Year: 2013

Event shapes and azimuthal correlations in Z + jets events in pp collisions at sqrt(s) = 7 TeV

CMS Collaboration; Chatrchyan, S; Khachatryan, V; Sirunyan, A M; et al; Chiochia, V; Kilminster, B; Robmann, P

Abstract: Measurements of event shapes and azimuthal correlations are presented for events where a Z boson is produced in association with jets in proton-proton collisions. The data collected with the CMS detector at the CERN LHC at sqrt(s) = 7 TeV correspond to an integrated luminosity of 5.0 inverse femtobarns. The analysis provides a test of predictions from perturbative QCD for a process that represents a substantial background to many physics channels. Results are presented as a function of jet multiplicity, for inclusive Z boson production and for Z bosons with transverse momenta greater than 150 GeV, and compared to predictions from Monte Carlo event generators that include leading-order multiparton matrix-element (with up to four hard partons in the final state) and next-to-leading-order simulations of Z + 1-jet events. The experimental results are corrected for detector effects, and can be compared directly with other QCD models.

DOI: https://doi.org/10.1016/j.physletb.2013.04.025

Originally published at:
CMS Collaboration; Chatrchyan, S; Khachatryan, V; Sirunyan, A M; et al; Chiochia, V; Kilminster, B; Robmann, P (2013). Event shapes and azimuthal correlations in Z + jets events in pp collisions at sqrt(s) = 7 TeV. Physics Letters B, 722(4-5):238-261.
DOI: https://doi.org/10.1016/j.physletb.2013.04.025

Physics Letters B 722 (2013) 238–261

Contents lists available at SciVerse ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Event shapes and azimuthal correlations in Z + jets events in pp collisions at $\sqrt{s} = 7$ TeV ☆

CMS Collaboration *

CERN, Switzerland

ARTICLE INFO

Article history:
Received 8 January 2013
Received in revised form 4 April 2013
Accepted 8 April 2013
Available online 12 April 2013
Editor: M. Doser

Keywords:
CMS
Physics
Event shape
QCD

ABSTRACT

Measurements of event shapes and azimuthal correlations are presented for events where a Z boson is produced in association with jets in proton–proton collisions. The data collected with the CMS detector at the CERN LHC at $\sqrt{s} = 7$ TeV correspond to an integrated luminosity of 5.0 fb^{-1}. The analysis provides a test of predictions from perturbative QCD for a process that represents a substantial background to many physics channels. Results are presented as a function of jet multiplicity, for inclusive Z boson production and for Z bosons with transverse momenta greater than 150 GeV, and compared to predictions from Monte Carlo event generators that include leading-order multiparton matrix-element (with up to four hard partons in the final state) and next-to-leading-order simulations of Z + 1-jet events. The experimental results are corrected for detector effects, and can be compared directly with other QCD models.

1. Introduction

A detailed study of the production of a Z boson in association with jets in pp collisions at the CERN Large Hadron Collider (LHC) is of great interest. Measurements of this process can be confronted with the predictions of perturbative quantum chromodynamics (QCD) at the highest accessible energies and for a broad range of kinematic configurations. Considerable theoretical progress has been made in this field, such as developments in next-to-leading-order (NLO) calculations for up to four hard partons produced in association with a Z boson [1], NLO predictions for Z + 1-jet production that can be interfaced to parton shower (PS) approximations [2–6], and leading-order (LO) multiparton matrix-element (ME) event generators such as ALPGEN [7], MADGRAPH [8], and SHERPA [9], with provision for PS development. In addition, Z + jets production corresponds to a major background to many other processes at the LHC, such as the production of top quarks, and it is important in searches for supersymmetric particles and Higgs boson physics. An improved understanding of Z + jets production over the largest possible regions of phase space can therefore provide a helpful tool for extracting small signals.

Previous studies of angular correlations between the Z and the “leading” jet (the one with the largest p_T) and between the two jets of largest p_T have been reported at the Tevatron by the D0 Collaboration [10] and at the LHC by the ATLAS Collaboration using 36 pb^{-1} of integrated luminosity [11]. In this Letter, the comparison of models with data for highly boosted Z bosons with $p_T^Z > 150$ GeV is of particular interest. This region of phase space is critical in searches for new phenomena that are based on a large apparent imbalance in the total transverse momentum. Such imbalance can be produced, e.g. by the $Z \to \nu\nu$ standard model (SM) background. The uncertainty of this background contribution is limited by the accuracy of current Monte Carlo (MC) models, which can be improved through studies of leptonic ($\ell^+\ell^-$) decays of Z bosons and their correlations with the associated jets.

In addition to azimuthal distributions, we provide the first measurements of variables that categorize the topological structure of Z + jets events. Multijet production at e^+e^- and ep colliders was used in the past to tune parton showers and fragmentation functions in MC event generators, as well as to measure the values of the strong coupling constant [12–16]. A set of event shape variables suitable for hadron colliders has been proposed in Ref. [17], which provides resummed perturbative predictions at next-to-leading-log (NLL) for these variables. A measurement of event shapes in multijet events was reported recently by the Compact Muon Solenoid (CMS) Collaboration [18].

This Letter extends measurements of angular correlations and event shapes in Z + jets events by probing the features of final states containing $Z \to \ell^+\ell^-$ decays, where $\ell = \mu$ or e. Such final states, often referred to as Drell–Yan (DY), include contributions from γ^* and Z/γ^* interference terms arising from the irreducible background of virtual photons (γ^*) from $q\bar{q} \to \gamma^* \to \ell^+\ell^-$ processes. The data were collected with the CMS detector at a center-of-mass energy of 7 TeV, and correspond to an integrated

---

☆ © CERN for the benefit of the CMS Collaboration.

* *E-mail address:* cms-publication-committee-chair@cern.ch.

0370-2693/ © 2013 CERN. Published by Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.physletb.2013.04.025

luminosity of 5.0 fb^{-1}. The observed angular distributions and event shapes in Z + jets production are compared with predictions from several MC generators, and comprise the first study of this kind to be reported at the LHC.

2. CMS detector

The origin of the CMS coordinate system is chosen at the center of the detector, with the z axis pointing along the direction of the counterclockwise proton beam. The azimuthal angle is denoted as ϕ, the polar angle as θ, and the pseudorapidity is defined as $\eta = -\ln[\tan(\theta/2)]$. The central feature of the CMS detector is a superconducting solenoid of 6 m internal diameter that produces an axial magnetic field of 3.8 T. A silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass/plastic-scintillator hadronic calorimeter (HCAL) are positioned within the field volume. Iron and quartz-fiber hadronic calorimeters are located outside the magnetic field volume, within each endcap region of the CMS detector, at $3 < |\eta| < 5$. Muons are measured using gas-ionization detectors embedded in the flux-return yoke outside of the solenoid. A detailed description of the CMS detector can be found in Ref. [19].

3. Monte Carlo simulation

All production processes of concern, namely the Z + jets signal and backgrounds corresponding to top–antitop quark pairs ($\mathrm{t\bar{t}}$), dibosons (WZ, ZZ, WW), single top, and W + jets events are generated with MadGraph (version 5.1.1.0) [8], which provides up to four-parton final states and is interfaced to pythia (version 6.4.24) [20] using the Z2 tune [21] to implement showering and hadronization of the partons. The CTEQ6L1 [22] parton distribution functions (PDF) are chosen for these calculations. Alternative models for signal include (i) sherpa (version 1.3.1) [9] (with up to four-parton final states) using the CTEQ6m PDF [22] and the default tune, (ii) powheg [2–5] for generating Z + 1-jet events at NLO using the CT10 PDF [23] and interfaced to pythia (version 6.4.24) with the Z2 tune for parton showering and hadronization, and (iii) stand-alone pythia (version 6.4.24) with the Z2 tune. The cross sections for electroweak Z and W boson production are normalized to match the next-to-next-to-leading-order (NNLO) prediction obtained with FEWZ [24] and the CTEQ6m PDF. The $\mathrm{t\bar{t}}$ cross section is normalized to the next-to-next-to-leading-log (NNLL) calculation from Ref. [25]. NLO precision obtained from mcfm [26] with CTEQ6m PDF is used for the cross section for diboson (WZ, ZZ, WW) and single top processes.

The detector response is simulated using a detailed description of the CMS detector based on the Geant4 package [27], and the MC simulated events are reconstructed following the same procedures as used for data. During the data taking, an average of ten minimum-bias interactions occurred in each bunch crossing (pileup). The prevailing beam conditions are taken into account by reweighting the MC simulation to match the spectrum of pileup interactions observed in data.

4. Event selection and reconstruction

Event selection starts by requiring two high-p_T leptons at the trigger level. For muons, this corresponds to an online p_T threshold of 13 GeV (17 GeV during periods of higher instantaneous luminosity) for the muon of largest p_T (leading muon), and 8 GeV for the subleading muon. For electrons, the corresponding trigger thresholds are 17 GeV and 8 GeV. Offline, muon candidates are reconstructed through a simultaneous fit to the hits recorded in the tracker and the muon detectors [28]. Electrons are reconstructed using both calorimeter and tracking information [29]. The two leptons of largest p_T (i.e. the two leading leptons) in the event are required to be of opposite electric charge and have $p_\mathrm{T} > 20$ GeV, $|\eta| < 2.4$, and invariant mass satisfying $71 < m_{\ell\ell} < 111$ GeV to be considered Z boson candidates. The lepton candidates are also required to be isolated from other energy depositions in the event. In particular, an isolation variable is computed using the scalar sum of transverse momenta of tracks and calorimetric energy depositions within a cone defined by $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.3$ around the direction of the lepton, where $\Delta\phi$ is in radians. The contribution from pileup to this p_T sum is estimated from the distribution of the energy per unit area in the η–ϕ plane in each event [30], and is subtracted from the calculated sum. This corrected sum is required to be less than 15% of the measured p_T of the lepton. Lepton reconstruction efficiencies are determined using simulation, and corrected for differences between data and simulation using the "tag-and-probe" technique described in Ref. [31].

The inputs to the CMS jet clustering algorithm are the four-momentum vectors of the particles reconstructed using the particle-flow (PF) technique [32,33], which combines information from different subdetectors. Jets are reconstructed using the anti-k_T clustering algorithm [34], with a size parameter of $R = 0.5$, by summing the four-momenta of individual PF particles according to the FastJet package of Refs. [35,36].

The reconstructed PF candidates are calibrated to account for any nonlinear or nonuniform response of the CMS calorimetric system to neutral hadrons. Charged hadrons and photons are sufficiently well-measured in the tracker and in the ECAL, and do not need such corrections. However, the resulting jets require small additional energy adjustments, mostly from thresholds set on reconstructed tracks and from the clustering procedure in the PF algorithm, but also from biases generated through inefficiencies in reconstruction. Jet-energy corrections are obtained using simulated events that are generated with pythia (version 6.4.22), processed through a CMS detector simulation based on Geant4, and then combined with measurements of exclusive two-jet and photon + jet events from data [37]. By design, jet energy corrections bring reconstructed jets from detector level to particle level [38], as opposed to the parton level. An offset correction is also applied to account for the extra energy clustered in jets from the presence of additional proton–proton interactions (in-time or out-of-time pileup) within the same or neighboring bunch crossings. The overall jet-energy corrections depend on the η and p_T values of jets, and are applied as multiplicative factors to the four-momentum vector of each jet. These factors range between 1.0 and 1.2, and are approximately uniform in η. The jets accepted for analysis are required to satisfy $p_\mathrm{T} > 50$ GeV and $|\eta| < 2.5$. In addition, all jet axes are required to be separated by $\Delta R > 0.4$ from those of lepton candidates from $Z \to \ell^+\ell^-$ decays. From MC studies, it is found that the selection efficiency of Z + jets candidates is almost independent of jet multiplicity.

