

Study of hadronic event-shape variables in multijet final states in pp collisions at $\sqrt{s} = 7$ TeV



The CMS collaboration

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

ABSTRACT: Event-shape variables, which are sensitive to perturbative and nonperturbative aspects of quantum chromodynamic (QCD) interactions, are studied in multijet events recorded in proton-proton collisions at $\sqrt{s} = 7$ TeV. Events are selected with at least one jet with transverse momentum $p_T > 110$ GeV and pseudorapidity $|\eta| < 2.4$, in a data sample corresponding to integrated luminosities of up to 5 fb^{-1} . The distributions of five event-shape variables in various leading jet p_T ranges are compared to predictions from different QCD Monte Carlo event generators.

KEYWORDS: Jets, Hadron-Hadron Scattering, Global features

ARXIV EPRINT: [1407.2856](https://arxiv.org/abs/1407.2856)

Contents

1	Introduction	1
2	The CMS detector	2
3	Event-shape variables	3
4	Event selection and Monte Carlo samples	4
5	Unfolding and systematic uncertainties	6
6	Results	7
7	Summary	10
	The CMS collaboration	16

1 Introduction

Event-shape variables measure the properties of the energy flow in the final states of high energy particle collisions. Their simplicity combined with their sensitivity to many important signatures of quantum chromodynamics (QCD) [1, 2] make them interesting observables extensively studied in hadronic final states of electron-positron (e^+e^-) and deep inelastic scattering (DIS) collisions [3–5]. Such event-shape variables are theoretically defined in an infrared- and collinear-safe manner and can be computed using perturbative techniques. Their measurements have improved our understanding of many perturbative and non-perturbative aspects of QCD including the determination of the strong coupling constant α_s , details of parton radiation and hadronization, tests of the colour structure of the theory, as well as modelling and validation of Monte Carlo (MC) event generators.

Measurements of event-shape variables in hadron-hadron collisions are more complicated than in e^+e^- or DIS collisions, because a larger fraction of the final-state activity is emitted at very forward pseudorapidities not covered by the detectors, and also because the elementary (parton-parton) kinematics cannot be determined as precisely. These difficulties have led to the redefinition of event-shape variables in the transverse plane, where the energy flow can be measured with small systematic uncertainty. A large set of event-shape variables in proton-proton (pp) collisions, which are sensitive to different aspects of the rich dynamics of the strong interaction from soft (hadronization) to hard (multijet radiation) scales has been proposed [1, 2]. These variables are normalized to the sum of the measured transverse momenta (p_T) of all reconstructed objects in the event to reduce the systematic uncertainty due to the jet energy scale.

Previous studies of event-shape variables at hadron colliders include those of the CDF experiment at the Tevatron [6], and early measurements at the LHC [7, 8]. More recently event-shape variables have been studied in the associated production of Z bosons with jets [9]. In the previous analysis of the CMS experiment with 3.2 pb^{-1} of data [7], the transverse thrust and thrust minor variables were studied to improve the modelling of multijet production in MC generators. This study is expanded here using a larger data set corresponding to an integrated luminosity of 5 fb^{-1} in pp collisions at $\sqrt{s} = 7 \text{ TeV}$ with an expanded set of five event-shape variables [1, 2]: the transverse thrust, jet broadening, jet mass (both total and in the transverse plane), and the third-jet resolution parameter. The significant increase in luminosity allows the measurement of variables with three jets, not accessible with earlier data, and the latter four observables are analysed in CMS for the first time. Therefore this analysis is sensitive to features of the event generators that were not probed in the previous CMS result.

The paper is organized as follows. In section 2, elements of the CMS detector relevant to this analysis are described. Section 3 introduces the event-shape variables studied in this work. The data and MC simulated event samples are summarized in section 4 along with the event selection criteria. Section 5 describes the unfolding technique employed and the propagated systematic uncertainties. Section 6 compares the five event-shape distributions in data with several QCD event generators. The results are summarized in section 7.

2 The CMS detector

The CMS experiment [10] uses a right-handed coordinate system, with the origin at the nominal interaction point, the x axis pointing to the centre of the LHC ring, the y axis pointing vertically up (perpendicular to the plane of the LHC ring), and the z axis along the anticlockwise-beam direction. The polar angle θ is measured from the positive z axis and the azimuthal angle ϕ is measured in the x - y plane in radians. Pseudorapidity is defined as $\eta = -\ln[\tan(\theta/2)]$.

The central feature of the CMS detector is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the field volume, there are silicon pixel and strip trackers, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a sampling hadron calorimeter made up of layers of brass plates and plastic scintillators. The calorimeters provide coverage in pseudorapidity up to $|\eta| = 3.0$. A preshower detector consisting of two planes of silicon sensors interleaved with lead is located in front of the ECAL at $1.7 < |\eta| < 2.6$. An iron and quartz fiber Cherenkov hadron calorimeter covers pseudorapidities $3.0 < |\eta| < 5.0$. The muons are measured in the pseudorapidity range $|\eta| < 2.4$, with detection planes made using three technologies: drift tubes, cathode strip chambers, and resistive plate chambers.

The particle-flow (PF) algorithm [11, 12] combines information on charged particles from the tracking system, energy deposits in the electromagnetic and hadron calorimeters, as well as signals in the preshower detector and muon systems to assign a four-momentum vector to particles, i.e. γ , e^\pm , μ^\pm , charged, and neutral hadrons. Jets are reconstructed using these particles. The energy calibration of individual particle types is performed

separately. At the PF level, the jet constituents are almost fully calibrated and require only a small correction (less than 10%) [13] due to tracking inefficiencies and threshold effects. The jet clustering is performed using the anti- k_T clustering algorithm [14, 15] with a distance parameter $R = 0.5$. The jets are ordered by descending p_T with $p_{T,1}$ and $p_{T,2}$ representing the transverse momenta of the leading and the second leading jets, respectively.

3 Event-shape variables

Five event-shape variables are analysed in this paper: the transverse thrust τ_\perp , the total jet broadening B_{tot} , the total jet mass ρ_{tot} , the total transverse jet mass ρ_{tot}^T and the third-jet resolution parameter Y_{23} . In the formulae below, $p_{T,i}$, η_i , and ϕ_i represent the transverse momentum, pseudorapidity, and azimuthal angle of the i th jet, and \hat{n}_T is the unit vector that maximizes the sum of the projections of $\vec{p}_{T,i}$. The transverse thrust axis \hat{n}_T and the beam form the so-called event plane. Based on the direction of \hat{n}_T , the transverse region is separated into an upper side \mathcal{C}_U , consisting of all jets with $\vec{p}_T \cdot \hat{n}_T > 0$, and a lower side \mathcal{C}_L , with $\vec{p}_T \cdot \hat{n}_T < 0$. The jet broadening and third-jet resolution variables require at least three selected jets, whereas the calculation of other variables requires at least two jets. The \hat{n}_T vector is defined only up to a global sign - choosing one sign or the other has no consequence since it simply exchanges the upper and lower event regions.

Transverse thrust: The event thrust observable in the transverse plane is defined as

$$\tau_\perp \equiv 1 - \max_{\hat{n}_T} \frac{\sum_i |\vec{p}_{T,i} \cdot \hat{n}_T|}{\sum_i p_{T,i}}. \quad (3.1)$$

This variable probes the hadronisation process and is sensitive to the modelling of two-jet and multijet topologies. In this paper “multijet” refers to “more-than-two-jet”. In the limit of a perfectly balanced two-jet event, τ_\perp is zero, while in isotropic multijet events it amounts to $(1 - 2/\pi)$.

