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Measurements of angular distance and momentum ratio distributions in three-jet and Z + two-jet final states in pp collisions

The CMS Collaboration*

Abstract

Collinear (small-angle) and large-angle, as well as soft and hard radiations are investigated in three-jet and Z + two-jet events collected in proton-proton collisions at the LHC. The normalized production cross sections are measured as a function of the ratio of transverse momenta of two jets and their angular separation. The measurements in the three-jet and Z + two-jet events are based on data collected at a center-of-mass energy of 8 TeV, corresponding to an integrated luminosity of 19.8 fb^{-1}. The Z + two-jet events are reconstructed in the dimuon decay channel of the Z boson. The three-jet measurement is extended to include $\sqrt{s} = 13$ TeV data corresponding to an integrated luminosity of 2.3 fb^{-1}. The results are compared to predictions from event generators that include parton showers, multiple parton interactions, and hadronization. The collinear and soft regions are in general well described by parton showers, whereas the regions of large angular separation are often best described by calculations using higher-order matrix elements.

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*See Appendix A for the list of collaboration members

1 Introduction

Collimated streams of particles, produced in interactions of quarks and gluons and reconstructed as jets, are described by the theory of strong interactions, quantum chromodynamics (QCD). Multijet events provide exemplary signatures in high-energy collider experiments, and modeling their characteristics plays an important role in precision measurements, as well as in searches for new physics. The understanding of the structure of multijet final states is therefore crucial for analyses of those events.

Theoretical predictions for multijet events are based on a matrix element (ME) expansion to a fixed perturbative order, supplemented by the parton shower (PS) approach to approximate higher-order perturbative contributions. The ME expansion incorporates color correlations between quarks and gluons, including interference terms, as well as kinematic correlations between the partons, without any approximation at fixed perturbative order. Its application is, however, currently limited to final states with just a few partons. The PS can simulate final states containing many partons, but with probabilities calculated using the approximations of soft and collinear kinematics and partial or averaged color structures. The best descriptions of multijet final states are based on a combination of both approaches [1–4]. Other features implemented in simulations, such as multiple parton interactions (MPI) and hadronization, also play an important role, e.g., in describing angular correlations between jets [5–7].

In this paper, we investigate collinear (small-angle) and large-angle radiation in different regions of jet transverse momentum (p_{T}) by concentrating on two different topologies, one using three-jet events and another with Z + two-jet events. We label the hardest jet, or Z boson as j_1, the next hardest as j_2, and the softest as j_3. We introduce two observables that are sensitive to the dynamic properties of multijet final states. One observable is the p_{T} ratio of j_3 to j_2, $p_{\mathrm{T3}}/p_{\mathrm{T2}}$. The other observable is the angular distance between the jet centers of j_2 and j_3 in the rapidity-azimuth (y-ϕ) phase space, $\Delta R_{23} = \sqrt{(y_3 - y_2)^2 + (\phi_3 - \phi_2)^2}$. As indicated in Fig. 1, we classify three-jet and Z + two-jet events into different categories using these two observables:

(i) soft ($p_{\mathrm{T3}}/p_{\mathrm{T2}} < 0.3$) or hard ($p_{\mathrm{T3}}/p_{\mathrm{T2}} > 0.6$) radiation, depending on the ratio $p_{\mathrm{T3}}/p_{\mathrm{T2}}$;

(ii) small-angle ($\Delta R_{23} < 1.0$) or large-angle ($\Delta R_{23} > 1.0$) radiation, depending on the angular separation ΔR_{23}.

According to these classifications, events in the soft and small-angle radiation region, as shown in Fig. 1 (a), should be better described when including the PS approach, while events in the hard and large-angle radiation region, as shown in Fig. 1 (d), would be better described when including the ME calculations. The events in Figs. 1 (b) and (c) are also of interest, since they should include effects from both the PS and ME.

We report on proton-proton (pp) collision data collected at the CMS experiment containing three-jet events at center-of-mass energies of 8 and 13 TeV, and Z + two-jet events at a center-of-mass energy of 8 TeV. The measurements are compared to calculations based on a leading-order (LO) or next-to-leading-order (NLO) ME supplemented with effects from PS, MPI, and hadronization. The measurements using three-jet final states are complementary to those with Z + two-jet events in a sense that different kinematic regions and initial-state flavor compositions are being probed. The jets are also fully color connected, while the Z boson is color neutral, so color coherence effects should not appear so strongly in Z + two-jet events.

The goal of the measurements is: (i) to untangle the different features of the radiation in the collinear and large-angle events; (ii) to investigate how well the PS approach describes the hard and large-angle radiation patterns; and (iii) to determine how effectively the ME calculations describe the soft and collinear events.

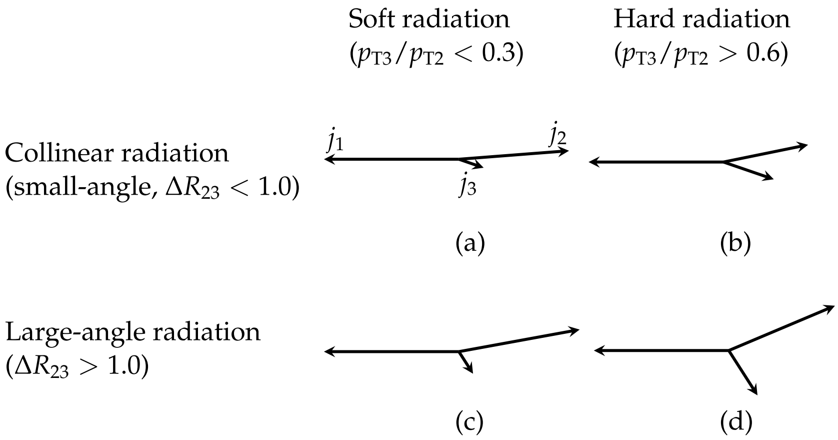

Figure 1: Four categories of parton radiation. (a) soft and small-angle radiation, (b) hard and small-angle radiation, (c) soft and large-angle radiation, (d) hard and large-angle radiation.

2 The CMS detector

The central feature of the CMS detector is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. A silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections, reside within the volume of the solenoid. Charged-particle trajectories are measured in the tracker with full azimuthal acceptance within pseudorapidities $|\eta| < 2.5$. The ECAL, which is equipped with a preshower detector in the endcaps, and the HCAL cover the region $|\eta| < 3.0$. Forward calorimeters extend the pseudorapidity coverage provided by the barrel and endcap detectors to the region $3.0 < |\eta| < 5.2$. Finally, muons are measured up to $|\eta| < 2.4$ in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. Events of interest are selected using a two-tiered trigger system [8]. The first level, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a fixed latency of about 4 μs. The second level, known as the high-level trigger (HLT), consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to around 1 kHz before data storage.

A more detailed description of the CMS detector, together with a definition of the coordinate system and the kinematic variables, is given in Ref. [9].

3 Event samples and selection

The data in this study were collected with the CMS detector at the LHC using pp collisions at center-of-mass energies of 8 and 13 TeV. The $\sqrt{s} = 8$ TeV data, taken in 2012 during LHC Run 1, correspond to an integrated luminosity of 19.8 fb^{-1}, and the $\sqrt{s} = 13$ TeV data, taken in 2015 during LHC Run 2, correspond to an integrated luminosity of 2.3 fb^{-1}.

Particles are reconstructed and identified using a particle-flow (PF) algorithm [10], that utilizes an optimized combination of information from the various elements of the CMS detector.

Jets are reconstructed by clustering the four-vectors of the PF candidates with the infrared and collinear-safe anti-k_T clustering algorithm [11] using a distance parameter $R_{jet} = 0.5$ (0.4) at $\sqrt{s} = 8\,(13)$ TeV. The clustering is performed with the FASTJET software package [12]. In addition, three-jet events use the charged-hadron subtraction (CHS) technique [10] to mitigate the effect of extraneous pp collisions in the same bunch crossing (pileup, PU). The CHS technique reduces the contribution to the reconstructed jets from PU by removing tracks identified as originating from PU vertices.

Three-jet events are collected using single jet HLT requirements that are not pre-scaled. The $\sqrt{s} = 8\,(13)$ TeV data use a 320 (450) GeV trigger p_T threshold. In the offline analyses, the p_T threshold starts at 510 GeV for both sets of data. The Z + two-jet events with the Z boson decaying into a pair of muons are collected at $\sqrt{s} = 8$ TeV with a single-muon HLT that requires a muon $p_T > 24$ GeV and $|\eta| < 2.1$.

In the three-jet systems, the leading jet is required to have a $p_T > 510$ GeV, because of a decreasing efficiency for single jet triggers below this value [8, 13, 14]. Events with at least three jets of $p_T > 30$ GeV are selected for further consideration. The leading and subleading jets must be within a rapidity range of $|y| < 2.5$, and the third jet is therefore implicitly restricted to $|y| < 4$ by requiring $\Delta R_{23} < 1.5$. A dijet topology with one of the jets radiating an additional jet is selected by requiring the difference in azimuthal angle between the first and second jet to be $\pi - 1 < \Delta\phi_{12} < \pi$. The missing transverse momentum vector $\vec{p}_T^{\,miss}$ is defined as the projection onto the plane perpendicular to the beam axis of the negative vector sum of the momentum of all reconstructed PF objects in an event. Its magnitude is referred to as p_T^{miss}. Events with a p_T^{miss} divided by the scalar sum of all transverse momenta > 0.3 are rejected to remove the contamination from W or Z boson decays. To avoid an overlap between j_2 and j_3, ΔR_{23} is required to be larger than the distance parameter R_{jet}. We thus require ΔR_{23} to be larger than 0.6 (0.5) for $\sqrt{s} = 8\,(13)$ TeV data. The maximum ΔR_{23} is set to 1.5 to ensure that j_3 is closer to j_2 than to j_1. We further require that $0.1 < p_{T3}/p_{T2} < 0.9$ to avoid p_{T3} threshold effects and to ensure p_T ordering for hard radiation.

In Z + two-jet events, the Z boson is reconstructed from a pair of oppositely charged muons with $p_T > 25$ (5) GeV and $|y| < 2.1$ (2.4) for the leading (subleading) muon. The dimuon invariant mass is required to be $70 < m_{\mu^+\mu^-} < 110$ GeV with the dimuon momentum satisfying $p_{T1} > 80$ GeV and $|y_1| < 2$. At least two jets are required in the final state with the leading jet (labeled j_2) satisfying $p_{T2} > 80$ GeV and $|y_2| < 1$ and the subleading jet (labeled j_3) required to have $p_{T3} > 20$ GeV with $|y_3| < 2.4$. The Z + two-jet topology is further restricted by requiring a difference in the azimuthal angle between the Z boson and j_2 of $\Delta\phi_{12} > 2$.

Table 1 shows a summary of the event selection requirements for both samples.

4 Theoretical models

Reconstructed data are compared to predictions from Monte Carlo (MC) event generators, where the generated events are passed through a full detector simulation based on GEANT4 [15] and the simulated events are reconstructed using standard CMS software. Reconstruction-level predictions are obtained for three-jet events at $\sqrt{s} = 8$ TeV with the MADGRAPH [16] software package matched to PYTHIA 6 [17] with the CTEQ6L1 [18] parton distribution function (PDF) set and the Z2Star tune [19], as well as with standalone PYTHIA 8.1 [20] with the CTEQ6L1 PDF set and the 4C [21] tune. At 13 TeV, MADGRAPH interfaced to PYTHIA 8.2 [22] and standalone PYTHIA 8.2 are used with the NNPDF2.3LO [23, 24] PDF set and the CUETP8M1 [25] tune. The SHERPA [26] event generator interfaced to CSSHOWER++ [27]

Table 1: Phase space selection for the three-jet and Z + two-jet analyses.

Three-jet events	
Transverse momentum of the leading jet (j_1)	$p_{T1} > 510\,\text{GeV}$
Transverse momentum of each jet and rapidity of $j_{1,2}$	$p_T > 30\,\text{GeV}$, $\|y_{1,2}\| < 2.5$
Azimuthal angle difference between j_1 and j_2	$\pi - 1 < \Delta\phi_{12} < \pi$
Transverse momentum ratio between j_2 and j_3	$0.1 < p_{T3}/p_{T2} < 0.9$
Angular distance between j_2 and j_3	$R_{\text{jet}} + 0.1 < \Delta R_{23} < 1.5$
Number of selected events at $\sqrt{s} = 8\,(13)$ TeV	777,618 (613,254)
Z + two-jet events	
Transverse momentum of the Z boson (j_1)	$p_{T1} > 80\,\text{GeV}$, $\|y_1\| < 2$
Transverse momentum and rapidity of j_2	$p_{T2} > 80\,\text{GeV}$, $\|y_2\| < 1$
Transverse momentum and rapidity of j_3	$p_{T3} > 20\,\text{GeV}$, $\|y_3\| < 2.4$
Azimuthal angle difference between Z and j_2	$2 < \|\Delta\phi_{12}\| < \pi$
Dimuon mass	$70 < m_{\mu^+\mu^-} < 110\,\text{GeV}$
Angular distance between j_3 and j_2	$0.5 < \Delta R_{23} < 1.5$
Number of selected events	15 466

with the CT10 [28] PDF set and the AMISIC++ [29] tune and MADGRAPH interfaced to PYTHIA 6 with the CTEQ6L1 PDF set and the Z2Star tune provide Z + two-jet events at 8 TeV. Table 2 summarizes the event generator versions, PDF sets and tunes.