5. Observable quantities

The observable quantities used to describe the properties of Z + jets events are the differential cross sections as functions of the azimuthal angles $\Delta\phi(\mathrm{Z}, j_i)$ between the transverse momentum vectors of the Z boson and the ith leading jet in the event; the azimuthal angles among the three jets of leading $p_\mathrm{T}\Delta\phi(j_i, j_k)$, with $i < k$, and i and k corresponding to 1, 2, or 3; and the transverse thrust τ_T, defined as [17]

$$\tau_\mathrm{T} \equiv 1 - \max_{\vec{n}_\tau} \frac{\sum_i |\vec{p}_{\mathrm{T},i} \cdot \vec{n}_\tau|}{\sum_i p_{\mathrm{T},i}}, \tag{1}$$

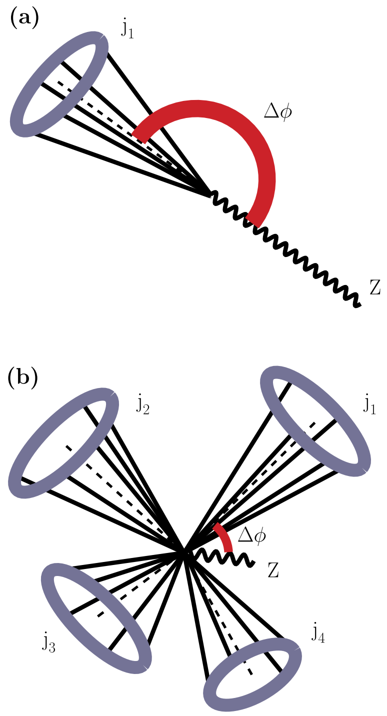

Fig. 1. Topology of $Z+\text{jets}$ events: (a) for $\ln\tau_T \to -\infty$ and $\Delta\phi(Z, j_1) \to \pi$; (b) for $\ln\tau_T \to -1$ and $\Delta\phi(Z, j_1) \ll \pi$.

where the four-momenta of the Z boson and the jets are used as inputs to calculate τ_T, with $\vec{p}_{T,i}$ being the transverse momentum vector of object i, and the sum running over the Z and each accepted jet in the event. The unit vector $\vec{n}_\tau$ that maximizes the sum, and thereby minimizes τ_T, is called the thrust axis. In the limit of the production of back-to-back $Z+1$-jet events, τ_T tends to zero (Fig. 1(a)). With additional jet emission (i.e. the appearance of a second jet), the values of thrust increase. Thrust is most sensitive to specifics of modeling of two-jet and three-jet topologies, while it is less sensitive to QCD modeling of larger jet multiplicities. For clarity of presentation, we display results in terms of $\ln\tau_T$ rather than τ_T. The largest possible value is reached in the limit of a spherical, isotropically distributed event, where $\ln\tau_T \to \ln(1 - 2/\pi) \approx -1$ (Fig. 1(b)). In this limiting case the term $2/\pi$ originates from the uniform azimuthal distribution of the transverse momenta.

To investigate the dependence of the topological properties on the complexity of the final state, the events are categorized as a function of jet multiplicity. In particular, the azimuthal distributions are reported in inclusive bins of one, two, or three jets. Furthermore, the phase space is characterized according to the p_T of the Z boson, and measurements are performed either for all p_T^Z or in the region of $p_T^Z > 150$ GeV. Figs. 2 and 3 show, respectively, the distributions in the associated jet multiplicity and the p_T of $\mu^+\mu^-$ and e^+e^- systems for $\geqslant 1$ jet events, prior to background subtraction. Both sets of distributions are presented at the detector level, and are within statistical uncertainty of the MC predictions for DY+jets, $t\bar{t}$, and other electroweak (EW) background sources. It should be noted that p_T^Z refers to the transverse momentum of the Z boson, following background subtraction and unfolding of detector effects.

6. Analysis procedure and systematic uncertainties

The analysis procedure consists of the following steps: $Z \to ee$ and $Z \to \mu\mu$ candidates are selected as described in Section 4; the background is then subtracted and the resulting distributions are unfolded to the particle level; finally, the two channels are combined. The dominant sources of systematic uncertainty arise from uncertainties in jet-energy scale, resolution of jet p_T, background subtraction, and the unfolding procedure. Individual steps of the analysis procedure are detailed below.

The $Z+\text{jets}$ candidates include several sources of SM background (Fig. 2), which are subtracted using predictions of the MadGraph MC event generator. The dominant background is from $t\bar{t}$ production, and is about 1.1%, 4%, and 8%, for the $N_\text{jets} \geqslant 1$, $\geqslant 2$, and $\geqslant 3$ inclusive bins of jet multiplicity. An independent evaluation of the background from $t\bar{t}$ events is also obtained from an $e\mu$ control sample in data, which is selected by requiring the presence of an electron and a muon of opposite charge, but otherwise using the same criteria as used for selecting the $Z+\text{jets}$ events. For each jet multiplicity bin, the estimates obtained from data and MC simulation agree within 6%. The two estimates are consistent, given the uncertainties on the integrated luminosity (2.2%) [39] and on the $t\bar{t}$ cross section (6%) [25]. Background originating from dibosons is 0.06%, 0.06% and 0.01% for the WW, WZ and ZZ channels, respectively. The contribution from $Z \to \tau\tau$ is $< 0.08\%$, largely because of the requirement on the Z mass of $71 < m_{\ell\ell} < 111$ GeV. Contributions from $W+\text{jets}$ to the two-electron final state are estimated to be 0.1%, and $< 0.1\%$ to the two-muon channel. The contribution from single top quark production is estimated as $< 0.1\%$. Background from multijet production, estimated using dilepton pairs of same electric charge, is found to be negligible. A total uncertainty of 10% is assigned to the expectation from all background sources. The limited contribution of backgrounds to the Z boson candidate sample is reflected in a $< 1\%$ uncertainty on the final measurement.

The particle level four-momentum vector of a lepton is computed in the MC simulation by adding the four-momentum vectors of any photons found within a radius of $\Delta R = 0.1$ of each lepton axis to the four-momentum vector of the lepton. For the observables of interest in this analysis, the use of this cone size makes the electron and muon channels essentially the same at the particle level. In this way, the difference in final-state radiation in the $Z \to \mu\mu$ and $Z \to ee$ channels is accounted for and the two channels can then be directly combined. The particle level jets in MC events are reconstructed by clustering the generated stable particles (after hadronization) using the same anti-k_T algorithm, with a parameter $R = 0.5$, as done in data. The selection criteria used in data are also applied to particle level leptons and jets: the two leading leptons are required to have $p_T > 20$ GeV and $|\eta| < 2.4$, while the jets must have $p_T > 50$ GeV and $|\eta| < 2.5$. An angular separation of $\Delta R(\ell, j) > 0.4$ is also required between the two leading leptons and any accepted jet. Finally, the unfolded distributions from the $Z \to ee$ and $Z \to \mu\mu$ channels are combined at the level of covariance matrices using the best linear unbiased estimator [40].

The background-subtracted, detector level distributions are mapped to the particle level by correcting for effects of detector resolution and efficiency. Migration of events among bins of inclusive jet multiplicity can be caused by detector resolution, especially from the mismeasurement of jet p_T. For example, an event containing a Z boson produced in association with N jets at the particle level, can migrate to the $N+1$ jets final state as a result of detector resolution. The opposite effect can also occur leading to loss of events that migrate out of the geometric and kinematic acceptance. Such migrations correspond to as much as 30% and are treated in the detector unfolding procedure summarized below. Detector effects are expressed through a response matrix, which is determined from MC simulation, separately for each lepton flavor and each observable, by associating the particle level values

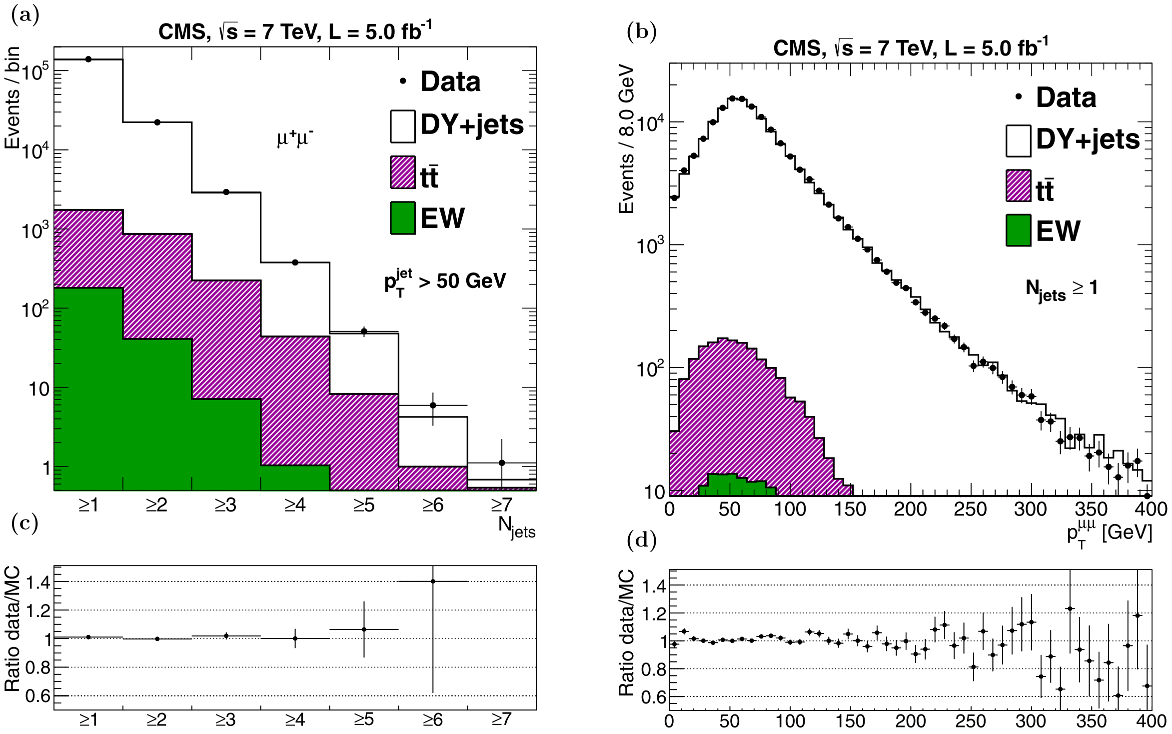

Fig. 2. Distributions for $Z \to \mu\mu$ candidate events in data, compared with expectations from simulated signal and background contributions using MADGRAPH simulations normalized to the integrated luminosity of the data: (a) as a function of associated jet multiplicity N_{jets}, and (b) as a function of p_T of the dimuon pair ($p_T^{\mu\mu}$) for $N_{\text{jets}} \geqslant 1$. The dibosons WW, WZ, ZZ and W + jets backgrounds are collectively denoted as EW in the legends. The plots in (c) and (d) show the ratios of the data to predictions from MC. The error bars on the data points represent only their statistical uncertainties and do not include systematic effects.