Jet broadening: The pseudorapidities and the azimuthal angles of the axes for the upper and lower event regions are defined by

$$\eta_X \equiv \frac{\sum_{i \in \mathcal{C}_X} p_{T,i} \eta_i}{\sum_{i \in \mathcal{C}_X} p_{T,i}}, \quad (3.2)$$

$$\phi_X \equiv \frac{\sum_{i \in \mathcal{C}_X} p_{T,i} \phi_i}{\sum_{i \in \mathcal{C}_X} p_{T,i}}, \quad (3.3)$$

where X refers to upper (U) or lower (L) side. From these, the jet broadening variable in each region is defined as

$$B_X \equiv \frac{1}{2 P_T} \sum_{i \in \mathcal{C}_X} p_{T,i} \sqrt{(\eta_i - \eta_X)^2 + (\phi_i - \phi_X)^2}, \quad (3.4)$$

where P_T is the scalar sum of the transverse momenta of all the jets. The total jet broadening is then defined as

$$B_{\text{tot}} \equiv B_U + B_L. \quad (3.5)$$

Jet masses: The normalized squared invariant mass of the jets in the upper and lower regions of the event is defined by

$$\rho_X \equiv \frac{M_X^2}{P^2}, \quad (3.6)$$

where M_X is the invariant mass of the constituents of the jets in the region X , and P is the scalar sum of the momenta of all constituents in both sides.

The jet mass variable is defined as the sum of the masses in the upper and lower regions,

$$\rho_{\text{tot}} \equiv \rho_U + \rho_L. \quad (3.7)$$

The corresponding jet mass in the transverse plane, ρ_{tot}^T , is also similarly calculated in transverse plane.

Third-jet resolution parameter: The third-jet resolution parameter is defined as

$$Y_{23} \equiv \frac{\min(p_{T,3}^2, [\min(p_{T,i}, p_{T,j})^2 \times (\Delta R_{ij})^2 / R^2])}{P_{12}^2}, \quad (3.8)$$

where i, j run over all three jets, $(\Delta R_{ij})^2 = (\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2$, and $p_{T,3}$ is the transverse momentum of the third jet in the event. If there are more than three jets in the event, they are iteratively merged using the k_T algorithm [16, 17] with a distance parameter $R = 0.6$. To compute P_{12} , three jets are merged into two using the procedure described above and P_{12} is then defined as the scalar sum of the transverse momenta of the two remaining jets.

The Y_{23} variable estimates the relative strength of the p_T of the third jet with respect to the other two jets. It vanishes for two-jet events, and a nonzero value of Y_{23} indicates the presence of hard parton emission, which tests the parton showering model of QCD event generators. A test like this is less sensitive to the details of the underlying event (UE) and parton hadronization models than the other event-shape variables [2].

4 Event selection and Monte Carlo samples

This analysis extends the phase space compared to the previous study [7] to $|\eta| < 2.4$, and considers several different p_T ranges for the leading jet. The events used are collected with single-jet triggers, which are reconstructed from calorimeter information only, where the p_T of at least one jet is above a certain threshold, $p_{T,\text{th}}$. Events are divided into five bins of $p_{T,1}$ where each bin uses data from one trigger path. The choice of $p_{T,1}$ ranges (table 1) has been determined by the trigger criteria, while the p_T threshold (>30 GeV) for the other jets and their geometric acceptance ($|\eta| < 2.4$) are restricted to give the good jet energy scale and resolution. Spurious jets, which are due to noise in the calorimeters or other noncollision backgrounds, are eliminated using jet quality criteria, e.g. jets must consist of at least two particles, including at least one charged hadron, and not more than 99% of

Trigger $p_{T,th}$ (GeV)	Range of $p_{T,1}$ (GeV)	Luminosity	Number of events	Fraction of events (%)			
				$N_{jet} = 2$	$N_{jet} = 3$	$N_{jet} = 4$	$N_{jet} > 4$
60	110–170	0.403 pb^{-1}	96833	57.9	32.6	7.8	1.7
110	170–250	7.15 pb^{-1}	228854	43.0	37.7	14.6	4.7
190	250–320	153 pb^{-1}	601554	34.8	37.8	19.1	8.3
240	320–390	521 pb^{-1}	497827	31.0	37.0	21.2	10.9
300	>390	4.98 fb^{-1}	2234304	28.4	35.6	22.5	13.5

Table 1. Characteristics of the data samples selected for this analysis, in categories of leading jet transverse momentum $p_{T,1}$: effective integrated luminosity, selected number of events, and relative abundances of the numbers of selected jets, N_{jet} , for jets with $p_T > 30 \text{ GeV}$ and $|\eta| < 2.4$.

the jet energy may be carried by neutral hadrons alone, or by photons alone. These jets that do not satisfy the identification requirements are not included in the calculation of the event-shape variables.

An event is discarded if

- any one of the two highest- p_T jets in the event lies outside the central region ($|\eta| < 2.4$); for the measurement of B_{tot} and Y_{23} a third jet satisfying the jet selection criteria is required within the same detector acceptance region;
- any one of the two highest- p_T jets is spurious;
- all selected jets of an event lie only on one side of the line perpendicular to \hat{n}_T . This criterion ensures that events will be rejected if jets are missed in the forward direction. Events of interest for this analysis should be well-balanced in p_T and hence have jets on both sides of this line.

Table 1 shows the numbers of events, as well as the fractions of events with two, three, four, or more jets, for various ranges of the leading jet $p_{T,1}$, along with the effective integrated luminosity for each data sample. The effective luminosities differ due to variations of the prescale factor of the trigger paths associated with each $p_{T,1}$. The average number of additional pp interactions per bunch crossing (pileup) on the collected dataset is ≈ 8 . The effect of pileup in the distributions of event-shape variables has been studied by grouping the events in different ranges of number of reconstructed primary vertices, and no bias has been found. This is expected due to fact that after the jet energy calibration, there is no residual pileup dependence.

Four MC generators, PYTHIA 6.426 (PYTHIA 6) [18], PYTHIA 8.153 (PYTHIA 8) [19], HERWIG++ 2.5.0 (HERWIG++) [20], and MADGRAPH 5.1.5.7 (MADGRAPH) [21] are chosen to generate multijet events. Particles with a lifetime larger than 30 ps are declared stable and handled by the full CMS detector simulation based on GEANT4 [22]. These generators reproduce the single differential jet spectra measured at the LHC [23–25]. The simulated events are then reconstructed in the same way for real data. The MC simulations are also used to obtain the unfolding corrections, described in the next section, and to estimate the associated uncertainties.

Events are generated with PYTHIA 6 using three different models: (i) D6T [26], which uses virtuality-ordered parton showering (PS) and is based on Tevatron data; and two models that use p_T -ordered PS: (ii) Perugia-P0 [27] based on LEP and Tevatron data, and (iii) Z2 [28] based on CMS data collected at $\sqrt{s} = 900$ GeV and 7 TeV. The generator PYTHIA 8 uses p_T -ordered PS, an UE description based on the multiple parton interaction (MPI) model of PYTHIA 6 interleaved with initial and final state radiation, and the tune4C [29] settings. The HERWIG++ generator is run with tune23 settings, where the PS evolution is based on angular ordering and an eikonal MPI model for the UE. Finally, the MADGRAPH MC employs matrix element (ME) calculations to generate events with two to four partons plus PYTHIA 6-tuneZ2 for the PS and UE. The MLM matching procedure [30] is imposed to avoid a double counting of jets between the ME and PS, for a minimum jet p_T threshold of 20 GeV.

All MC generators use the CTEQ6L1 parametrization as the choice of parton distribution function (PDF), except for Perugia-P0 which uses CTEQ5L [31].

5 Unfolding and systematic uncertainties

Jets at generator level are defined as a collection of stable particles with the same kinematic criteria used for the real data. The distribution of a variable obtained using parton- and detector-level information differs because of the finite energy and angular resolutions of the experimental apparatus. In order to correct the measured distributions for bin migrations due to detector effects, a response matrix is constructed with simulated events. The D’Agostini method [32] is employed to unfold the experimental data, using the response matrix obtained from PYTHIA 6-tuneZ2, PYTHIA 8, and MADGRAPH samples. Although the results are consistent for the generators, small differences (<3%) are observed, which are taken as a systematic uncertainty. Another source of systematic uncertainty in the unfolding procedure is the choice of the unsmearing method. A regularized unfolding method based on singular value decomposition (SVD) of the response matrix [33] is also used as a consistency check. The difference between the D’Agostini and SVD unfolding methods is less than 5% for the τ_\perp distribution. It can be as high as 20% for the distributions of other event-shape variables, which require more than three jets in the event, mainly as a consequence of the lower number of events in the lower ranges of $p_{T,1}$.

