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Azimuthal separation in nearly back-to-back jet topologies in inclusive 2- and 3-jet events in pp collisions at $\sqrt{s} = 13$ TeV

CMS Collaboration[*]

CERN, 1211 Geneva 23, Switzerland

Abstract A measurement for inclusive 2- and 3-jet events of the azimuthal correlation between the two jets with the largest transverse momenta, $\Delta\phi_{12}$, is presented. The measurement considers events where the two leading jets are nearly collinear ("back-to-back") in the transverse plane and is performed for several ranges of the leading jet transverse momentum. Proton-proton collision data collected with the CMS experiment at a center-of-mass energy of 13 TeV and corresponding to an integrated luminosity of $35.9\,\mathrm{fb}^{-1}$ are used. Predictions based on calculations using matrix elements at leading-order and next-to-leading-order accuracy in perturbative quantum chromodynamics supplemented with leading-log parton showers and hadronization are generally in agreement with the measurements. Discrepancies between the measurement and theoretical predictions are as large as 15%, mainly in the region $177° < \Delta\phi_{12} < 180°$. The 2- and 3-jet measurements are not simultaneously described by any of models.

1 Introduction

Collimated streams of particles (jets) can be produced in highly energetic parton-parton interactions in proton-proton (s) collisions, and their properties are described by the theory of strong interactions, quantum chromodynamics (QCD). In the lowest order perturbative QCD (pQCD), two jets with high transverse momenta p_T are produced "back-to-back" in the transverse plane. Higher order corrections lead to deviations from this configuration. Experimentally, this can be investigated by the measurement of the azimuthal separation, $\Delta\phi_{12} = |\phi_{\mathrm{jet1}} - \phi_{\mathrm{jet2}}|$, between the two leading p_T jets in the transverse plane. Within the framework of pQCD, a final state with three or more partons is required for significant deviations from $\Delta\phi_{12} = 180°$. However, when deviations of $\Delta\phi_{12}$ from 180° are small, a pQCD calculation at a fixed order in the strong coupling α_S becomes unstable and a resummation of soft parton emissions to all orders in α_S has

to be performed. This resummation is approximated through the use of parton showers in Monte Carlo (MC) event generators.

Azimuthal correlations in inclusive 2-jet events have been measured previously by the D0 Collaboration in $p\bar{p}$ collisions at a center-of-mass energy of $\sqrt{s} = 1.96$ TeV [1,2], in pp collisions by the ATLAS Collaboration at $\sqrt{s} = 7$ TeV [3], and by the CMS Collaboration at $\sqrt{s} = 7$, 8, and 13 TeV [4–6], but none of the measurements considered in detail the region close to the back-to-back configuration. A detailed study of azimuthal correlations close to the back-to-back configuration allows a more precise test of different resummation strategies, and it is a first step towards an improved understanding of the effects of soft initial and final state gluons [7,8]. The leading- and next-to-leading-logarithm contributions to the dijet azimuthal angular correlation have been investigated in [9–11]. The effects of applying a transverse momentum dependent parton showering to the dijet azimuthal angular correlation were studied in [12].

In this article measurements are reported of the normalized inclusive 2-jet distribution as a function of the azimuthal separation $\Delta\phi_{12}$ between the two leading p_T jets (jets 1 and 2),

$$\frac{1}{\sigma_{p_T^{\max}}} \frac{d\sigma}{d\Delta\phi_{12}}, \tag{1}$$

in several intervals of the leading jet p_T ($p_T^{\max}$) within the rapidity range $|y| < 2.5$. The total dijet cross section $\sigma_{p_T^{\max}}$ is measured within each range of $p_T^{\max}$ integrated over the full range in $\Delta\phi_{12}$. The binning of the measurement presented here is much finer than that of Ref. [6]. We consider $\Delta\phi_{12}$ in the range $170° < \Delta\phi_{12} \le 180°$.

The inclusive 3-jet distributions, differential in $\Delta\phi_{12}$ and $p_T^{\max}$, with the p_T of third highest p_T jet typically being 1-2 orders of magnitude smaller than $p_T^{\max}$, are also suitable to test resummation effects arising from the presence of multiple scales in the interaction. Measurements of the inclusive

[*] e-mail: cms-publication-committee-chair@cern.ch

3-jet distribution normalized to $\sigma_{p_{\mathrm{T}}^{\max}}$ are also presented, for several ranges of $p_{\mathrm{T}}^{\max}$, and within $|y| < 2.5$.

The measurements are performed using data collected from pp collisions at $\sqrt{s} = 13$ TeV during 2016 with the CMS experiment at the CERN LHC, corresponding to an integrated luminosity of $35.9\,\mathrm{fb}^{-1}$.

2 The CMS detector

The central feature of the CMS detector is a superconducting solenoid, 13 m in length and 6 m in inner diameter, providing an axial magnetic field of 3.8 T. Within the solenoid volume are 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. Charged-particle trajectories are measured by the tracker with full azimuthal coverage 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 $|\eta| < 2.4$ by gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. A detailed description of the CMS detector together with a definition of the coordinate system used and the relevant kinematic variables can be found in Ref. [13].

3 Theoretical predictions

Simulations from leading-order (LO) and next-to-LO (NLO) MC event generators are investigated. Among the LO event generators, both PYTHIA 8 [14] (version 8.219) and HERWIG++ [15] (version 2.7.1) are used for predictions because they feature different parton showering (PS) algorithms for soft and collinear parton radiation at leading-log accuracy. In PYTHIA 8 the PS emissions cover a region of phase space ordered in x (fraction of the proton momentum carried by the parton) and the p_{T} of the emitted parton, whereas in HERWIG++ the parton emissions are ordered in x and the angle of the radiated parton (angular ordering). The Lund string model [16] is used for hadronization in PYTHIA 8 [14], whereas in HERWIG++ the cluster fragmentation model [17] is applied. Multiparton interactions (MPI) are simulated in PYTHIA 8 (tune CUETP8M1 [18] with the parton distribution function (PDF) set NNPDF2.3LO [19,20]) and in HERWIG++ (tune CUETHppS1 [18] with the PDF set CTEQ6L1 [21]) with parameters tuned to measurements in pp collisions at the LHC and p$\bar{\mathrm{p}}$ collisions at the Tevatron.

The MADGRAPH5_aMC@NLO [22] version 2.3.3 event generator (labelled as MADGRAPH in the following) inter-

faced with PYTHIA 8 with tune CUETP8M1 is also used in the analysis. Processes with up to 4 final-state partons at LO accuracy are calculated using the NNPDF2.3LO PDF set. The k_{T}-MLM matching procedure [23] is used with a matching scale of 10 GeV.

Among the NLO event generators, predictions obtained using the POWHEG BOX library [24–26] (version 2) with the PDF set NNPDF3.0NLO [27] are considered. The event generators PYTHIA 8 (tune CUETP8M1) and HERWIG++ (tune CUETHppS1) are used to simulate PS, hadronization, and MPI. The POWHEG generator in dijet mode [28], referred to as PH- 2J, provides an NLO dijet calculation, which is accurate to LO for the azimuthal correlation between the leading jets. The POWHEG generator in three-jet mode [29] (using the MiNLO scheme [30,31]), referred to as PH- 3J, provides an NLO $2 \to 3$ calculation. For the PH- 2J matrix elements (ME), a minimum p_{T} of 100 GeV is required on the partons in the Born process, while for the PH- 3J ME the minimum is lowered to 10 GeV to ensure coverage of the full phase space. These thresholds are applied to optimize the generation of events in the phase space of interest. The matching between the POWHEG matrix element calculations and the PYTHIA 8 underlying event (UE) [18] simulation is performed by using the shower-veto procedure (UserHook option 2 [14]). The matching between the POWHEG matrix element calculations and the HERWIG++ UE [18] is performed by using a truncated shower [24].

Events generated by PYTHIA 8 (tune CUETP8M1), HERWIG++ (tune CUETHppS1), and MADGRAPH interfaced with PYTHIA 8 (tune CUETP8M1) are passed through a full detector simulation based on GEANT4 [32]. The simulated events events are reconstructed with standard CMS programs.

Table 1 summarizes the theoretical predictions used in the present analysis.

4 Jet reconstruction and event selection

The measurements are based on data samples collected with single-jet high-level triggers [33,34]. The five single-jet triggers require at least one jet in the event with $p_{\mathrm{T}} > 140, 200, 320, 400,$ or 450 GeV within the full rapidity coverage of the CMS calorimetry. Table 2 shows the various $p_{\mathrm{T}}^{\max}$ regions accessed by the various triggers and the integrated luminosity for each trigger in the analysis. Each trigger is fully efficient for jets in the corresponding p_{T} range in Table 2.

Particles are reconstructed and identified using a particle-flow (PF) algorithm [35], which 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 [36] with a distance parameter $R = 0.4$. The clustering is performed with the FASTJET pack-

Table 1 Monte Carlo event generators, parton densities, and underlying event tunes used for comparison with measurements

Matrix element generator	Simulated diagrams	PDF set	Tune
PYTHIA 8.219 [14]	2→2 (LO)	NNPDF2.3LO [19,20]	CUETP8M1 [18]
HERWIG++ 2.7.1 [15]	2→2 (LO)	CTEQ6L1 [21]	CUETHppS1 [18]
MADGRAPH [22,23]+ PYTHIA 8.219 [14]	2→2, 2→3, 2→4 (LO)	NNPDF2.3LO [19,20]	CUETP8M1 [18]
PH- 2J [24–26] + PYTHIA 8.219 [14]	2→2 (NLO)	NNPDF3.0NLO [27]	CUETP8M1 [18]
PH- 2J [24–26] + HERWIG++ 2.7.1 [15]	2→2 (NLO)	NNPDF3.0NLO [27]	CUETHppS1 [18]
PH- 3J [24–26] + PYTHIA 8.219 [14]	2→3 (NLO)	NNPDF3.0NLO [27]	CUETP8M1 [18]

Table 2 The integrated luminosity for each trigger sample in the analysis, and trigger used for each p_T^{max} range

HLT p_T threshold (GeV)	140	200	320	400	450
$\mathcal{L}$ (fb^{-1})	0.024	0.11	1.77	5.2	36
p_T^{max} region (GeV)	200–300	300–400	400–500	500–600	> 600

age [37]. To reduce the contribution to the reconstructed jets from additional pp interactions within the same bunch crossing (pileup), the charged-hadron subtraction technique [38] is used to remove tracks identified as originating from pileup vertices. The average number of pileup interactions per single bunch crossing observed in the data is about 27. The pileup contribution from neutral hadrons is corrected using a jet-area-based correction technique [39].

For this analysis, jets with rapidity $|y| < 5.0$ are reconstructed. For both the inclusive 2- and 3-jet samples, the events are selected by requiring the two highest p_T jets to have $|y| < 2.5$ and $p_T > 100$ GeV. For the inclusive 3-jet events a third jet with $p_T > 30$ GeV and $|y| < 2.5$ is required. Contributions from pileup are negligible because the pileup removal algorithm has an efficiency of ∼99% for jets with $30 < p_T < 50$ GeV and $|y| < 2.5$ [40].

5 Measurements of the normalized inclusive 2- and 3-jet distributions

The normalized inclusive 2- and 3-jet distributions as a function of $\Delta\phi_{12}$ are corrected for detector resolution. We achieve this by unfolding the observables to the level of stable final-state particles. In this way, a direct comparison of these measurements to results from other experiments and to QCD predictions is possible. Particles are considered stable if their mean decay length is larger than 1 cm.

The unfolding procedure is based on the D'Agostini algorithm [41], which is implemented in the ROOUNFOLD package [42], by using a response matrix that maps the generated jets onto the jets reconstructed by the CMS detector. The regularization (number of iterations) of the unfolding procedure is chosen by comparing the difference in χ^2 between data

and MC at detector level to that between data and MC at particle level. The consistency of the unfolding procedure is checked against the alternative TUNFOLD package [43,44], which uses a least square minimization with Tikhonov regularization. Both methods provide equivalent results. The unfolding is performed in $\Delta\phi_{12}$. The response matrices are obtained using simulated events from the PYTHIA 8 event generator with the tune CUETP8M1. The difference between the unfolded distributions and the distributions at detector level range from ∼1% for the low p_T^{max} regions up to ∼5% for the high p_T^{max} regions.