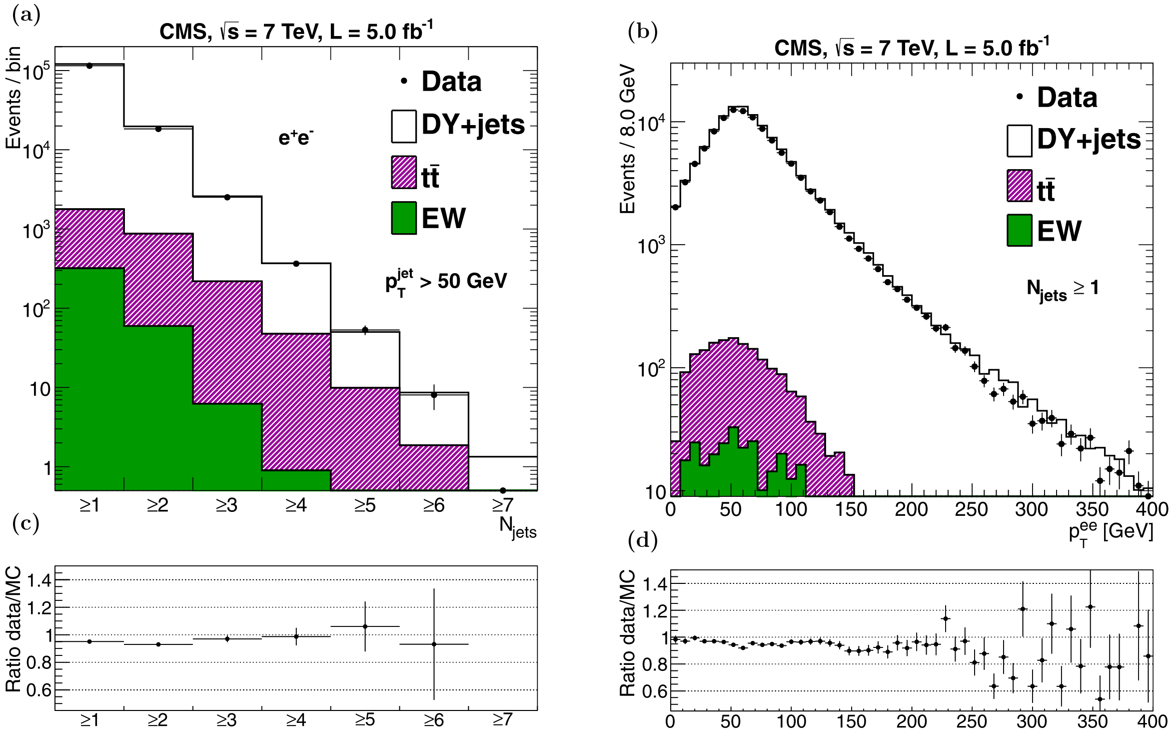

Fig. 3. Distributions for $Z \to ee$ candidate events in data, compared with expectations from simulated signal and background contributions using MADGRAPH simulations normalized to the integrated luminosity of the data: (a) as a function of associated jet multiplicity N_{jets}, and (b) as a function of p_T of the dielectron pair (p_T^{ee}) for $N_{\text{jets}} \geqslant 1$. The dibosons WW, WZ, ZZ and W + jets backgrounds are collectively denoted as EW in the legends. The plots in (c) and (d) show the ratios of the data to predictions from MC. The error bars on the data points represent only their statistical uncertainties and do not include systematic effects.

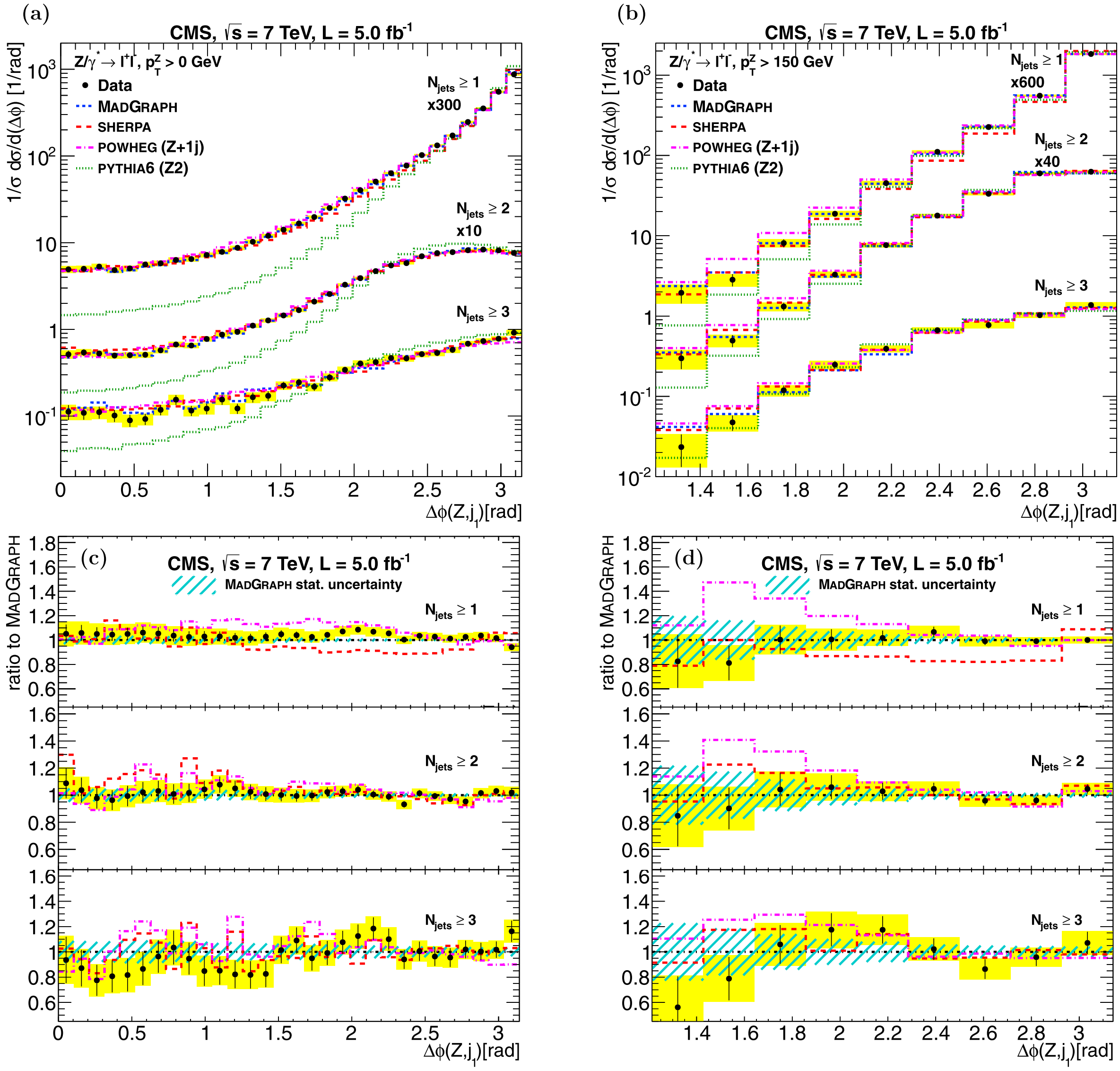

Fig. 4. Normalized $\Delta\phi(\mathrm{Z}, j_1)$ distributions for the leading jet in the inclusive jet multiplicity bins $N_{\text{jets}} \geqslant 1, \geqslant 2$, and $\geqslant 3$: (a) all $p_{\mathrm{T}}^{\mathrm{Z}}$ and (b) $p_{\mathrm{T}}^{\mathrm{Z}} > 150$ GeV. Plots in (c) and (d) show the corresponding ratios of the data (solid points), and of other MC predictions, relative to MadGraph. The ratio for pythia MC is not included in these plots. The error bars on the data points represent their statistical uncertainties, the solid yellow shaded band around the points represents the sum of statistical and systematic uncertainties taken in quadrature, while the cross-hatched (cyan) bands reflect the statistical uncertainties on the MadGraph calculations. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this Letter.)

to their reconstructed quantities. Two alternative representations of the response matrix, one generated from MadGraph (baseline) and the other from sherpa, are used in this procedure, and half of the difference of the propagated results is used to define their systematic uncertainty. The unfolding of data to the particle level is performed using the Singular Value Decomposition method [41], implemented in the RooUnfold package [42]. The total systematic uncertainty due to the unfolding procedure is < 5% for azimuthal correlations and < 2% for the thrust analysis.

Among the azimuthal observables, the distribution of $\Delta\phi(\mathrm{Z}, j_1)$ has the largest systematic uncertainty. This variable is particularly sensitive to the jet-energy scale, which can affect jet multiplicity, and thus the acceptance of events that enter in the $\Delta\phi(\mathrm{Z}, j_1)$ distribution. The uncertainty on jet-energy scale varies between 1 and 3% [37], and results in an uncertainty of 2–4% on the distribution in $\Delta\phi(\mathrm{Z}, j_1)$, increasing monotonically for decreasing angles. The impact from the resolution on p_{T} is estimated by changing jet resolutions by ±10% (corresponding to about one standard deviation) [37], and comparing the unfolding correction before and after these changes. This yields a dependence of ≈ 1% in the normalized azimuthal distributions. The uncertainty from pileup is estimated by changing in simulation the number of generated minimum-bias interactions by ±5%. The resulting uncertainty is 4% for $\Delta\phi(Z, j_1) \approx 0$, which decreases to a negligible uncertainty for $\Delta\phi(Z, j_1) \approx \pi$. The overall systematic uncertainty on $\Delta\phi(\mathrm{Z}, j_1)$ is about 5–6% at values of $\Delta\phi(\mathrm{Z}, j_1) \approx 0$ and about 2% at values close to π.

The dominant systematic uncertainty on the thrust distribution, which corresponds to about 2%, is from the uncertainty in jet-energy scale, and can be understood as follows. When the energy scale is increased, more jets enter the two sums in Eq. (1), and both sums tend to shift to larger values. Conversely, when the jet-energy scale is decreased, their values decrease. The contribution from uncertainty in jet-energy resolution is found to affect