Other sources of systematic uncertainty include the finite jet energy and angular resolutions and the jet energy scale [13]. In order to propagate the uncertainties due to the jet resolutions, the unfolded response matrix is obtained with jets randomly spread at the generator level with increasing and decreasing values of the resolution parameters. The corresponding differences in the unfolded data distributions are considered as systematic uncertainties, which are found to be less than 2% in most cases, but can be as high as 5% in some corners of phase space. Similarly, the jet energy scale is increased and decreased by one standard deviation with respect to its central value and the unfolded distributions are compared with the nominal one to estimate the effect of this scale correction, the resulting uncertainty is less than 3%. The effect of pileup on the event-shape variables is found to be negligible.

6 Results

The distributions of the logarithms of the five event-shape variables analysed (τ_{\perp} , B_{tot} , jet mass (both ρ_{tot} and $\rho_{\text{tot}}^{\text{T}}$), and Y_{23}) are shown in figures 1–5 for the five leading jet p_{T} ranges listed in table 1. All distributions are unfolded, normalized to unitary; they are compared to the predictions from the six generator models. The error bars around the data points indicate the statistical uncertainties and the shaded bands represent the sum in quadrature of statistical and systematic uncertainties. The corresponding ratios between the model predictions and the data are shown in the lower plots. The distributions are plotted in a logarithmic horizontal axis scale so that the details at small values of the event-shape variables are also visible.

Overall, the models tend to reproduce the transverse thrust τ_{\perp} , total transverse jet mass $\rho_{\text{tot}}^{\text{T}}$, and third-jet resolution parameter Y_{23} distributions better than the total jet mass ρ_{tot} and jet broadening B_{tot} ones. The model that consistently reproduces all the distributions within the uncertainties is the MADGRAPH matrix-element calculator combined with PYTHIA 6-tuneZ2 for the PS and UE.

Similar data-MC comparisons are performed using these different jet clustering algorithms: (i) anti- k_{T} with a distance parameter $R = 0.7$, (ii) k_{T} with a distance parameter $R = 0.4$, and (iii) energy deposits using calorimeter information only instead of PF candidates. In all cases, the results are similar and in agreement with each other. Also, the effect due to the choice of a particular PDF set in the MC predictions has been estimated using the MSTW2008lo68cl set [34, 35]. A negligible effect has been found by varying the PDF eigenvalues within one standard deviation.

The transverse thrust variable τ_{\perp} (figure 1) is insensitive to the longitudinal component of the particles' momenta, and thus to the modelling of MPI and colour connection between soft scatters and beam remnants. The data-MC agreement for this observable is at the 5–10% level for all p_{T} bins except at the highest τ_{\perp} where differences as large as 20% are observed. The agreement is better than the other event-shape variables, which are more sensitive to MPI and colour connection effects. The τ_{\perp} distributions also reveal that the predictions for the lower p_{T} bins from PYTHIA 8, HERWIG++, MADGRAPH, and PYTHIA 6 (with model D6T) are closer to the data than the ones from PYTHIA 6 with model Z2 and Perugia-P0.

The jet broadening distribution (figure 2) is poorly described by all the models at both low and high B_{tot} values except for the MADGRAPH generator. This variable is insensitive to the UE and hadronization details, but a precise modelling of the ME and PS is crucial in order to correctly predict its distribution. Both model ingredients are expected to be more adequately described in MADGRAPH, where the multijet final-states are directly obtained from the hard ME calculations, unlike PYTHIA and HERWIG++ parton showers, which work best for 2→2 processes. In addition, the jet broadening is sensitive to colour coherence effects, which have an improved description [36] in the current version of HERWIG++, which explains the best relative agreement of this model compared to all PYTHIA models. Similar arguments are also applicable for the total jet mass ρ_{tot} and the third-jet resolution parameter Y_{23} .

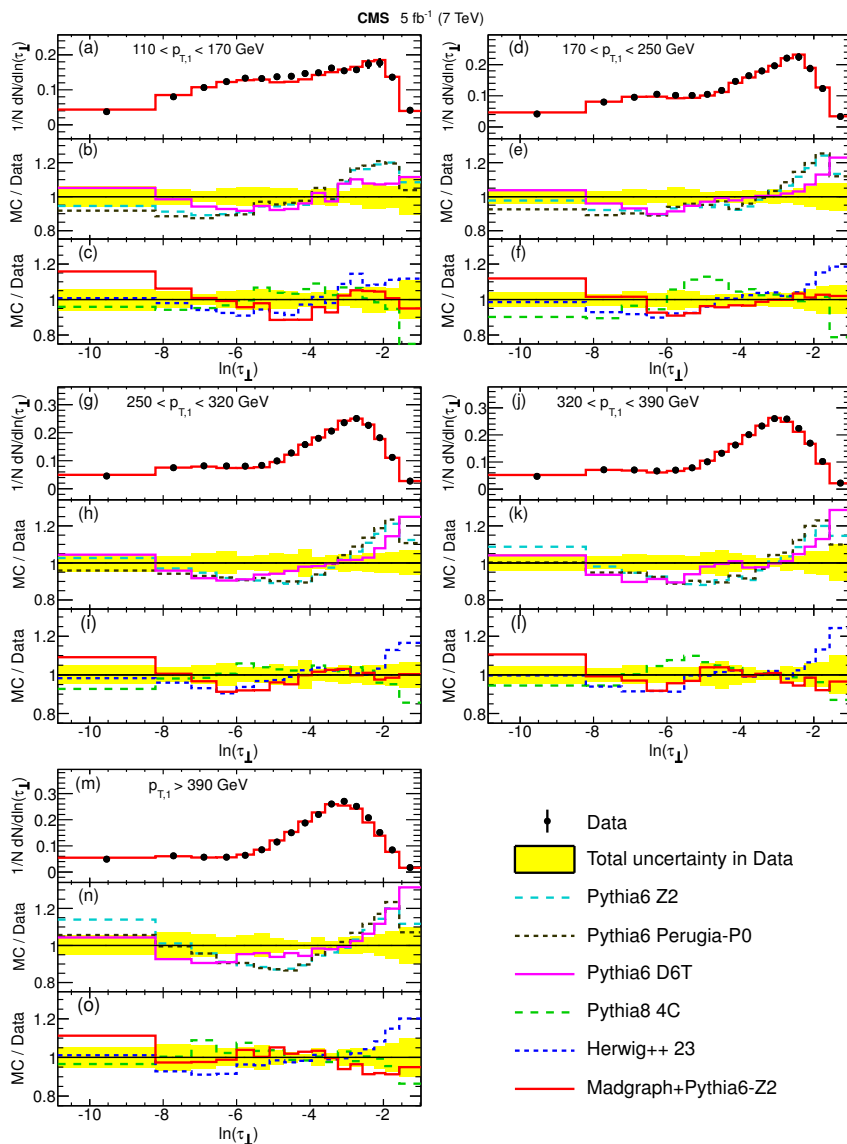


Figure 1. (a,d,g,j,m) Comparison between the transverse thrust τ_{\perp} distributions in data and MADGRAPH+PYTHIA 6-Z2 event generator in five different ranges of $p_{T,1}$. The error bars around the data points indicate the statistical uncertainties in data. The panels (b,e,h,k,n) show the ratios of different models of the PYTHIA 6 event generator over data in each momentum range and panels (c,f,i,l,o) show the ratios for other generators. The shaded bands represent statistical and systematic uncertainties in data.

The total jet mass ρ_{tot} distribution (figure 3) shows a similar behaviour between the measurement and the different model predictions as observed for the jet broadening case. MADGRAPH and HERWIG++ reproduce this observable better than the various PYTHIA models. This variable is more sensitive to (initial-state) forward radiation than the jet broadening [2], which indicates that such QCD emission is adequately described in the former two models.