The sources of systematic uncertainties arise primarily from the jet energy scale calibration (JES), the jet energy resolution (JER), the $\Delta\phi_{12}$ resolution, and the model dependence of the unfolding matrix. The effect of migrations between p_T^{max} regions is very small because of the normalization of the cross sections in each p_T^{max} range and therefore is neglected.

The $\Delta\phi_{12}$ resolution is ∼0.5°, as obtained from fully simulated event samples from PYTHIA 8 and MADGRAPH. A bin size of 1° is a compromise between the ability to study the back-to-back region and the impact of the unfolding correction of ∼2%. In Ref. [6] the study is focused on a different $\Delta\phi_{12}$ region, and a coarser bin size is chosen to account for the smaller size of the data sample.

Alternative response matrices are obtained by using the $\Delta\phi_{12}$ resolution determined from fully simulated events. This resolution is varied by ±10%, an amount that is motivated by the observed difference between data and simulation. The resulting uncertainty is estimated to be below 1%.

An additional systematic uncertainty is caused by the dependence of the response matrix on the choice of the MC generator. Alternative response matrices are built using the HERWIG++ and MADGRAPH + PYTHIA 8 event generators.
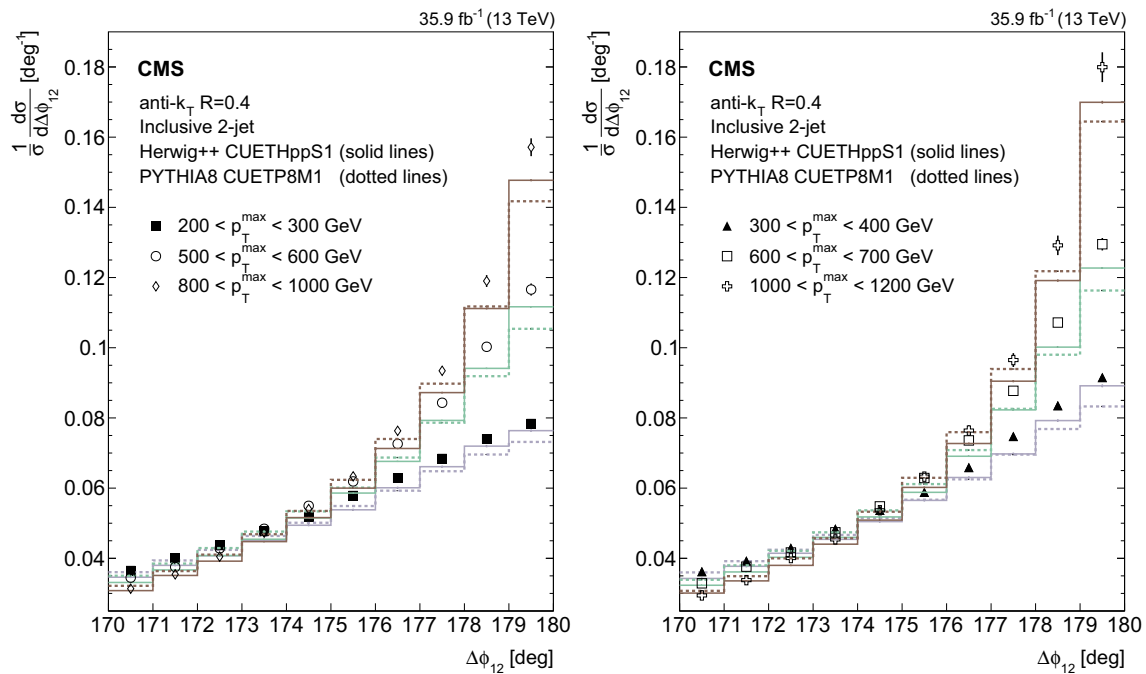
Fig. 1 Normalized inclusive 2-jet distributions as a function of the azimuthal separation of the two leading jets $\Delta\phi_{12}$ for different p_T^{max} regions. The data are represented by the markers and the theory by histograms. Overlaid with the data are predictions from the HERWIG++ event generator (solid lines) and PYTHIA 8 (dotted lines). The total experimental uncertainty is depicted as error bars on the measurement

Because this analysis uses a finer binning compared with that of Ref. [6], the sensitivity to the uncertainty in the unfolding is increased. The observed effect from bin migration is less than 2%.

The JER and shifts in the JES can cause events to migrate between the p_T^{max} regions. The JES uncertainties on the energy measurement are estimated to be 1–2% [38]. The resulting JES uncertainties in the normalized inclusive 2-jet distributions due to bin migrations are less than 2%, whereas for the normalized inclusive 3-jet distributions they are less than 3%. The effect of the JER uncertainties [38] is estimated by varying the JER parameters by one standard deviation up and down and comparing the results before and after the changes. The JER-induced uncertainties are less than 0.2% for the inclusive 2-jet $\Delta\phi_{12}$ measurement and below 0.4% for the normalized inclusive 3-jet measurement.

6 Comparison to theoretical predictions

In this section the measurements are compared with different theoretical predictions introduced in Sect. 3. In all figures displaying ratios, the solid band indicates the total experimental uncertainty and the error bars represent the statistical uncertainties from the simulation. In the figures displaying the normalized distributions, the error bars on the data represent the total experimental uncertainty and the error bars

on the predictions represent the statistical uncertainty of the simulation. The uncertainties are often so small that the bars are not visible.

The unfolded normalized inclusive 2-jet distribution as a function of $\Delta\phi_{12}$ is shown in Fig. 1, and compared with the predictions from HERWIG++ (solid lines) and PYTHIA 8 (dotted lines) for different p_T^{max} regions. The distributions are strongly peaked at 180° and become steeper with increasing p_T^{max}. The ratio of the PYTHIA 8, HERWIG++, and MAD-GRAPH + PYTHIA 8 event generator predictions to data are depicted in Fig. 2 for the inclusive 2-jet distributions in the nine p_T^{max} ranges. Among the event generators, PYTHIA 8 and HERWIG++ show the largest deviations from the measurements for the $p_T^{max} < 800$ GeV regions in the inclusive 2-jet case, and the MADGRAPH + PYTHIA 8 event generator gives the best description in the same regions. The three generators show large deviations from the measurements in the $p_T^{max} > 800$ GeV regions. The nonperturbative corrections are estimated to be small (below 1.5%) by comparing the predictions from PYTHIA 8 without the simulation of multi-parton interactions and hadronization (dashed blue curve) to the predictions from PYTHIA 8 when these effects are included (solid blue curve). The nonperturbative correction factors are available in HepData.

The ratios of the NLO predictions to data for the unfolded normalized inclusive 2-jet distributions for the different p_T^{max} regions are shown in Fig. 3. The NLO calculations consid-

Fig. 2 Ratios of the normalized inclusive 2-jet distributions for the PYTHIA 8, HERWIG++, and MADGRAPH + PYTHIA 8 predictions to data as a function of the azimuthal separation of the two leading jets $\Delta\phi_{12}$, for all the p_T^{max} regions. The solid band indicates the total experimental uncertainty and the error bars on the MC points represent the statistical uncertainty of the simulated data
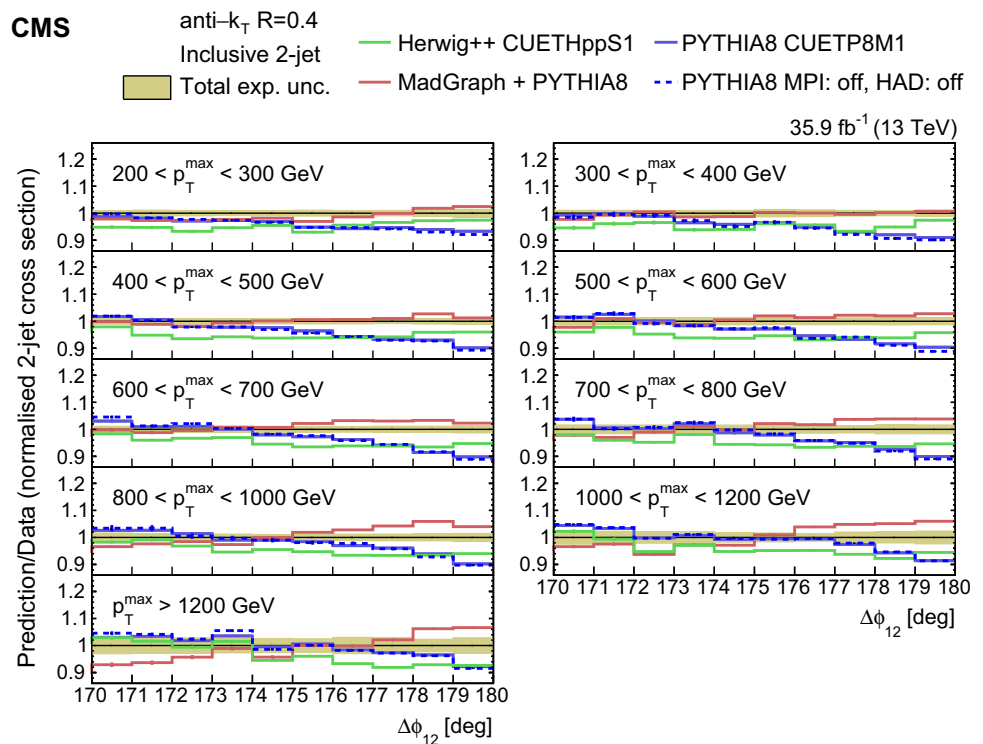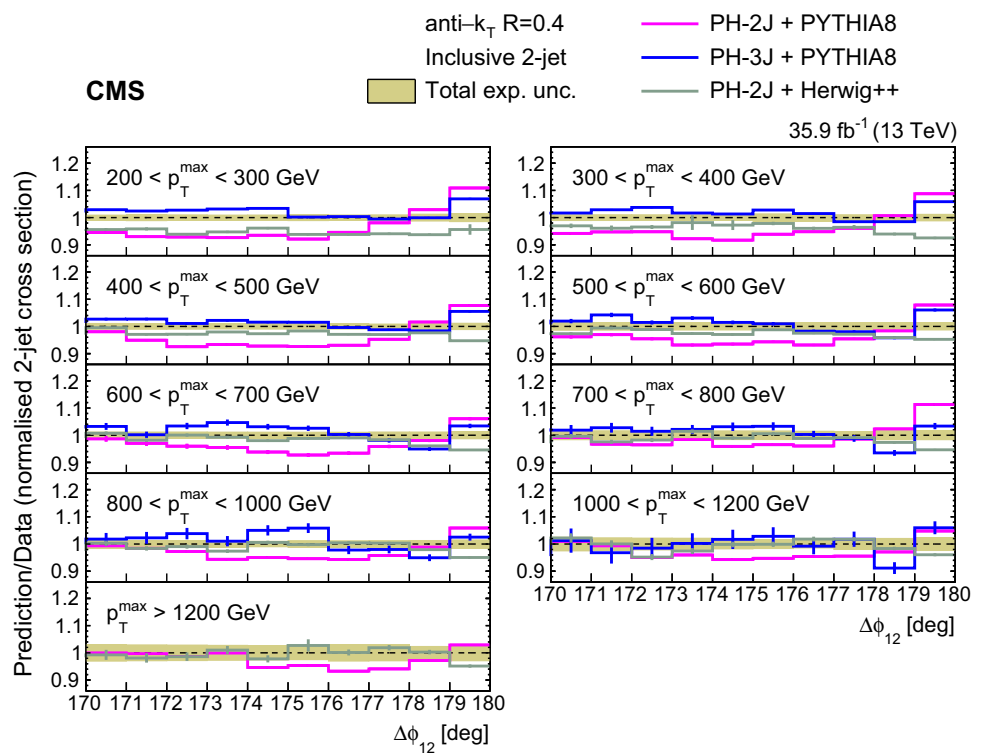

Fig. 3 Ratios of the normalized inclusive 2-jet distributions for the PH- 2J + PYTHIA 8, PH- 3J + PYTHIA 8, and PH- 2J + HERWIG++ predictions to data as a function of the azimuthal separation of the two leading jets $\Delta\phi_{12}$, for all the p_T^{max} regions. The solid band indicates the total experimental uncertainty and the error bars on the MC points represent the statistical uncertainty of the simulated data. The PH- 3J prediction is not shown for the highest bin in p_T^{max} because of the large statistical fluctuations

ered are PH- 2J + PYTHIA 8, PH- 2J + HERWIG++, and PH- 3J + PYTHIA 8. Among these NLO predictions PH- 3J + PYTHIA 8 agrees better with the data. The PH- 2J + HERWIG++ prediction is similar to the one of PH- 3J + PYTHIA 8, except for the lowest p_T^{max} region.