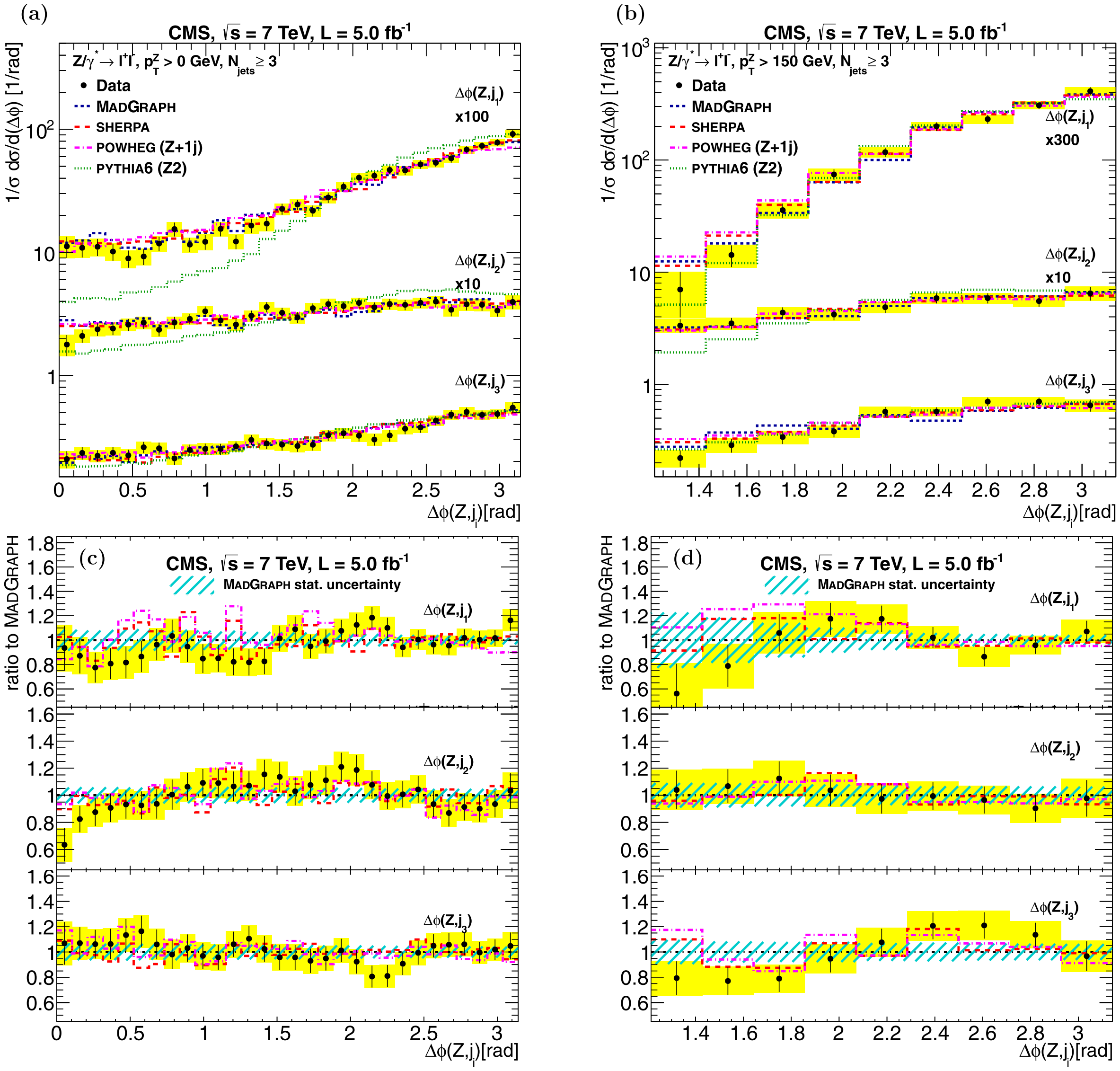

Fig. 5. Normalized $\Delta\phi(\mathrm{Z}, j_i)$ distributions for the inclusive $N_{\mathrm{jets}} \geqslant 3$ jet multiplicity bin: (a) all $p_{\mathrm{T}}^{\mathrm{Z}}$ and (b) $p_{\mathrm{T}}^{\mathrm{Z}} > 150$ GeV. Plots in (c) and (d) show the ratios of the data and other MC predictions, relative to MadGraph, as described in Fig. 4.

the transverse thrust by 1%, and the uncertainties from selection efficiencies are $< 2\%$ for the entire range of $\ln\tau_{\mathrm{T}}$, while the uncertainties from pileup and background subtraction have negligible impact. The first conclusion is implied in Eq. (1), as soft additional pileup energy added to the hard jets contributes simultaneously to both the numerator and denominator and, to first order, cancels in the ratio. The second conclusion follows from the fact that the transverse thrust is measured in the inclusive Z + ⩾1-jet sample, where the signal purity is almost 99%, and background subtraction has therefore only a minimal impact on the measurement of $\ln\tau_{\mathrm{T}}$.

For $p_{\mathrm{T}}^{\mathrm{Z}} > 150$ GeV the uncertainties on the azimuthal variables and on $\ln\tau_{\mathrm{T}}$ are evaluated following the same procedure as described above. However, in addition to the uncertainties originating from previously discussed effects, the statistical limitations of the MC samples become important and the systematic uncertainty on the result therefore increases. The impact of the uncertainties on the electron and muon selection efficiencies due to energy scale, trigger and resolution has been assessed and found to be negligible.

7. Results

The corrected differential cross sections (normalized to unity) are compared to the predictions of MadGraph, sherpa, powheg Z + 1-jet (NLO), and pythia generators. The differential cross sections in the $\Delta\phi$ and $\ln\tau_{\mathrm{T}}$ variables are divided by the total Z + jets cross section for the range defined by the lepton and jet kinematic selection criteria, i.e. $p_{\mathrm{T}} > 20$ GeV and $|\eta| < 2.4$ for leptons, and $p_{\mathrm{T}} > 50$ GeV and $|\eta| < 2.5$ for jets, and $\Delta R > 0.4$ for jet–lepton separation. The distributions in data and MC are therefore normalized to unity. Fig. 4 shows $\Delta\phi(\mathrm{Z}, j_1)$ as a function of jet multiplicity for inclusive $\mathrm{Z} + N_{\mathrm{jets}}$ production, with $N_{\mathrm{jets}} \geqslant 1, 2,$ and 3. Figs. 5 and 6 show the $\Delta\phi(\mathrm{Z}, j_i)$ and $\Delta\phi(j_i, j_k)$ distributions, where i, k represent jet indices in order of decreasing p_{T}, for $N_{\mathrm{jets}} \geqslant 3$. For the sake of comparison, the $\Delta\phi(\mathrm{Z}, j_1)$ results for $N_{\mathrm{jets}} \geqslant 3$ from Fig. 4 are also included in Fig. 5. These distributions characterize essentially all the azimuthal correlations in the $N_{\mathrm{jets}} \geqslant 3$ inclusive jet multiplicity bin. Finally, the Z + jets distributions in $\ln\tau_{\mathrm{T}}$ are presented in Fig. 7. For both azimuthal and $\ln\tau_{\mathrm{T}}$ distributions, the sum of statistical and systematic uncertainties

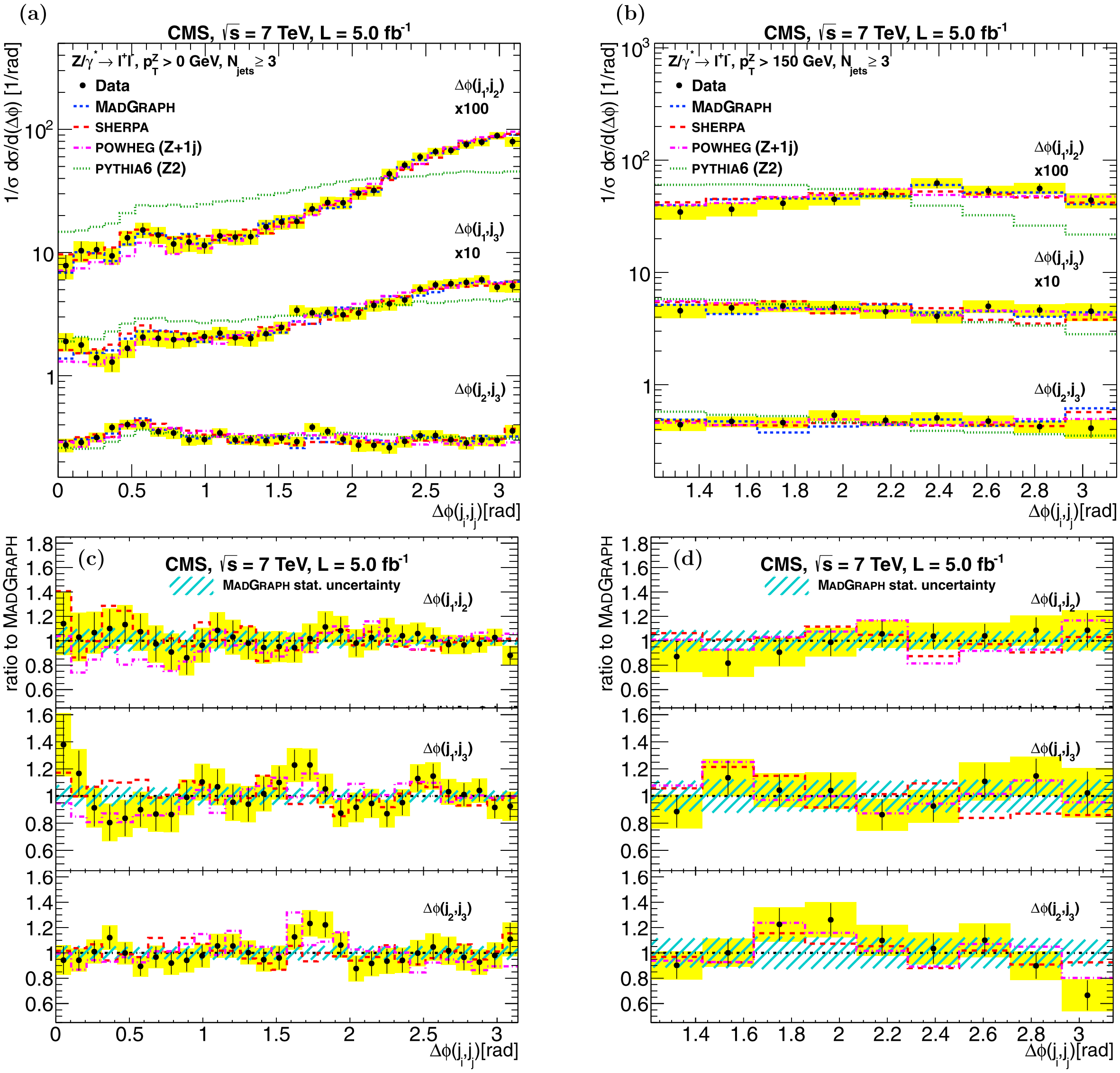

Fig. 6. Normalized $\Delta\phi(j_i, j_j)$ distributions for the inclusive $N_{\text{jets}} \geqslant 3$ jet multiplicity bin: (a) all p_T^Z and (b) $p_T^Z > 150$ GeV. Plots in (c) and (d) show the ratios of the data and other MC predictions, relative to MADGRAPH, as described in Fig. 4.

taken in quadrature are presented as solid yellow shaded bands. The statistical uncertainty from the MADGRAPHMC is displayed as a cross-hatched band for each distribution.

Overall, the measured distributions in $\Delta\phi(\mathrm{Z}, j_1)$ agree within uncertainties with the predictions from MADGRAPH. The predictions from SHERPA underestimate the measured distributions by about 10% whereas POWHEG predictions overestimate by about 10%. The disagreements with SHERPA and POWHEG (as well as between the two models) become less pronounced at larger inclusive jet multiplicities (Fig. 4). For $N_{\text{jets}} = 1$, the Z boson and the accompanying parton are completely correlated, and $\Delta\phi(\mathrm{Z}, j_1) \approx \pi$ (Fig. 1(a)). When $\Delta\phi(\mathrm{Z}, j_1) \ll \pi$, the presence of additional hard QCD radiation is implied. Certain configurations of jets with $\Delta\phi(\mathrm{Z}, j_1) < \pi/2$ probe events where the Z boson is in the same hemisphere as the leading jet, and the $\vec{p}_T$ of the Z boson is therefore balanced by at least two (or more) subleading jets emitted in the opposite hemisphere (Fig. 1(b)). The importance of the multiparton LO + PS approach, as reflected in MADGRAPH and SHERPA, can be seen when the data are compared to stand-alone PYTHIA at $\Delta\phi(\mathrm{Z}, j_1) < 2.5$ and $N_{\text{jets}} \geqslant 1$. For higher jet multiplicities of $N_{\text{jets}} \geqslant 2$ and $\geqslant 3$, the distribution in $\Delta\phi(\mathrm{Z}, j_1)$ becomes more isotropic, although a strong correlation remains at $\Delta\phi = \pi$.

Within uncertainties, good agreement is observed between the data and MADGRAPH, SHERPA, and POWHEG event generators for $N_{\text{jets}} \geqslant 3$. Stand-alone PYTHIA is also consistent with the distributions in $\Delta\phi(\mathrm{Z}, j_3)$ and $\Delta\phi(j_2, j_3)$. In PYTHIA, these high-multiplicity configurations are generated exclusively from the PS contribution. The important role of the PS approximation in modifying the kinematics predicted from fixed-order calculations is emphasized in POWHEG, where its predictive power in a multijet environment ($N_{\text{jets}} \geqslant 3$) is evident in Figs. 4–6. While POWHEG represents an NLO prediction only for the leading jet, and additional radiation is modeled exclusively using parton showers, good agreement is observed for data with $N_{\text{jets}} \geqslant 3$.

For the region $p_T^Z > 150$ GeV, the $\Delta\phi(\mathrm{Z}, j_1)$ distributions become more isotropic as jet multiplicity increases. In addition, and contrary to the result for all p_T^Z, the angular distributions between the subleading jets $\Delta\phi(j_i, j_k)$ also become isotropic (Fig. 6(b)). The improved performance of PYTHIA in this region is consistent with the increased phase space available for parton emission. A similar

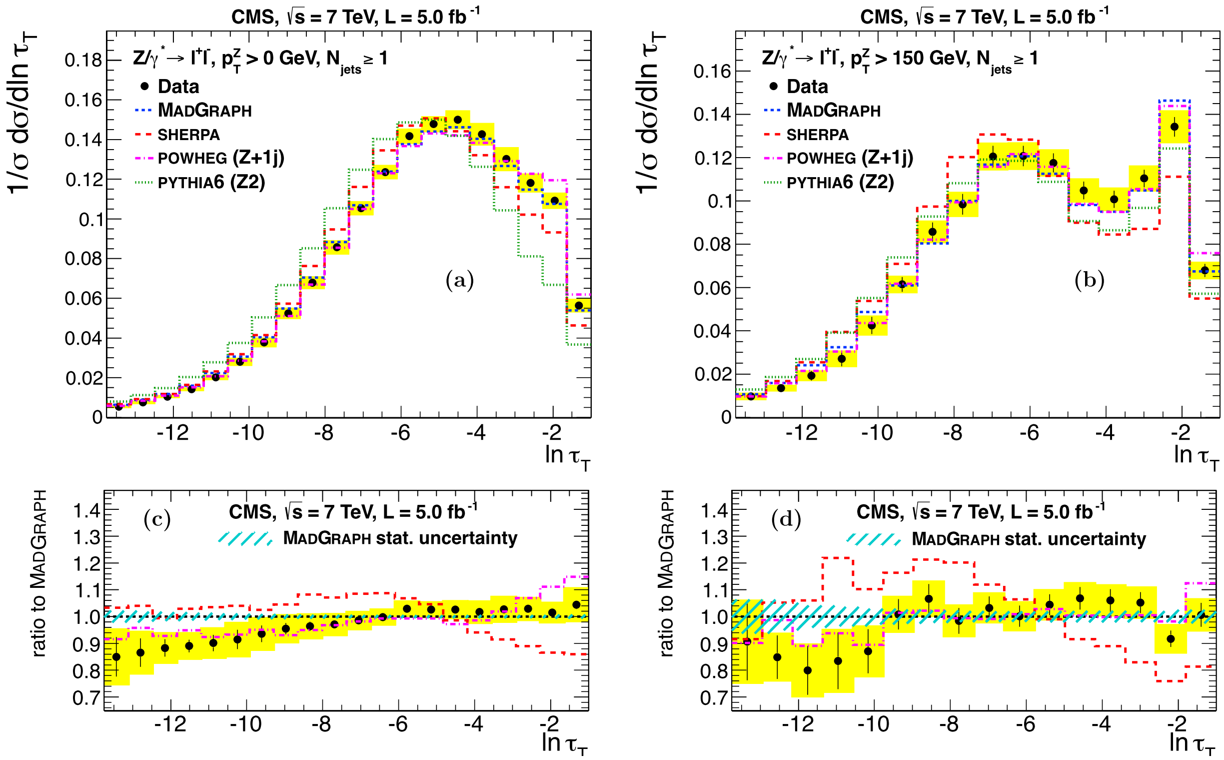

Fig. 7. Normalized distributions in $\ln\tau_T$ for (a) all p_T^Z and $N_{\text{jets}} \geqslant 1$ data, and (b) for $p_T^Z > 150$ GeV and $N_{\text{jets}} \geqslant 1$. Plots in (c) and (d) show the ratios of the data and other MC predictions, relative to MadGraph, as described in Fig. 4.

observation can be made for distributions in $\ln\tau_T$, which are discussed below. The level of agreement between PYTHIA and data for distributions in $\ln\tau_T$ improves for $p_T^Z > 150$ GeV (Fig. 7).

The corrected normalized differential distributions in $\ln\tau_T$ are displayed in Fig. 7. The distributions for large p_T^Z indicate an accumulation of events at values of $\ln\tau_T \approx -2$, as could be expected, because this region of phase space corresponds to contributions from events with a large spherical component, corresponding to production of two or more jets. Among the four examined models, POWHEG and MadGraph are more consistent with the data, being within 10% of the measured distributions, except at large negative values of $\ln\tau_T$, where ≈ 15–20% deviations are observed. The level of agreement of SHERPA with data corresponds to 10–15% for most of the bins, while PYTHIA shows discrepancies of $> 20\%$. PYTHIA and SHERPA also predict too small values of $\ln\tau_T$, especially at values dominated by configurations in which the leading jet is produced back-to-back with the Z boson. This yields a larger proportion of back-to-back Z + 1-jet events relative to data at small $\ln\tau_T$, an effect that can also be observed in the $\Delta\phi(\text{Z}, j_1)$ distribution of Fig. 4.

8. Summary

This Letter reports studies of angular correlations among the objects in Z+jets final states. The measurements are based on data corresponding to an integrated luminosity of 5.0 fb^{-1}, collected with the CMS detector at the LHC in proton–proton collisions at $\sqrt{s} = 7$ TeV.

Azimuthal correlations among the Z boson and the accompanying jets, $\Delta\phi(\text{Z}, j_i)$ and $\Delta\phi(j_i, j_k)$, are measured as functions of inclusive jet multiplicity ($N_{\text{jets}} \geqslant 1, \geqslant 2,$ and $\geqslant 3$). In addition, the transverse thrust event shape variable $\ln\tau_T$ is used to characterize the events. Two regions of phase space are probed: (i) all events, independent of p_T^Z, and (ii) the more highly boosted subset of events with $p_T^Z > 150$ GeV. The systematic uncertainties are smaller than those arising from statistical sources, which dominate in the extreme regions of phase space.

The data are compared with predictions from MadGraph, SHERPA, POWHEG Z+1-jet (at NLO), and stand-alone PYTHIA Z+1-jet (at LO). PYTHIA corresponds to the simplest model, and is used to gauge the importance of additional corrections from LO and NLO ME formulations that are interfaced with programs that evolve parton showers. Stand-alone PYTHIA provides an adequate description of event topologies when the phase space available for parton emission is large, e.g. for the highly boosted selection on p_T^Z. The MC models that combine multiparton QCD LO ME interfaced to parton shower evolution tend to agree with the data. The Z + 1-jet ME calculation (at NLO) provided by POWHEG shows agreement with data at large jet multiplicity in the entire phase space probed in this study, despite the fact that, beyond the subleading jet, additional radiation comes exclusively from parton showers.

The measurements presented in this study provide a detailed description of the topological structure of Z + jets production that is complementary to existing measurements of rates and associated jet multiplicities. As theoretical understanding evolves, these results can be used as additional probes of the validity of QCD predictions, while also providing confidence in the current MC models as useful tools for the description of SM processes and their application for determining background in searches for new phenomena.

Acknowledgements

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: BMWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MEYS (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES (Croatia); RPF (Cyprus); MoER, SF0690030s09 and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NKTH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); NRF and WCU (Republic of Korea); LAS (Lithuania); CINVESTAV, CONACYT, SEP, and UASLP-FAI (Mexico); MSI (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Armenia, Belarus, Georgia, Ukraine, Uzbekistan); MON, RosAtom, RAS and RFBR (Russia); MSTD (Serbia); SEIDI and CPAN (Spain); Swiss Funding Agencies (Switzerland); NSC (Taipei); ThEPCenter, IPST and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