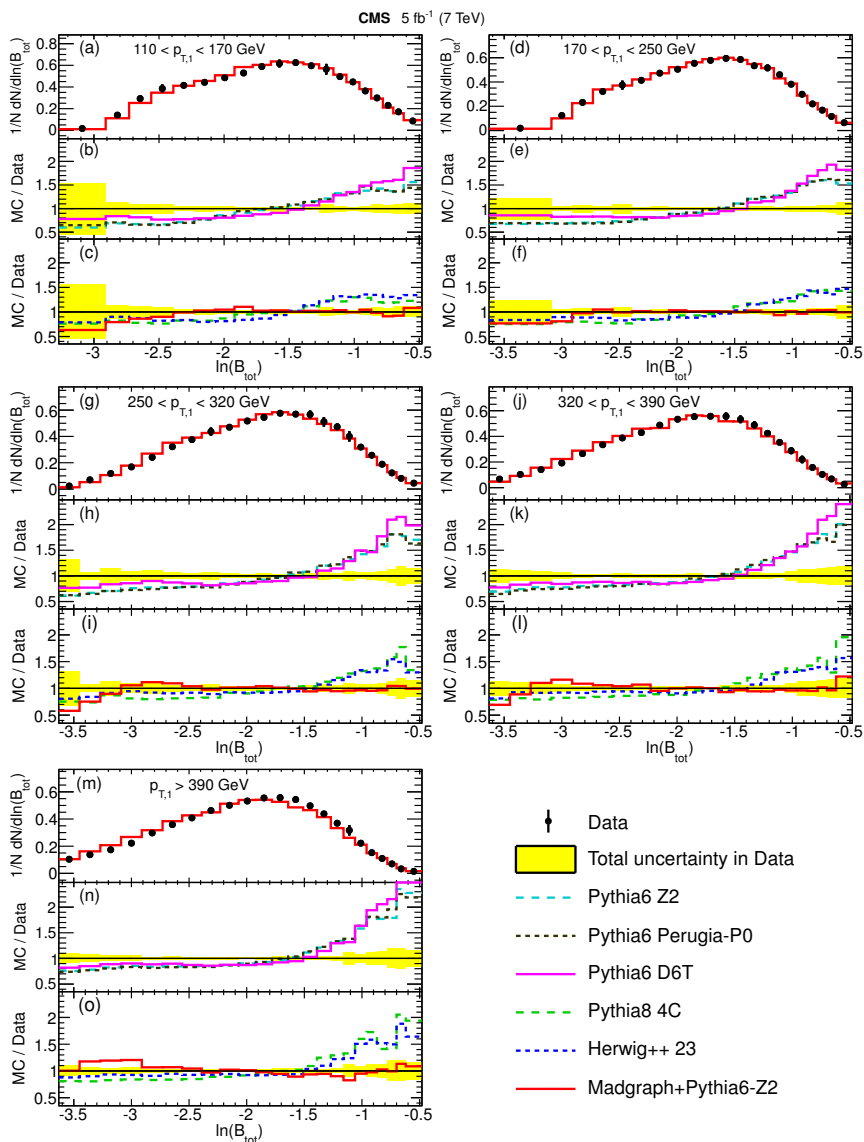


Figure 2. Comparison between the jet broadening B_{tot} distributions in data and various Monte Carlo models. The p_T bins and other details are the same as in figure 1.

The transverse jet mass ρ_{tot}^T distributions (figure 4) show agreement between data and predictions within 20%, which is better than that seen for the total jet mass ρ_{tot} . This is expected for ρ_{tot} , because transverse variables are less sensitive to the longitudinal energy flow [2] and to colour connection effects. Among the PYTHIA 6 models, D6T one shows the best agreement with the data.

The third-jet resolution parameter Y_{23} distribution (figure 5) is sensitive to the properties of multijet emission and it is robust with respect to the modelling of the UE and hadronization. The MADGRAPH generator shows again, for such a ME-sensitive observable, a better data-model agreement than the rest of MC simulations.

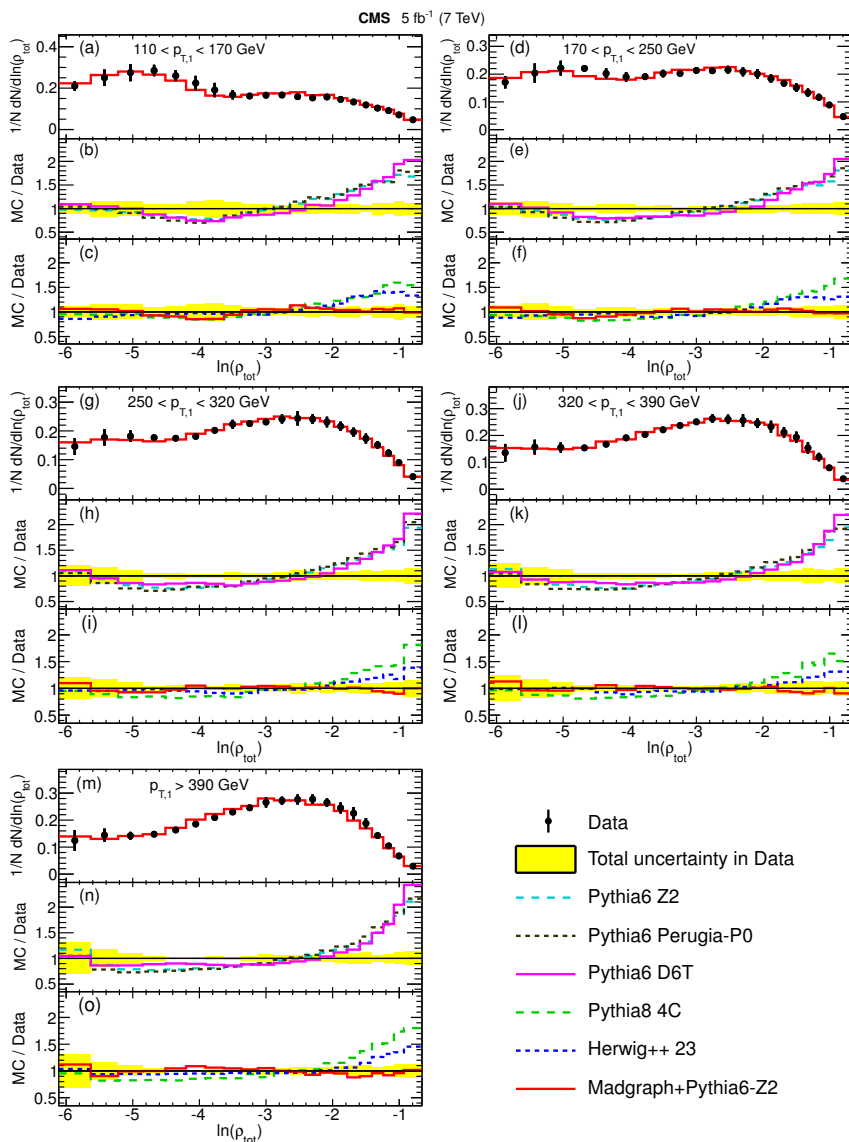


Figure 3. Comparison between the total jet mass ρ_{tot} distributions in data and various Monte Carlo models. The p_T bins and other details are the same as in figure 1.

7 Summary

An extended set of five event-shape variables (the transverse thrust τ_{\perp} , the jet broadening B_{tot} , the total jet mass ρ_{tot} , the total transverse jet mass ρ_{tot}^T , and the third-jet resolution parameter Y_{23}) have been studied in multijet final states measured in pp collisions at $\sqrt{s} = 7$ TeV. Such observables are sensitive to perturbative and nonperturbative aspects of QCD, and allow the validation of hadronic event generators. The experimental distributions have been measured in five different ranges of leading jet transverse momenta from $110 < p_T < 170$ GeV up to $p_T > 390$ GeV, and compared to the predictions of six different event generators.