In Fig. 4 the unfolded normalized inclusive 3-jet distribution as a function of $\Delta\phi_{12}$ are compared with the predictions from HERWIG++ (solid lines) and PYTHIA 8 (dotted lines) for different p_T^{max} regions. The ratios of the normalized inclusive 3-jet distributions for the PYTHIA 8, HER-
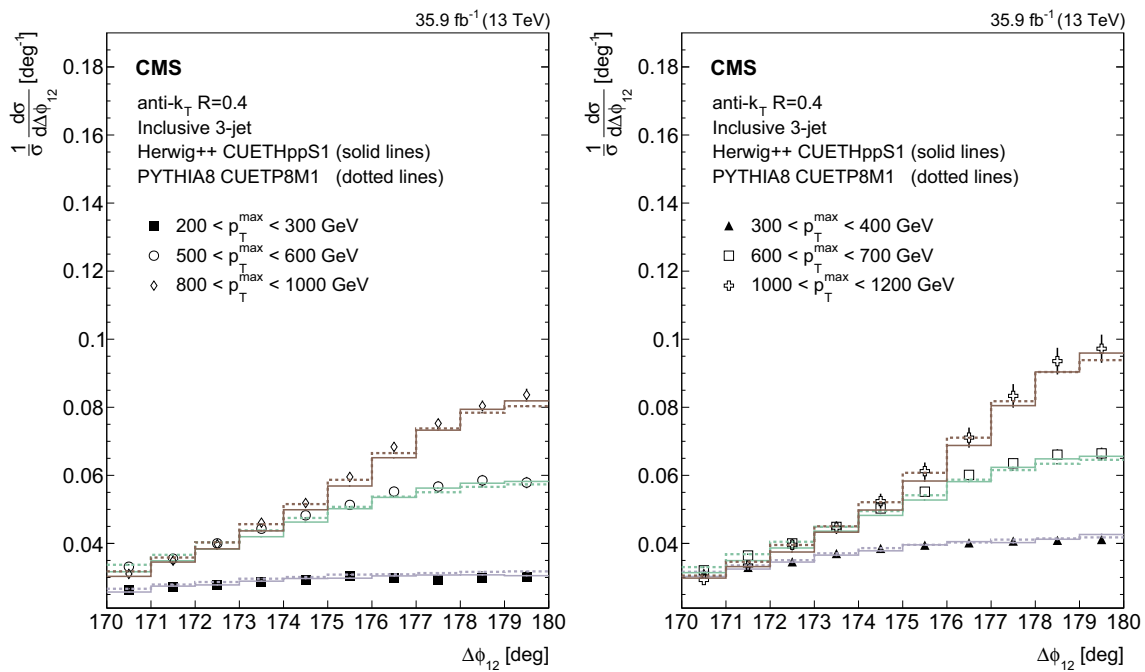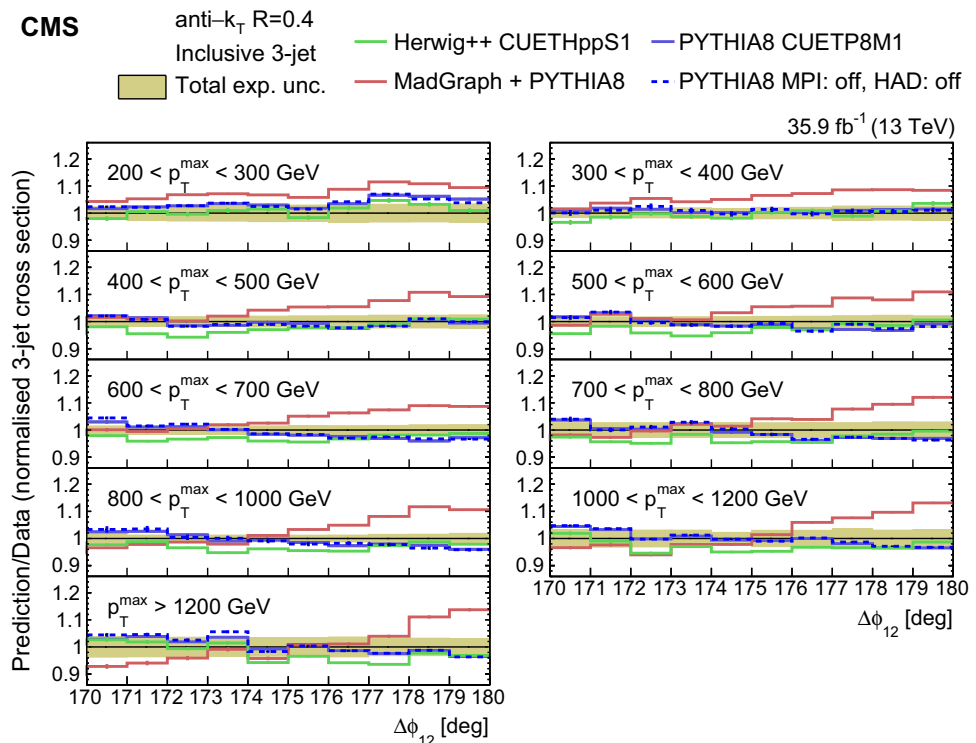
Fig. 4 Normalized inclusive 3-jet distributions as a function of the azimuthal separation of the two leading jets $\Delta\phi_{12}$ for different p_T^{max} regions. The data are represented by the markers and the theory by histograms. Overlaid with the data are predictions from the HERWIG++ event generator (solid lines) and PYTHIA 8 (dotted lines). The total experimental uncertainty is depicted as error bars on the measurement
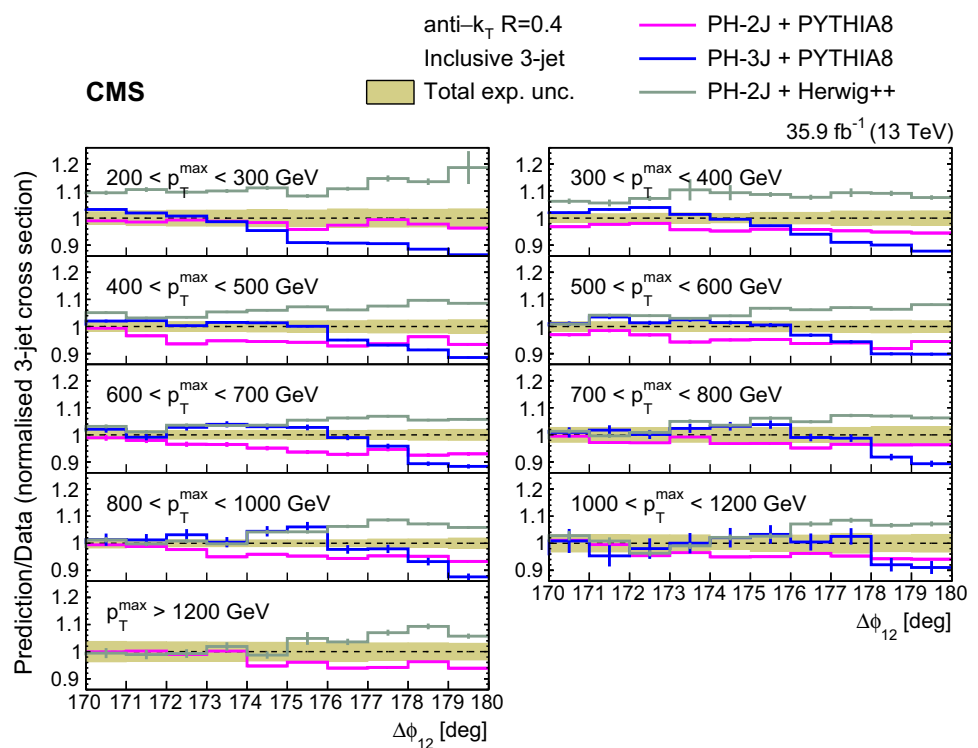
Fig. 5 Ratios of the normalized inclusive 3-jet distributions for the PYTHIA 8, HERWIG++, and MADGRAPH + PYTHIA 8 predictions to data as a function of the azimuthal separation of the two leading jets $\Delta\phi_{12}$, for all the p_T^{max} regions. The solid band indicates the total experimental uncertainty and the error bars on the MC points represent the statistical uncertainty of the simulated data

WIG++, and MADGRAPH + PYTHIA 8 predictions to data are shown in Fig. 5 for the different p_T^{max} regions. In contrast to the 2-jet case, MADGRAPH + PYTHIA 8 shows the largest deviations from the measurements close to 180°, whereas PYTHIA 8 and HERWIG++ give a good description of the data.

Fig. 6 Ratios of the normalized inclusive 3-jet distributions for the PH- 2J + PYTHIA 8, PH- 3J + PYTHIA 8, and PH- 2J + HERWIG++ predictions to data as a function of the azimuthal separation of the two leading jets $\Delta\phi_{12}$, for all p_T^{max} regions. The solid band indicates the total experimental uncertainty and the error bars on the MC points represent the statistical uncertainty of the simulated data. The PH- 3J prediction is not shown for the highest bin in p_T^{max} because of the large statistical fluctuations

The ratios of the NLO predictions from PH- 2J + PYTHIA 8, PH- 2J + HERWIG++, and PH- 3J + PYTHIA 8 to data for the normalized inclusive 3-jet distributions are shown in Fig. 6. All the considered NLO+PS predictions fail to describe the measurements close to 180°. The predictions from PH- 3J and MADGRAPH (Fig. 5) behave very differently, in contrast to their similar trend in the inclusive 2-jet case.

Since PYTHIA 8, PH- 2J + PYTHIA 8, PH- 3J + PYTHIA 8, and MADGRAPH + PYTHIA 8 use the same parton shower, the observed differences in the predictions can be attributed to the treatment of the additional partons present in the POWHEG and MADGRAPH ME.

In general we observe that the $\Delta\phi_{12}$ region close to 180° is not well described by the predictions. The predictions agree better with the measurements for increasing p_T^{max} and moving further away from the back-to-back region in $\Delta\phi_{12}$, where the contribution of resummation effects becomes smaller [10]. The fact that none of the generators is able to describe the 2- and 3-jet measurements simultaneously suggests that the observed differences (of the order of 10%) are related to the way soft partons are simulated within the PS. The observed differences between p_T and angular ordered PS for the LO generators PYTHIA 8 and HERWIG++ are small (Figs. 2, 5) compared to the MADGRAPH predictions, which can be attributed to the presence of higher order ME.

The theoretical calculations have an intrinsic uncertainty arising from the freedom of choice of the renormalization and factorization scales (μ_r and μ_f), the choice of the PDF

and $\alpha_S(m_Z)$, and the modeling of nonperturbative effects and PS. The total theoretical uncertainty is the quadratic sum of the uncertainties from the scale, PDF, α_S, and PS variations. Despite the better agreement of PH- 3J, the PH- 2J event generator is used instead for the estimation of the scale, PDF, and α_S uncertainties, because of the larger event sample. For the estimation of the PS uncertainty PYTHIA 8 is utilized. The following four sources of theoretical uncertainties are analyzed:

– The uncertainties due to the renormalization and factorization scales of the hard process are evaluated by varying the default choice $\mu_r = \mu_f = p_T$ of the underlying Born configuration between $p_T/2$ and $2p_T$. The envelope of the following seven combinations is considered: $(\mu_r/p_T, \mu_f/p_T) = (0.5, 0.5), (0.5, 1), (1, 0.5), (1, 1), (1, 2), (2, 1),$ and $(2, 2)$.

– The PDF uncertainties are evaluated according to the prescriptions for the NNPDF3.0 NLO PDF set. There are 100 replicas of the NNPDF3.0 NLO PDF set. For each replica the cross section is calculated and the uncertainty is taken as the envelope from all the replicas.

– The uncertainty due to the value of the strong coupling α_S is obtained by a variation of $\alpha_S(m_Z)$ by ±0.001, as recommended in Ref. [45].