Open access

References

[1] H. Ita, Z. Bern, L.J. Dixon, F. Febres Cordero, D.A. Kosower, D. Maitre, Phys. Rev. D 85 (2012) 031501, http://dx.doi.org/10.1103/PhysRevD.85.031501.
[2] P. Nason, JHEP 0411 (2004) 040, http://dx.doi.org/10.1088/1126-6708/2004/11/040.
[3] S. Frixione, P. Nason, C. Oleari, JHEP 0711 (2007) 070, http://dx.doi.org/10.1088/1126-6708/2007/11/070.
[4] S. Alioli, P. Nason, C. Oleari, E. Re, JHEP 1006 (2010) 043, http://dx.doi.org/10.1007/JHEP06(2010)043.
[5] S. Alioli, P. Nason, C. Oleari, E. Re, JHEP 1101 (2011) 095, http://dx.doi.org/10.1007/JHEP01(2011)095.
[6] S. Frixione, B.R. Webber, JHEP 0206 (2002) 029, http://dx.doi.org/10.1088/1126-6708/2002/06/029.
[7] M.L. Mangano, M. Moretti, F. Piccinini, R. Pittau, A.D. Polosa, JHEP 0307 (2003) 001, http://dx.doi.org/10.1088/1126-6708/2003/07/001.
[8] J. Alwall, M. Herquet, F. Maltoni, O. Mattelaer, T. Stelzer, JHEP 1106 (2011) 128, http://dx.doi.org/10.1007/JHEP06(2011)128.
[9] T. Gleisberg, S. Höche, F. Krauss, M. Schönherr, S. Schumann, F. Siegert, J. Winter, JHEP 0902 (2009) 007, http://dx.doi.org/10.1088/1126-6708/2009/02/007.
[10] V.M. Abazov, et al., D0 Collaboration, Phys. Lett. B 682 (2010) 370, http://dx.doi.org/10.1016/j.physletb.2009.11.012.
[11] ATLAS Collaboration, Phys. Rev. D 85 (2012) 032009, http://dx.doi.org/10.1103/PhysRevD.85.032009.
[12] A. Aktas, et al., H1 Collaboration, Eur. Phys. J. C 46 (2006) 343, http://dx.doi.org/10.1140/epjc/s2006-02493-x.
[13] S. Chekanov, et al., ZEUS Collaboration, Nucl. Phys. B 767 (2007) 1, http://dx.doi.org/10.1016/j.nuclphysb.2006.05.016.
[14] P. Abreu, et al., DELPHI Collaboration, Z. Phys. C 73 (1996) 11, http://dx.doi.org/10.1007/s002880050295.
[15] G. Dissertori, A. Gehrmann-De Ridder, T. Gehrmann, E.W.N. Glover, G. Heinrich, G. Luisoni, H. Stenzel, JHEP 0908 (2009) 036, http://dx.doi.org/10.1088/1126-6708/2009/08/036.
[16] R. Barate, et al., ALEPH Collaboration, Phys. Rept. 294 (1998) 1, http://dx.doi.org/10.1016/S0370-1573(97)00045-8.
[17] A. Banfi, G.P. Salam, G. Zanderighi, JHEP 0408 (2004) 062, http://dx.doi.org/10.1088/1126-6708/2004/08/062.
[18] CMS Collaboration, Phys. Lett. B 699 (2011) 48, http://dx.doi.org/10.1016/j.physletb.2011.03.060.
[19] CMS Collaboration, JINST 3 (2008) S08004, http://dx.doi.org/10.1088/1748-0221/3/08/S08004.
[20] T. Sjöstrand, S. Mrenna, P. Skands, JHEP 0605 (2006) 026, http://dx.doi.org/10.1088/1126-6708/2006/05/026.
[21] CMS Collaboration, JHEP 1109 (2011) 109, http://dx.doi.org/10.1007/JHEP09(2011)109.
[22] J. Pumplin, D.R. Stump, J. Huston, H.L. Lai, P.M. Nadolsky, W.-K. Tung, JHEP 0207 (2002) 012, http://dx.doi.org/10.1088/1126-6708/2002/07/012.
[23] H.L. Lai, M. Guzzi, J. Huston, Z. Li, P.M. Nadolsky, J. Pumplin, C.-P. Yuan, Phys. Rev. D 82 (2010) 074024, http://dx.doi.org/10.1103/PhysRevD.82.074024.
[24] K. Melnikov, F. Petriello, Phys. Rev. D 74 (2006) 114017, http://dx.doi.org/10.1103/PhysRevD.74.114017.
[25] N. Kidonakis, Higher-order corrections to top-antitop pair and single top quark production, arXiv:0909.0037, 2009.
[26] J.M. Campbell, R.K. Ellis, Nucl. Phys. B (Proc. Suppl.) 205–206 (2010) 10, http://dx.doi.org/10.1016/j.nuclphysbps.2010.08.011, arXiv:1007.3492.
[27] S. Agostinelli, et al., GEANT4 Collaboration, Nucl. Instrum. Meth. A 506 (2003) 250, http://dx.doi.org/10.1016/S0168-9002(03)01368-8.
[28] CMS Collaboration, JINST 7 (2012) P10002, http://dx.doi.org/10.1088/1748-0221/7/10/P10002.
[29] CMS Collaboration, Electron reconstruction and identification at $\sqrt{s} = 7$ TeV, CMS Physics Analysis Summary CMS-PAS-EGM-10-004, https://cdsweb.cern.ch/record/1299116, 2010.
[30] M. Cacciari, G.P. Salam, Phys. Lett. B 659 (2008) 119, http://dx.doi.org/10.1016/j.physletb.2007.09.077.
[31] CMS Collaboration, JHEP 1110 (2011) 132, http://dx.doi.org/10.1007/JHEP10(2011)132.
[32] CMS Collaboration, Particle-flow event reconstruction in CMS and performance for jets, taus, and E_T^{miss}, CMS Physics Analysis Summary CMS-PAS-PFT-09-001, http://cdsweb.cern.ch/record/1194487, 2009.
[33] CMS Collaboration, Commissioning of the particle-flow event reconstruction with the first LHC collisions recorded in the CMS detector, CMS Physics Analysis Summary CMS-PAS-PFT-10-002, http://cdsweb.cern.ch/record/1247373, 2010.
[34] M. Cacciari, G.P. Salam, G. Soyez, JHEP 0804 (2008) 063, http://dx.doi.org/10.1088/1126-6708/2008/04/063.
[35] M. Cacciari, G.P. Salam, Phys. Lett. B 641 (2006) 57, http://dx.doi.org/10.1016/j.physletb.2006.08.037.
[36] M. Cacciari, G.P. Salam, G. Soyez, Eur. Phys. J. C 72 (2012) 1896, http://dx.doi.org/10.1140/epjc/s10052-012-1896-2.
[37] CMS Collaboration, JINST 6 (2011) P11002, http://dx.doi.org/10.1088/1748-0221/6/11/P11002.
[38] C. Buttar, et al., Standard model handles and candles working group: Tools and jets summary report, arXiv:0803.0678, 2008.
[39] CMS Collaboration, Absolute calibration of the luminosity measurement at CMS: Winter 2012 update, CMS Physics Analysis Summary CMS-PAS-SMP-12-008, https://cdsweb.cern.ch/record/1434360, 2012.
[40] L. Lyons, D. Gibaut, P. Clifford, Nucl. Instrum. Meth. A 270 (1988) 110, http://dx.doi.org/10.1016/0168-9002(88)90018-6.
[41] A. Höcker, V. Kartvelishvili, Nucl. Instrum. Meth. A 372 (1996) 469, http://dx.doi.org/10.1016/0168-9002(95)01478-0.
[42] T. Adye, Unfolding algorithms and tests using RooUnfold, arXiv:1105.1160, 2011.

CMS Collaboration

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

Yerevan Physics Institute, Yerevan, Armenia

W. Adam, E. Aguilo, T. Bergauer, M. Dragicevic, J. Erö, C. Fabjan [1], M. Friedl, R. Frühwirth [1], V.M. Ghete, N. Hörmann, J. Hrubec, M. Jeitler [1], W. Kiesenhofer, V. Knünz, M. Krammer [1], I. Krätschmer, D. Liko,

I. Mikulec, M. Pernicka[†], D. Rabady[2], B. Rahbaran, C. Rohringer, H. Rohringer, R. Schöfbeck, J. Strauss, A. Taurok, W. Waltenberger, C.-E. Wulz[1]

Institut für Hochenergiephysik der OeAW, Wien, Austria

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

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

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

Universiteit Antwerpen, Antwerpen, Belgium

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

Vrije Universiteit Brussel, Brussel, Belgium

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

Université Libre de Bruxelles, Bruxelles, 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, M. Sigamani, N. Strobbe, F. Thyssen, M. Tytgat, S. Walsh, E. Yazgan, N. Zaganidis

Ghent University, Ghent, Belgium

S. Basegmez, G. Bruno, R. Castello, L. Ceard, C. Delaere, T. du Pree, D. Favart, L. Forthomme, A. Giammanco[3], J. Hollar, V. Lemaitre, J. Liao, O. Militaru, C. Nuttens, D. Pagano, A. Pin, K. Piotrzkowski, J.M. Vizan Garcia

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

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

Université de Mons, Mons, Belgium

G.A. Alves, M. Correa Martins Junior, T. Martins, M.E. Pol, M.H.G. Souza

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

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

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

T.S. Anjos[b], C.A. Bernardes[b], F.A. Dias[a,4], T.R. Fernandez Perez Tomei[a], E.M. Gregores[b], C. Lagana[a], F. Marinho[a], P.G. Mercadante[b], S.F. Novaes[a], Sandra S. Padula[a]

[a] *Universidade Estadual Paulista, São Paulo, Brazil*
[b] *Universidade Federal do ABC, São Paulo, Brazil*

V. Genchev[2], P. Iaydjiev[2], S. Piperov, M. Rodozov, S. Stoykova, G. Sultanov, V. Tcholakov, R. Trayanov, M. Vutova

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria

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

University of Sofia, Sofia, Bulgaria

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

Institute of High Energy Physics, Beijing, China

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

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China

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

Universidad de Los Andes, Bogota, Colombia

N. Godinovic, D. Lelas, R. Plestina[5], D. Polic, I. Puljak[2]

Technical University of Split, Split, Croatia

Z. Antunovic, M. Kovac

University of Split, Split, Croatia

V. Brigljevic, S. Duric, K. Kadija, J. Luetic, D. Mekterovic, S. Morovic, L. Tikvica

Institute Rudjer Boskovic, Zagreb, Croatia

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

University of Cyprus, Nicosia, Cyprus

M. Finger, M. Finger Jr.

Charles University, Prague, Czech Republic

Y. Assran[6], S. Elgammal[7], A. Ellithi Kamel[8], M.A. Mahmoud[9], A. Mahrous[10], A. Radi[11,12]

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

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

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

P. Eerola, G. Fedi, M. Voutilainen

Department of Physics, University of Helsinki, 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

Helsinki Institute of Physics, Helsinki, Finland

A. Korpela, T. Tuuva

Lappeenranta University of Technology, Lappeenranta, Finland

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, M. Titov

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

S. Baffioni, F. Beaudette, L. Benhabib, L. Bianchini, M. Bluj[13], P. Busson, C. Charlot, N. Daci, T. Dahms, M. Dalchenko, L. Dobrzynski, A. Florent, R. Granier de Cassagnac, M. Haguenauer, P. Miné, C. Mironov, I.N. Naranjo, M. Nguyen, C. Ochando, P. Paganini, D. Sabes, R. Salerno, Y. Sirois, C. Veelken, A. Zabi

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

J.-L. Agram[14], J. Andrea, D. Bloch, D. Bodin, J.-M. Brom, M. Cardaci, E.C. Chabert, C. Collard, E. Conte[14], F. Drouhin[14], J.-C. Fontaine[14], D. Gelé, U. Goerlach, P. Juillot, A.-C. Le Bihan, P. Van Hove

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

S. Beauceron, N. Beaupere, O. Bondu, G. Boudoul, S. Brochet, J. Chasserat, R. Chierici[2], D. Contardo, P. Depasse, H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, T. Kurca, M. Lethuillier, L. Mirabito, S. Perries, L. Sgandurra, V. Sordini, Y. Tschudi, P. Verdier, S. Viret

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

Z. Tsamalaidze[15]

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

C. Autermann, S. Beranek, B. Calpas, 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. Zhukov[16]

RWTH Aachen University, I. Physikalisches Institut, 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, M. Merschmeyer, A. Meyer, M. Olschewski, P. Papacz, H. Pieta, H. Reithler, S.A. Schmitz, L. Sonnenschein, J. Steggemann, D. Teyssier, S. Thüer, M. Weber

RWTH Aachen University, III. Physikalisches Institut A, 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, J. Lingemann[2], A. Nowack, L. Perchalla, O. Pooth, P. Sauerland, A. Stahl

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

M. Aldaya Martin, J. Behr, W. Behrenhoff, U. Behrens, M. Bergholz[17], A. Bethani, K. Borras, A. Burgmeier, A. Cakir, L. Calligaris, A. Campbell, E. Castro, F. Costanza, D. Dammann, C. Diez Pardos, T. Dorland, 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, J. Leonard, W. Lohmann[17], B. Lutz, R. Mankel, I. Marfin, M. Marienfeld, I.-A. Melzer-Pellmann, A.B. Meyer, J. Mnich, A. Mussgiller, S. Naumann-Emme, O. Novgorodova, F. Nowak, J. Olzem, H. Perrey, A. Petrukhin, D. Pitzl, A. Raspereza, P.M. Ribeiro Cipriano, C. Riedl, E. Ron, M. Rosin, J. Salfeld-Nebgen, R. Schmidt[17], T. Schoerner-Sadenius, N. Sen, A. Spiridonov, M. Stein, R. Walsh, C. Wissing

Deutsches Elektronen-Synchrotron, Hamburg, Germany

V. Blobel, H. Enderle, J. Erfle, U. Gebbert, M. Görner, M. Gosselink, J. Haller, T. Hermanns, R.S. Höing, K. Kaschube, G. Kaussen, H. Kirschenmann, R. Klanner, J. Lange, T. Peiffer, N. Pietsch, D. Rathjens, C. Sander, H. Schettler, P. Schleper, E. Schlieckau, A. Schmidt, M. Schröder, T. Schum, M. Seidel, J. Sibille[18], V. Sola, H. Stadie, G. Steinbrück, J. Thomsen, L. Vanelderen

University of Hamburg, Hamburg, Germany

C. Barth, J. Berger, C. Böser, T. Chwalek, W. De Boer, A. Descroix, A. Dierlamm, M. Feindt, M. Guthoff[2], C. Hackstein, F. Hartmann[2], T. Hauth[2], M. Heinrich, H. Held, K.H. Hoffmann, U. Husemann, I. Katkov[16], 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, F.-P. Schilling, G. Schott, H.J. Simonis, F.M. Stober, D. Troendle, R. Ulrich, J. Wagner-Kuhr, S. Wayand, T. Weiler, M. Zeise

Institut für Experimentelle Kernphysik, Karlsruhe, Germany

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

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

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

University of Athens, Athens, Greece

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

University of Ioánnina, Ioánnina, Greece

G. Bencze, C. Hajdu, P. Hidas, D. Horvath[19], F. Sikler, V. Veszpremi, G. Vesztergombi[20], A.J. Zsigmond

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

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

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

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

University of Debrecen, Debrecen, Hungary

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

Panjab University, Chandigarh, India

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

University of Delhi, Delhi, India

S. Banerjee, S. Bhattacharya, K. Chatterjee, S. Dutta, B. Gomber, Sa. Jain, Sh. Jain, R. Khurana, A. Modak, S. Mukherjee, D. Roy, S. Sarkar, M. Sharan

Saha Institute of Nuclear Physics, Kolkata, India

A. Abdulsalam, D. Dutta, S. Kailas, V. Kumar, A.K. Mohanty[2], L.M. Pant, P. Shukla

Bhabha Atomic Research Centre, Mumbai, India

T. Aziz, R.M. Chatterjee, S. Ganguly, M. Guchait[21], A. Gurtu[22], M. Maity[23], G. Majumder, K. Mazumdar, G.B. Mohanty, B. Parida, K. Sudhakar, N. Wickramage

Tata Institute of Fundamental Research – EHEP, Mumbai, India

S. Banerjee, S. Dugad

Tata Institute of Fundamental Research – HECR, Mumbai, India

H. Arfaei[24], H. Bakhshiansohi, S.M. Etesami[25], A. Fahim[24], M. Hashemi[26], H. Hesari, A. Jafari, M. Khakzad, M. Mohammadi Najafabadi, S. Paktinat Mehdiabadi, B. Safarzadeh[27], M. Zeinali

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

M. Abbrescia[a,b], L. Barbone[a,b], C. Calabria[a,b,2], S.S. Chhibra[a,b], A. Colaleo[a], D. Creanza[a,c], N. De Filippis[a,c,2], M. De Palma[a,b], L. Fiore[a], G. Iaselli[a,c], G. Maggi[a,c], M. Maggi[a], B. Marangelli[a,b], S. My[a,c], S. Nuzzo[a,b], N. Pacifico[a], A. Pompili[a,b], G. Pugliese[a,c], G. Selvaggi[a,b], L. Silvestris[a], G. Singh[a,b], R. Venditti[a,b], P. Verwilligen[a], G. Zito[a]

[a] *INFN Sezione di Bari, Bari, Italy*
[b] *Università di Bari, Bari, Italy*
[c] *Politecnico di Bari, Bari, 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], P. Giacomelli[a], C. Grandi[a], L. Guiducci[a,b], S. Marcellini[a], G. Masetti[a], M. Meneghelli[a,b,2], 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.P. Siroli[a,b], N. Tosi, R. Travaglini[a,b]

[a] *INFN Sezione di Bologna, Bologna, Italy*
[b] *Università di Bologna, Bologna, 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]

[a] *INFN Sezione di Catania, Catania, Italy*
[b] *Università di Catania, Catania, 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,b]

[a] *INFN Sezione di Firenze, Firenze, Italy*
[b] *Università di Firenze, Firenze, Italy*

L. Benussi, S. Bianco, S. Colafranceschi[28], F. Fabbri, D. Piccolo

INFN Laboratori Nazionali di Frascati, Frascati, Italy

P. Fabbricatore[a], R. Musenich[a], S. Tosi[a,b]

[a] *INFN Sezione di Genova, Genova, Italy*
[b] *Università di Genova, Genova, Italy*

A. Benaglia[a], F. De Guio[a,b], L. Di Matteo[a,b,2], S. Fiorendi[a,b], S. Gennai[a,2], A. Ghezzi[a,b], S. Malvezzi[a], R.A. Manzoni[a,b], A. Martelli[a,b], A. Massironi[a,b], D. Menasce[a], L. Moroni[a], M. Paganoni[a,b], D. Pedrini[a], S. Ragazzi[a,b], N. Redaelli[a], T. Tabarelli de Fatis[a,b]

[a] *INFN Sezione di Milano–Bicocca, Milano, Italy*
[b] *Università di Milano–Bicocca, Milano, Italy*

S. Buontempo[a], N. Cavallo[a,c], A. De Cosa[a,b,2], O. Dogangun[a,b], F. Fabozzi[a,c], A.O.M. Iorio[a,b], L. Lista[a], S. Meola[a,d,29], M. Merola[a], P. Paolucci[a,2]

[a] *INFN Sezione di Napoli, Napoli, Italy*
[b] *Università di Napoli 'Federico II', Napoli, Italy*
[c] *Università della Basilicata (Potenza), Napoli, Italy*
[d] *Università G. Marconi (Roma), Napoli, Italy*

P. Azzi[a], N. Bacchetta[a,2], M. Bellato[a], D. Bisello[a,b], A. Branca[a,b,2], R. Carlin[a,b], P. Checchia[a], T. Dorigo[a], F. 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], J. Pazzini[a,b], N. Pozzobon[a,b], P. Ronchese[a,b], F. Simonetto[a,b], E. Torassa[a], M. Tosi[a,b], S. Vanini[a,b], P. Zotto[a,b], A. Zucchetta[a,b], G. Zumerle[a,b]

[a] *INFN Sezione di Padova, Padova, Italy*
[b] *Università di Padova, Padova, Italy*
[c] *Università di Trento (Trento), Padova, Italy*

M. Gabusi[a,b], S.P. Ratti[a,b], C. Riccardi[a,b], P. Torre[a,b], P. Vitulo[a,b]

[a] *INFN Sezione di Pavia, Pavia, Italy*
[b] *Università di Pavia, Pavia, Italy*

M. Biasini[a,b], G.M. Bilei[a], L. Fanò[a,b], P. Lariccia[a,b], 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]

[a] *INFN Sezione di Perugia, Perugia, Italy*
[b] *Università di Perugia, Perugia, Italy*

P. Azzurri[a,c], G. Bagliesi[a], J. Bernardini[a], T. Boccali[a], G. Broccolo[a,c], R. Castaldi[a], R.T. D'Agnolo[a,c,2], R. Dell'Orso[a], F. Fiori[a,b,2], L. Foà[a,c], A. Giassi[a], A. Kraan[a], F. Ligabue[a,c], T. Lomtadze[a], L. Martini[a,30], A. Messineo[a,b], F. Palla[a], A. Rizzi[a,b], A.T. Serban[a,31], P. Spagnolo[a], P. Squillacioti[a,2], R. Tenchini[a], G. Tonelli[a,b], A. Venturi[a], P.G. Verdini[a]

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

L. Barone[a,b], F. Cavallari[a], D. Del Re[a,b], M. Diemoz[a], C. Fanelli[a,b], M. Grassi[a,b,2], E. Longo[a,b], P. Meridiani[a,2], F. Micheli[a,b], S. Nourbakhsh[a,b], G. Organtini[a,b], R. Paramatti[a], S. Rahatlou[a,b], L. Soffi[a,b]

[a] *INFN Sezione di Roma, Roma, Italy*
[b] *Università di Roma, Roma, Italy*

N. Amapane[a,b], R. Arcidiacono[a,c], S. Argiro[a,b], M. Arneodo[a,c], C. Biino[a], N. Cartiglia[a], S. Casasso[a,b], M. Costa[a,b], N. Demaria[a], C. Mariotti[a,2], S. Maselli[a], E. Migliore[a,b], V. Monaco[a,b], M. Musich[a,2], 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] *INFN Sezione di Torino, Torino, Italy*
[b] *Università di Torino, Torino, Italy*
[c] *Università del Piemonte Orientale (Novara), Torino, Italy*

S. Belforte[a], V. Candelise[a,b], M. Casarsa[a], F. Cossutti[a], G. Della Ricca[a,b], B. Gobbo[a], M. Marone[a,b,2], D. Montanino[a,b,2], A. Penzo[a], A. Schizzi[a,b]

[a] *INFN Sezione di Trieste, Trieste, Italy*
[b] *Università di Trieste, Trieste, Italy*

T.Y. Kim, S.K. Nam

Kangwon National University, Chunchon, Republic of Korea

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

Kyungpook National University, Daegu, Republic of Korea

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

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

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

Korea University, Seoul, Republic of Korea

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

University of Seoul, Seoul, Republic of Korea

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

Sungkyunkwan University, Suwon, Republic of Korea

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

Vilnius University, Vilnius, Lithuania

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

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

S. Carrillo Moreno, F. Vazquez Valencia

Universidad Iberoamericana, Mexico City, Mexico

H.A. Salazar Ibarguen

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

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

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

D. Krofcheck

University of Auckland, Auckland, New Zealand

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

University of Canterbury, Christchurch, New Zealand

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

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

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

National Centre for Nuclear Research, Swierk, Poland

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

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

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

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

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

Joint Institute for Nuclear Research, Dubna, 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

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

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

Institute for Nuclear Research, Moscow, Russia

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

Institute for Theoretical and Experimental Physics, Moscow, Russia

A. Belyaev, E. Boos, M. Dubinin[4], 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

Moscow State University, Moscow, Russia

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

P.N. Lebedev Physical Institute, Moscow, Russia

I. Azhgirey, I. Bayshev, S. Bitioukov, V. Grishin [2], V. Kachanov, D. Konstantinov, V. Krychkine, V. Petrov, R. Ryutin, A. Sobol, L. Tourtchanovitch, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

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

P. Adzic [32], M. Djordjevic, M. Ekmedzic, D. Krpic [32], J. Milosevic

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

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

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

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

Universidad Autónoma de Madrid, Madrid, Spain

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

Universidad de Oviedo, Oviedo, Spain

J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, S.H. Chuang, J. Duarte Campderros, M. Felcini [33], 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, I. Vila, R. Vilar Cortabitarte

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

D. Abbaneo, E. Auffray, G. Auzinger, M. Bachtis, P. Baillon, A.H. Ball, D. Barney, J.F. Benitez, C. Bernet [5], 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. Girone, M. Giunta, F. Glege, R. Gomez-Reino Garrido, P. Govoni, S. Gowdy, R. Guida, S. Gundacker, J. Hammer, 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, N. Magini, T. Mäki, M. Malberti, L. Malgeri, M. Mannelli, L. Masetti, F. Meijers, S. Mersi, E. Meschi, R. Moser, M. Mulders, P. Musella, E. Nesvold, 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. Rolandi [34], C. Rovelli [35], M. Rovere, H. Sakulin, F. Santanastasio, C. Schäfer, C. Schwick, I. Segoni, S. Sekmen, A. Sharma, P. Siegrist, P. Silva, M. Simon, P. Sphicas [36], D. Spiga, A. Tsirou, G.I. Veres [20], J.R. Vlimant, H.K. Wöhri, S.D. Worm [37], W.D. Zeuner

CERN, European Organization for Nuclear Research, Geneva, 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

Paul Scherrer Institut, Villigen, Switzerland

L. Bäni, P. Bortignon, M.A. Buchmann, B. Casal, N. Chanon, A. Deisher, G. Dissertori, M. Dittmar, M. Donegà, M. Dünser, P. Eller, 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. Nägeli [38], P. Nef, F. Nessi-Tedaldi, F. Pandolfi, L. Pape, F. Pauss, M. Peruzzi, F.J. Ronga, M. Rossini, L. Sala, A.K. Sanchez, A. Starodumov [39],

B. Stieger, M. Takahashi, L. Tauscher[†], A. Thea, K. Theofilatos, D. Treille, C. Urscheler, R. Wallny, H.A. Weber, L. Wehrli

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland

C. Amsler[40], V. Chiochia, S. De Visscher, C. Favaro, M. Ivova Rikova, B. Kilminster, B. Millan Mejias, P. Otiougova, P. Robmann, H. Snoek, S. Tupputi, M. Verzetti

Universität Zürich, Zurich, Switzerland

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

National Central University, Chung-Li, 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

National Taiwan University (NTU), Taipei, Taiwan

B. Asavapibhop, N. Srimanobhas, N. Suwonjandee

Chulalongkorn University, Bangkok, Thailand

A. Adiguzel, M.N. Bakirci[41], S. Cerci[42], C. Dozen, I. Dumanoglu, E. Eskut, S. Girgis, G. Gokbulut, E. Gurpinar, I. Hos, E.E. Kangal, T. Karaman, G. Karapinar[43], A. Kayis Topaksu, G. Onengut, K. Ozdemir, S. Ozturk[44], A. Polatoz, K. Sogut[45], D. Sunar Cerci[42], B. Tali[42], H. Topakli[41], L.N. Vergili, M. Vergili

Cukurova University, Adana, 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

Middle East Technical University, Physics Department, Ankara, Turkey

E. Gülmez, B. Isildak[46], M. Kaya[47], O. Kaya[47], S. Ozkorucuklu[48], N. Sonmez[49]

Bogazici University, Istanbul, Turkey

H. Bahtiyar, E. Barlas, K. Cankocak, Y.O. Günaydin[50], F.I. Vardarlı, M. Yücel

Istanbul Technical University, Istanbul, Turkey

L. Levchuk

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

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. Newbold[37], K. Nirunpong, A. Poll, S. Senkin, V.J. Smith, T. Williams

University of Bristol, Bristol, United Kingdom

L. Basso[51], K.W. Bell, A. Belyaev[51], 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

Rutherford Appleton Laboratory, Didcot, 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. Nikitenko[39], J. Pela, M. Pesaresi, K. Petridis, M. Pioppi[52], D.M. Raymond,

S. Rogerson, A. Rose, C. Seez, P. Sharp[†], A. Sparrow, M. Stoye, A. Tapper, M. Vazquez Acosta, T. Virdee, S. Wakefield, N. Wardle, T. Whyntie

Imperial College, London, 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

Brunel University, Uxbridge, United Kingdom

K. Hatakeyama, H. Liu, T. Scarborough

Baylor University, Waco, USA

O. Charaf, C. Henderson, P. Rumerio

The University of Alabama, Tuscaloosa, USA

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

Boston University, Boston, USA

J. Alimena, S. Bhattacharya, G. Christopher, D. Cutts, Z. Demiragli, A. Ferapontov, A. Garabedian, U. Heintz, S. Jabeen, G. Kukartsev, E. Laird, G. Landsberg, M. Luk, M. Narain, M. Segala, T. Sinthuprasith, T. Speer

Brown University, Providence, 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, O. Mall, T. Miceli, D. Pellett, F. Ricci-Tam, B. Rutherford, M. Searle, J. Smith, M. Squires, M. Tripathi, R. Vasquez Sierra, R. Yohay

University of California, Davis, Davis, USA

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

University of California, Los Angeles, USA

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

University of California, Riverside, Riverside, USA

W. Andrews, J.G. Branson, G.B. Cerati, S. Cittolin, D. Evans, 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. Wasserbaech[53], F. Würthwein, A. Yagil, J. Yoo

University of California, San Diego, La Jolla, USA

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

University of California, Santa Barbara, Santa Barbara, 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

California Institute of Technology, Pasadena, USA

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

Carnegie Mellon University, Pittsburgh, USA

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

University of Colorado at Boulder, Boulder, USA

J. Alexander, A. Chatterjee, N. Eggert, L.K. Gibbons, B. Heltsley, W. Hopkins, 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

Cornell University, Ithaca, USA

D. Winn

Fairfield University, Fairfield, USA

S. Abdullin, M. Albrow, J. Anderson, G. Apollinari, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, 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. Klima, S. Kunori, S. Kwan, C. Leonidopoulos[54], J. Linacre, D. Lincoln, R. Lipton, J. Lykken, K. Maeshima, J.M. Marraffino, V.I. Martinez Outschoorn, S. Maruyama, D. Mason, P. McBride, K. Mishra, S. Mrenna, Y. Musienko[55], C. Newman-Holmes, V. O'Dell, E. Sexton-Kennedy, S. Sharma, W.J. Spalding, L. Spiegel, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, R. Vidal, J. Whitmore, W. Wu, F. Yang, J.C. Yun

Fermi National Accelerator Laboratory, Batavia, 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. Milenovic[56], G. Mitselmakher, L. Muniz, M. Park, R. Remington, A. Rinkevicius, P. Sellers, N. Skhirtladze, M. Snowball, J. Yelton, M. Zakaria

University of Florida, Gainesville, USA

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

Florida International University, Miami, 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 State University, Tallahassee, USA

M.M. Baarmand, B. Dorney, M. Hohlmann, H. Kalakhety, I. Vodopiyanov, F. Yumiceva

Florida Institute of Technology, Melbourne, USA

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

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

U. Akgun, E.A. Albayrak, B. Bilki[57], W. Clarida, F. Duru, S. Griffiths, J.-P. Merlo, H. Mermerkaya[58], A. Mestvirishvili, A. Moeller, J. Nachtman, C.R. Newsom, E. Norbeck, Y. Onel, F. Ozok[59], S. Sen, P. Tan, E. Tiras, J. Wetzel, T. Yetkin, K. Yi

The University of Iowa, Iowa City, USA

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

Johns Hopkins University, Baltimore, USA

P. Baringer, A. Bean, G. Benelli, R.P. Kenny III, M. Murray, D. Noonan, S. Sanders, R. Stringer, G. Tinti, J.S. Wood

The University of Kansas, Lawrence, USA

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

Kansas State University, Manhattan, USA

J. Gronberg, D. Lange, F. Rebassoo, D. Wright

Lawrence Livermore National Laboratory, Livermore, USA

A. Baden, 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

University of Maryland, College Park, USA

A. Apyan, G. Bauer, J. Bendavid, W. Busza, E. Butz, I.A. Cali, M. Chan, V. Dutta, G. Gomez Ceballos, M. Goncharov, Y. Kim, M. Klute, K. Krajczar[60], A. Levin, 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, V. Zhukova

Massachusetts Institute of Technology, Cambridge, 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 Minnesota, Minneapolis, USA

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

University of Mississippi, Oxford, USA

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

University of Nebraska-Lincoln, Lincoln, USA

A. Godshalk, I. Iashvili, S. Jain, A. Kharchilava, A. Kumar, S. Rappoccio, Z. Wan

State University of New York at Buffalo, Buffalo, USA

G. Alverson[*], E. Barberis, D. Baumgartel, M. Chasco, J. Haley, D. Nash, T. Orimoto, D. Trocino, D. Wood, J. Zhang

Northeastern University, Boston, USA

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

Northwestern University, Evanston, USA

D. Berry, A. Brinkerhoff, K.M. Chan, 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

University of Notre Dame, Notre Dame, USA

L. Antonelli, 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

The Ohio State University, Columbus, USA

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

Princeton University, Princeton, USA

E. Brownson, A. Lopez, H. Mendez, J.E. Ramirez Vargas

University of Puerto Rico, Mayaguez, 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, West Lafayette, USA

S. Guragain, N. Parashar

Purdue University Calumet, Hammond, USA

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

Rice University, Houston, USA

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

University of Rochester, Rochester, USA

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

The Rockefeller University, NY, 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, M. Walker

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

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

University of Tennessee, Knoxville, USA

R. Eusebi, W. Flanagan, J. Gilmore, T. Kamon[61], 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 A&M University, College Station, USA

N. Akchurin, J. Damgov, C. Dragoiu, P.R. Dudero, C. Jeong, K. Kovitanggoon, S.W. Lee, T. Libeiro, I. Volobouev

Texas Tech University, Lubbock, USA

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

Vanderbilt University, Nashville, USA

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

University of Virginia, Charlottesville, USA

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

Wayne State University, Detroit, USA

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

University of Wisconsin, Madison, USA

[*] Corresponding author.
E-mail address: George.Alverson@cern.ch (G. Alverson).

[†] Deceased.

[1] Also at Vienna University of Technology, Vienna, Austria.

[2] Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.

[3] Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia.

[4] Also at California Institute of Technology, Pasadena, USA.

[5] Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France.

[6] Also at Suez Canal University, Suez, Egypt.

[7] Also at Zewail City of Science and Technology, Zewail, Egypt.

[8] Also at Cairo University, Cairo, Egypt.

[9] Also at Fayoum University, El-Fayoum, Egypt.

[10] Also at Helwan University, Cairo, Egypt.

[11] Also at British University in Egypt, Cairo, Egypt.

[12] Now at Ain Shams University, Cairo, Egypt.

[13] Also at National Centre for Nuclear Research, Swierk, Poland.

[14] Also at Université de Haute-Alsace, Mulhouse, France.

[15] Also 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 The University of Kansas, Lawrence, USA.

[19] Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.

[20] Also at Eötvös Loránd University, Budapest, Hungary.

[21] Also at Tata Institute of Fundamental Research – HECR, Mumbai, India.

[22] Now at King Abdulaziz University, Jeddah, Saudi Arabia.

[23] Also at University of Visva-Bharati, Santiniketan, India.

[24] Also at Sharif University of Technology, Tehran, Iran.

[25] Also at Isfahan University of Technology, Isfahan, Iran.

[26] Also at Shiraz University, Shiraz, Iran.

[27] Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran.

[28] Also at Facoltà Ingegneria, Università di Roma, Roma, Italy.

[29] Also at Università degli Studi Guglielmo Marconi, Roma, Italy.

[30] Also at Università degli Studi di Siena, Siena, Italy.

[31] Also at University of Bucharest, Faculty of Physics, Bucuresti-Magurele, Romania.

[32] Also at Faculty of Physics of University of Belgrade, Belgrade, Serbia.

[33] Also at University of California, Los Angeles, USA.

[34] Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy.

[35] Also at INFN Sezione di Roma, Roma, Italy.

[36] Also at University of Athens, Athens, Greece.

[37] Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.

[38] Also at Paul Scherrer Institut, Villigen, Switzerland.

[39] Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.

[40] Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland.

[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 Kahramanmaras Sütcü Imam University, Kahramanmaras, Turkey.
[51] Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
[52] Also at INFN Sezione di Perugia; Università di Perugia, Perugia, Italy.
[53] Also at Utah Valley University, Orem, USA.
[54] Now at University of Edinburgh, Scotland, Edinburgh, United Kingdom.
[55] Also at Institute for Nuclear Research, Moscow, Russia.
[56] Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.
[57] Also at Argonne National Laboratory, Argonne, USA.
[58] Also at Erzincan University, Erzincan, Turkey.
[59] Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.
[60] Also at KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary.
[61] Also at Kyungpook National University, Daegu, Republic of Korea.