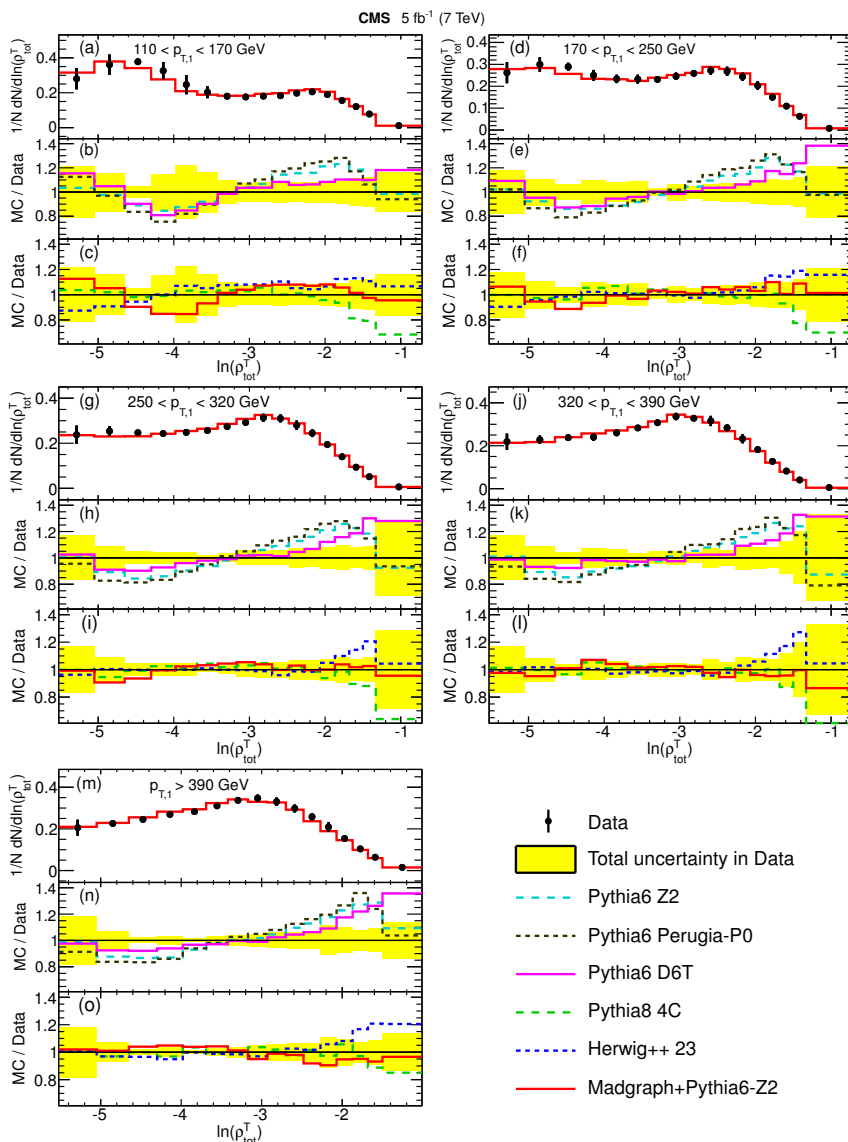


Figure 4. Comparison between the total jet transverse mass ρ_{tot}^T distributions in data and various Monte Carlo models. The p_T bins and other details are the same as in figure 1.

For the transverse thrust, all generators show an overall agreement with the data within 10%, with PYTHIA 8 and HERWIG++ exhibiting a better agreement than the others. A 20% level of agreement is also found for the total transverse jet mass distributions. However, event-shape variables that are more sensitive to the longitudinal energy flow (such as the total jet mass) or to hard parton emissions (such as the jet broadening) show a larger discrepancy between data and parton shower MC simulations. The predictions of PYTHIA 6-D6T show better agreement with data for the event-shape variables that make use only of the jet p_T , but have worse agreement for Y_{23} compared to other PYTHIA 6 models. The modelling of colour connection between the soft scatters and beam remnants, and initial- and final-state radiations are the major sources of differences between the various

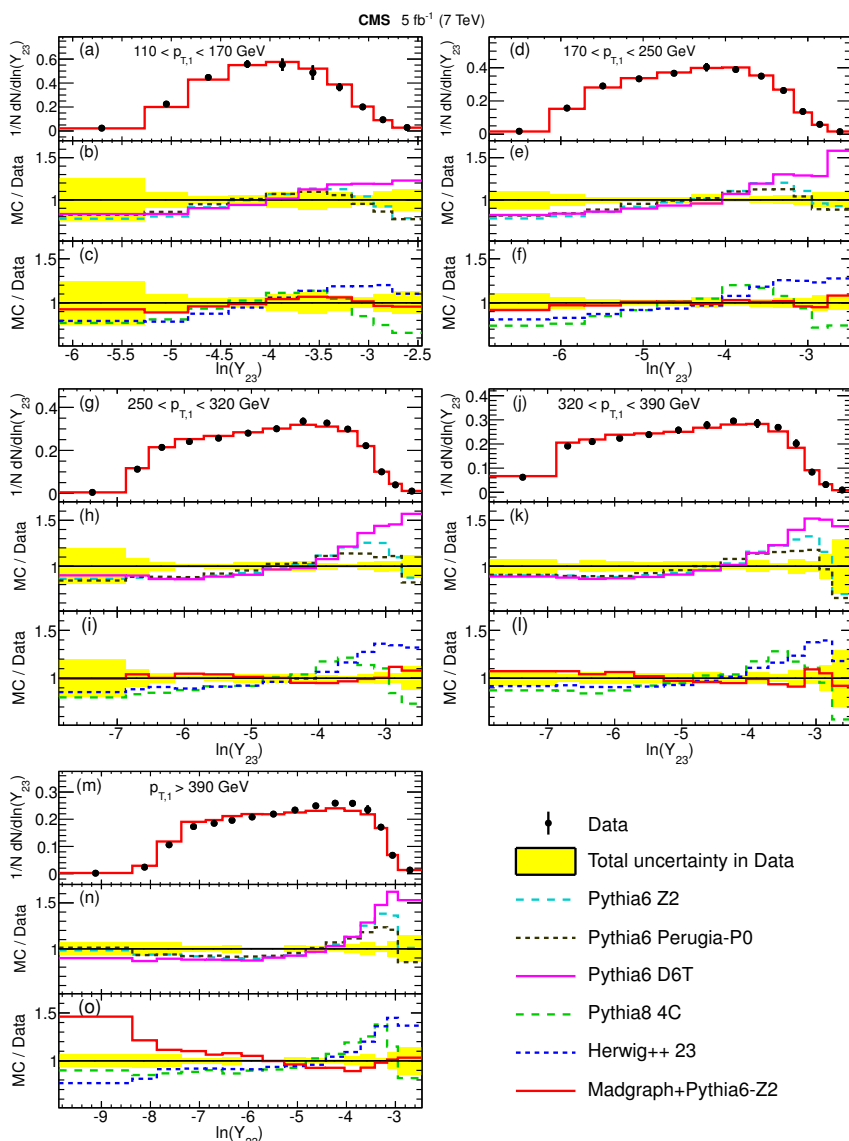


Figure 5. Comparison between the third-jet resolution parameter Y_{23} in data and various Monte Carlo models. The $p_{T,1}$ bins and other details are the same as in figure 1.

QCD event generators. The generator that consistently reproduces all distributions within the uncertainties is the MADGRAPH matrix-element calculator combined with PYTHIA 6-tuneZ2 for multiparton interactions and parton showering and hadronization. The study of infrared- and collinear-safe event-shape variables presented here provides detailed information to further improve the modelling of parton radiation and hadronization in event generators for high energy hadronic collisions.

Acknowledgments

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

Individuals have received support from the Marie-Curie programme and the European Research Council and EPLANET (European Union); the Leventis Foundation; the A. P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Council of Science and Industrial Research, India; the HOMING PLUS programme of Foundation for Polish Science, cofinanced from European Union, Regional Development Fund; the Compagnia di San Paolo (Torino); the Consorzio per la Fisica (Trieste); MIUR project 20108T4XTM (Italy); the Thalís and Aristeia programmes cofinanced by EU-ESF and the Greek NSRF; and the National Priorities Research Program by Qatar National Research Fund.

Open Access. This article is distributed under the terms of the Creative Commons Attribution License ([CC-BY 4.0](https://creativecommons.org/licenses/by/4.0/)), which permits any use, distribution and reproduction in any medium, provided the original author(s) and source are credited.

References

- [1] A. Banfi, G.P. Salam and G. Zanderighi, *Resummed event shapes at hadron-hadron colliders*, *JHEP* **08** (2004) 062 [[hep-ph/0407287](https://arxiv.org/abs/hep-ph/0407287)] [[INSPIRE](https://inspirehep.net/literature/1041781)].