– The uncertainty due to PS is evaluated with the PYTHIA 8 event generator by varying the default renormalization scale choice $\mu_r = p_T$ of the branching in initial state

Fig. 7 Ratios of the normalized inclusive 2-jet distributions for the PH- 2J + PYTHIA 8 predictions to data as a function of the azimuthal separation of the two leading jets $\Delta\phi_{12}$, for all p_T^{max} regions. The solid beige band indicates the total experimental uncertainty and the hatched band represents the total theoretical uncertainty
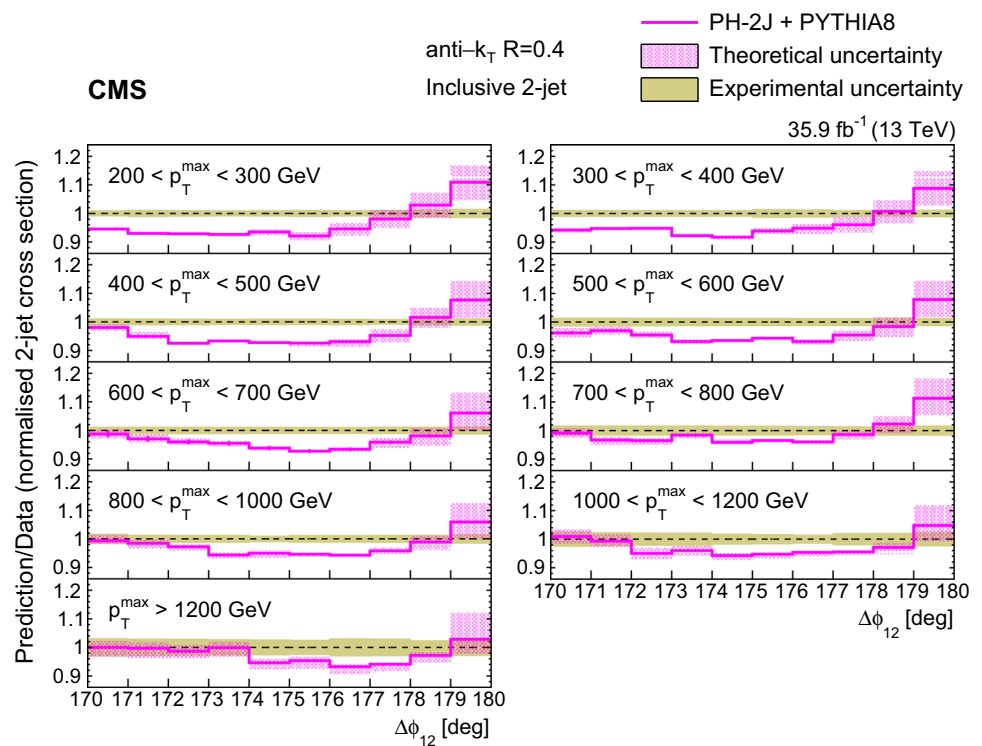
(ISR) and final state radiation (FSR) between $\mu_r/2$ and $2\mu_r$. The envelope of the following nine combinations is considered: (ISR μ_r/p_T, FSR μ_r/p_T) = (0.5, 0.5), (0.5, 1), (0.5, 2), (1, 0.5), (1, 1), (1, 2), (2, 0.5), (2, 1), and (2, 2).

The nonperturbative contributions (MPI and hadronization) are included in the calculations above. The uncertainty from these contributions are estimated from the different choices of the UE tune and found to be negligible.

The uncertainty from PS dominates for the normalized inclusive 2-jet distributions. It is one order of magnitude larger than the rest of the sources near $\Delta\phi_{12} = 180°$. On the other hand, for the normalized inclusive 3-jet distributions, the main contributions come from PS and PDF uncertainties. The predictions from PH- 2J + PYTHIA 8 and PH- 2J + HER-WIG++ (Fig. 3) show the differences from using different PS models together with different matching procedures.

Figure 7 (8) show the ratios of the PH- 2J predictions to data for the normalized inclusive 2(3)-jet distributions for the different p_T^{max} regions. The solid beige band indicates the total experimental uncertainty, and the hatched band represents the total theoretical uncertainty.

For the inclusive 2-jet distributions, the theoretical uncertainty is larger than the experimental one in the region close to $\Delta\phi_{12} = 180°$ (Fig. 7). This is because the contribution from PS dominates in this region, and its uncertainty is large. For the inclusive 3-jet distributions (Fig. 8), the theoretical uncertainty is smaller in the region close to 180°. In this case, the

region close to 180° is not filled by the partons from the PS, but by the third parton from PH- 2J, leading to a smaller PS uncertainty.

7 Summary

Measurements of the normalized inclusive 2- and 3-jet distributions as a function of the azimuthal separation $\Delta\phi_{12}$ between the two jets with the highest transverse momentum p_T, in the collinear back-to-back region, are presented for several p_T^{max} ranges of the leading jet. The measurements are performed using data collected with the CMS experiment at the LHC, corresponding to an integrated luminosity of 35.9 fb^{-1} of pp collisions at a center-of-mass energy of 13 TeV.

The measured $\Delta\phi_{12}$ distributions generally agree with predictions from PYTHIA 8, HERWIG++, MADGRAPH + PYTHIA 8, PH- 2J + HERWIG++, and POWHEG (PH- 2J and PH-3J) matched to PYTHIA 8. Discrepancies between the measurement and theoretical predictions are as large as 15%, mainly in the region $177° < \Delta\phi_{12} < 180°$. The predictions agree better with the measurements for larger p_T^{max} and smaller $\Delta\phi_{12}$, where the contribution of resummation effects becomes smaller. The 2- and 3-jet measurements are not simultaneously described by any of models.

The tree-level multijet event generator MADGRAPH in combination with PYTHIA 8 for showering, hadronization, and multiparton interactions, shows deviations from the mea-

Fig. 8 Ratios of the normalized inclusive 3-jet distributions for the PH- 2J + PYTHIA 8 predictions to data as a function of the azimuthal separation of the two leading jets $\Delta\phi_{12}$, for all p_T^{max} regions. The solid beige band indicates the total experimental uncertainty, the hatched band represents the total theoretical uncertainty
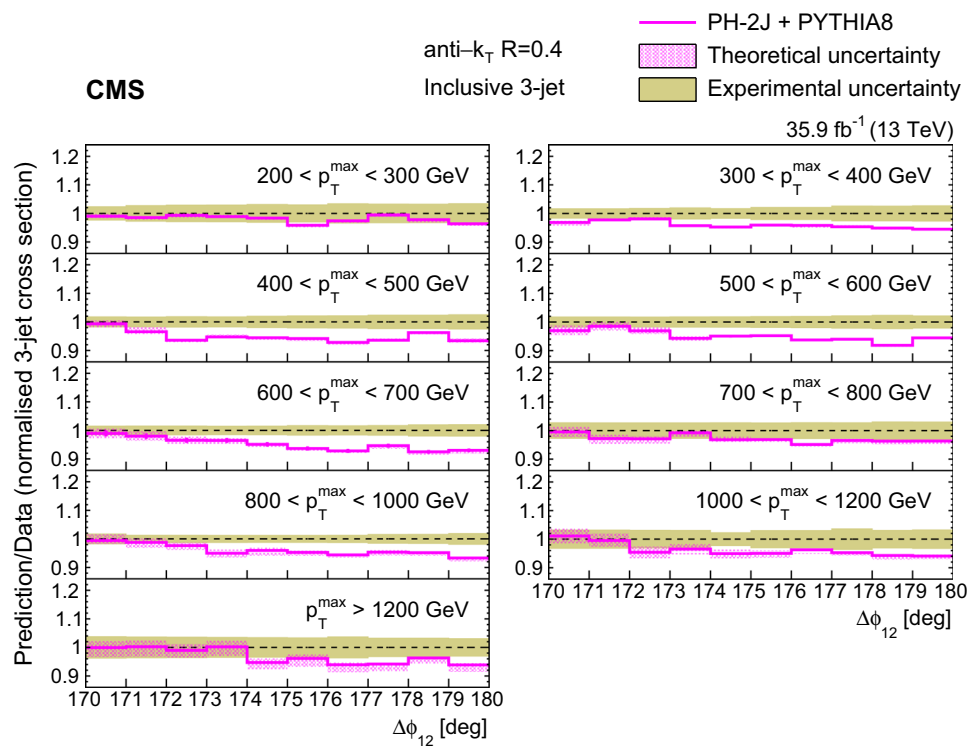
sured $\Delta\phi_{12}$ for the inclusive 2-jet case, and even larger deviations for the 3-jet case. The PYTHIA 8 and HERWIG++ predictions show deviations (up to 10%) for the 2-jet inclusive distributions, whereas their predictions are in reasonable agreement with the inclusive 3-jet distributions.

The next-to-leading-order PH- 2J + PYTHIA 8 prediction does not describe the data and a different trend compared to PYTHIA 8 and HERWIG++ towards $\Delta\phi_{12} = 180°$ is observed. The PH- 3J + PYTHIA 8 predictions agree with the measurements except for the last bin in the low p_T^{max} intervals. The PH- 2J + HERWIG++ prediction agrees well with the measurement in the highest p_T^{max} ranges. For the inclusive 3-jet case, PH- 2J + PYTHIA 8 performs similarly to PYTHIA 8 and HERWIG++ in the whole $\Delta\phi_{12}$ range for high p_T^{max} intervals. MADGRAPH + PYTHIA 8, PH- 3J + PYTHIA 8, and PH- 2J + HERWIG++ show deviations from the measurements of up to 15%.

The measurement of correlations for collinear back–to–back dijet configurations probes the multiple scales involved in the event and, therefore, the differences observed between predictions and the measurements illustrate the importance of improving the models of soft parton radiation accompanying the hard process.

Data Availability Statement This manuscript has no associated data or the data will not be deposited. [Authors' comment: Release and preservation of data used by the CMS Collaboration as the basis for publications is guided by the CMS policy as written in its document "CMS data preservation, re-use and open access policy" (https://cms-docdb.cern.ch/cgi-bin/PublicDocDB/RetrieveFile?docid=6032&filename=CMSDataPolicyV1.2.pdf&version=2).]

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CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia

A. M. Sirunyan, A. Tumasyan

Institut für Hochenergiephysik, Vienna, Austria

W. Adam, F. Ambrogi, E. Asilar, T. Bergauer, J. Brandstetter, E. Brondolin, M. Dragicevic, J. Erö, A. Escalante Del Valle, M. Flechl, R. Frühwirth[1], V. M. Ghete, J. Hrubec, M. Jeitler[1], N. Krammer, I. Krätschmer, D. Liko, T. Madlener, I. Mikulec, N. Rad, H. Rohringer, J. Schieck[1], R. Schöfbeck, M. Spanring, D. Spitzbart, A. Taurok, W. Waltenberger, J. Wittmann, C.-E. Wulz[1], M. Zarucki

Institute for Nuclear Problems, Minsk, Belarus

V. Chekhovsky, V. Mossolov, J. Suarez Gonzalez

Universiteit Antwerpen, Antwerp, Belgium

E. A. De Wolf, D. Di Croce, X. Janssen, J. Lauwers, M. Pieters, M. Van De Klundert, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel

Vrije Universiteit Brussel, Brussels, Belgium

S. Abu Zeid, F. Blekman, J. D'Hondt, I. De Bruyn, J. De Clercq, K. Deroover, G. Flouris, D. Lontkovskyi, S. Lowette, I. Marchesini, S. Moortgat, L. Moreels, Q. Python, K. Skovpen, S. Tavernier, W. Van Doninck, P. Van Mulders, I. Van Parijs

Université Libre de Bruxelles, Brussels, Belgium

D. Beghin, B. Bilin, H. Brun, B. Clerbaux, G. De Lentdecker, H. Delannoy, B. Dorney, G. Fasanella, L. Favart, R. Goldouzian, A. Grebenyuk, A. K. Kalsi, T. Lenzi, J. Luetic, N. Postiau, E. Starling, L. Thomas, C. Vander Velde, P. Vanlaer, D. Vannerom, Q. Wang

Ghent University, Ghent, Belgium

T. Cornelis, D. Dobur, A. Fagot, M. Gul, I. Khvastunov[2], D. Poyraz, C. Roskas, D. Trocino, M. Tytgat, W. Verbeke, B. Vermassen, M. Vit, N. Zaganidis

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
H. Bakhshiansohi, O. Bondu, S. Brochet, G. Bruno, P. David, C. Delaere, M. Delcourt, B. Francois, A. Giammanco,
G. Krintiras, V. Lemaitre, A. Magitteri, A. Mertens, M. Musich, K. Piotrzkowski, A. Saggio, M. Vidal Marono, S. Wertz,
J. Zobec

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
F. L. Alves, G. A. Alves, L. Brito, G. Correia Silva, C. Hensel, A. Moraes, M. E. Pol, P. Rebello Teles

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato[3], E. Coelho, E. M. Da Costa, G. G. Da Silveira[4],
D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, H. Malbouisson, D. Matos Figueiredo,
M. Melo De Almeida, C. Mora Herrera, L. Mundim, H. Nogima, W. L. Prado Da Silva, L. J. Sanchez Rosas, A. Santoro,
A. Sznajder, M. Thiel, E. J. Tonelli Manganote[3], F. Torres Da Silva De Araujo, A. Vilela Pereira

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

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

University of Sofia, Sofia, Bulgaria
A. Dimitrov, L. Litov, B. Pavlov, P. Petkov

Beihang University, Beijing, China
W. Fang[5], X. Gao[5], L. Yuan

Institute of High Energy Physics, Beijing, China
M. Ahmad, J. G. Bian, G. M. Chen, H. S. Chen, M. Chen, Y. Chen, C. H. Jiang, D. Leggat, H. Liao, Z. Liu, F. Romeo,
S. M. Shaheen, A. Spiezia, J. Tao, C. Wang, Z. Wang, E. Yazgan, H. Zhang, J. Zhao

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
Y. Ban, G. Chen, A. Levin, J. Li, L. Li, Q. Li, Y. Mao, S. J. Qian, D. Wang, Z. Xu

Tsinghua University, Beijing, China
Y. Wang

Universidad de Los Andes, Bogota, Colombia
C. Avila, A. Cabrera, C. A. Carrillo Montoya, L. F. Chaparro Sierra, C. Florez, C. F. González Hernández,
M. A. Segura Delgado

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia
B. Courbon, 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, K. Kadija, B. Mesic, A. Starodumov[6], T. Susa

University of Cyprus, Nicosia, Cyprus
M. W. Ather, A. Attikis, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P. A. Razis, H. Rykaczewski

Charles University, Prague, Czech Republic
M. Finger[7], M. Finger Jr.[7]

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
A. Ellithi Kamel[8], M. A. Mahmoud[9,10], E. Salama[10,11]

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
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, H. Kirschenmann, J. Pekkanen, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland
J. Havukainen, J. K. Heikkilä, T. Järvinen, V. Karimäki, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Laurila, S. Lehti, T. Lindén, P. Luukka, T. Mäenpää, H. Siikonen, E. Tuominen, J. Tuominiemi

Lappeenranta University of Technology, Lappeenranta, Finland
T. Tuuva

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
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, C. Leloup, E. Locci, J. Malcles, G. Negro, J. Rander, A. Rosowsky, M. Ö. Sahin, M. Titov

Laboratoire Leprince-Ringuet, Ecole polytechnique, CNRS/IN2P3, Université Paris-Saclay, Palaiseau, France
A. Abdulsalam[12], C. Amendola, I. Antropov, F. Beaudette, P. Busson, C. Charlot, R. Granier de Cassagnac, I. Kucher, S. Lisniak, A. Lobanov, J. Martin Blanco, M. Nguyen, C. Ochando, G. Ortona, P. Pigard, R. Salerno, J. B. Sauvan, Y. Sirois, A. G. Stahl Leiton, A. Zabi, A. Zghiche

Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France
J.-L. Agram[13], J. Andrea, D. Bloch, J.-M. Brom, E. C. Chabert, V. Cherepanov, C. Collard, E. Conte[13], J.-C. Fontaine[13], D. Gelé, U. Goerlach, M. Jansová, A.-C. Le Bihan, N. Tonon, P. Van Hove

Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France
S. Gadrat

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France
S. Beauceron, C. Bernet, G. Boudoul, N. Chanon, R. Chierici, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, L. Finco, S. Gascon, M. Gouzevitch, G. Grenier, B. Ille, F. Lagarde, I. B. Laktineh, H. Lattaud, M. Lethuillier, L. Mirabito, A. L. Pequegnot, S. Perries, A. Popov[14], V. Sordini, M. Vander Donckt, S. Viret, S. Zhang

Georgian Technical University, Tbilisi, Georgia
A. Khvedelidze[7]

Tbilisi State University, Tbilisi, Georgia
Z. Tsamalaidze[7]

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
C. Autermann, L. Feld, M. K. Kiesel, K. Klein, M. Lipinski, M. Preuten, M. P. Rauch, C. Schomakers, J. Schulz, M. Teroerde, B. Wittmer, V. Zhukov[14]

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
A. Albert, D. Duchardt, M. Endres, M. Erdmann, T. Esch, R. Fischer, S. Ghosh, A. Güth, T. Hebbeker, C. Heidemann, K. Hoepfner, H. Keller, S. Knutzen, L. Mastrolorenzo, M. Merschmeyer, A. Meyer, P. Millet, S. Mukherjee, T. Pook, M. Radziej, H. Reithler, M. Rieger, F. Scheuch, A. Schmidt, D. Teyssier

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
G. Flügge, O. Hlushchenko, B. Kargoll, T. Kress, A. Künsken, T. Müller, A. Nehrkorn, A. Nowack, C. Pistone, O. Pooth, H. Sert, A. Stahl[15]

Deutsches Elektronen-Synchrotron, Hamburg, Germany

M. Aldaya Martin, T. Arndt, C. Asawatangtrakuldee, I. Babounikau, K. Beernaert, O. Behnke, U. Behrens, A. Bermúdez Martínez, D. Bertsche, A. A. Bin Anuar, K. Borras[16], V. Botta, A. Campbell, P. Connor, C. Contreras-Campana, F. Costanza, V. Danilov, A. De Wit, M. M. Defranchis, C. Diez Pardos, D. Domínguez Damiani, G. Eckerlin, T. Eichhorn, A. Elwood, E. Eren, E. Gallo[17], A. Geiser, J. M. Grados Luyando, A. Grohsjean, P. Gunnellini, M. Guthoff, M. Haranko, A. Harb, J. Hauk, H. Jung, M. Kasemann, J. Keaveney, C. Kleinwort, J. Knolle, D. Krücker, W. Lange, A. Lelek, T. Lenz, K. Lipka, W. Lohmann[18], R. Mankel, I.-A. Melzer-Pellmann, A. B. Meyer, M. Meyer, M. Missiroli, G. Mittag, J. Mnich, V. Myronenko, S. K. Pflitsch, D. Pitzl, A. Raspereza, M. Savitskyi, P. Saxena, P. Schütze, C. Schwanenberger, R. Shevchenko, A. Singh, N. Stefaniuk, H. Tholen, A. Vagnerini, G. P. Van Onsem, R. Walsh, Y. Wen, K. Wichmann, C. Wissing, O. Zenaiev

University of Hamburg, Hamburg, Germany

R. Aggleton, S. Bein, L. Benato, A. Benecke, V. Blobel, M. Centis Vignali, T. Dreyer, E. Garutti, D. Gonzalez, J. Haller, A. Hinzmann, A. Karavdina, G. Kasieczka, R. Klanner, R. Kogler, N. Kovalchuk, S. Kurz, V. Kutzner, J. Lange, D. Marconi, J. Multhaup, M. Niedziela, D. Nowatschin, A. Perieanu, A. Reimers, O. Rieger, C. Scharf, P. Schleper, S. Schumann, J. Schwandt, J. Sonneveld, H. Stadie, G. Steinbrück, F. M. Stober, M. Stöver, D. Troendle, A. Vanhoefer, B. Vormwald

Karlsruher Institut fuer Technologie, Karlsruhe, Germany

M. Akbiyik, C. Barth, M. Baselga, S. Baur, E. Butz, R. Caspart, T. Chwalek, F. Colombo, W. De Boer, A. Dierlamm, N. Faltermann, B. Freund, M. Giffels, M. A. Harrendorf, F. Hartmann[15], S. M. Heindl, U. Husemann, F. Kassel[15], I. Katkov[14], S. Kudella, H. Mildner, S. Mitra, M. U. Mozer, Th. Müller, M. Plagge, G. Quast, K. Rabbertz, M. Schröder, I. Shvetsov, G. Sieber, H. J. Simonis, R. Ulrich, S. Wayand, M. Weber, T. Weiler, S. Williamson, C. Wöhrmann, R. Wolf

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece

G. Anagnostou, G. Daskalakis, T. Geralis, A. Kyriakis, D. Loukas, G. Paspalaki, I. Topsis-Giotis

National and Kapodistrian University of Athens, Athens, Greece

G. Karathanasis, S. Kesisoglou, P. Kontaxakis, A. Panagiotou, N. Saoulidou, E. Tziaferi, K. Vellidis

National Technical University of Athens, Athens, Greece

K. Kousouris, I. Papakrivopoulos, G. Tsipolitis

University of Ioánnina, Ioánnina, Greece

I. Evangelou, C. Foudas, P. Gianneios, P. Katsoulis, P. Kokkas, S. Mallios, N. Manthos, I. Papadopoulos, E. Paradas, J. Strologas, F. A. Triantis, D. Tsitsonis

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

M. Bartók[19], M. Csanad, N. Filipovic, P. Major, M. I. Nagy, G. Pasztor, O. Surányi, G. I. Veres

Wigner Research Centre for Physics, Budapest, Hungary

G. Bencze, C. Hajdu, D. Horvath[20], Á. Hunyadi, F. Sikler, T. Á. Vámi, V. Veszpremi, G. Vesztergombi[†]

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

N. Beni, S. Czellar, J. Karancsi[21], A. Makovec, J. Molnar, Z. Szillasi

Institute of Physics, University of Debrecen, Debrecen, Hungary

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

Indian Institute of Science (IISc), Bangalore, India

S. Choudhury, J. R. Komaragiri, P. C. Tiwari

National Institute of Science Education and Research, HBNI, Bhubaneswar, India

S. Bahinipati[22], C. Kar, P. Mal, K. Mandal, A. Nayak[23], D. K. Sahoo[22], S. K. Swain

Panjab University, Chandigarh, India

S. Bansal, S. B. Beri, V. Bhatnagar, S. Chauhan, R. Chawla, N. Dhingra, R. Gupta, A. Kaur, A. Kaur, M. Kaur, S. Kaur, R. Kumar, P. Kumari, M. Lohan, A. Mehta, K. Sandeep, S. Sharma, J. B. Singh, G. Walia

University of Delhi, Delhi, India

A. Bhardwaj, B. C. Choudhary, R. B. Garg, M. Gola, S. Keshri, Ashok Kumar, S. Malhotra, M. Naimuddin, P. Priyanka, K. Ranjan, Aashaq Shah, R. Sharma

Saha Institute of Nuclear Physics, HBNI, Kolkata, India

R. Bhardwaj[24], M. Bharti, R. Bhattacharya, S. Bhattacharya, U. Bhawandeep[24], D. Bhowmik, S. Dey, S. Dutt[24], S. Dutta, S. Ghosh, K. Mondal, S. Nandan, A. Purohit, P. K. Rout, A. Roy, S. Roy Chowdhury, S. Sarkar, M. Sharan, B. Singh, S. Thakur[24]

Indian Institute of Technology Madras, Madras, India

P. K. Behera

Bhabha Atomic Research Centre, Mumbai, India

R. Chudasama, D. Dutta, V. Jha, V. Kumar, P. K. Netrakanti, L. M. Pant, P. Shukla

Tata Institute of Fundamental Research-A, Mumbai, India

T. Aziz, M. A. Bhat, S. Dugad, G. B. Mohanty, N. Sur, B. Sutar, RavindraKumar Verma

Tata Institute of Fundamental Research-B, Mumbai, India

S. Banerjee, S. Bhattacharya, S. Chatterjee, P. Das, M. Guchait, Sa. Jain, S. Karmakar, S. Kumar, M. Maity[25], G. Majumder, K. Mazumdar, N. Sahoo, T. Sarkar[25]

Indian Institute of Science Education and Research (IISER), Pune, India

S. Chauhan, S. Dube, V. Hegde, A. Kapoor, K. Kothekar, S. Pandey, A. Rane, S. Sharma

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

S. Chenarani[26], E. Eskandari Tadavani, S. M. Etesami[26], M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, F. Rezaei Hosseinabadi, B. Safarzadeh[27], M. Zeinali