Table 2: Event generator versions, PDF sets, and tunes used to produce MC samples at reconstruction level.

Event generator	PDF set	Tune
Three-jet events at $\sqrt{s} = 8$ TeV		
MADGRAPH 5.1.3.30 + PYTHIA 6.425	CTEQ6L1	Z2Star
PYTHIA 8.153	CTEQ6L1	4C
Three-jet events at $\sqrt{s} = 13$ TeV		
MADGRAPH 5.2.3.3 + PYTHIA 8.219	NNPDF2.3LO	CUETP8M1
PYTHIA 8.219	NNPDF2.3LO	CUETP8M1
Z + two-jet events		
SHERPA 1.4.0 + CSSHOWER++	CT10	AMISIC++
MADGRAPH 5.1.3.30 + PYTHIA 6.425	CTEQ6L1	Z2Star

Results corrected to stable-particle level are compared to predictions obtained with the models presented below. An overview of these models is given in Table 3.

The PYTHIA 8 [22] event generator provides hard-scattering events using a ME calculated at LO supplemented with PS. These event samples are labeled as "PYTHIA LO 2j+PS" for the three-jet and as "PYTHIA LO Z+1j+PS" for Z + two-jet events. The PDF set NNPDF2.3LO and the CUETP8M1 parameter set for the simulation of the UE are used with free parameters adjusted to measurements in pp collisions at the LHC and proton-antiproton collisions at the Fermilab Tevatron. The Lund string model [30] is applied for the hadronization process.

The MADGRAPH5_aMC@NLO event generator, labeled as "MADGRAPH" in the following, is used to simulate hard processes with up to 4 final-state partons at LO accuracy. It is interfaced to PYTHIA 8 with the CUETP8M1 tune and the NNPDF2.3LO PDF set for the simulation of PS, hadronization, and MPI, for three-jet, and to PYTHIA 6 with the Z2Star tune and the CTEQ6L1 PDF set for Z + two-jet events. The three-jet sample is labeled as "MADGRAPH LO 4j+PS" and the Z + two-jet sample is labeled as "MADGRAPH LO Z+4j+PS". The k_T-MLM procedure [31] is used to match jets from the ME and PS with a matching scale of 10 GeV.

Predictions are also included using the POWHEG BOX library [32–34], with the CT10 NLO [28] PDFs and with the PYTHIA 8 CUETP8M1 tune applied to simulate PS, MPI, and hadronization. The POWHEG generator is run in the dijet mode [35] providing an NLO $2 \rightarrow 2$ calculation, labeled as "POWHEG NLO 2j+PS". The matching between the POWHEG ME calculations and the PYTHIA UE [25] simulation is performed using the shower-veto procedure (UserHook option 2 [22]).

The SHERPA software package is used to simulate Z + two-jet events. The hard process is calculated at LO for a ME with up to four final-state partons and the CT10 PDF set is used. This sample is labeled as "SHERPA LO Z+4j+PS". The SHERPA generator has its own PS [27], hadronization, and MPI tune [29].

Finally, the MADGRAPH5_aMC@NLO generator is also used in the MC@NLO mode, providing a Z + one-jet ME at NLO accuracy. This event generator is interfaced to PYTHIA 8, using the CUETP8M1 tune and the NNPDF3.0NLO [36] PDF set, to produce Z + two-jet events. The sample is labeled as "aMC@NLO NLO Z+1j+PS".

Table 3: MC event generators and version numbers, parton-level processes, PDF sets, and UE tunes used for the comparison with measurements.

Event generator	Parton-level process	PDF set	Tune
Three-jet events			
PYTHIA 8.219	LO 2j+PS	NNPDF2.3LO	CUETP8M1
MADGRAPH 5.2.3.3 + PYTHIA 8.219	LO 4j+PS	NNPDF2.3LO	CUETP8M1
POWHEG 2 + PYTHIA 8.219	NLO 2j+PS	CT10 NLO	CUETP8M1
Z + two-jet events			
PYTHIA 8.219	LO Z+1j+PS	NNPDF2.3LO	CUETP8M1
MADGRAPH 5.1.3.30 + PYTHIA 6.425	LO Z+4j+PS	CTEQ6L1	Z2Star
SHERPA 1.4.0 + CSSHOWER++	LO Z+4j+PS	CT10	AMISIC++
aMC@NLO + PYTHIA 8.223	NLO Z+1j+PS	NNPDF30_nlo_nf_5_pdfas	CUETP8M1

5 Data correction and study of systematic and theoretical uncertainties

To facilitate the comparison of data with theory, the data are unfolded from reconstruction to stable-particle level, defined by a mean decay length larger than 1 cm, so that measurement effects are removed and that the true distributions in the observables are determined. The unfolding is performed using the D'Agostini algorithm [37] as implemented in the ROOUNFOLD software package [38] for three-jet events, while the singular value decomposition method [39] is used for Z + two-jet events. The response matrices are obtained from the full detector simulation using MADGRAPH for three-jet events and SHERPA for Z + two-jet events.

The distributions are normalized to the integral of the spectra for three-jet events and to the number of inclusive Z + one-jet events in the Z + two-jet analysis. The Z + two-jet analysis normalization thus reflects the probability to have more than one jet in the event.

Systematic uncertainties associated to the jet energy scale (JES) calibration, the jet energy resolution (JER), PU modeling, model dependence, as well as the unfolding method, are estimated. Each uncertainty is quoted as the maximum change caused by the corresponding systematic effect.

The systematic uncertainty from the JES is 0.15 (0.24)% at $\sqrt{s} = 8\,(13)$ TeV for the three-jet case and 5–10% for the Z + two-jet events. The JER observed in data differs from that obtained from simulation and simulated jets are therefore smeared to obtain the same resolution as in the data [40]. The systematic uncertainty from JER is estimated by varying the simulated JER uncertainty up and down by one standard deviation, which results in a systematic uncertainty of 0.16 (0.12)% at $\sqrt{s} = 8\,(13)$ TeV for three-jet and 2–3% for Z + two-jet events. When the distributions of Z + two-jet events are normalized to the integrals of the histograms, instead of the number of Z + one-jet events, the systematic uncertainties due to the JES and JER decrease to 0.3–0.5%, except for the p_{T3}/p_{T2} shape, which is still sensitive to the JES with changes of up to 3%.

The distribution in the number of primary vertices is sensitive to PU and to differences in the underlying event (UE) in data and simulation. To estimate the uncertainty due to the PU modeling, the number of PU events in simulation is changed by shifting the total inelastic cross section by $\pm 5\%$ [41]. The resulting PU uncertainties are 0.10 (0.17)% at $\sqrt{s} = 8\,(13)$ TeV for the three-jet and 1% for the Z + two-jet events.

The dependence on the event generator used for the unfolding is estimated with MC event samples from MADGRAPH and PYTHIA for three-jet, and SHERPA and MADGRAPH for the Z + two-jet events. The means of both sets of unfolded data are used as the nominal values. This uncertainty is $\approx$ 1.1 (0.25)% at $\sqrt{s} = 8\,(13)$ TeV for the three-jet and 1% for the Z + two-jet events, which is half of the difference between the results obtained with the respective event generators. The difference in uncertainties comes mainly from the difference in the number of events in the corresponding simulated samples.

Table 4 summarizes the systematic uncertainties in the measurements.

Table 4: Systematic uncertainties in the measurements in %.

Source	three-jet 8/13 TeV	Z + two-jet 8 TeV
Jet energy scale	0.15/0.24	5–10
Jet energy resolution	0.16/0.12	2–3
Pileup	0.1/0.17	1
Unfolding and model dependence	1.1/0.25	1

The systematic uncertainties from various sources are similar for the three-jet samples at $\sqrt{s} =$ 8 and 13 TeV, except for unfolding and model dependence at $\sqrt{s} = 8$ TeV. The systematic uncertainties between the three-jet and Z + two-jet analysis cannot be compared directly because each analysis uses a different normalization and also differs in statistical significance. The JES uncertainty is especially sensitive to the jet p_T range, and the Z + two-jet phase space has a lower p_T threshold than the one used in the three-jet events.

The figures of Sec. 6 show the total systematic uncertainty as a band in the panels displaying the ratio of predictions over data.

The uncertainties in the PDF and in the renormalization and factorization scales are investigated for the POWHEG and aMC@NLO models. Other theoretical predictions are expected to have comparable uncertainties. The PDF uncertainties are estimated following the PDF4LHC recipe [42], i.e., obtaining the variance in the predictions from changing the PDF at each point. The renormalization and factorization scales are varied by a factor 2 up and down, excluding the (2,1/2) and (1/2,2) cases. Finally, the theoretical uncertainties are obtained as the quadratic sum of the PDF variance and the envelope of the scale variations, and displayed as a band around the theoretical predictions in the figures of Sec. 6.

6 Results

We compare the distributions in the ratio p_{T3}/p_{T2} in data to predictions for events with small-angle ($\Delta R_{23} < 1.0$) and large-angle radiation ($\Delta R_{23} > 1.0$). We also compare the ΔR_{23} distributions in data to predictions with soft ($p_{T3}/p_{T2} < 0.3$) and hard radiation ($p_{T3}/p_{T2} > 0.6$). The events with $0.3 < p_{T3}/p_{T2} < 0.6$ are not used in the comparisons because we focus on the limits in soft and hard radiation. This classification is summarized in Fig. 1, within the phase space defined in Table 1.

6.1 Three-jet selection

We show the $\sqrt{s} = 8$ TeV measurements of p_{T3}/p_{T2} in Fig. 2 and of ΔR_{23} in Fig. 3, and compare them to theoretical expectations. In Figs. 4 and 5 the distributions are given for $\sqrt{s} = 13$ TeV. Figure 2 (left) shows the p_{T3}/p_{T2} distribution for the small ΔR_{23} region. All predictions show significant deviations from the measurements. Interestingly, the LO 4j+PS prediction shows different behavior compared with LO 2j+PS and NLO 2j+PS. We see that the number of partons in the ME calculation and the merging method with the PS in the present simulations lead to different shapes of the predicted distributions. In Fig. 2 (right) the p_{T3}/p_{T2} distribution is shown for large ΔR_{23}. This region of phase space is well described by the LO 4j+PS calculations, while the LO 2j+PS and NLO 2j+PS predictions show large deviations from the measurements.

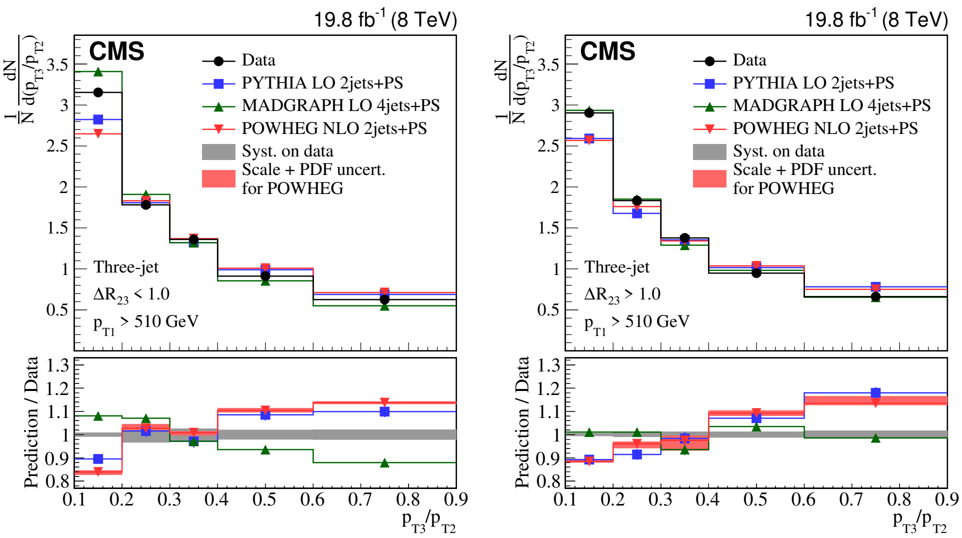

Figure 2: Three-jet events at $\sqrt{s} = 8$ TeV compared to theory: (left) p_{T3}/p_{T2} for small-angle radiation ($\Delta R_{23} < 1.0$), (right) p_{T3}/p_{T2} for large-angle radiation ($\Delta R_{23} > 1.0$).