- [2] A. Banfi, G.P. Salam and G. Zanderighi, *Phenomenology of event shapes at hadron colliders*, *JHEP* **06** (2010) 038 [[arXiv:1001.4082](#)] [[INSPIRE](#)].
- [3] M. Dasgupta and G.P. Salam, *Event shapes in e^+e^- annihilation and deep inelastic scattering*, *J. Phys. G* **30** (2004) R143 [[hep-ph/0312283](#)] [[INSPIRE](#)].
- [4] H1 collaboration, A. Aktas et al., *Measurement of event shape variables in deep-inelastic scattering at HERA*, *Eur. Phys. J. C* **46** (2006) 343 [[hep-ex/0512014](#)] [[INSPIRE](#)].
- [5] L3 collaboration, P. Achard et al., *Study of hadronic event shape in flavour tagged events in e^+e^- annihilation at $\sqrt{s} = 197$ GeV*, *PMC Phys. A* **2** (2008) 6 [[arXiv:0907.2658](#)] [[INSPIRE](#)].
- [6] CDF collaboration, T. Aaltonen et al., *Measurement of event shapes in proton-antiproton collisions at center-of-mass energy 1.96 TeV*, *Phys. Rev. D* **83** (2011) 112007 [[arXiv:1103.5143](#)] [[INSPIRE](#)].
- [7] CMS collaboration, *First measurement of hadronic event shapes in pp collisions at $\sqrt{s} = 7$ TeV*, *Phys. Lett. B* **699** (2011) 48 [[arXiv:1102.0068](#)] [[INSPIRE](#)].
- [8] ATLAS collaboration, *Measurement of event shapes at large momentum transfer with the ATLAS detector in pp collisions at $\sqrt{s} = 7$ TeV*, *Eur. Phys. J. C* **72** (2012) 2211 [[arXiv:1206.2135](#)] [[INSPIRE](#)].
- [9] CMS collaboration, *Event shapes and azimuthal correlations in Z + jets events in pp collisions at $\sqrt{s} = 7$ TeV*, *Phys. Lett. B* **722** (2013) 238 [[arXiv:1301.1646](#)] [[INSPIRE](#)].
- [10] CMS collaboration, *The CMS experiment at the CERN LHC*, 2008 *JINST* **3** S08004 [[INSPIRE](#)].
- [11] CMS collaboration, *Commissioning of the particle-flow event reconstruction with the first LHC collisions recorded in the CMS detector*, CMS-PAS-PFT-10-001 (2010).
- [12] CMS collaboration, *Commissioning of the particle-flow reconstruction in minimum-bias and jet events from pp collisions at 7 TeV*, CMS-PAS-PFT-10-002 (2010).
- [13] CMS collaboration, *Determination of jet energy calibration and transverse momentum resolution in CMS*, 2011 *JINST* **6** P11002 [[arXiv:1107.4277](#)] [[INSPIRE](#)].
- [14] M. Cacciari, G.P. Salam and G. Soyez, *The anti- k_t jet clustering algorithm*, *JHEP* **04** (2008) 063 [[arXiv:0802.1189](#)] [[INSPIRE](#)].
- [15] M. Cacciari, G.P. Salam and G. Soyez, *FastJet user manual*, *Eur. Phys. J. C* **72** (2012) 1896 [[arXiv:1111.6097](#)] [[INSPIRE](#)].
- [16] S. Catani, Y.L. Dokshitzer, M.H. Seymour and B.R. Webber, *Longitudinally invariant k_{\perp} clustering algorithms for hadron hadron collisions*, *Nucl. Phys. B* **406** (1993) 187 [[INSPIRE](#)].
- [17] S.D. Ellis and D.E. Soper, *Successive combination jet algorithm for hadron collisions*, *Phys. Rev. D* **48** (1993) 3160 [[hep-ph/9305266](#)] [[INSPIRE](#)].
- [18] T. Sjöstrand, S. Mrenna and P.Z. Skands, *PYTHIA 6.4 physics and manual*, *JHEP* **05** (2006) 026 [[hep-ph/0603175](#)] [[INSPIRE](#)].
- [19] T. Sjöstrand, S. Mrenna and P.Z. Skands, *A brief introduction to PYTHIA 8.1*, *Comput. Phys. Commun.* **178** (2008) 852 [[arXiv:0710.3820](#)] [[INSPIRE](#)].
- [20] M. Bähr et al., *Herwig++ physics and manual*, *Eur. Phys. J. C* **58** (2008) 639 [[arXiv:0803.0883](#)].

- [21] J. Alwall, M. Herquet, F. Maltoni, O. Mattelaer and T. Stelzer, *MadGraph 5: going beyond*, *JHEP* **06** (2011) 128 [[arXiv:1106.0522](#)] [[INSPIRE](#)].
- [22] GEANT4 collaboration, S. Agostinelli et al., *GEANT4 — A simulation toolkit*, *Nucl. Instrum. Meth. A* **506** (2003) 250 [[INSPIRE](#)].
- [23] CMS collaboration, *Measurement of the inclusive jet cross section in pp collisions at $\sqrt{s} = 7$ TeV*, *Phys. Rev. Lett.* **107** (2011) 132001 [[arXiv:1106.0208](#)] [[INSPIRE](#)].
- [24] CMS collaboration, *Measurement of the inclusive production cross sections for forward jets and for dijet events with one forward and one central jet in pp collisions at $\sqrt{s} = 7$ TeV*, *JHEP* **06** (2012) 036 [[arXiv:1202.0704](#)] [[INSPIRE](#)].
- [25] CMS collaboration, *Measurement of four-jet production in proton-proton collisions at $\sqrt{s} = 7$ TeV*, *Phys. Rev. D* **89** (2014) 092010 [[arXiv:1312.6440](#)] [[INSPIRE](#)].
- [26] R. Field, *Physics at the Tevatron*, *Acta Phys. Polon.* **B 39** (2008) 2611 [[INSPIRE](#)].
- [27] P.Z. Skands, *Tuning Monte Carlo generators: the Perugia tunes*, *Phys. Rev. D* **82** (2010) 074018 [[arXiv:1005.3457](#)] [[INSPIRE](#)].
- [28] R. Field, *Min-bias and the underlying event at the LHC*, *Acta Phys. Polon.* **B 42** (2011) 2631 [[arXiv:1110.5530](#)] [[INSPIRE](#)].
- [29] R. Corke and T. Sjöstrand, *Interleaved parton showers and tuning prospects*, *JHEP* **03** (2011) 032 [[arXiv:1011.1759](#)] [[INSPIRE](#)].
- [30] S. Mrenna and P. Richardson, *Matching matrix elements and parton showers with HERWIG and PYTHIA*, *JHEP* **05** (2004) 040 [[hep-ph/0312274](#)] [[INSPIRE](#)].
- [31] D. Stump et al., *Inclusive jet production, parton distributions and the search for new physics*, *JHEP* **10** (2003) 046 [[hep-ph/0303013](#)] [[INSPIRE](#)].
- [32] G. D’Agostini, *A Multidimensional unfolding method based on Bayes’ theorem*, *Nucl. Instrum. Meth. A* **362** (1995) 487 [[INSPIRE](#)].
- [33] A. Hocker and V. Kartvelishvili, *SVD approach to data unfolding*, *Nucl. Instrum. Meth. A* **372** (1996) 469 [[hep-ph/9509307](#)] [[INSPIRE](#)].
- [34] A.D. Martin, W.J. Stirling, R.S. Thorne and G. Watt, *Parton distributions for the LHC*, *Eur. Phys. J. C* **63** (2009) 189 [[arXiv:0901.0002](#)] [[INSPIRE](#)].
- [35] A.D. Martin, W.J. Stirling, R.S. Thorne and G. Watt, *Uncertainties on α_s in global PDF analyses and implications for predicted hadronic cross sections*, *Eur. Phys. J. C* **64** (2009) 653 [[arXiv:0905.3531](#)] [[INSPIRE](#)].
- [36] CMS collaboration, *Probing color coherence effects in pp collisions at $\sqrt{s} = 7$ TeV*, *Eur. Phys. J. C* **74** (2014) 2901 [[arXiv:1311.5815](#)] [[INSPIRE](#)].