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}, C. Calabria^{a,b}, A. Colaleo^a, D. Creanza^{a,c}, L. Cristella^{a,b}, N. De Filippis^{a,c}, M. De Palma^{a,b}, A. Di Florio^{a,b}, F. Errico^{a,b}, L. Fiore^a, A. Gelmi^{a,b}, G. Iaselli^{a,c}, S. Lezki^{a,b}, G. Maggi^{a,c}, M. Maggi^a, G. Miniello^{a,b}, S. My^{a,b}, S. Nuzzo^{a,b}, A. Pompili^{a,b}, G. Pugliese^{a,c}, R. Radogna^a, A. Ranieri^a, A. Sharma^a, L. Silvestris^{a,15}, R. Venditti^a, P. Verwilligen^a, G. Zito^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,b}, S. Braibant-Giacomelli^{a,b}, R. Campanini^{a,b}, P. Capiluppi^{a,b}, A. Castro^{a,b}, F. R. Cavallo^a, S. S. Chhibra^{a,b}, C. Ciocca^a, G. Codispoti^{a,b}, M. Cuffiani^{a,b}, G. M. Dallavalle^a, F. Fabbri^a, A. Fanfani^{a,b}, P. Giacomelli^a, C. Grandi^a, L. Guiducci^{a,b}, F. Iemmi^{a,b}, S. Marcellini^a, G. Masetti^a, A. Montanari^a, F. L. Navarria^{a,b}, A. Perrotta^a, F. Primavera^{a,b,15}, 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}, A. Di Mattia^a, R. Potenza^{a,b}, A. Tricomi^{a,b}, C. Tuve^{a,b}

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

G. Barbagli^a, K. Chatterjee^{a,b}, V. Ciulli^{a,b}, C. Civinini^a, R. D'Alessandro^{a,b}, E. Focardi^{a,b}, G. Latino, P. Lenzi^{a,b}, M. Meschini^a, S. Paoletti^a, L. Russo^{a,28}, G. Sguazzoni^a, D. Strom^a, L. Viliani^a

INFN Laboratori Nazionali di Frascati, Frascati, Italy

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

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

F. Ferro^a, F. Ravera^{a,b}, E. Robutti^a, S. Tosi^{a,b}

INFN Sezione di Milano-Bicocca^a, Università di Milano-Bicocca^b, Milan, Italy
A. Benaglia^a, A. Beschi^b, L. Brianza^{a,b}, F. Brivio^{a,b}, V. Ciriolo^{a,b,15}, S. Di Guida^{a,d,15}, M. E. Dinardo^{a,b}, S. Fiorendi^{a,b}, S. Gennai^a, A. Ghezzi^{a,b}, P. Govoni^{a,b}, M. Malberti^{a,b}, S. Malvezzi^a, A. Massironi^{a,b}, D. Menasce^a, L. Moroni^a, M. Paganoni^{a,b}, D. Pedrini^a, S. Ragazzi^{a,b}, T. Tabarelli de Fatis^{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, Rome, Italy
S. Buontempo^a, N. Cavallo^{a,c}, A. Di Crescenzo^{a,b}, F. Fabozzi^{a,c}, F. Fienga^a, G. Galati^a, A. O. M. Iorio^{a,b}, W. A. Khan^a, L. Lista^a, S. Meola^{a,d,15}, P. Paolucci^{a,15}, 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}, A. Bragagnolo, R. Carlin^{a,b}, P. Checchia^a, M. Dall'Osso^{a,b}, P. De Castro Manzano^a, T. Dorigo^a, U. Dosselli^a, F. Gasparini^{a,b}, U. Gasparini^{a,b}, A. Gozzelino^a, S. Lacaprara^a, P. Lujan, M. Margoni^{a,b}, A. T. Meneguzzo^{a,b}, P. Ronchese^{a,b}, R. Rossin^{a,b}, F. Simonetto^{a,b}, A. Tiko, E. Torassa^a, M. Zanetti^{a,b}, P. Zotto^{a,b}, G. Zumerle^{a,b}

INFN Sezione di Pavia^a, Università di Pavia^b, Pavia, Italy
A. Braghieri^a, A. Magnani^a, 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,b}, P. Vitulo^{a,b}

INFN Sezione di Perugia^a, Università di Perugia^b, Perugia, Italy
L. Alunni Solestizi^{a,b}, M. Biasini^{a,b}, G. M. Bilei^a, C. Cecchi^{a,b}, D. Ciangottini^{a,b}, L. Fanò^{a,b}, P. Lariccia^{a,b}, E. Manoni^a, G. Mantovani^{a,b}, V. Mariani^{a,b}, M. Menichelli^a, A. Rossi^{a,b}, A. Santocchia^{a,b}, D. Spiga^a

INFN Sezione di Pisa^a, Università di Pisa^b, Scuola Normale Superiore di Pisa^c, Pisa, Italy
K. Androsov^a, P. Azzurri^a, G. Bagliesi^a, L. Bianchini^a, T. Boccali^a, L. Borrello, R. Castaldi^a, M. A. Ciocci^{a,b}, R. Dell'Orso^a, G. Fedi^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, A. Rizzi^{a,b}, P. Spagnolo^a, R. Tenchini^a, G. Tonelli^{a,b}, A. Venturi^a, P. G. Verdini^a

INFN Sezione di Roma^a, Sapienza Università di Roma^b, Rome, Italy
L. Barone^{a,b}, F. Cavallari^a, M. Cipriani^{a,b}, N. Daci, D. Del Re^{a,b}, E. Di Marco^{a,b}, M. Diemoz^a, S. Gelli^{a,b}, E. Longo^{a,b}, B. Marzocchi^{a,b}, P. Meridiani^a, G. Organtini^{a,b}, F. Pandolfi^a, R. Paramatti^{a,b}, F. Preiato^{a,b}, S. Rahatlou^{a,b}, C. Rovelli^a, F. Santanastasio^{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}, C. Biino^a, N. Cartiglia^a, F. Cenna^{a,b}, S. Cometti, M. Costa^{a,b}, R. Covarelli^{a,b}, N. Demaria^a, B. Kiani^{a,b}, 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}, L. Pacher^{a,b}, N. Pastrone^a, M. Pelliccioni^a, G. L. Pinna Angioni^{a,b}, A. Romero^{a,b}, M. Ruspa^{a,c}, R. Sacchi^{a,b}, K. Shchelina^{a,b}, V. Sola^a, A. Solano^{a,b}, D. Soldi, A. Staiano^a

INFN Sezione di Trieste^a, Università di Trieste^b, Trieste, Italy
S. Belforte^a, V. Candelise^{a,b}, M. Casarsa^a, F. Cossutti^a, G. Della Ricca^{a,b}, F. Vazzoler^{a,b}, A. Zanetti^a

Kyungpook National University, Daegu, Korea
D. H. Kim, G. N. Kim, M. S. Kim, J. Lee, S. Lee, S. W. Lee, C. S. Moon, Y. D. Oh, S. Sekmen, D. C. Son, Y. C. Yang

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

Hanyang University, Seoul, Korea
J. Goh, T. J. Kim

Korea University, Seoul, Korea
S. Cho, S. Choi, Y. Go, D. Gyun, S. Ha, B. Hong, Y. Jo, K. Lee, K. S. Lee, S. Lee, J. Lim, S. K. Park, Y. Roh

Sejong University, Seoul, Korea
H. S. Kim

Seoul National University, Seoul, Korea
J. Almond, J. Kim, J. S. Kim, H. Lee, K. Lee, K. Nam, S. B. Oh, B. C. Radburn-Smith, S. h. Seo, U. K. Yang, H. D. Yoo,
G. B. Yu

University of Seoul, Seoul, Korea
D. Jeon, H. Kim, J. H. Kim, J. S. H. Lee, I. C. Park

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

Vilnius University, Vilnius, Lithuania
V. Dudenas, A. Juodagalvis, J. Vaitkus

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
I. Ahmed, Z. A. Ibrahim, M. A. B. Md Ali[29], F. Mohamad Idris[30], W. A. T. Wan Abdullah, M. N. Yusli, Z. Zolkapli

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
H. Castilla-Valdez, E. De La Cruz-Burelo, M. C. Duran-Osuna, I. Heredia-De La Cruz[31], R. Lopez-Fernandez,
J. Mejia Guisao, R. I. Rabadan-Trejo, G. Ramirez-Sanchez, R Reyes-Almanza, A. Sanchez-Hernandez

Universidad Iberoamericana, Mexico City, Mexico
S. Carrillo Moreno, C. Oropeza Barrera, 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 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. Ahmad, M. I. Asghar, Q. Hassan, H. R. Hoorani, A. Saddique, M. A. Shah, M. Shoaib, M. Waqas

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

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
K. Bunkowski, A. Byszuk[32], K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski,
A. Pyskir, M. Walczak

Laboratório de Instrumentação e Física Experimental de Partículas, Lisbon, Portugal
P. Bargassa, C. Beirão Da Cruz E Silva, A. Di Francesco, P. Faccioli, B. Galinhas, M. Gallinaro, J. Hollar, N. Leonardo,
L. Lloret Iglesias, M. V. Nemallapudi, J. Seixas, G. Strong, O. Toldaiev, D. Vadruccio, J. Varela

Joint Institute for Nuclear Research, Dubna, Russia
A. Golunov, I. Golutvin, V. Karjavin, V. Korenkov, G. Kozlov, A. Lanev, A. Malakhov, V. Matveev[33,34], V. V. Mitsyn,
P. Moisenz, V. Palichik, V. Perelygin, S. Shmatov, S. Shulha, V. Smirnov, V. Trofimov, B. S. Yuldashev[35], A. Zarubin,
V. Zhiltsov

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia
V. Golovtsov, Y. Ivanov, V. Kim[36], E. Kuznetsova[37], P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov,
V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev

Institute for Nuclear Research, Moscow, Russia

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

Institute for Theoretical and Experimental Physics, Moscow, Russia

V. Epshteyn, V. Gavrilov, N. Lychkovskaya, V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, A. Stepennov, V. Stolin, 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

M. Chadeeva[38], P. Parygin, D. Philippov, S. Polikarpov[38], E. Popova, V. Rusinov

P.N. Lebedev Physical Institute, Moscow, Russia

V. Andreev, M. Azarkin[34], I. Dremin[34], M. Kirakosyan[34], S. V. Rusakov, A. Terkulov

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia

A. Baskakov, A. Belyaev, E. Boos, M. Dubinin[39], L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, I. Miagkov, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev

Novosibirsk State University (NSU), Novosibirsk, Russia

V. Blinov[40], T. Dimova[40], L. Kardapoltsev[40], D. Shtol[40], Y. Skovpen[40]

Institute for High Energy Physics of National Research Centre 'Kurchatov Institute', Protvino, Russia

I. Azhgirey, I. Bayshev, S. Bitioukov, D. Elumakhov, A. Godizov, V. Kachanov, A. Kalinin, D. Konstantinov, P. Mandrik, V. Petrov, R. Ryutin, S. Slabospitskii, A. Sobol, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

National Research Tomsk Polytechnic University, Tomsk, Russia

A. Babaev, S. Baidali

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

P. Adzic[41], P. Cirkovic, D. Devetak, M. Dordevic, J. Milosevic

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

J. Alcaraz Maestre, A. Álvarez Fernández, I. Bachiller, M. Barrio Luna, J. A. Brochero Cifuentes, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, C. Fernandez Bedoya, J. P. Fernández Ramos, J. Flix, M. C. Fouz, O. Gonzalez Lopez, S. Goy Lopez, J. M. Hernandez, M. I. Josa, D. Moran, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, L. Romero, M. S. Soares, A. Triossi

Universidad Autónoma de Madrid, Madrid, Spain

C. Albajar, J. F. de Trocóniz

Universidad de Oviedo, Oviedo, Spain

J. Cuevas, C. Erice, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, J. R. González Fernández, E. Palencia Cortezon, V. Rodríguez Bouza, S. Sanchez Cruz, P. Vischia, J. M. Vizan Garcia

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, A. García Alonso, J. Garcia-Ferrero, G. Gomez, A. Lopez Virto, J. Marco, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, J. Piedra Gomez, C. Prieels, T. Rodrigo, A. Ruiz-Jimeno, L. Scodellaro, N. Trevisani, I. Vila, R. Vilar Cortabitarte

CERN, European Organization for Nuclear Research, Geneva, Switzerland

D. Abbaneo, B. Akgun, E. Auffray, P. Baillon, A. H. Ball, D. Barney, J. Bendavid, M. Bianco, A. Bocci, C. Botta, T. Camporesi, M. Cepeda, G. Cerminara, E. Chapon, Y. Chen, G. Cucciati, D. d'Enterria, A. Dabrowski, V. Daponte, A. David, A. De Roeck, N. Deelen, M. Dobson, T. du Pree, M. Dünser, N. Dupont, A. Elliott-Peisert, P. Everaerts, F. Fallavollita[42], D. Fasanella, G. Franzoni, J. Fulcher, W. Funk, D. Gigi, A. Gilbert, K. Gill, F. Glege, M. Guilbaud, D. Gulhan, J. Hegeman, V. Innocente, A. Jafari, P. Janot, O. Karacheban[18], J. Kieseler, A. Kornmayer, M. Krammer[1], C. Lange, P. Lecoq, C. Lourenço, L. Malgeri, M. Mannelli, F. Meijers, J. A. Merlin, S. Mersi, E. Meschi, P. Milenovic[43],

F. Moortgat, M. Mulders, J. Ngadiuba, S. Orfanelli, L. Orsini, F. Pantaleo[15], L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, F. M. Pitters, D. Rabady, A. Racz, T. Reis, G. Rolandi[44], M. Rovere, H. Sakulin, C. Schäfer, C. Schwick, M. Seidel, M. Selvaggi, A. Sharma, P. Silva, P. Sphicas[45], A. Stakia, J. Steggemann, M. Tosi, D. Treille, A. Tsirou, V. Veckalns[46], W. D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland
L. Caminada[47], K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H. C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe, S. A. Wiederkehr

ETH Zurich-Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland
M. Backhaus, L. Bäni, P. Berger, N. Chernyavskaya, G. Dissertori, M. Dittmar, M. Donegà, C. Dorfer, C. Grab, C. Heidegger, D. Hits, J. Hoss, T. Klijnsma, W. Lustermann, R. A. Manzoni, M. Marionneau, M. T. Meinhard, F. Micheli, P. Musella, F. Nessi-Tedaldi, J. Pata, F. Pauss, G. Perrin, L. Perrozzi, S. Pigazzini, M. Quittnat, D. Ruini, D. A. Sanz Becerra, M. Schönenberger, L. Shchutska, V. R. Tavolaro, K. Theofilatos, M. L. Vesterbacka Olsson, R. Wallny, D. H. Zhu

Universität Zürich, Zurich, Switzerland
T. K. Aarrestad, C. Amsler[48], D. Brzhechko, M. F. Canelli, A. De Cosa, R. Del Burgo, S. Donato, C. Galloni, T. Hreus, B. Kilminster, I. Neutelings, D. Pinna, G. Rauco, P. Robmann, D. Salerno, K. Schweiger, C. Seitz, Y. Takahashi, A. Zucchetta

National Central University, Chung-Li, Taiwan
Y. H. Chang, K. y. Cheng, T. H. Doan, Sh. Jain, R. Khurana, C. M. Kuo, W. Lin, A. Pozdnyakov, S. S. Yu

National Taiwan University (NTU), Taipei, Taiwan
P. Chang, Y. Chao, K. F. Chen, P. H. Chen, W.-S. Hou, Arun Kumar, Y. y. Li, R.-S. Lu, E. Paganis, A. Psallidas, A. Steen, J. f. Tsai

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

Physics Department, Science and Art Faculty, Çukurova University, Adana, Turkey
A. Bat, F. Boran, S. Cerci[49], S. Damarseckin, Z. S. Demiroglu, F. Dolek, C. Dozen, I. Dumanoglu, E. Eskut, S. Girgis, G. Gokbulut, Y. Guler, E. Gurpinar, I. Hos[50], C. Isik, E. E. Kangal[51], O. Kara, A. Kayis Topaksu, U. Kiminsu, M. Oglakci, G. Onengut, K. Ozdemir[52], S. Ozturk[53], A. Polatoz, U. G. Tok, S. Turkcapar, I. S. Zorbakir, C. Zorbilmez

Middle East Technical University, Physics Department, Ankara, Turkey
B. Isildak[54], G. Karapinar[55], M. Yalvac, M. Zeyrek

Bogazici University, Istanbul, Turkey
I. O. Atakisi, E. Gülmez, M. Kaya[56], O. Kaya[57], S. Tekten, E. A. Yetkin[58]

Istanbul Technical University, Istanbul, Turkey
M. N. Agaras, S. Atay, A. Cakir, K. Cankocak, Y. Komurcu, S. Sen[59]

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, UK
F. Ball, L. Beck, J. J. Brooke, D. Burns, E. Clement, D. Cussans, O. Davignon, H. Flacher, J. Goldstein, G. P. Heath, H. F. Heath, L. Kreczko, D. M. Newbold[60], S. Paramesvaran, B. Penning, T. Sakuma, D. Smith, V. J. Smith, J. Taylor, A. Titterton

Rutherford Appleton Laboratory, Didcot, UK
K. W. Bell, A. Belyaev[61], C. Brew, R. M. Brown, D. Cieri, D. J. A. Cockerill, J. A. Coughlan, K. Harder, S. Harper, J. Linacre, E. Olaiya, D. Petyt, C. H. Shepherd-Themistocleous, A. Thea, I. R. Tomalin, T. Williams, W. J. Womersley

Imperial College, London, UK

G. Auzinger, R. Bainbridge, P. Bloch, J. Borg, S. Breeze, O. Buchmuller, A. Bundock, S. Casasso, D. Colling, L. Corpe, P. Dauncey, G. Davies, M. Della Negra, R. Di Maria, Y. Haddad, G. Hall, G. Iles, T. James, M. Komm, C. Laner, L. Lyons, A.-M. Magnan, S. Malik, A. Martelli, J. Nash[62], A. Nikitenko[6], V. Palladino, M. Pesaresi, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, T. Strebler, S. Summers, A. Tapper, K. Uchida, T. Virdee[15], N. Wardle, D. Winterbottom, J. Wright, S. C. Zenz

Brunel University, Uxbridge, UK

J. E. Cole, P. R. Hobson, A. Khan, P. Kyberd, C. K. Mackay, A. Morton, I. D. Reid, L. Teodorescu, S. Zahid

Baylor University, Waco, USA

K. Call, J. Dittmann, K. Hatakeyama, H. Liu, C. Madrid, B. Mcmaster, N. Pastika, C. Smith

Catholic University of America, Washington DC, USA

R. Bartek, A. Dominguez

The University of Alabama, Tuscaloosa, USA

A. Buccilli, S. I. Cooper, C. Henderson, P. Rumerio, C. West

Boston University, Boston, USA

D. Arcaro, T. Bose, D. Gastler, D. Rankin, C. Richardson, J. Rohlf, L. Sulak, D. Zou

Brown University, Providence, USA

G. Benelli, X. Coubez, D. Cutts, M. Hadley, J. Hakala, U. Heintz, J. M. Hogan[63], K. H. M. Kwok, E. Laird, G. Landsberg, J. Lee, Z. Mao, M. Narain, J. Pazzini, S. Piperov, S. Sagir[64], R. Syarif, E. Usai, D. Yu

University of California, Davis, Davis, USA

R. Band, C. Brainerd, R. Breedon, D. Burns, M. Calderon De La Barca Sanchez, M. Chertok, J. Conway, R. Conway, P. T. Cox, R. Erbacher, C. Flores, G. Funk, W. Ko, O. Kukral, R. Lander, C. Mclean, M. Mulhearn, D. Pellett, J. Pilot, S. Shalhout, M. Shi, D. Stolp, D. Taylor, K. Tos, M. Tripathi, Z. Wang

University of California, Los Angeles, USA

M. Bachtis, C. Bravo, R. Cousins, A. Dasgupta, A. Florent, J. Hauser, M. Ignatenko, N. Mccoll, S. Regnard, D. Saltzberg, C. Schnaible, V. Valuev

University of California, Riverside, Riverside, USA

E. Bouvier, K. Burt, R. Clare, J. W. Gary, S. M. A. Ghiasi Shirazi, G. Hanson, G. Karapostoli, E. Kennedy, F. Lacroix, O. R. Long, M. Olmedo Negrete, M. I. Paneva, W. Si, L. Wang, H. Wei, S. Wimpenny, B. R. Yates

University of California, San Diego, La Jolla, USA

J. G. Branson, S. Cittolin, M. Derdzinski, R. Gerosa, D. Gilbert, B. Hashemi, A. Holzner, D. Klein, G. Kole, V. Krutelyov, J. Letts, M. Masciovecchio, D. Olivito, S. Padhi, M. Pieri, M. Sani, V. Sharma, S. Simon, M. Tadel, A. Vartak, S. Wasserbaech[65], J. Wood, F. Würthwein, A. Yagil, G. Zevi Della Porta

Department of Physics, University of California, Santa Barbara, Santa Barbara, USA

N. Amin, R. Bhandari, J. Bradmiller-Feld, C. Campagnari, M. Citron, A. Dishaw, V. Dutta, M. Franco Sevilla, L. Gouskos, R. Heller, J. Incandela, A. Ovcharova, H. Qu, J. Richman, D. Stuart, I. Suarez, S. Wang, J. Yoo

California Institute of Technology, Pasadena, USA

D. Anderson, A. Bornheim, J. M. Lawhorn, H. B. Newman, T. Q. Nguyen, M. Spiropulu, J. R. Vlimant, R. Wilkinson, S. Xie, Z. Zhang, R. Y. Zhu

Carnegie Mellon University, Pittsburgh, USA

M. B. Andrews, T. Ferguson, T. Mudholkar, M. Paulini, M. Sun, I. Vorobiev, M. Weinberg

University of Colorado Boulder, Boulder, USA

J. P. Cumalat, W. T. Ford, F. Jensen, A. Johnson, M. Krohn, S. Leontsinis, E. MacDonald, T. Mulholland, K. Stenson, K. A. Ulmer, S. R. Wagner

Cornell University, Ithaca, USA

J. Alexander, J. Chaves, Y. Cheng, J. Chu, A. Datta, K. Mcdermott, N. Mirman, J. R. Patterson, D. Quach, A. Rinkevicius, A. Ryd, L. Skinnari, L. Soffi, S. M. Tan, Z. Tao, J. Thom, J. Tucker, 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, J. Berryhill, P. C. Bhat, G. Bolla[†], K. Burkett, J. N. Butler, A. Canepa, G. B. Cerati, H. W. K. Cheung, F. Chlebana, M. Cremonesi, J. Duarte, V. D. Elvira, J. Freeman, Z. Gecse, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, J. Hanlon, R. M. Harris, S. Hasegawa, J. Hirschauer, Z. Hu, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, B. Klima, M. J. Kortelainen, B. Kreis, S. Lammel, D. Lincoln, R. Lipton, M. Liu, T. Liu, J. Lykken, K. Maeshima, J. M. Marraffino, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, V. O'Dell, K. Pedro, O. Prokofyev, G. Rakness, L. Ristori, A. Savoy-Navarro[66], B. Schneider, E. Sexton-Kennedy, A. Soha, W. J. Spalding, L. Spiegel, S. Stoynev, J. Strait, N. Strobbe, L. Taylor, S. Tkaczyk, N. V. Tran, L. Uplegger, E. W. Vaandering, C. Vernieri, M. Verzocchi, R. Vidal, M. Wang, H. A. Weber, A. Whitbeck

University of Florida, Gainesville, USA

D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, A. Brinkerhoff, L. Cadamuro, A. Carnes, M. Carver, D. Curry, R. D. Field, S. V. Gleyzer, B. M. Joshi, J. Konigsberg, A. Korytov, P. Ma, K. Matchev, H. Mei, G. Mitselmakher, K. Shi, D. Sperka, J. Wang, S. Wang

Florida International University, Miami, USA

Y. R. Joshi, S. Linn

Florida State University, Tallahassee, USA

A. Ackert, T. Adams, A. Askew, S. Hagopian, V. Hagopian, K. F. Johnson, T. Kolberg, G. Martinez, T. Perry, H. Prosper, A. Saha, A. Santra, V. Sharma, R. Yohay

Florida Institute of Technology, Melbourne, USA

M. M. Baarmand, V. Bhopatkar, S. Colafranceschi, M. Hohlmann, D. Noonan, M. Rahmani, T. Roy, F. Yumiceva

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

M. R. Adams, L. Apanasevich, D. Berry, R. R. Betts, R. Cavanaugh, X. Chen, S. Dittmer, O. Evdokimov, C. E. Gerber, D. A. Hangal, D. J. Hofman, K. Jung, J. Kamin, C. Mills, I. D. Sandoval Gonzalez, M. B. Tonjes, N. Varelas, H. Wang, X. Wang, Z. Wu, J. Zhang

The University of Iowa, Iowa City, USA

M. Alhusseini, B. Bilki[67], W. Clarida, K. Dilsiz[68], S. Durgut, R. P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul[69], Y. Onel, F. Ozok[70], A. Penzo, C. Snyder, E. Tiras, J. Wetzel

Johns Hopkins University, Baltimore, USA

B. Blumenfeld, A. Cocoros, N. Eminizer, D. Fehling, L. Feng, A. V. Gritsan, W. T. Hung, P. Maksimovic, J. Roskes, U. Sarica, M. Swartz, M. Xiao, C. You

The University of Kansas, Lawrence, USA

A. Al-bataineh, P. Baringer, A. Bean, S. Boren, J. Bowen, A. Bylinkin[34], J. Castle, S. Khalil, A. Kropivnitskaya, D. Majumder, W. Mcbrayer, M. Murray, C. Rogan, S. Sanders, E. Schmitz, J. D. Tapia Takaki, Q. Wang

Kansas State University, Manhattan, USA

A. Ivanov, K. Kaadze, D. Kim, Y. Maravin, D. R. Mendis, T. Mitchell, A. Modak, A. Mohammadi, L. K. Saini, N. Skhirtladze

Lawrence Livermore National Laboratory, Livermore, USA

F. Rebassoo, D. Wright

University of Maryland, College Park, USA

A. Baden, O. Baron, A. Belloni, S. C. Eno, Y. Feng, C. Ferraioli, N. J. Hadley, S. Jabeen, G. Y. Jeng, R. G. Kellogg, J. Kunkle, A. C. Mignerey, F. Ricci-Tam, Y. H. Shin, A. Skuja, S. C. Tonwar, K. Wong

Massachusetts Institute of Technology, Cambridge, USA

D. Abercrombie, B. Allen, V. Azzolini, A. Baty, G. Bauer, R. Bi, S. Brandt, W. Busza, I. A. Cali, M. D'Alfonso,
Z. Demiragli, G. Gomez Ceballos, M. Goncharov, P. Harris, D. Hsu, M. Hu, Y. Iiyama, G. M. Innocenti, M. Klute,
D. Kovalskyi, Y.-J. Lee, P. D. Luckey, B. Maier, A. C. Marini, C. Mcginn, C. Mironov, S. Narayanan, X. Niu, C. Paus,
C. Roland, G. Roland, G. S. F. Stephans, K. Sumorok, K. Tatar, D. Velicanu, J. Wang, T. W. Wang, B. Wyslouch,
S. Zhaozhong

University of Minnesota, Minneapolis, USA

A. C. Benvenuti, R. M. Chatterjee, A. Evans, P. Hansen, S. Kalafut, Y. Kubota, Z. Lesko, J. Mans, S. Nourbakhsh,
N. Ruckstuhl, R. Rusack, J. Turkewitz, M. A. Wadud

University of Mississippi, Oxford, USA

J. G. Acosta, S. Oliveros

University of Nebraska-Lincoln, Lincoln, USA

E. Avdeeva, K. Bloom, D. R. Claes, C. Fangmeier, F. Golf, R. Gonzalez Suarez, R. Kamalieddin, I. Kravchenko,
J. Monroy, J. E. Siado, G. R. Snow, B. Stieger

State University of New York at Buffalo, Buffalo, USA

A. Godshalk, C. Harrington, I. Iashvili, A. Kharchilava, D. Nguyen, A. Parker, S. Rappoccio, B. Roozbahani

Northeastern University, Boston, USA

G. Alverson, E. Barberis, C. Freer, A. Hortiangtham, D. M. Morse, T. Orimoto, R. Teixeira De Lima, T. Wamorkar,
B. Wang, A. Wisecarver, D. Wood

Northwestern University, Evanston, USA

S. Bhattacharya, O. Charaf, K. A. Hahn, N. Mucia, N. Odell, M. H. Schmitt, K. Sung, M. Trovato, M. Velasco

University of Notre Dame, Notre Dame, USA

R. Bucci, N. Dev, M. Hildreth, K. Hurtado Anampa, C. Jessop, D. J. Karmgard, N. Kellams, K. Lannon, W. Li, N. Loukas,
N. Marinelli, F. Meng, C. Mueller, Y. Musienko[33], M. Planer, A. Reinsvold, R. Ruchti, P. Siddireddy, G. Smith, S. Taroni,
M. Wayne, A. Wightman, M. Wolf, A. Woodard

The Ohio State University, Columbus, USA

J. Alimena, L. Antonelli, B. Bylsma, L. S. Durkin, S. Flowers, B. Francis, A. Hart, C. Hill, W. Ji, T. Y. Ling, W. Luo,
B. L. Winer, H. W. Wulsin

Princeton University, Princeton, USA

S. Cooperstein, P. Elmer, J. Hardenbrook, P. Hebda, S. Higginbotham, A. Kalogeropoulos, D. Lange, M. T. Lucchini,
J. Luo, D. Marlow, K. Mei, I. Ojalvo, J. Olsen, C. Palmer, P. Piroué, J. Salfeld-Nebgen, D. Stickland, C. Tully

University of Puerto Rico, Mayaguez, USA

S. Malik, S. Norberg

Purdue University, West Lafayette, USA

A. Barker, V. E. Barnes, L. Gutay, M. Jones, A. W. Jung, A. Khatiwada, B. Mahakud, D. H. Miller, N. Neumeister,
C. C. Peng, H. Qiu, J. F. Schulte, J. Sun, F. Wang, R. Xiao, W. Xie

Purdue University Northwest, Hammond, USA

T. Cheng, J. Dolen, N. Parashar

Rice University, Houston, USA

Z. Chen, K. M. Ecklund, S. Freed, F. J. M. Geurts, M. Kilpatrick, W. Li, B. Michlin, B. P. Padley, J. Roberts, J. Rorie,
W. Shi, Z. Tu, J. Zabel, A. Zhang

University of Rochester, Rochester, USA

A. Bodek, P. de Barbaro, R. Demina, Y. t. Duh, J. L. Dulemba, C. Fallon, T. Ferbel, M. Galanti, A. Garcia-Bellido, J. Han,
O. Hindrichs, A. Khukhunaishvili, K. H. Lo, P. Tan, R. Taus, M. Verzetti

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

A. Agapitos, J. P. Chou, Y. Gershtein, T. A. Gómez Espinosa, E. Halkiadakis, M. Heindl, E. Hughes, S. Kaplan, R. Kunnawalkam Elayavalli, S. Kyriacou, A. Lath, R. Montalvo, K. Nash, M. Osherson, H. Saka, S. Salur, S. Schnetzer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen, M. Walker

University of Tennessee, Knoxville, USA

A. G. Delannoy, J. Heideman, G. Riley, K. Rose, S. Spanier, K. Thapa

Texas A & M University, College Station, USA

O. Bouhali[71], A. Castaneda Hernandez[71], A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, T. Kamon[72], S. Luo, R. Mueller, Y. Pakhotin, R. Patel, A. Perloff, L. Perniè, D. Rathjens, A. Safonov, A. Tatarinov

Texas Tech University, Lubbock, USA

N. Akchurin, J. Damgov, F. De Guio, P. R. Dudero, S. Kunori, K. Lamichhane, S. W. Lee, T. Mengke, S. Muthumuni, T. Peltola, S. Undleeb, I. Volobouev, Z. Wang

Vanderbilt University, Nashville, USA

S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, A. Melo, H. Ni, K. Padeken, J. D. Ruiz Alvarez, P. Sheldon, S. Tuo, J. Velkovska, M. Verweij, Q. Xu

University of Virginia, Charlottesville, USA

M. W. Arenton, P. Barria, B. Cox, R. Hirosky, M. Joyce, A. Ledovskoy, H. Li, C. Neu, T. Sinthuprasith, Y. Wang, E. Wolfe, F. Xia

Wayne State University, Detroit, USA

R. Harr, P. E. Karchin, N. Poudyal, J. Sturdy, P. Thapa, S. Zaleski

University of Wisconsin-Madison, Madison, WI, USA

M. Brodski, J. Buchanan, C. Caillol, D. Carlsmith, S. Dasu, L. Dodd, S. Duric, B. Gomber, M. Grothe, M. Herndon, A. Hervé, U. Hussain, P. Klabbers, A. Lanaro, A. Levine, K. Long, R. Loveless, T. Ruggles, A. Savin, N. Smith, W. H. Smith, N. Woods

† **Deceased**

 1: Also at Vienna University of Technology, Vienna, Austria
 2: Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
 3: Also at Universidade Estadual de Campinas, Campinas, Brazil
 4: Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil
 5: Also at Université Libre de Bruxelles, Bruxelles, Belgium
 6: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
 7: Also at Joint Institute for Nuclear Research, Dubna, Russia
 8: Now at Cairo University, Cairo, Egypt
 9: Also at Fayoum University, El-Fayoum, Egypt
10: Now at British University in Egypt, Cairo, Egypt
11: Now at Ain Shams University, Cairo, Egypt
12: Also at Department of Physics, King Abdulaziz University, Jeddah, Saudi Arabia
13: Also at Université de Haute Alsace, Mulhouse, France
14: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
15: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
16: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
17: Also at University of Hamburg, Hamburg, Germany
18: Also at Brandenburg University of Technology, Cottbus, Germany
19: Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
20: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
21: Also at Institute of Physics, University of Debrecen, Debrecen, Hungary
22: Also at Indian Institute of Technology Bhubaneswar, Bhubaneswar, India

23: Also at Institute of Physics, Bhubaneswar, India
24: Also at Shoolini University, Solan, India
25: Also at University of Visva-Bharati, Santiniketan, India
26: Also at Isfahan University of Technology, Isfahan, Iran
27: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
28: Also at Università degli Studi di Siena, Siena, Italy
29: Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia
30: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia
31: Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
32: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
33: Also at Institute for Nuclear Research, Moscow, Russia
34: Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
35: Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan
36: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
37: Also at University of Florida, Gainesville, USA
38: Also at P.N. Lebedev Physical Institute, Moscow, Russia
39: Also at California Institute of Technology, Pasadena, USA
40: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
41: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
42: Also at INFN Sezione di Pavia^a, Università di Pavia^b, Pavia, Italy
43: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
44: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy
45: Also at National and Kapodistrian University of Athens, Athens, Greece
46: Also at Riga Technical University, Riga, Latvia
47: Also at Universität Zürich, Zurich, Switzerland
48: Also at Stefan Meyer Institute for Subatomic Physics (SMI), Vienna, Austria
49: Also at Adiyaman University, Adiyaman, Turkey
50: Also at Istanbul Aydin University, Istanbul, Turkey
51: Also at Mersin University, Mersin, Turkey
52: Also at Piri Reis University, Istanbul, Turkey
53: Also at Gaziosmanpasa University, Tokat, Turkey
54: Also at Ozyegin University, Istanbul, Turkey
55: Also at Izmir Institute of Technology, Izmir, Turkey
56: Also at Marmara University, Istanbul, Turkey
57: Also at Kafkas University, Kars, Turkey
58: Also at Istanbul Bilgi University, Istanbul, Turkey
59: Also at Hacettepe University, Ankara, Turkey
60: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
61: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
62: Also at Monash University, Faculty of Science, Clayton, Australia
63: Also at Bethel University, St. Paul, USA
64: Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
65: Also at Utah Valley University, Orem, USA
66: Also at Purdue University, West Lafayette, USA
67: Also at Beykent University, Istanbul, Turkey
68: Also at Bingol University, Bingol, Turkey
69: Also at Sinop University, Sinop, Turkey
70: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
71: Also at Texas A&M University at Qatar, Doha, Qatar
72: Also at Kyungpook National University, Daegu, Korea