In Fig. 3, the ΔR_{23} distribution is shown for two regions of p_{T3}/p_{T2}. Figure 3 (left) shows $p_{T3}/p_{T2} < 0.3$. The predictions from LO 2j+PS and NLO 2j+PS describe the measurement well, while the prediction from LO 4j+PS shows a larger deviation from the data. In Fig. 3 (right) the ΔR_{23} distribution is shown for $p_{T3}/p_{T2} > 0.6$. In contrast to Fig. 3 (left), the predictions for distributions from LO 2j+PS differ from the measurement, whereas the predictions from NLO 2j+PS and LO 4j+PS agree well with it. This indicates that in this region the contribution from higher-order ME calculations supplemented with PS should be included. The same comparisons are performed for the $\sqrt{s} = 13$ TeV measurements as shown in Figs. 4 and 5. A similar behavior is observed for $\sqrt{s} = 8$ TeV. In conclusion, none of the simulations simultaneously

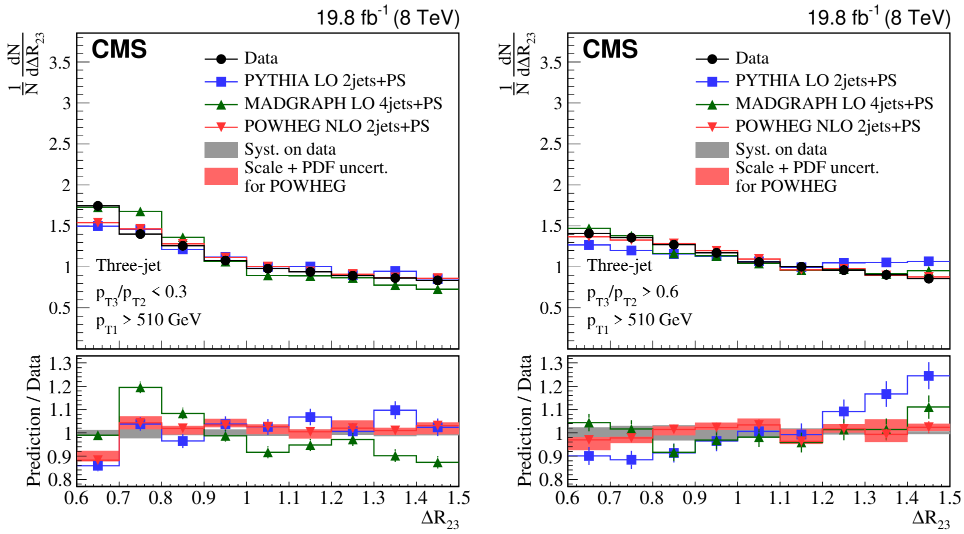

Figure 3: Three-jet events at $\sqrt{s} = 8\,\text{TeV}$ and comparison to theoretical predictions: (left) ΔR_{23} for soft radiation ($p_{T3}/p_{T2} < 0.3$), (right) ΔR_{23} for hard radiation ($p_{T3}/p_{T2} > 0.6$).

describes to simultaneously describe both the p_{T3}/p_{T2} and the ΔR_{23} distributions in three-jet events.

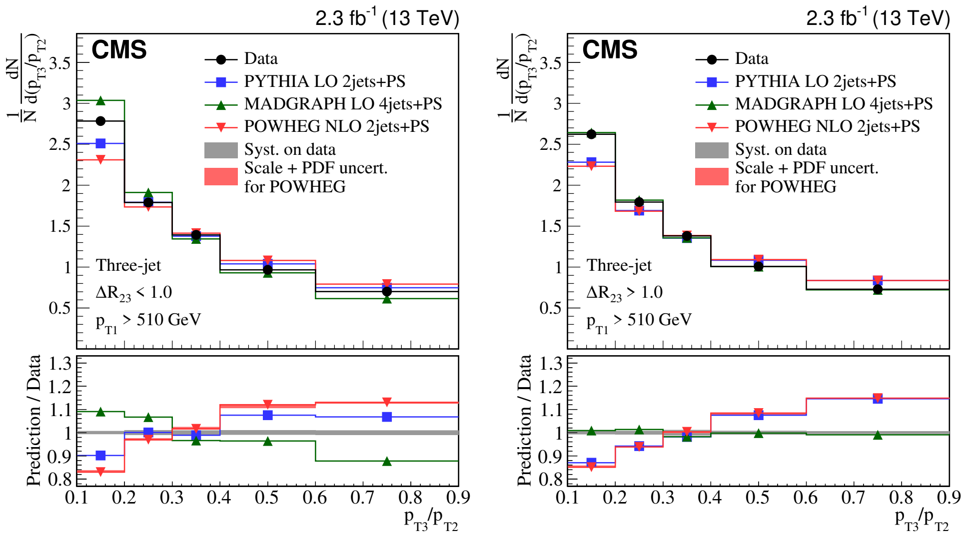

Figure 4: Three-jet events at $\sqrt{s} = 13\,\text{TeV}$ compared to theory: (left) p_{T3}/p_{T2} for small-angle radiation ($\Delta R_{23} < 1.0$), (right) p_{T3}/p_{T2} for large-angle radiation ($\Delta R_{23} > 1.0$).

6.2 Z + two-jet selection

The measurement of p_{T3}/p_{T2} for Z + two-jet events is presented in Fig. 6 for data at $\sqrt{s} = 8\,\text{TeV}$. All distributions are normalized to the selected number of Z + one-jet events. All predictions from PYTHIA, SHERPA, MADGRAPH, and aMC@NLO agree with data within the uncertainties of the measurement except for the bins with hard radiation.

Figure 7 shows the measurement as a function of ΔR_{23}. The aMC@NLO prediction deviates from the data at high ΔR_{23} and small p_{T3}/p_{T2}, while PYTHIA, SHERPA, MADGRAPH, and aMC@NLO describe the shape of the distribution in the high-p_{T3}/p_{T2} range, but underestimate the data due to a smaller contribution from production of j_3. This feature is based on the normalization

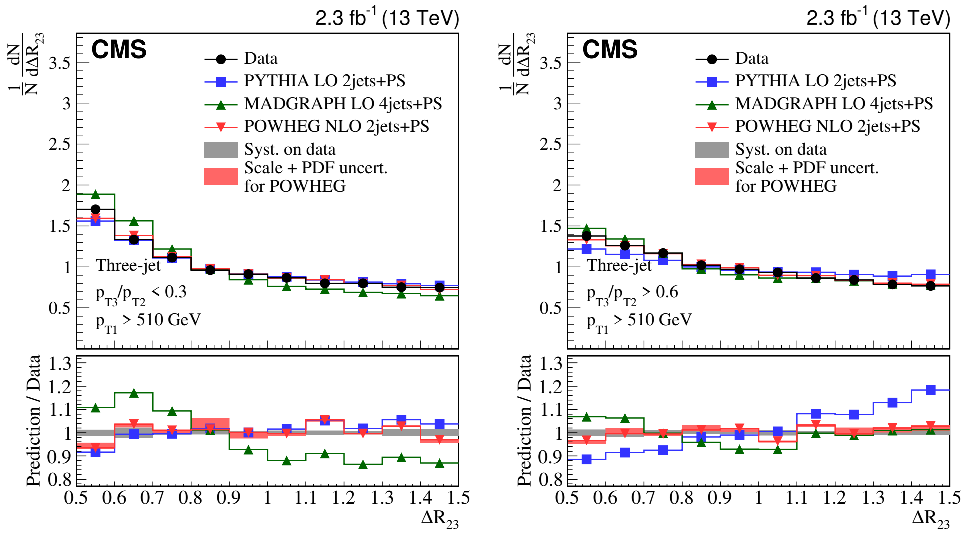

Figure 5: Three-jet events at $\sqrt{s} = 13\,\text{TeV}$ and comparison to theoretical predictions: (left) ΔR_{23} for soft radiation ($p_{\text{T3}}/p_{\text{T2}} < 0.3$), (right) ΔR_{23} for hard radiation ($p_{\text{T3}}/p_{\text{T2}} > 0.6$).

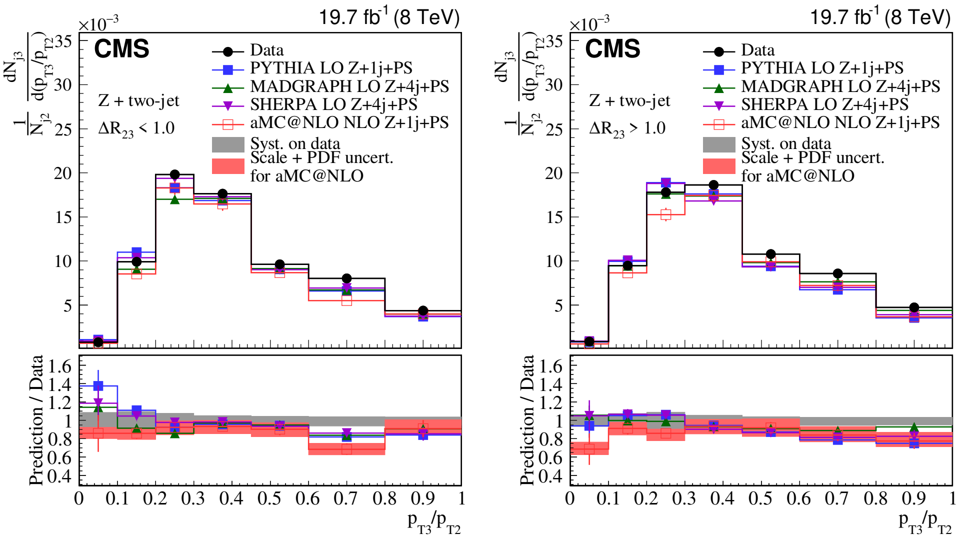

Figure 6: Z + two-jet events at $\sqrt{s} = 8\,\text{TeV}$ compared to theory: (left) $p_{\text{T3}}/p_{\text{T2}}$ for small-angle radiation ($\Delta R_{23} < 1.0$), (right) $p_{\text{T3}}/p_{\text{T2}}$ for large-angle radiation ($\Delta R_{23} > 1.0$).

of Z + two-jet distributions by the number of inclusive Z + one-jet events selected.

Figures 8 and 9 compare the event distributions with predictions from PYTHIA 8 with the final-state PS and MPI switched off. The initial-state PS was kept, because one of the jets must originate from PS when Z + two-jet events are selected. Multiple parton interactions play a very minor role, while the final-state PS in PYTHIA 8 is very important. When the final-state PS is switched off, events where both jets come from the initial-state PS are kept with a tendency to be close to each other in ΔR_{23}.

The results of the Z + two-jet events are, in general, described by all theoretical predictions, except for the underestimation of j_3 emission. However, the three-jet events display significant differences; only in the region of large ΔR_{23} and large $p_{\text{T3}}/p_{\text{T2}}$ (hard and large-angle radiation) do the theoretical predictions agree with the measurement. The accessible range in p_{T} is rather small in Z + two-jet events because of the limit in the p_{T} of the Z bosons ($p_{\text{T1}} > 80\,\text{GeV}$), while

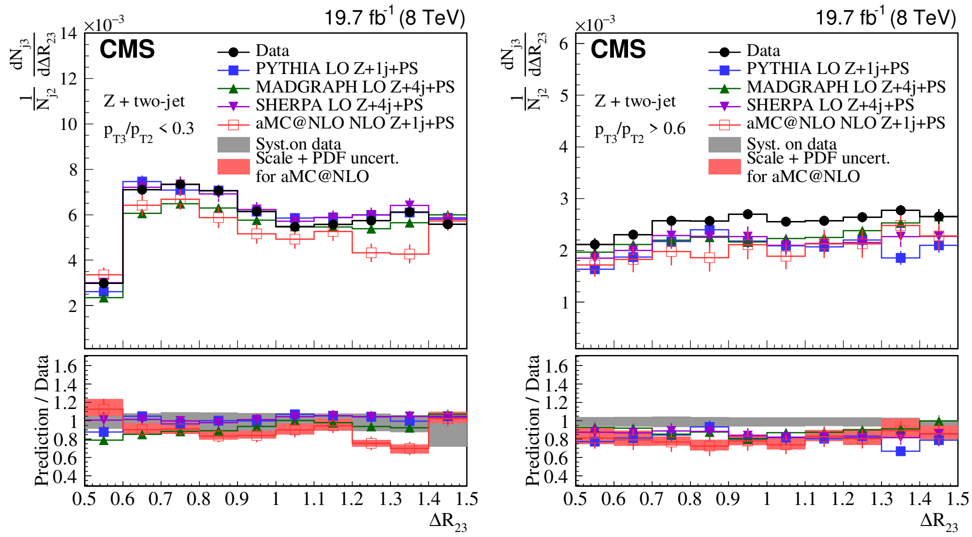

Figure 7: Z + two-jet events at $\sqrt{s} = 8\,\text{TeV}$ compared to theory: (left) ΔR_{23} for soft radiation ($p_{T3}/p_{T2} < 0.3$), (right) ΔR_{23} for hard radiation ($p_{T3}/p_{T2} > 0.6$).

the three-jet selection, on the contrary, can have a rather large range ($p_{T1} > 510\,\text{GeV}$). This may explain why the region of small p_{T3}/p_{T2} is better described by predictions that include PS in the latter case. In addition, the large-angle radiation is best described by fixed-order ME calculations.

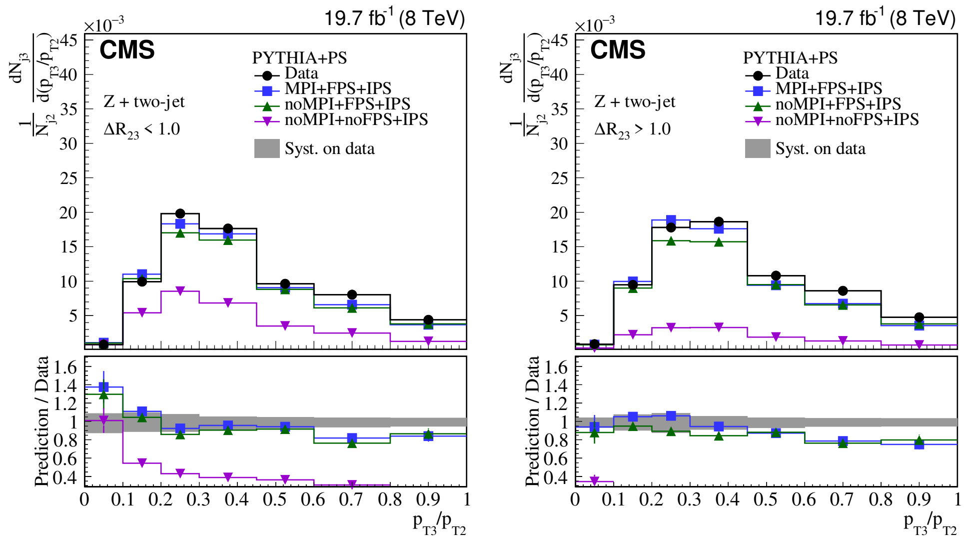

Figure 8: Z + two-jet events at $\sqrt{s} = 8\,\text{TeV}$ compared to theoretical predictions from PYTHIA 8 without initial-state parton showers (IPS), final-state parton showers (FPS), and MPI: (left) p_{T3}/p_{T2} for small-angle radiation ($\Delta R_{23} < 1.0$), (right) p_{T3}/p_{T2} for large-angle radiation ($\Delta R_{23} > 1.0$).

In conclusion, the Z + two-jet measurement has a different distribution in p_{T3}/p_{T2}, which originates from the different kinematic selection criteria relative to three-jet events, thus reducing the sensitivity in the soft and collinear region. Within the available phase space, the measurements are in reasonable agreement with both PS and ME calculations, apart from the emission of j_3 in the high-p_{T3}/p_{T2} region.

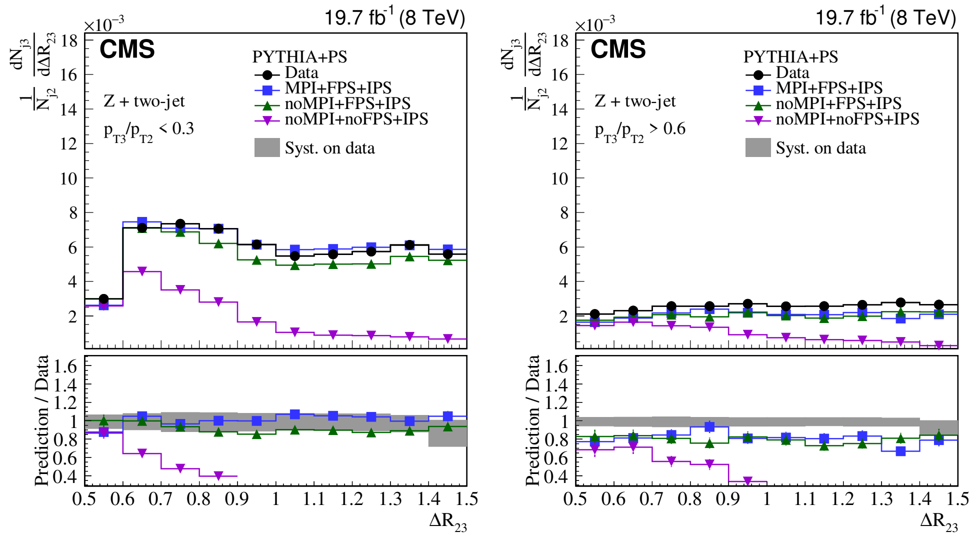

Figure 9: Z + two-jet events at $\sqrt{s} = 8$ TeV and comparison to theoretical predictions from PYTHIA 8 without initial-state parton showers (IPS), final-state parton showers (FPS), and MPI: (left) ΔR_{23} for soft radiation ($p_{T3}/p_{T2} < 0.3$), (right) ΔR_{23} for hard radiation ($p_{T3}/p_{T2} > 0.6$).

7 Summary

Two kinematic variables are introduced to quantify the radiation pattern in multijet events: (i) the transverse momentum ratio (p_{T3}/p_{T2}) of two jets, and (ii) their angular separation (ΔR_{23}). The variable p_{T3}/p_{T2} is used to distinguish between soft and hard radiation, while ΔR_{23} classifies events into small- and large-angle radiation types. Events with three or more energetic jets as well as inclusive Z + two-jet events are selected for study using data collected at $\sqrt{s} = 8$ TeV corresponding to an integrated luminosity of 19.8 fb^{-1}. Three-jet events at $\sqrt{s} = 13$ TeV corresponding to an integrated luminosity of 2.3 fb^{-1} are also analyzed. No significant dependence on the center-of-mass energy is observed in the differential distributions of p_{T3}/p_{T2} and ΔR_{23}.

Overall, large-angle radiation (large ΔR_{23}) and hard radiation (large p_{T3}/p_{T2}) are well described by the matrix element (ME) calculations (using LO 4j+PS formulations), while the parton shower (PS) approach (LO 2j+PS and NLO 2j+PS) fail to describe the regions of large-angle and hard radiation. The collinear region (small ΔR_{23}) is not well described; LO 2j+PS, NLO 2j+PS, and LO 4j+PS distributions show deviations from the measurements. In the soft region (small p_{T3}/p_{T2}), the PS approach describes the measurement also in the large-angle region (full range in ΔR_{23}), while for large p_{T3}/p_{T2} higher-order ME contributions are needed to describe the three-jet measurements. The distributions in Z + two-jet events are reasonably described by all tested generators. Nevertheless, we find an underestimation of third-jet emission at large p_{T3}/p_{T2} both in the collinear and large-angle regions, for all of the tested models. These results illustrate how well the collinear/soft, and large-angle/hard regions are described by different approaches. The different kinematic regions and initial-state flavor composition may be the reason why the three-jet measurements are less consistent with the theoretical predictions relative to the Z + two-jet final states. These results clearly indicate that the methods of merging ME with PS calculations are not yet optimal for describing the full region of phase space.

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A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia
A.M. Sirunyan[†], A. Tumasyan

Institut für Hochenergiephysik, Wien, Austria
W. Adam, T. Bergauer, M. Dragicevic, J. Erö, A. Escalante Del Valle, R. Frühwirth[1], M. Jeitler[1], N. Krammer, L. Lechner, D. Liko, T. Madlener, I. Mikulec, F.M. Pitters, N. Rad, J. Schieck[1], R. Schöfbeck, M. Spanring, S. Templ, W. Waltenberger, C.-E. Wulz[1], M. Zarucki

Institute for Nuclear Problems, Minsk, Belarus
V. Chekhovsky, A. Litomin, V. Makarenko

Universiteit Antwerpen, Antwerpen, Belgium
M.R. Darwish[2], E.A. De Wolf, D. Di Croce, X. Janssen, T. Kello[3], A. Lelek, M. Pieters, H. Rejeb Sfar, H. Van Haevermaet, P. Van Mechelen, S. Van Putte, N. Van Remortel

Vrije Universiteit Brussel, Brussel, Belgium
F. Blekman, E.S. Bols, S.S. Chhibra, J. D'Hondt, J. De Clercq, D. Lontkovskyi, S. Lowette, I. Marchesini, S. Moortgat, A. Morton, Q. Python, S. Tavernier, W. Van Doninck, P. Van Mulders

Université Libre de Bruxelles, Bruxelles, Belgium
D. Beghin, B. Bilin, B. Clerbaux, G. De Lentdecker, B. Dorney, L. Favart, A. Grebenyuk, A.K. Kalsi, I. Makarenko, L. Moureaux, L. Pétré, A. Popov, N. Postiau, E. Starling, L. Thomas, C. Vander Velde, P. Vanlaer, D. Vannerom, L. Wezenbeek

Ghent University, Ghent, Belgium
T. Cornelis, D. Dobur, M. Gruchala, I. Khvastunov[4], M. Niedziela, C. Roskas, K. Skovpen, M. Tytgat, W. Verbeke, B. Vermassen, M. Vit

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
G. Bruno, F. Bury, C. Caputo, P. David, C. Delaere, M. Delcourt, I.S. Donertas, A. Giammanco, V. Lemaitre, K. Mondal, J. Prisciandaro, A. Taliercio, M. Teklishyn, P. Vischia, S. Wertz, S. Wuyckens, J. Zobec

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
G.A. Alves, C. Hensel, A. Moraes

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
W.L. Aldá Júnior, E. Belchior Batista Das Chagas, H. BRANDAO MALBOUISSON, W. Carvalho, J. Chinellato[5], E. Coelho, E.M. Da Costa, G.G. Da Silveira[6], D. De Jesus Damiao, S. Fonseca De Souza, J. Martins[7], D. Matos Figueiredo, M. Medina Jaime[8], C. Mora Herrera, L. Mundim, H. Nogima, P. Rebello Teles, L.J. Sanchez Rosas, A. Santoro, S.M. Silva Do Amaral, A. Sznajder, M. Thiel, F. Torres Da Silva De Araujo, A. Vilela Pereira

Universidade Estadual Paulista [a], Universidade Federal do ABC [b], São Paulo, Brazil
C.A. Bernardes[a,a], L. Calligaris[a], T.R. Fernandez Perez Tomei[a], E.M. Gregores[a,b], D.S. Lemos[a], P.G. Mercadante[a,b], S.F. Novaes[a], Sandra S. Padula[a]

Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria
A. Aleksandrov, G. Antchev, I. Atanasov, R. Hadjiiska, P. Iaydjiev, M. Misheva, M. Rodozov, M. Shopova, G. Sultanov

University of Sofia, Sofia, Bulgaria
M. Bonchev, A. Dimitrov, T. Ivanov, L. Litov, B. Pavlov, P. Petkov, A. Petrov

Beihang University, Beijing, China
W. Fang[3], Q. Guo, H. Wang, L. Yuan

Department of Physics, Tsinghua University, Beijing, China
M. Ahmad, Z. Hu, Y. Wang

Institute of High Energy Physics, Beijing, China
E. Chapon, G.M. Chen[9], H.S. Chen[9], M. Chen, T. Javaid[9], A. Kapoor, D. Leggat, H. Liao, Z. Liu, R. Sharma, A. Spiezia, J. Tao, J. Thomas-wilsker, J. Wang, H. Zhang, S. Zhang[9], J. Zhao

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
A. Agapitos, Y. Ban, C. Chen, Q. Huang, A. Levin, Q. Li, M. Lu, X. Lyu, Y. Mao, S.J. Qian, D. Wang, Q. Wang, J. Xiao

Sun Yat-Sen University, Guangzhou, China
Z. You

Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) - Fudan University, Shanghai, China
X. Gao[3]

Zhejiang University, Hangzhou, China
M. Xiao

Universidad de Los Andes, Bogota, Colombia
C. Avila, A. Cabrera, C. Florez, J. Fraga, A. Sarkar, M.A. Segura Delgado

Universidad de Antioquia, Medellin, Colombia
J. Jaramillo, J. Mejia Guisao, F. Ramirez, J.D. Ruiz Alvarez, C.A. Salazar González, N. Vanegas Arbelaez

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia
D. Giljanovic, N. Godinovic, D. Lelas, I. Puljak, T. Sculac

University of Split, Faculty of Science, Split, Croatia
Z. Antunovic, M. Kovac

Institute Rudjer Boskovic, Zagreb, Croatia
V. Brigljevic, D. Ferencek, D. Majumder, M. Roguljic, A. Starodumov[10], T. Susa

University of Cyprus, Nicosia, Cyprus
M.W. Ather, A. Attikis, E. Erodotou, A. Ioannou, G. Kole, M. Kolosova, S. Konstantinou, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski, H. Saka, D. Tsiakkouri

Charles University, Prague, Czech Republic
M. Finger[11], M. Finger Jr.[11], A. Kveton, J. Tomsa

Escuela Politecnica Nacional, Quito, Ecuador
E. Ayala

Universidad San Francisco de Quito, Quito, Ecuador
E. Carrera Jarrin

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
H. Abdalla[12], A.A. Abdelalim[13,14], S. Elgammal[15]

Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt
M.A. Mahmoud, Y. Mohammed[16]

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
S. Bhowmik, A. Carvalho Antunes De Oliveira, R.K. Dewanjee, K. Ehataht, M. Kadastik, M. Raidal, C. Veelken

Department of Physics, University of Helsinki, Helsinki, Finland
P. Eerola, L. Forthomme, H. Kirschenmann, K. Osterberg, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland
E. Brücken, F. Garcia, J. Havukainen, V. Karimäki, M.S. Kim, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, H. Siikonen, E. Tuominen, J. Tuominiemi

Lappeenranta University of Technology, Lappeenranta, Finland
P. Luukka, T. Tuuva

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
C. Amendola, M. Besancon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, B. Lenzi, E. Locci, J. Malcles, J. Rander, A. Rosowsky, M.Ö. Sahin, A. Savoy-Navarro[17], M. Titov, G.B. Yu

Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France
S. Ahuja, F. Beaudette, M. Bonanomi, A. Buchot Perraguin, P. Busson, C. Charlot, O. Davignon, B. Diab, G. Falmagne, R. Granier de Cassagnac, A. Hakimi, I. Kucher, A. Lobanov, C. Martin Perez, M. Nguyen, C. Ochando, P. Paganini, J. Rembser, R. Salerno, J.B. Sauvan, Y. Sirois, A. Zabi, A. Zghiche

Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France
J.-L. Agram[18], J. Andrea, D. Bloch, G. Bourgatte, J.-M. Brom, E.C. Chabert, C. Collard, J.-C. Fontaine[18], D. Gelé, U. Goerlach, C. Grimault, A.-C. Le Bihan, P. Van Hove

Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France
E. Asilar, S. Beauceron, C. Bernet, G. Boudoul, C. Camen, A. Carle, N. Chanon, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, Sa. Jain, I.B. Laktineh, H. Lattaud, A. Lesauvage, M. Lethuillier, L. Mirabito, L. Torterotot, G. Touquet, M. Vander Donckt, S. Viret

Georgian Technical University, Tbilisi, Georgia
G. Adamov, Z. Tsamalaidze[11]

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
L. Feld, K. Klein, M. Lipinski, D. Meuser, A. Pauls, M. Preuten, M.P. Rauch, J. Schulz, M. Teroerde

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
D. Eliseev, M. Erdmann, P. Fackeldey, B. Fischer, S. Ghosh, T. Hebbeker, K. Hoepfner, H. Keller, L. Mastrolorenzo, M. Merschmeyer, A. Meyer, G. Mocellin, S. Mondal, S. Mukherjee, D. Noll, A. Novak, T. Pook, A. Pozdnyakov, Y. Rath, H. Reithler, J. Roemer, A. Schmidt, S.C. Schuler, A. Sharma, S. Wiedenbeck, S. Zaleski

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
C. Dziwok, G. Flügge, W. Haj Ahmad[19], O. Hlushchenko, T. Kress, A. Nowack, C. Pistone, O. Pooth, D. Roy, H. Sert, A. Stahl[20], T. Ziemons

Deutsches Elektronen-Synchrotron, Hamburg, Germany
H. Aarup Petersen, M. Aldaya Martin, P. Asmuss, I. Babounikau, S. Baxter, O. Behnke, A. Bermúdez Martínez, A.A. Bin Anuar, K. Borras[21], V. Botta, D. Brunner, A. Campbell, A. Cardini, P. Connor, S. Consuegra Rodríguez, V. Danilov, A. De Wit, M.M. Defranchis, L. Didukh, D. Domínguez Damiani, G. Eckerlin, D. Eckstein, T. Eichhorn, L.I. Estevez Banos, E. Gallo[22], A. Geiser, A. Giraldi, A. Grohsjean, M. Guthoff, A. Harb, A. Jafari[23], N.Z. Jomhari, H. Jung, A. Kasem[21], M. Kasemann, H. Kaveh, C. Kleinwort, J. Knolle, D. Krücker, W. Lange, T. Lenz, J. Lidrych, K. Lipka, W. Lohmann[24], R. Mankel, I.-A. Melzer-Pellmann, J. Metwally, A.B. Meyer, M. Meyer, M. Missiroli, J. Mnich, A. Mussgiller, V. Myronenko, Y. Otarid, D. Pérez Adán, S.K. Pflitsch, D. Pitzl, A. Raspereza, A. Saggio, A. Saibel, M. Savitskyi, V. Scheurer, C. Schwanenberger, A. Singh, R.E. Sosa Ricardo, N. Tonon, O. Turkot, A. Vagnerini, M. Van De Klundert, R. Walsh, D. Walter, Y. Wen, K. Wichmann, C. Wissing, S. Wuchterl, O. Zenaiev, R. Zlebcik

University of Hamburg, Hamburg, Germany
R. Aggleton, S. Bein, L. Benato, A. Benecke, K. De Leo, T. Dreyer, A. Ebrahimi, M. Eich, F. Feindt, A. Fröhlich, C. Garbers, E. Garutti, P. Gunnellini, J. Haller, A. Hinzmann, A. Karavdina, G. Kasieczka, R. Klanner, R. Kogler, V. Kutzner, J. Lange, T. Lange, A. Malara, C.E.N. Niemeyer, A. Nigamova, K.J. Pena Rodriguez, O. Rieger, P. Schleper, S. Schumann, J. Schwandt, D. Schwarz, J. Sonneveld, H. Stadie, G. Steinbrück, B. Vormwald, I. Zoi

Karlsruher Institut fuer Technologie, Karlsruhe, Germany
S. Baur, J. Bechtel, T. Berger, E. Butz, R. Caspart, T. Chwalek, W. De Boer, A. Dierlamm, A. Droll, K. El Morabit, N. Faltermann, K. Flöh, M. Giffels, A. Gottmann, F. Hartmann[20], C. Heidecker, U. Husemann, M.A. Iqbal, I. Katkov[25], P. Keicher, R. Koppenhöfer, S. Maier, M. Metzler, S. Mitra, D. Müller, Th. Müller, M. Musich, G. Quast, K. Rabbertz, J. Rauser, D. Savoiu, D. Schäfer, M. Schnepf, M. Schröder, D. Seith, I. Shvetsov, H.J. Simonis, R. Ulrich, M. Wassmer, M. Weber, R. Wolf, S. Wozniewski

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece
G. Anagnostou, P. Asenov, G. Daskalakis, T. Geralis, A. Kyriakis, D. Loukas, G. Paspalaki, A. Stakia

National and Kapodistrian University of Athens, Athens, Greece
M. Diamantopoulou, D. Karasavvas, G. Karathanasis, P. Kontaxakis, C.K. Koraka, A. Manousakis-katsikakis, A. Panagiotou, I. Papavergou, N. Saoulidou, K. Theofilatos, K. Vellidis, E. Vourliotis

National Technical University of Athens, Athens, Greece
G. Bakas, K. Kousouris, I. Papakrivopoulos, G. Tsipolitis, A. Zacharopoulou

University of Ioánnina, Ioánnina, Greece
I. Evangelou, C. Foudas, P. Gianneios, P. Katsoulis, P. Kokkas, K. Manitara, N. Manthos, I. Papadopoulos, J. Strologas

MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University,

Budapest, Hungary
M. Bartók[26], R. Chudasama, M. Csanad, M.M.A. Gadallah[27], S. Lökös[28], P. Major, K. Mandal, A. Mehta, G. Pasztor, O. Surányi, G.I. Veres

Wigner Research Centre for Physics, Budapest, Hungary
G. Bencze, C. Hajdu, D. Horvath[29], F. Sikler, V. Veszpremi, G. Vesztergombi[†]

Institute of Nuclear Research ATOMKI, Debrecen, Hungary
S. Czellar, J. Karancsi[26], J. Molnar, Z. Szillasi, D. Teyssier

Institute of Physics, University of Debrecen, Debrecen, Hungary
P. Raics, Z.L. Trocsanyi, B. Ujvari

Eszterhazy Karoly University, Karoly Robert Campus, Gyongyos, Hungary
T. Csorgo, F. Nemes, T. Novak

Indian Institute of Science (IISc), Bangalore, India
S. Choudhury, J.R. Komaragiri, D. Kumar, L. Panwar, P.C. Tiwari

National Institute of Science Education and Research, HBNI, Bhubaneswar, India
S. Bahinipati[30], D. Dash, C. Kar, P. Mal, T. Mishra, V.K. Muraleedharan Nair Bindhu, A. Nayak[31], D.K. Sahoo[30], N. Sur, S.K. Swain

Panjab University, Chandigarh, India
S. Bansal, S.B. Beri, V. Bhatnagar, S. Chauhan, N. Dhingra[32], R. Gupta, A. Kaur, S. Kaur, P. Kumari, M. Meena, K. Sandeep, S. Sharma, J.B. Singh, A.K. Virdi

University of Delhi, Delhi, India
A. Ahmed, A. Bhardwaj, B.C. Choudhary, R.B. Garg, M. Gola, S. Keshri, A. Kumar, M. Naimuddin, P. Priyanka, K. Ranjan, A. Shah

Saha Institute of Nuclear Physics, HBNI, Kolkata, India
M. Bharti[33], R. Bhattacharya, S. Bhattacharya, D. Bhowmik, S. Dutta, S. Ghosh, B. Gomber[34], M. Maity[35], S. Nandan, P. Palit, P.K. Rout, G. Saha, B. Sahu, S. Sarkar, M. Sharan, B. Singh[33], S. Thakur[33]

Indian Institute of Technology Madras, Madras, India
P.K. Behera, S.C. Behera, P. Kalbhor, A. Muhammad, R. Pradhan, P.R. Pujahari, A. Sharma, A.K. Sikdar

Bhabha Atomic Research Centre, Mumbai, India
D. Dutta, V. Kumar, K. Naskar[36], P.K. Netrakanti, L.M. Pant, P. Shukla

Tata Institute of Fundamental Research-A, Mumbai, India
T. Aziz, M.A. Bhat, S. Dugad, R. Kumar Verma, G.B. Mohanty, U. Sarkar

Tata Institute of Fundamental Research-B, Mumbai, India
S. Banerjee, S. Bhattacharya, S. Chatterjee, M. Guchait, S. Karmakar, S. Kumar, G. Majumder, K. Mazumdar, S. Mukherjee, D. Roy

Indian Institute of Science Education and Research (IISER), Pune, India
S. Dube, B. Kansal, S. Pandey, A. Rane, A. Rastogi, S. Sharma

Department of Physics, Isfahan University of Technology, Isfahan, Iran
H. Bakhshiansohi[37], M. Zeinali[38]

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
S. Chenarani[39], S.M. Etesami, M. Khakzad, M. Mohammadi Najafabadi

University College Dublin, Dublin, Ireland
M. Felcini, M. Grunewald

INFN Sezione di Bari [a], Università di Bari [b], Politecnico di Bari [c], Bari, Italy
M. Abbrescia[a,b], R. Aly[a,b,40], C. Aruta[a,b], A. Colaleo[a], D. Creanza[a,c], N. De Filippis[a,c], M. De Palma[a,b], A. Di Florio[a,b], A. Di Pilato[a,b], W. Elmetenawee[a,b], L. Fiore[a], A. Gelmi[a,b], M. Gul[a], G. Iaselli[a,c], M. Ince[a,b], S. Lezki[a,b], G. Maggi[a,c], M. Maggi[a], I. Margjeka[a,b], V. Mastrapasqua[a,b], J.A. Merlin[a], S. My[a,b], S. Nuzzo[a,b], A. Pompili[a,b], G. Pugliese[a,c], A. Ranieri[a], G. Selvaggi[a,b], L. Silvestris[a], F.M. Simone[a,b], R. Venditti[a], P. Verwilligen[a]

INFN Sezione di Bologna [a], Università di Bologna [b], Bologna, Italy
G. Abbiendi[a], C. Battilana[a,b], D. Bonacorsi[a,b], L. Borgonovi[a], S. Braibant-Giacomelli[a,b], R. Campanini[a,b], P. Capiluppi[a,b], A. Castro[a,b], F.R. Cavallo[a], C. Ciocca[a], M. Cuffiani[a,b], G.M. Dallavalle[a], T. Diotalevi[a,b], F. Fabbri[a], A. Fanfani[a,b], E. Fontanesi[a,b], P. Giacomelli[a], C. Grandi[a], L. Guiducci[a,b], F. Iemmi[a,b], S. Lo Meo[a,41], S. Marcellini[a], G. Masetti[a], F.L. Navarria[a,b], A. Perrotta[a], F. Primavera[a,b], A.M. Rossi[a,b], T. Rovelli[a,b], G.P. Siroli[a,b], N. Tosi[a]

INFN Sezione di Catania [a], Università di Catania [b], Catania, Italy
S. Albergo[a,b,42], S. Costa[a,b,42], A. Di Mattia[a], R. Potenza[a,b], A. Tricomi[a,b,42], C. Tuve[a,b]

INFN Sezione di Firenze [a], Università di Firenze [b], Firenze, Italy
G. Barbagli[a], A. Cassese[a], R. Ceccarelli[a,b], V. Ciulli[a,b], C. Civinini[a], R. D'Alessandro[a,b], F. Fiori[a], E. Focardi[a,b], G. Latino[a,b], P. Lenzi[a,b], M. Lizzo[a,b], M. Meschini[a], S. Paoletti[a], R. Seidita[a,b], G. Sguazzoni[a], L. Viliani[a]

INFN Laboratori Nazionali di Frascati, Frascati, Italy
L. Benussi, S. Bianco, D. Piccolo

INFN Sezione di Genova [a], Università di Genova [b], Genova, Italy
M. Bozzo[a,b], F. Ferro[a], R. Mulargia[a,b], E. Robutti[a], S. Tosi[a,b]

INFN Sezione di Milano-Bicocca [a], Università di Milano-Bicocca [b], Milano, Italy
A. Benaglia[a], A. Beschi[a,b], F. Brivio[a,b], F. Cetorelli[a,b], V. Ciriolo[a,b,20], F. De Guio[a,b], M.E. Dinardo[a,b], P. Dini[a], S. Gennai[a], A. Ghezzi[a,b], P. Govoni[a,b], L. Guzzi[a,b], M. Malberti[a], S. Malvezzi[a], D. Menasce[a], F. Monti[a,b], L. Moroni[a], M. Paganoni[a,b], D. Pedrini[a], S. Ragazzi[a,b], T. Tabarelli de Fatis[a,b], D. Valsecchi[a,b,20], D. Zuolo[a,b]

INFN Sezione di Napoli [a], Università di Napoli 'Federico II' [b], Napoli, Italy, Università della Basilicata [c], Potenza, Italy, Università G. Marconi [d], Roma, Italy
S. Buontempo[a], N. Cavallo[a,c], A. De Iorio[a,b], F. Fabozzi[a,c], F. Fienga[a], A.O.M. Iorio[a,b], L. Lista[a,b], S. Meola[a,d,20], P. Paolucci[a,20], B. Rossi[a], C. Sciacca[a,b], E. Voevodina[a,b]

INFN Sezione di Padova [a], Università di Padova [b], Padova, Italy, Università di Trento [c], Trento, Italy
P. Azzi[a], N. Bacchetta[a], D. Bisello[a,b], A. Boletti[a,b], P. Bortignon[a], A. Bragagnolo[a,b], R. Carlin[a,b], P. Checchia[a], P. De Castro Manzano[a], T. Dorigo[a], F. Gasparini[a,b], U. Gasparini[a,b], S.Y. Hoh[a,b], L. Layer[a,43], M. Margoni[a,b], A.T. Meneguzzo[a,b], M. Presilla[a,b], P. Ronchese[a,b], R. Rossin[a,b], F. Simonetto[a,b], G. Strong[a], A. Tiko[a], M. Tosi[a,b], H. YARAR[a,b], M. Zanetti[a,b], P. Zotto[a,b], A. Zucchetta[a,b], G. Zumerle[a,b]

INFN Sezione di Pavia [a], Università di Pavia [b], Pavia, Italy
C. Aime'[a,b], A. Braghieri[a], S. Calzaferri[a,b], D. Fiorina[a,b], P. Montagna[a,b], S.P. Ratti[a,b], V. Re[a], M. Ressegotti[a,b], C. Riccardi[a,b], P. Salvini[a], I. Vai[a], P. Vitulo[a,b]

INFN Sezione di Perugia [a], Università di Perugia [b], Perugia, Italy
M. Biasini[a,b], G.M. Bilei[a], D. Ciangottini[a,b], L. Fanò[a,b], P. Lariccia[a,b], G. Mantovani[a,b], V. Mariani[a,b], M. Menichelli[a], F. Moscatelli[a], A. Piccinelli[a,b], A. Rossi[a,b], A. Santocchia[a,b], D. Spiga[a], T. Tedeschi[a,b]

INFN Sezione di Pisa [a], Università di Pisa [b], Scuola Normale Superiore di Pisa [c], Pisa Italy, Università di Siena [d], Siena, Italy
K. Androsov[a], P. Azzurri[a], G. Bagliesi[a], V. Bertacchi[a,c], L. Bianchini[a], T. Boccali[a], R. Castaldi[a], M.A. Ciocci[a,b], R. Dell'Orso[a], M.R. Di Domenico[a,d], S. Donato[a], L. Giannini[a,c], A. Giassi[a], M.T. Grippo[a], F. Ligabue[a,c], E. Manca[a,c], G. Mandorli[a,c], A. Messineo[a,b], F. Palla[a], G. Ramirez-Sanchez[a,c], A. Rizzi[a,b], G. Rolandi[a,c], S. Roy Chowdhury[a,c], A. Scribano[a], N. Shafiei[a,b], P. Spagnolo[a], R. Tenchini[a], G. Tonelli[a,b], N. Turini[a,d], A. Venturi[a], P.G. Verdini[a]

INFN Sezione di Roma [a], Sapienza Università di Roma [b], Rome, Italy
F. Cavallari[a], M. Cipriani[a,b], D. Del Re[a,b], E. Di Marco[a], M. Diemoz[a], E. Longo[a,b], P. Meridiani[a], G. Organtini[a,b], F. Pandolfi[a], R. Paramatti[a,b], C. Quaranta[a,b], S. Rahatlou[a,b], C. Rovelli[a], F. Santanastasio[a,b], L. Soffi[a,b], R. Tramontano[a,b]

INFN Sezione di Torino [a], Università di Torino [b], Torino, Italy, Università del Piemonte Orientale [c], Novara, Italy
N. Amapane[a,b], R. Arcidiacono[a,c], S. Argiro[a,b], M. Arneodo[a,c], N. Bartosik[a], R. Bellan[a,b], A. Bellora[a,b], C. Biino[a], A. Cappati[a,b], N. Cartiglia[a], S. Cometti[a], M. Costa[a,b], R. Covarelli[a,b], N. Demaria[a], B. Kiani[a,b], F. Legger[a], C. Mariotti[a], S. Maselli[a], E. Migliore[a,b], V. Monaco[a,b], E. Monteil[a,b], M. Monteno[a], M.M. Obertino[a,b], G. Ortona[a], L. Pacher[a,b], N. Pastrone[a], M. Pelliccioni[a], G.L. Pinna Angioni[a,b], M. Ruspa[a,c], R. Salvatico[a,b], F. Siviero[a,b], V. Sola[a], A. Solano[a,b], D. Soldi[a,b], A. Staiano[a], D. Trocino[a,b]

INFN Sezione di Trieste [a], Università di Trieste [b], Trieste, Italy
S. Belforte[a], V. Candelise[a,b], M. Casarsa[a], F. Cossutti[a], A. Da Rold[a,b], G. Della Ricca[a,b], F. Vazzoler[a,b]

Kyungpook National University, Daegu, Korea
S. Dogra, C. Huh, B. Kim, D.H. Kim, G.N. Kim, J. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, S.I. Pak, B.C. Radburn-Smith, S. Sekmen, Y.C. Yang

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
H. Kim, D.H. Moon

Hanyang University, Seoul, Korea
B. Francois, T.J. Kim, J. Park

Korea University, Seoul, Korea
S. Cho, S. Choi, Y. Go, S. Ha, B. Hong, K. Lee, K.S. Lee, J. Lim, J. Park, S.K. Park, J. Yoo

Kyung Hee University, Department of Physics, Seoul, Republic of Korea
J. Goh, A. Gurtu

Sejong University, Seoul, Korea
H.S. Kim, Y. Kim

Seoul National University, Seoul, Korea
J. Almond, J.H. Bhyun, J. Choi, S. Jeon, J. Kim, J.S. Kim, S. Ko, H. Kwon, H. Lee, K. Lee, S. Lee, K. Nam, B.H. Oh, M. Oh, S.B. Oh, H. Seo, U.K. Yang, I. Yoon

University of Seoul, Seoul, Korea
D. Jeon, J.H. Kim, B. Ko, J.S.H. Lee, I.C. Park, Y. Roh, D. Song, I.J. Watson

Yonsei University, Department of Physics, Seoul, Korea
H.D. Yoo

Sungkyunkwan University, Suwon, Korea
Y. Choi, C. Hwang, Y. Jeong, H. Lee, Y. Lee, I. Yu

Riga Technical University, Riga, Latvia
V. Veckalns[44]

Vilnius University, Vilnius, Lithuania
A. Juodagalvis, A. Rinkevicius, G. Tamulaitis

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

Universidad de Sonora (UNISON), Hermosillo, Mexico
J.F. Benitez, A. Castaneda Hernandez, J.A. Murillo Quijada, L. Valencia Palomo

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
G. Ayala, H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz[45], R. Lopez-Fernandez, C.A. Mondragon Herrera, D.A. Perez Navarro, A. Sanchez-Hernandez

Universidad Iberoamericana, Mexico City, Mexico
S. Carrillo Moreno, C. Oropeza Barrera, M. Ramirez-Garcia, F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
J. Eysermans, I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

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

University of Montenegro, Podgorica, Montenegro
J. Mijuskovic[4], N. Raicevic

University of Auckland, Auckland, New Zealand
D. Krofcheck

University of Canterbury, Christchurch, New Zealand
S. Bheesette, P.H. Butler

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
A. Ahmad, M.I. Asghar, A. Awais, M.I.M. Awan, H.R. Hoorani, W.A. Khan, M.A. Shah, M. Shoaib, M. Waqas

AGH University of Science and Technology Faculty of Computer Science, Electronics and Telecommunications, Krakow, Poland
V. Avati, L. Grzanka, M. Malawski

National Centre for Nuclear Research, Swierk, Poland
H. Bialkowska, M. Bluj, B. Boimska, T. Frueboes, M. Górski, M. Kazana, M. Szleper, P. Traczyk, P. Zalewski

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
K. Bunkowski, A. Byszuk[46], K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Olszewski, M. Walczak

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
M. Araujo, P. Bargassa, D. Bastos, P. Faccioli, M. Gallinaro, J. Hollar, N. Leonardo, T. Niknejad, J. Seixas, K. Shchelina, O. Toldaiev, J. Varela

Joint Institute for Nuclear Research, Dubna, Russia
V. Alexakhin, P. Bunin, M. Gavrilenko, A. Golunov, A. Golunov, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavine, V. Korenkov, A. Lanev, A. Malakhov, V. Matveev[47,48], V. Palichik, V. Perelygin, M. Savina, S. Shmatov, S. Shulha, V. Smirnov, O. Teryaev, N. Voytishin, A. Zarubin

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia
G. Gavrilov, V. Golovtcov, Y. Ivanov, V. Kim[49], E. Kuznetsova[50], V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov, V. Sulimov, L. Uvarov, S. Volkov, A. Vorobyev

Institute for Nuclear Research, Moscow, Russia
Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, M. Kirsanov, N. Krasnikov, A. Pashenkov, G. Pivovarov, D. Tlisov[†], A. Toropin

Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC 'Kurchatov Institute', Moscow, Russia
V. Epshteyn, V. Gavrilov, N. Lychkovskaya, A. Nikitenko[51], V. Popov, G. Safronov, A. Spiridonov, A. Stepennov, M. Toms, E. Vlasov, A. Zhokin

Moscow Institute of Physics and Technology, Moscow, Russia
T. Aushev

National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
O. Bychkova, M. Chadeeva[52], D. Philippov, E. Popova, V. Rusinov

P.N. Lebedev Physical Institute, Moscow, Russia
V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, A. Terkulov

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
A. Belyaev, E. Boos, M. Dubinin[53], L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev

Novosibirsk State University (NSU), Novosibirsk, Russia
V. Blinov[54], T. Dimova[54], L. Kardapoltsev[54], I. Ovtin[54], Y. Skovpen[54]

Institute for High Energy Physics of National Research Centre 'Kurchatov Institute', Protvino, Russia
I. Azhgirey, I. Bayshev, V. Kachanov, A. Kalinin, D. Konstantinov, V. Petrov, R. Ryutin, A. Sobol, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

National Research Tomsk Polytechnic University, Tomsk, Russia
A. Babaev, A. Iuzhakov, V. Okhotnikov, L. Sukhikh

Tomsk State University, Tomsk, Russia
V. Borchsh, V. Ivanchenko, E. Tcherniaev

University of Belgrade: Faculty of Physics and VINCA Institute of Nuclear Sciences, Belgrade, Serbia
P. Adzic[55], P. Cirkovic, M. Dordevic, P. Milenovic, J. Milosevic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
M. Aguilar-Benitez, J. Alcaraz Maestre, A. Álvarez Fernández, I. Bachiller, M. Barrio Luna, Cristina F. Bedoya, J.A. Brochero Cifuentes, C.A. Carrillo Montoya, M. Cepeda, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, J.P. Fernández Ramos, J. Flix, M.C. Fouz, A. García Alonso, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, J. León Holgado, D. Moran, Á. Navarro Tobar, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, L. Romero, S. Sánchez Navas, M.S. Soares, A. Triossi, L. Urda Gómez, C. Willmott

Universidad Autónoma de Madrid, Madrid, Spain
C. Albajar, J.F. de Trocóniz, R. Reyes-Almanza

Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain
B. Alvarez Gonzalez, J. Cuevas, C. Erice, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, E. Palencia Cortezon, C. Ramón Álvarez, J. Ripoll Sau, V. Rodríguez Bouza, S. Sanchez Cruz, A. Trapote

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
I.J. Cabrillo, A. Calderon, B. Chazin Quero, J. Duarte Campderros, M. Fernandez, P.J. Fernández Manteca, G. Gomez, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, J. Piedra Gomez, C. Prieels, F. Ricci-Tam, T. Rodrigo, A. Ruiz-Jimeno, L. Scodellaro, I. Vila, J.M. Vizan Garcia

University of Colombo, Colombo, Sri Lanka
MK Jayananda, B. Kailasapathy[56], D.U.J. Sonnadara, DDC Wickramarathna

University of Ruhuna, Department of Physics, Matara, Sri Lanka
W.G.D. Dharmaratna, K. Liyanage, N. Perera, N. Wickramage

CERN, European Organization for Nuclear Research, Geneva, Switzerland
T.K. Aarrestad, D. Abbaneo, B. Akgun, E. Auffray, G. Auzinger, J. Baechler, P. Baillon, A.H. Ball, D. Barney, J. Bendavid, N. Beni, M. Bianco, A. Bocci, E. Bossini, E. Brondolin, T. Camporesi, G. Cerminara, L. Cristella, D. d'Enterria, A. Dabrowski, N. Daci, V. Daponte, A. David, A. De Roeck, M. Deile, R. Di Maria, M. Dobson, M. Dünser, N. Dupont, A. Elliott-Peisert, N. Emriskova, F. Fallavollita[57], D. Fasanella, S. Fiorendi, A. Florent, G. Franzoni, J. Fulcher, W. Funk, S. Giani, D. Gigi, K. Gill, F. Glege, L. Gouskos, M. Guilbaud, D. Gulhan, M. Haranko, J. Hegeman, Y. Iiyama, V. Innocente, T. James, P. Janot, J. Kaspar, J. Kieseler, M. Komm, N. Kratochwil, C. Lange, S. Laurila, P. Lecoq, K. Long, C. Lourenço, L. Malgeri, S. Mallios, M. Mannelli, A. Massironi, F. Meijers, S. Mersi, E. Meschi, F. Moortgat, M. Mulders, J. Niedziela, S. Orfanelli, L. Orsini, F. Pantaleo[20], L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, T. Quast, D. Rabady, A. Racz, M. Rieger, M. Rovere, H. Sakulin, J. Salfeld-Nebgen, S. Scarfi, C. Schäfer, C. Schwick, M. Selvaggi, A. Sharma, P. Silva, W. Snoeys, P. Sphicas[58], S. Summers, V.R. Tavolaro, D. Treille, A. Tsirou, G.P. Van Onsem, A. Vartak, M. Verzetti, K.A. Wozniak, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland
L. Caminada[59], W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe

ETH Zurich - Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland
M. Backhaus, P. Berger, A. Calandri, N. Chernyavskaya, A. De Cosa, G. Dissertori, M. Dittmar, M. Donegà, C. Dorfer, T. Gadek, T.A. Gómez Espinosa, C. Grab, D. Hits, W. Lustermann, A.-M. Lyon, R.A. Manzoni, M.T. Meinhard, F. Micheli, F. Nessi-Tedaldi, F. Pauss, V. Perovic, G. Perrin, L. Perrozzi, S. Pigazzini, M.G. Ratti, M. Reichmann, C. Reissel, T. Reitenspiess, B. Ristic, D. Ruini, D.A. Sanz Becerra, M. Schönenberger, V. Stampf, M.L. Vesterbacka Olsson, R. Wallny, D.H. Zhu

Universität Zürich, Zurich, Switzerland
C. Amsler[60], C. Botta, D. Brzhechko, M.F. Canelli, R. Del Burgo, J.K. Heikkilä, M. Huwiler, A. Jofrehei, B. Kilminster, S. Leontsinis, A. Macchiolo, P. Meiring, V.M. Mikuni, U. Molinatti, I. Neutelings, G. Rauco, A. Reimers, P. Robmann, K. Schweiger, Y. Takahashi

National Central University, Chung-Li, Taiwan
C. Adloff[61], C.M. Kuo, W. Lin, A. Roy, T. Sarkar[35], S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan
L. Ceard, P. Chang, Y. Chao, K.F. Chen, P.H. Chen, W.-S. Hou, Y.y. Li, R.-S. Lu, E. Paganis, A. Psallidas, A. Steen, E. Yazgan

Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand
B. Asavapibhop, C. Asawatangtrakuldee, N. Srimanobhas

Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey
F. Boran, S. Damarseckin[62], Z.S. Demiroglu, F. Dolek, C. Dozen[63], I. Dumanoglu[64], E. Eskut, G. Gokbulut, Y. Guler, E. Gurpinar Guler[65], I. Hos[66], C. Isik, E.E. Kangal[67], O. Kara, A. Kayis Topaksu, U. Kiminsu, G. Onengut, K. Ozdemir[68], A. Polatoz, A.E. Simsek, B. Tali[69], U.G. Tok, S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

Middle East Technical University, Physics Department, Ankara, Turkey
B. Isildak[70], G. Karapinar[71], K. Ocalan[72], M. Yalvac[73]

Bogazici University, Istanbul, Turkey
I.O. Atakisi, E. Gülmez, M. Kaya[74], O. Kaya[75], Ö. Özçelik, S. Tekten[76], E.A. Yetkin[77]

Istanbul Technical University, Istanbul, Turkey
A. Cakir, K. Cankocak[64], Y. Komurcu, S. Sen[78]

Istanbul University, Istanbul, Turkey
F. Aydogmus Sen, S. Cerci[69], B. Kaynak, S. Ozkorucuklu, D. Sunar Cerci[69]

Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine
B. Grynyov

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine
L. Levchuk

University of Bristol, Bristol, United Kingdom
E. Bhal, S. Bologna, J.J. Brooke, E. Clement, D. Cussans, H. Flacher, J. Goldstein, G.P. Heath, H.F. Heath, L. Kreczko, B. Krikler, S. Paramesvaran, T. Sakuma, S. Seif El Nasr-Storey, V.J. Smith, J. Taylor, A. Titterton

Rutherford Appleton Laboratory, Didcot, United Kingdom
K.W. Bell, A. Belyaev[79], C. Brew, R.M. Brown, D.J.A. Cockerill, K.V. Ellis, K. Harder,

S. Harper, J. Linacre, K. Manolopoulos, D.M. Newbold, E. Olaiya, D. Petyt, T. Reis, T. Schuh, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams

Imperial College, London, United Kingdom
R. Bainbridge, P. Bloch, S. Bonomally, J. Borg, S. Breeze, O. Buchmuller, A. Bundock, V. Cepaitis, G.S. Chahal[80], D. Colling, P. Dauncey, G. Davies, M. Della Negra, G. Fedi, G. Hall, G. Iles, J. Langford, L. Lyons, A.-M. Magnan, S. Malik, A. Martelli, V. Milosevic, J. Nash[81], V. Palladino, M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, M. Stoye, A. Tapper, K. Uchida, T. Virdee[20], N. Wardle, S.N. Webb, D. Winterbottom, A.G. Zecchinelli

Brunel University, Uxbridge, United Kingdom
J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, C.K. Mackay, I.D. Reid, L. Teodorescu, S. Zahid

Baylor University, Waco, USA
A. Brinkerhoff, K. Call, B. Caraway, J. Dittmann, K. Hatakeyama, A.R. Kanuganti, C. Madrid, B. McMaster, N. Pastika, S. Sawant, C. Smith, J. Wilson

Catholic University of America, Washington, DC, USA
R. Bartek, A. Dominguez, R. Uniyal, A.M. Vargas Hernandez

The University of Alabama, Tuscaloosa, USA
A. Buccilli, O. Charaf, S.I. Cooper, S.V. Gleyzer, C. Henderson, P. Rumerio, C. West

Boston University, Boston, USA
A. Akpinar, A. Albert, D. Arcaro, C. Cosby, Z. Demiragli, D. Gastler, J. Rohlf, K. Salyer, D. Sperka, D. Spitzbart, I. Suarez, S. Yuan, D. Zou

Brown University, Providence, USA
G. Benelli, B. Burkle, X. Coubez[21], D. Cutts, Y.t. Duh, M. Hadley, U. Heintz, J.M. Hogan[82], K.H.M. Kwok, E. Laird, G. Landsberg, K.T. Lau, J. Lee, M. Narain, S. Sagir[83], R. Syarif, E. Usai, W.Y. Wong, D. Yu, W. Zhang

University of California, Davis, Davis, USA
R. Band, C. Brainerd, R. Breedon, M. Calderon De La Barca Sanchez, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, C. Flores, G. Funk, F. Jensen, W. Ko[†], O. Kukral, R. Lander, M. Mulhearn, D. Pellett, J. Pilot, M. Shi, D. Taylor, K. Tos, M. Tripathi, Y. Yao, F. Zhang

University of California, Los Angeles, USA
M. Bachtis, R. Cousins, A. Dasgupta, D. Hamilton, J. Hauser, M. Ignatenko, T. Lam, N. Mccoll, W.A. Nash, S. Regnard, D. Saltzberg, C. Schnaible, B. Stone, V. Valuev

University of California, Riverside, Riverside, USA
K. Burt, Y. Chen, R. Clare, J.W. Gary, S.M.A. Ghiasi Shirazi, G. Hanson, G. Karapostoli, O.R. Long, N. Manganelli, M. Olmedo Negrete, M.I. Paneva, W. Si, S. Wimpenny, Y. Zhang

University of California, San Diego, La Jolla, USA
J.G. Branson, P. Chang, S. Cittolin, S. Cooperstein, N. Deelen, J. Duarte, R. Gerosa, D. Gilbert, V. Krutelyov, J. Letts, M. Masciovecchio, S. May, S. Padhi, M. Pieri, V. Sharma, M. Tadel, F. Würthwein, A. Yagil

University of California, Santa Barbara - Department of Physics, Santa Barbara, USA
N. Amin, C. Campagnari, M. Citron, A. Dorsett, V. Dutta, J. Incandela, B. Marsh, H. Mei, A. Ovcharova, H. Qu, M. Quinnan, J. Richman, U. Sarica, D. Stuart, S. Wang

California Institute of Technology, Pasadena, USA
D. Anderson, A. Bornheim, O. Cerri, I. Dutta, J.M. Lawhorn, N. Lu, J. Mao, H.B. Newman,

J. Ngadiuba, T.Q. Nguyen, J. Pata, M. Spiropulu, J.R. Vlimant, C. Wang, S. Xie, Z. Zhang, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, USA
J. Alison, M.B. Andrews, T. Ferguson, T. Mudholkar, M. Paulini, M. Sun, I. Vorobiev

University of Colorado Boulder, Boulder, USA
J.P. Cumalat, W.T. Ford, E. MacDonald, T. Mulholland, R. Patel, A. Perloff, K. Stenson, K.A. Ulmer, S.R. Wagner

Cornell University, Ithaca, USA
J. Alexander, Y. Cheng, J. Chu, D.J. Cranshaw, A. Datta, A. Frankenthal, K. Mcdermott, J. Monroy, J.R. Patterson, D. Quach, A. Ryd, W. Sun, S.M. Tan, Z. Tao, J. Thom, P. Wittich, M. Zientek

Fermi National Accelerator Laboratory, Batavia, USA
S. Abdullin, M. Albrow, M. Alyari, G. Apollinari, A. Apresyan, A. Apyan, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, D. Berry, J. Berryhill, P.C. Bhat, K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, M. Cremonesi, V.D. Elvira, J. Freeman, Z. Gecse, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, R.M. Harris, S. Hasegawa, R. Heller, T.C. Herwig, J. Hirschauer, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, P. Klabbers, T. Klijnsma, B. Klima, M.J. Kortelainen, S. Lammel, D. Lincoln, R. Lipton, M. Liu, T. Liu, J. Lykken, K. Maeshima, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, V. O'Dell, V. Papadimitriou, K. Pedro, C. Pena[53], O. Prokofyev, F. Ravera, A. Reinsvold Hall, L. Ristori, B. Schneider, E. Sexton-Kennedy, N. Smith, A. Soha, W.J. Spalding, L. Spiegel, S. Stoynev, J. Strait, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, H.A. Weber, A. Woodard

University of Florida, Gainesville, USA
D. Acosta, P. Avery, D. Bourilkov, L. Cadamuro, V. Cherepanov, F. Errico, R.D. Field, D. Guerrero, B.M. Joshi, M. Kim, J. Konigsberg, A. Korytov, K.H. Lo, K. Matchev, N. Menendez, G. Mitselmakher, D. Rosenzweig, K. Shi, J. Sturdy, J. Wang, S. Wang, X. Zuo

Florida State University, Tallahassee, USA
T. Adams, A. Askew, D. Diaz, R. Habibullah, S. Hagopian, V. Hagopian, K.F. Johnson, R. Khurana, T. Kolberg, G. Martinez, H. Prosper, C. Schiber, R. Yohay, J. Zhang

Florida Institute of Technology, Melbourne, USA
M.M. Baarmand, S. Butalla, T. Elkafrawy[84], M. Hohlmann, D. Noonan, M. Rahmani, M. Saunders, F. Yumiceva

University of Illinois at Chicago (UIC), Chicago, USA
M.R. Adams, L. Apanasevich, H. Becerril Gonzalez, R. Cavanaugh, X. Chen, S. Dittmer, O. Evdokimov, C.E. Gerber, D.A. Hangal, D.J. Hofman, C. Mills, G. Oh, T. Roy, M.B. Tonjes, N. Varelas, J. Viinikainen, X. Wang, Z. Wu

The University of Iowa, Iowa City, USA
M. Alhusseini, K. Dilsiz[85], S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, O.K. Köseyan, J.-P. Merlo, A. Mestvirishvili[86], A. Moeller, J. Nachtman, H. Ogul[87], Y. Onel, F. Ozok[88], A. Penzo, C. Snyder, E. Tiras, J. Wetzel, K. Yi[89]

Johns Hopkins University, Baltimore, USA
O. Amram, B. Blumenfeld, L. Corcodilos, M. Eminizer, A.V. Gritsan, S. Kyriacou, P. Maksimovic, C. Mantilla, J. Roskes, M. Swartz, T.Á. Vámi

The University of Kansas, Lawrence, USA
C. Baldenegro Barrera, P. Baringer, A. Bean, A. Bylinkin, T. Isidori, S. Khalil, J. King, G. Krintiras, A. Kropivnitskaya, C. Lindsey, N. Minafra, M. Murray, C. Rogan, C. Royon, S. Sanders, E. Schmitz, J.D. Tapia Takaki, Q. Wang, J. Williams, G. Wilson

Kansas State University, Manhattan, USA
S. Duric, A. Ivanov, K. Kaadze, D. Kim, Y. Maravin, T. Mitchell, A. Modak, A. Mohammadi

Lawrence Livermore National Laboratory, Livermore, USA
F. Rebassoo, D. Wright

University of Maryland, College Park, USA
E. Adams, A. Baden, O. Baron, A. Belloni, S.C. Eno, Y. Feng, N.J. Hadley, S. Jabeen, G.Y. Jeng, R.G. Kellogg, T. Koeth, A.C. Mignerey, S. Nabili, M. Seidel, A. Skuja, S.C. Tonwar, L. Wang, K. Wong

Massachusetts Institute of Technology, Cambridge, USA
D. Abercrombie, B. Allen, R. Bi, S. Brandt, W. Busza, I.A. Cali, Y. Chen, M. D'Alfonso, G. Gomez Ceballos, M. Goncharov, P. Harris, D. Hsu, M. Hu, M. Klute, D. Kovalskyi, J. Krupa, Y.-J. Lee, P.D. Luckey, B. Maier, A.C. Marini, C. Mcginn, C. Mironov, S. Narayanan, X. Niu, C. Paus, D. Rankin, C. Roland, G. Roland, Z. Shi, G.S.F. Stephans, K. Sumorok, K. Tatar, D. Velicanu, J. Wang, T.W. Wang, Z. Wang, B. Wyslouch

University of Minnesota, Minneapolis, USA
R.M. Chatterjee, A. Evans, S. Guts[†], P. Hansen, J. Hiltbrand, Sh. Jain, M. Krohn, Y. Kubota, Z. Lesko, J. Mans, M. Revering, R. Rusack, R. Saradhy, N. Schroeder, N. Strobbe, M.A. Wadud

University of Mississippi, Oxford, USA
J.G. Acosta, S. Oliveros

University of Nebraska-Lincoln, Lincoln, USA
K. Bloom, S. Chauhan, D.R. Claes, C. Fangmeier, L. Finco, F. Golf, J.R. González Fernández, I. Kravchenko, J.E. Siado, G.R. Snow[†], B. Stieger, W. Tabb, F. Yan

State University of New York at Buffalo, Buffalo, USA
G. Agarwal, H. Bandyopadhyay, C. Harrington, L. Hay, I. Iashvili, A. Kharchilava, C. McLean, D. Nguyen, J. Pekkanen, S. Rappoccio, B. Roozbahani

Northeastern University, Boston, USA
G. Alverson, E. Barberis, C. Freer, Y. Haddad, A. Hortiangtham, J. Li, G. Madigan, B. Marzocchi, D.M. Morse, V. Nguyen, T. Orimoto, A. Parker, L. Skinnari, A. Tishelman-Charny, T. Wamorkar, B. Wang, A. Wisecarver, D. Wood

Northwestern University, Evanston, USA
S. Bhattacharya, J. Bueghly, Z. Chen, A. Gilbert, T. Gunter, K.A. Hahn, N. Odell, M.H. Schmitt, K. Sung, M. Velasco

University of Notre Dame, Notre Dame, USA
R. Bucci, N. Dev, R. Goldouzian, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, K. Lannon, N. Loukas, N. Marinelli, I. Mcalister, F. Meng, K. Mohrman, Y. Musienko[47], R. Ruchti, P. Siddireddy, S. Taroni, M. Wayne, A. Wightman, M. Wolf, L. Zygala

The Ohio State University, Columbus, USA
J. Alimena, B. Bylsma, B. Cardwell, L.S. Durkin, B. Francis, C. Hill, A. Lefeld, B.L. Winer, B.R. Yates

Princeton University, Princeton, USA
P. Das, G. Dezoort, P. Elmer, B. Greenberg, N. Haubrich, S. Higginbotham, A. Kalogeropoulos, G. Kopp, S. Kwan, D. Lange, M.T. Lucchini, J. Luo, D. Marlow, K. Mei, I. Ojalvo, J. Olsen, C. Palmer, P. Piroué, D. Stickland, C. Tully

University of Puerto Rico, Mayaguez, USA
S. Malik, S. Norberg

Purdue University, West Lafayette, USA
V.E. Barnes, R. Chawla, S. Das, L. Gutay, M. Jones, A.W. Jung, G. Negro, N. Neumeister, C.C. Peng, S. Piperov, A. Purohit, H. Qiu, J.F. Schulte, M. Stojanovic[17], N. Trevisani, F. Wang, R. Xiao, W. Xie

Purdue University Northwest, Hammond, USA
T. Cheng, J. Dolen, N. Parashar

Rice University, Houston, USA
A. Baty, S. Dildick, K.M. Ecklund, S. Freed, F.J.M. Geurts, M. Kilpatrick, A. Kumar, W. Li, B.P. Padley, R. Redjimi, J. Roberts[†], J. Rorie, W. Shi, A.G. Stahl Leiton

University of Rochester, Rochester, USA
A. Bodek, P. de Barbaro, R. Demina, J.L. Dulemba, C. Fallon, T. Ferbel, M. Galanti, A. Garcia-Bellido, O. Hindrichs, A. Khukhunaishvili, E. Ranken, R. Taus

Rutgers, The State University of New Jersey, Piscataway, USA
B. Chiarito, J.P. Chou, A. Gandrakota, Y. Gershtein, E. Halkiadakis, A. Hart, M. Heindl, E. Hughes, S. Kaplan, O. Karacheban[24], I. Laflotte, A. Lath, R. Montalvo, K. Nash, M. Osherson, S. Salur, S. Schnetzer, S. Somalwar, R. Stone, S.A. Thayil, S. Thomas, H. Wang

University of Tennessee, Knoxville, USA
H. Acharya, A.G. Delannoy, S. Spanier

Texas A&M University, College Station, USA
O. Bouhali[90], M. Dalchenko, A. Delgado, R. Eusebi, J. Gilmore, T. Huang, T. Kamon[91], H. Kim, S. Luo, S. Malhotra, R. Mueller, D. Overton, L. Perniè, D. Rathjens, A. Safonov

Texas Tech University, Lubbock, USA
N. Akchurin, J. Damgov, V. Hegde, S. Kunori, K. Lamichhane, S.W. Lee, T. Mengke, S. Muthumuni, T. Peltola, S. Undleeb, I. Volobouev, Z. Wang, A. Whitbeck

Vanderbilt University, Nashville, USA
E. Appelt, S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, A. Melo, H. Ni, K. Padeken, F. Romeo, P. Sheldon, S. Tuo, J. Velkovska, M. Verweij

University of Virginia, Charlottesville, USA
M.W. Arenton, B. Cox, G. Cummings, J. Hakala, R. Hirosky, M. Joyce, A. Ledovskoy, A. Li, C. Neu, B. Tannenwald, Y. Wang, E. Wolfe, F. Xia

Wayne State University, Detroit, USA
P.E. Karchin, N. Poudyal, P. Thapa

University of Wisconsin - Madison, Madison, WI, USA
K. Black, T. Bose, J. Buchanan, C. Caillol, S. Dasu, I. De Bruyn, P. Everaerts, C. Galloni, H. He, M. Herndon, A. Hervé, U. Hussain, A. Lanaro, A. Loeliger, R. Loveless, J. Madhusudanan Sreekala, A. Mallampalli, D. Pinna, T. Ruggles, A. Savin, V. Shang, V. Sharma, W.H. Smith, J. Steggemann, D. Teague, S. Trembath-reichert, W. Vetens

†: Deceased
1: Also at Vienna University of Technology, Vienna, Austria
2: Also at Institute of Basic and Applied Sciences, Faculty of Engineering, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt, Alexandria, Egypt
3: Also at Université Libre de Bruxelles, Bruxelles, Belgium
4: Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
5: Also at Universidade Estadual de Campinas, Campinas, Brazil
6: Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil
7: Also at UFMS, Nova Andradina, Brazil
8: Also at Universidade Federal de Pelotas, Pelotas, Brazil
9: Also at University of Chinese Academy of Sciences, Beijing, China
10: Also at Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC 'Kurchatov Institute', Moscow, Russia
11: Also at Joint Institute for Nuclear Research, Dubna, Russia
12: Also at Cairo University, Cairo, Egypt
13: Also at Helwan University, Cairo, Egypt
14: Now at Zewail City of Science and Technology, Zewail, Egypt
15: Now at British University in Egypt, Cairo, Egypt
16: Now at Fayoum University, El-Fayoum, Egypt
17: Also at Purdue University, West Lafayette, USA
18: Also at Université de Haute Alsace, Mulhouse, France
19: Also at Erzincan Binali Yildirim University, Erzincan, Turkey
20: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
21: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
22: Also at University of Hamburg, Hamburg, Germany
23: Also at Department of Physics, Isfahan University of Technology, Isfahan, Iran, Isfahan, Iran
24: Also at Brandenburg University of Technology, Cottbus, Germany
25: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
26: Also at Institute of Physics, University of Debrecen, Debrecen, Hungary, Debrecen, Hungary
27: Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt
28: Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary, Budapest, Hungary
29: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
30: Also at IIT Bhubaneswar, Bhubaneswar, India, Bhubaneswar, India
31: Also at Institute of Physics, Bhubaneswar, India
32: Also at G.H.G. Khalsa College, Punjab, India
33: Also at Shoolini University, Solan, India
34: Also at University of Hyderabad, Hyderabad, India
35: Also at University of Visva-Bharati, Santiniketan, India
36: Also at Indian Institute of Technology (IIT), Mumbai, India
37: Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany
38: Also at Sharif University of Technology, Tehran, Iran
39: Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran
40: Now at INFN Sezione di Bari [a], Università di Bari [b], Politecnico di Bari [c], Bari, Italy
41: Also at Italian National Agency for New Technologies, Energy and Sustainable Economic

Development, Bologna, Italy
42: Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
43: Also at Università di Napoli 'Federico II', NAPOLI, Italy
44: Also at Riga Technical University, Riga, Latvia, Riga, Latvia
45: Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
46: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
47: Also at Institute for Nuclear Research, Moscow, Russia
48: Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
49: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
50: Also at University of Florida, Gainesville, USA
51: Also at Imperial College, London, United Kingdom
52: Also at P.N. Lebedev Physical Institute, Moscow, Russia
53: Also at California Institute of Technology, Pasadena, USA
54: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
55: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
56: Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka
57: Also at INFN Sezione di Pavia [a], Università di Pavia [b], Pavia, Italy, Pavia, Italy
58: Also at National and Kapodistrian University of Athens, Athens, Greece
59: Also at Universität Zürich, Zurich, Switzerland
60: Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria, Vienna, Austria
61: Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France
62: Also at Şırnak University, Sirnak, Turkey
63: Also at Department of Physics, Tsinghua University, Beijing, China, Beijing, China
64: Also at Near East University, Research Center of Experimental Health Science, Nicosia, Turkey
65: Also at Beykent University, Istanbul, Turkey, Istanbul, Turkey
66: Also at Istanbul Aydin University, Application and Research Center for Advanced Studies (App. & Res. Cent. for Advanced Studies), Istanbul, Turkey
67: Also at Mersin University, Mersin, Turkey
68: Also at Piri Reis University, Istanbul, Turkey
69: Also at Adiyaman University, Adiyaman, Turkey
70: Also at Ozyegin University, Istanbul, Turkey
71: Also at Izmir Institute of Technology, Izmir, Turkey
72: Also at Necmettin Erbakan University, Konya, Turkey
73: Also at Bozok Universitetesi Rektörlügü, Yozgat, Turkey, Yozgat, Turkey
74: Also at Marmara University, Istanbul, Turkey
75: Also at Milli Savunma University, Istanbul, Turkey
76: Also at Kafkas University, Kars, Turkey
77: Also at Istanbul Bilgi University, Istanbul, Turkey
78: Also at Hacettepe University, Ankara, Turkey
79: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
80: Also at IPPP Durham University, Durham, United Kingdom
81: Also at Monash University, Faculty of Science, Clayton, Australia
82: Also at Bethel University, St. Paul, Minneapolis, USA, St. Paul, USA
83: Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
84: Also at Ain Shams University, Cairo, Egypt

85: Also at Bingol University, Bingol, Turkey
86: Also at Georgian Technical University, Tbilisi, Georgia
87: Also at Sinop University, Sinop, Turkey
88: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
89: Also at Nanjing Normal University Department of Physics, Nanjing, China
90: Also at Texas A&M University at Qatar, Doha, Qatar
91: Also at Kyungpook National University, Daegu, Korea, Daegu, Korea