The CMS collaboration

Yerevan Physics Institute, Yerevan, Armenia

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

Institut für Hochenergiephysik der OeAW, Wien, Austria

W. Adam, T. Bergauer, M. Dragicevic, J. Erö, C. Fabjan¹, M. Friedl, R. Frühwirth¹, V.M. Ghete, C. Hartl, N. Hörmann, J. Hrubec, M. Jeitler¹, W. Kiesenhofer, V. Knünz, M. Krammer¹, I. Krätschmer, D. Liko, I. Mikulec, D. Rabady², B. Rahbaran, H. Rohringer, R. Schöfbeck, J. Strauss, A. Taurok, W. Treberer-Treberspurg, W. Waltenberger, C.-E. Wulz¹

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

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

Universiteit Antwerpen, Antwerpen, Belgium

S. Alderweireldt, M. Bansal, S. Bansal, T. Cornelis, E.A. De Wolf, X. Janssen, A. Knutsson, S. Luyckx, S. Ochesanu, B. Roland, R. Rougny, M. Van De Klundert, H. Van Haeevermaet, P. Van Mechelen, N. Van Remortel, A. Van Spilbeeck

Vrije Universiteit Brussel, Brussel, Belgium

F. Blekman, S. Blyweert, J. D'Hondt, N. Daci, N. Heracleous, A. Kalogeropoulos, J. Keaveney, T.J. Kim, S. Lowette, M. Maes, A. Olbrechts, Q. Python, D. Strom, S. Tavernier, W. Van Doninck, P. Van Mulders, G.P. Van Onsem, I. Villella

Université Libre de Bruxelles, Bruxelles, Belgium

C. Caillol, B. Clerbaux, G. De Lentdecker, D. Dobur, L. Favart, A.P.R. Gay, A. Grebenyuk, A. Léonard, A. Mohammadi, L. Pernie², T. Reis, T. Seva, L. Thomas, C. Vander Velde, P. Vanlaer, J. Wang

Ghent University, Ghent, Belgium

V. Adler, K. Beernaert, L. Benucci, A. Cimmino, S. Costantini, S. Crucy, S. Dildick, A. Fagot, G. Garcia, B. Klein, J. Mccartin, A.A. Ocampo Rios, D. Ryckbosch, S. Salva Diblen, M. Sigamani, N. Strobbe, F. Thyssen, M. Tytgat, E. Yazgan, N. Zaganidis

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

S. Basegmez, C. Beluffi³, G. Bruno, R. Castello, A. Caudron, L. Ceard, G.G. Da Silveira, C. Delaere, T. du Pree, D. Favart, L. Forthomme, A. Giammanco⁴, J. Hollar, P. Jez, M. Komm, V. Lemaître, J. Liao, C. Nuttens, D. Pagano, L. Perrini, A. Pin, K. Piotrkowski, A. Popov⁵, L. Quertenmont, M. Selvaggi, M. Vidal Marono, J.M. Vizan Garcia

Université de Mons, Mons, Belgium

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

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

W.L. Aldá Júnior, G.A. Alves, M. Correa Martins Junior, T. Dos Reis Martins, M.E. Pol

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

W. Carvalho, J. Chinellato⁶, A. Custódio, E.M. Da Costa, D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, H. Malbouisson, M. Malek, D. Matos Figueiredo, L. Mundim, H. Nogima, W.L. Prado Da Silva, J. Santaolalla, A. Santoro, A. Sznajder, E.J. Tonelli Manganote⁶, A. Vilela Pereira

Universidade Estadual Paulista ^a, Universidade Federal do ABC ^b, São Paulo, Brazil

C.A. Bernardes^b, F.A. Dias^{a,7}, T.R. Fernandez Perez Tomei^a, E.M. Gregores^b, P.G. Mercadante^b, S.F. Novaes^a, Sandra S. Padula^a

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria

A. Aleksandrov, V. Genchev², P. Iaydjiev, A. Marinov, S. Piperov, M. Rodozov, G. Sultanov, M. Vutova

University of Sofia, Sofia, Bulgaria

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

Institute of High Energy Physics, Beijing, China

J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, R. Du, C.H. Jiang, D. Liang, S. Liang, R. Plestina⁸, J. Tao, X. Wang, Z. Wang

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

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

Universidad de Los Andes, Bogota, Colombia

C. Avila, L.F. Chaparro Sierra, C. Florez, J.P. Gomez, B. Gomez Moreno, J.C. Sanabria

Technical University of Split, Split, Croatia

N. Godinovic, D. Lelas, D. Polic, I. Puljak

University of Split, Split, Croatia

Z. Antunovic, M. Kovac

Institute Rudjer Boskovic, Zagreb, Croatia

V. Brigljevic, K. Kadija, J. Luetic, D. Mekterovic, L. Sudic

University of Cyprus, Nicosia, Cyprus

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

Charles University, Prague, Czech Republic

M. Bodlak, M. Finger, M. Finger Jr.⁹

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

Y. Assran¹⁰, A. Ellithi Kamel¹¹, M.A. Mahmoud¹², A. Radi^{13,14}

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

M. Kadastik, M. Murumaa, M. Raidal, A. Tiko

Department of Physics, University of Helsinki, Helsinki, Finland

P. Eerola, G. Fedi, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland

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

Lappeenranta University of Technology, Lappeenranta, Finland

T. Tuuva

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

M. Besancon, F. Couderc, M. Dejardin, D. Denegri, B. Fabbro, J.L. Faure, C. Favaro, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, E. Locci, J. Malcles, J. Rander, A. Rosowsky, M. Titov

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

S. Baffioni, F. Beaudette, P. Busson, C. Charlot, T. Dahms, M. Dalchenko, L. Dobrzynski, N. Filipovic, A. Florent, R. Granier de Cassagnac, L. Mastrolorenzo, P. Miné, C. Mironov, I.N. Naranjo, M. Nguyen, C. Ochando, P. Paganini, R. Salerno, J.B. Sauvan, Y. Sirois, C. Veelken, Y. Yilmaz, A. Zabi

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

J.-L. Agram¹⁵, J. Andrea, A. Aubin, D. Bloch, J.-M. Brom, E.C. Chabert, C. Collard, E. Conte¹⁵, J.-C. Fontaine¹⁵, D. Gelé, U. Goerlach, C. Goetzmann, A.-C. Le Bihan, 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, N. Beaupere, G. Boudoul², S. Brochet, C.A. Carrillo Montoya, J. Chasserat, R. Chierici, D. Contardo², P. Depasse, H. El Mamouni, J. Fan, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, T. Kurca, M. Lethuillier, L. Mirabito, S. Perries, J.D. Ruiz Alvarez, D. Sabes, L. Sgandurra, V. Sordini, M. Vander Donckt, P. Verdier, S. Viret, H. Xiao

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

Z. Tsamalaidze⁹

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

C. Autermann, S. Beranek, M. Bontenackels, M. Edelhoff, L. Feld, O. Hindrichs, K. Klein, A. Ostapchuk, A. Perieanu, F. Raupach, J. Sammet, S. Schael, D. Sprenger, H. Weber, B. Wittmer, V. Zhukov⁵

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

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

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

V. Cherepanov, Y. Erdogan, G. Flüge, H. Geenen, M. Geisler, W. Haj Ahmad, F. Hoehle, B. Kargoll, T. Kress, Y. Kuessel, J. Lingemann², A. Nowack, I.M. Nugent, L. Perchalla, O. Pooth, A. Stahl

Deutsches Elektronen-Synchrotron, Hamburg, Germany

I. Asin, N. Bartosik, J. Behr, W. Behrenhoff, U. Behrens, A.J. Bell, M. Bergholz¹⁶, A. Bethani, K. Borras, A. Burgmeier, A. Cakir, L. Calligaris, A. Campbell, S. Choudhury, F. Costanza, C. Diez Pardos, S. Dooling, T. Dorland, G. Eckerlin, D. Eckstein, T. Eichhorn, G. Flucke, J. Garay Garcia, A. Geiser, P. Gunnellini, J. Hauk, G. Hellwig, M. Hempel, D. Horton, H. Jung, M. Kasemann, P. Katsas, J. Kieseler, C. Kleinwort, D. Krücker, W. Lange, J. Leonard, K. Lipka, A. Lobanov, W. Lohmann¹⁶, B. Lutz, R. Mankel, I. Marfin, I.-A. Melzer-Pellmann, A.B. Meyer, J. Mnich, A. Mussgiller, S. Naumann-Emme, A. Nayak, O. Novgorodova, F. Nowak, E. Ntomari, H. Perrey, D. Pitzl, R. Placakyte, A. Raspereza, P.M. Ribeiro Cipriano, E. Ron, M.Ö. Sahin, J. Salfeld-Nebgen, P. Saxena, R. Schmidt¹⁶, T. Schoerner-Sadenius, M. Schröder, S. Spannagel, A.D.R. Vargas Trevino, R. Walsh, C. Wissing

University of Hamburg, Hamburg, Germany

M. Aldaya Martin, V. Blobel, M. Centis Vignali, J. Erfle, E. Garutti, K. Goebel, M. Görner, M. Gosselink, J. Haller, M. Hoffmann, R.S. Höing, H. Kirschenmann, R. Klanner, R. Kogler, J. Lange, T. Lapsien, T. Lenz, I. Marchesini, J. Ott, T. Peiffer, N. Pietsch, D. Rathjens, C. Sander, H. Schettler, P. Schleper, E. Schlieckau, A. Schmidt, M. Seidel, J. Sibille¹⁷, V. Sola, H. Stadie, G. Steinbrück, D. Troendle, E. Usai, L. Vanelderen

Institut für Experimentelle Kernphysik, Karlsruhe, Germany

C. Barth, C. Baus, J. Berger, C. Böser, E. Butz, T. Chwalek, W. De Boer, A. Descroix, A. Dierlamm, M. Feindt, F. Frensch, M. Giffels, F. Hartmann², T. Hauth², U. Husemann, I. Katkov⁵, A. Kornmayer², E. Kuznetsova, P. Lobelle Pardo, M.U. Mozer, Th. Müller, A. Nürnberg, G. Quast, K. Rabbertz, F. Ratnikov, S. Röcker, H.J. Simonis, F.M. Stober, R. Ulrich, J. Wagner-Kuhr, S. Wayand, T. Weiler, R. Wolf

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

G. Anagnostou, G. Daskalakis, T. Gerasis, V.A. Giakoumopoulou, A. Kyriakis, D. Loukas, A. Markou, C. Markou, A. Psallidas, I. Topsis-Giotis

University of Athens, Athens, Greece

A. Panagiotou, N. Saoulidou, E. Stiliaris

University of Ioánnina, Ioánnina, Greece

X. Aslanoglou, I. Evangelou, G. Flouris, C. Foudas, P. Kokkas, N. Manthos, I. Papadopoulos, E. Paradas

Wigner Research Centre for Physics, Budapest, Hungary

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

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

N. Beni, S. Czellar, J. Karancsi²⁰, J. Molnar, J. Palinkas, Z. Szillasi

University of Debrecen, Debrecen, Hungary

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

National Institute of Science Education and Research, Bhubaneswar, India

S.K. Swain

Panjab University, Chandigarh, India

S.B. Beri, V. Bhatnagar, N. Dhingra, R. Gupta, A.K. Kalsi, M. Kaur, M. Mittal, N. Nishu, J.B. Singh

University of Delhi, Delhi, India

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

Saha Institute of Nuclear Physics, Kolkata, India

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

Bhabha Atomic Research Centre, Mumbai, India

A. Abdulsalam, D. Dutta, S. Kailas, V. Kumar, A.K. Mohanty², L.M. Pant, P. Shukla, A. Topkar

Tata Institute of Fundamental Research, Mumbai, India

T. Aziz, S. Banerjee, S. Bhowmik²¹, R.M. Chatterjee, R.K. Dewanjee, S. Dugad, S. Ganguly, S. Ghosh, M. Guchait, A. Gurtu²², G. Kole, S. Kumar, M. Maity²¹, G. Majumder, K. Mazumdar, G.B. Mohanty, B. Parida, K. Sudhakar, N. Wickramage²³

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

H. Bakhshiansohi, H. Behnamian, S.M. Etesami²⁴, A. Fahim²⁵, R. Goldouzian, A. Jafari, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi, B. Safarzadeh²⁶, 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, ItalyM. Abbrescia^{a,b}, L. Barbone^{a,b}, C. Calabria^{a,b}, S.S. Chhibra^{a,b}, A. Colaleo^a, D. Creanza^{a,c}, N. De Filippis^{a,c}, M. De Palma^{a,b}, L. Fiore^a, G. Iaselli^{a,c}, G. Maggi^{a,c}, M. Maggi^a, S. My^{a,c}, S. Nuzzo^{a,b}, A. Pompili^{a,b}, G. Pugliese^{a,c}, R. Radogna^{a,b,2}, G. Selvaggi^{a,b}, L. Silvestris^{a,2}, G. Singh^{a,b}, R. Venditti^{a,b}, P. Verwilligen^a, G. Zito^a**INFN Sezione di Bologna ^a, Università di Bologna ^b, Bologna, Italy**G. Abbiendi^a, A.C. Benvenuti^a, D. Bonacorsi^{a,b}, S. Braibant-Giacomelli^{a,b}, L. Brigliadori^{a,b}, R. Campanini^{a,b}, P. Capiluppi^{a,b}, A. Castro^{a,b}, F.R. Cavallo^a, G. Codispoti^{a,b}, M. Cuffiani^{a,b}, G.M. Dallavalle^a, F. Fabbri^a, A. Fanfani^{a,b}, D. Fasanella^{a,b}, P. Giacomelli^a, C. Grandi^a, L. Guiducci^{a,b}, S. Marcellini^a, G. Masetti^{a,2}, A. Montanari^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,b}, R. Travaglini^{a,b}**INFN Sezione di Catania ^a, Università di Catania ^b, CSFNSM ^c, Catania, Italy**S. Albergo^{a,b}, G. Cappello^a, M. Chiorboli^{a,b}, S. Costa^{a,b}, F. Giordano^{a,2}, R. Potenza^{a,b}, A. Tricomi^{a,b}, C. Tuve^{a,b}**INFN Sezione di Firenze ^a, Università di Firenze ^b, Firenze, Italy**G. Barbagli^a, V. Ciulli^{a,b}, C. Civinini^a, R. D'Alessandro^{a,b}, E. Focardi^{a,b}, E. Gallo^a, S. Gonzi^{a,b}, V. Gori^{a,b,2}, P. Lenzi^{a,b}, M. Meschini^a, S. Paoletti^a, G. Sguazzoni^a, A. Tropiano^{a,b}**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, ItalyF. Ferro^a, M. Lo Vetere^{a,b}, E. Robutti^a, S. Tosi^{a,b}**INFN Sezione di Milano-Bicocca ^a, Università di Milano-Bicocca ^b, Milano, Italy**M.E. Dinardo^{a,b}, S. Fiorendi^{a,b,2}, S. Gennai^{a,2}, R. Gerosa², A. Ghezzi^{a,b}, P. Govoni^{a,b}, M.T. Lucchini^{a,b,2}, S. Malvezzi^a, R.A. Manzoni^{a,b}, A. Martelli^{a,b}, B. Marzocchi, D. Menasce^a, L. Moroni^a, M. Paganoni^{a,b}, D. Pedrini^a, S. Ragazzi^{a,b}, N. Redaelli^a, T. Tabarelli de Fatis^{a,b}**INFN Sezione di Napoli ^a, Università di Napoli 'Federico II' ^b, Università della Basilicata (Potenza) ^c, Università G. Marconi (Roma) ^d, Napoli, Italy**S. Buontempo^a, N. Cavallo^{a,c}, S. Di Guida^{a,d,2}, F. Fabozzi^{a,c}, A.O.M. Iorio^{a,b}, L. Lista^a, S. Meola^{a,d,2}, M. Merola^a, P. Paolucci^{a,2}**INFN Sezione di Padova ^a, Università di Padova ^b, Università di Trento (Trento) ^c, Padova, Italy**P. Azzi^a, N. Bacchetta^a, M. Biasotto^{a,27}, A. Branca^{a,b}, M. Dall'Osso^{a,b}, T. Dorigo^a, U. Dosselli^a, F. Fanzago^a, M. Galanti^{a,b}, F. Gasparini^{a,b}, P. Giubilato^{a,b}, F. