, Y. Lu, M. Marionneau, A.C. Mignerey, K. Pedro, A. Peterman, A. Skuja, J. Temple, M.B. Tonjes, S.C. Tonwar, E. Twedt

Massachusetts Institute of Technology, Cambridge, USA

A. Apyan, G. Bauer, J. Bendavid, W. Busza, E. Butz, I.A. Cali, M. Chan, V. Dutta, G. Gomez Ceballos, M. Goncharov, K.A. Hahn, Y. Kim, M. Klute, K. Krajczar⁵⁸, W. Li, P.D. Luckey, T. Ma, S. Nahn, C. Paus, D. Ralph, C. Roland, G. Roland, M. Rudolph, G.S.F. Stephans, F. Stöckli, K. Sumorok, K. Sung, D. Velicanu, E.A. Wenger, R. Wolf, B. Wyslouch, M. Yang, Y. Yilmaz, A.S. Yoon, M. Zanetti

University of Minnesota, Minneapolis, USA

S.I. Cooper, B. Dahmes, A. De Benedetti, G. Franzoni, A. Gude, S.C. Kao, K. Klapoetke, Y. Kubota, J. Mans, N. Pastika, R. Rusack, M. Sasseville, A. Singovsky, N. Tambe, J. Turkewitz

University of Mississippi, University, USA

L.M. Cremaldi, R. Kroeger, L. Perera, R. Rahmat, D.A. Sanders

University of Nebraska-Lincoln, Lincoln, USA

E. Avdeeva, K. Bloom, S. Bose, J. Butt, D.R. Claes, A. Dominguez, M. Eads, J. Keller, I. Kravchenko, J. Lazo-Flores, H. Malbouisson, S. Malik, G.R. Snow

State University of New York at Buffalo, Buffalo, USA

U. Baur, A. Godshalk, I. Iashvili, S. Jain, A. Kharchilava, A. Kumar, S.P. Shipkowski, K. Smith

Northeastern University, Boston, USA

G. Alverson, E. Barberis, D. Baumgartel, M. Chasco, J. Haley, D. Nash, D. Trocino, D. Wood, J. Zhang

Northwestern University, Evanston, USA

A. Anastassov, A. Kubik, N. Mucia, N. Odell, R.A. Ofierzynski, B. Pollack, A. Pozdnyakov, M. Schmitt, S. Stoynev, M. Velasco, S. Won

University of Notre Dame, Notre Dame, USA

L. Antonelli, D. Berry, A. Brinkerhoff, M. Hildreth, C. Jessop, D.J. Karmgard, J. Kolb, K. Lannon, W. Luo, S. Lynch, N. Marinelli, D.M. Morse, T. Pearson, M. Planer, R. Ruchti, J. Slaunwhite, N. Valls, M. Wayne, M. Wolf

The Ohio State University, Columbus, USA

B. Bylsma, L.S. Durkin, C. Hill, R. Hughes, K. Kotov, T.Y. Ling, D. Puigh, M. Rodenburg, C. Vuosalo, G. Williams, B.L. Winer

Princeton University, Princeton, USA

N. Adam, E. Berry, P. Elmer, D. Gerbaudo, V. Halyo, P. Hebda, J. Hegeman, A. Hunt, P. Jindal, D. Lopes Pegna, P. Lujan, D. Marlow, T. Medvedeva, M. Mooney, J. Olsen, P. Piroué, X. Quan, A. Raval, B. Safdi, H. Saka, D. Stickland, C. Tully, J.S. Werner, A. Zuranski

University of Puerto Rico, Mayaguez, USA

J.G. Acosta, E. Brownson, X.T. Huang, A. Lopez, H. Mendez, S. Oliveros, J.E. Ramirez Vargas, A. Zatserklyani

Purdue University, West Lafayette, USA

E. Alagoz, V.E. Barnes, D. Benedetti, G. Bolla, D. Bortoletto, M. De Mattia, A. Everett, Z. Hu, M. Jones, O. Koybasi, M. Kress, A.T. Laasanen, N. Leonardo, V. Maroussov, P. Merkel, D.H. Miller, N. Neumeister, I. Shipsey, D. Silvers, A. Svyatkovskiy, M. Vidal Marono, H.D. Yoo, J. Zablocki, Y. Zheng

Purdue University Calumet, Hammond, USA

S. Guragain, N. Parashar

Rice University, Houston, USA

A. Adair, C. Boulahouache, K.M. Ecklund, F.J.M. Geurts, B.P. Padley, R. Redjimi, J. Roberts, J. Zabel

University of Rochester, Rochester, USA

B. Betchart, A. Bodek, Y.S. Chung, R. Covarelli, P. de Barbaro, R. Demina, Y. Eshaq, A. Garcia-Bellido, P. Goldenzweig, J. Han, A. Harel, D.C. Miner, D. Vishnevskiy, M. Zielinski

The Rockefeller University, New York, USA

A. Bhatti, R. Ciesielski, L. Demortier, K. Goulios, G. Lungu, S. Malik, C. Mesropian

Rutgers, the State University of New Jersey, Piscataway, USA

S. Arora, A. Barker, J.P. Chou, C. Contreras-Campana, E. Contreras-Campana, D. Duggan, D. Ferencek, Y. Gershtein, R. Gray, E. Halkiadakis, D. Hidas, A. Lath, S. Panwalkar, M. Park, R. Patel, V. Rekovic, J. Robles, K. Rose, S. Salur, S. Schnetzer, C. Seitz, S. Somalwar, R. Stone, S. Thomas

University of Tennessee, Knoxville, USA

G. Cerizza, M. Hollingsworth, S. Spanier, Z.C. Yang, A. York

Texas A&M University, College Station, USA

R. Eusebi, W. Flanagan, J. Gilmore, T. Kamon⁵⁹, V. Khotilovich, R. Montalvo, I. Osipenkov, Y. Pakhotin, A. Perloff, J. Roe, A. Safonov, T. Sakuma, S. Sengupta, I. Suarez, A. Tatarinov, D. Toback

Texas Tech University, Lubbock, USA

N. Akchurin, J. Damgov, P.R. Duderod, C. Jeong, K. Kovitanggoon, S.W. Lee, T. Libeiro, Y. Roh, I. Volobouev

Vanderbilt University, Nashville, USA

E. Appelt, A.G. Delannoy, C. Florez, S. Greene, A. Gurrola, W. Johns, C. Johnston, P. Kurt, C. Maguire, A. Melo, M. Sharma, P. Sheldon, B. Snook, S. Tuo, J. Velkovska

University of Virginia, Charlottesville, USA

M.W. Arenton, M. Balazs, S. Boutle, B. Cox, B. Francis, J. Goodell, R. Hirosky, A. Ledovskoy, C. Lin, C. Neu, J. Wood, R. Yohay

Wayne State University, Detroit, USA

S. Gollapinni, R. Harr, P.E. Karchin, C. Kottachchi Kankanamge Don, P. Lamichhane, A. Sakharov

University of Wisconsin, Madison, USA

M. Anderson, M. Bachtis, D. Belknap, L. Borrello, D. Carlsmith, M. Cepeda, S. Dasu, L. Gray, K.S. Grogg, M. Grothe, R. Hall-Wilton, M. Herndon, A. Hervé, P. Klabbers, J. Klukas, A. Lanaro, C. Lazaridis, J. Leonard, R. Loveless, A. Mohapatra, I. Ojalvo, F. Palmonari, G.A. Pierro, I. Ross, A. Savin, W.H. Smith, J. Swanson

†: Deceased

1: Also at Vienna University of Technology, Vienna, Austria

2: Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

3: Also at Universidade Federal do ABC, Santo Andre, Brazil

4: Also at California Institute of Technology, Pasadena, USA

- 5: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
- 6: Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
- 7: Also at Suez Canal University, Suez, Egypt
- 8: Also at Zewail City of Science and Technology, Zewail, Egypt
- 9: Also at Cairo University, Cairo, Egypt
- 10: Also at Fayoum University, El-Fayoum, Egypt
- 11: Also at Ain Shams University, Cairo, Egypt
- 12: Now at British University, Cairo, Egypt
- 13: Also at Soltan Institute for Nuclear Studies, Warsaw, Poland
- 14: Also at Université de Haute-Alsace, Mulhouse, France
- 15: Now at Joint Institute for Nuclear Research, Dubna, Russia
- 16: Also at Moscow State University, Moscow, Russia
- 17: Also at Brandenburg University of Technology, Cottbus, Germany
- 18: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
- 19: Also at Eötvös Loránd University, Budapest, Hungary
- 20: Also at Tata Institute of Fundamental Research - HECR, Mumbai, India
- 21: Also at University of Visva-Bharati, Santiniketan, India
- 22: Also at Sharif University of Technology, Tehran, Iran
- 23: Also at Isfahan University of Technology, Isfahan, Iran
- 24: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Teheran, Iran
- 25: Also at Facoltà Ingegneria Università di Roma, Roma, Italy
- 26: Also at Università della Basilicata, Potenza, Italy
- 27: Also at Università degli Studi Guglielmo Marconi, Roma, Italy
- 28: Also at Università degli studi di Siena, Siena, Italy
- 29: Also at University of Bucharest, Faculty of Physics, Bucuresti-Magurele, Romania
- 30: Also at Faculty of Physics of University of Belgrade, Belgrade, Serbia
- 31: Also at University of Florida, Gainesville, USA
- 32: Also at University of California, Los Angeles, Los Angeles, USA
- 33: Also at Scuola Normale e Sezione dell' INFN, Pisa, Italy
- 34: Also at INFN Sezione di Roma; Università di Roma "La Sapienza", Roma, Italy
- 35: Also at University of Athens, Athens, Greece
- 36: Also at Chulalongkorn University, Bangkok, Thailand
- 37: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
- 38: Also at The University of Kansas, Lawrence, USA
- 39: Also at Paul Scherrer Institut, Villigen, Switzerland
- 40: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
- 41: Also at Gaziosmanpasa University, Tokat, Turkey
- 42: Also at Adiyaman University, Adiyaman, Turkey
- 43: Also at Izmir Institute of Technology, Izmir, Turkey
- 44: Also at The University of Iowa, Iowa City, USA
- 45: Also at Mersin University, Mersin, Turkey
- 46: Also at Ozyegin University, Istanbul, Turkey
- 47: Also at Kafkas University, Kars, Turkey
- 48: Also at Suleyman Demirel University, Isparta, Turkey
- 49: Also at Ege University, Izmir, Turkey
- 50: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
- 51: Also at INFN Sezione di Perugia; Università di Perugia, Perugia, Italy

52: Also at University of Sydney, Sydney, Australia

53: Also at Utah Valley University, Orem, USA

54: Also at Institute for Nuclear Research, Moscow, Russia

55: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia

56: Also at Argonne National Laboratory, Argonne, USA

57: Also at Erzincan University, Erzincan, Turkey

58: Also at KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary

59: Also at Kyungpook National University, Daegu, Korea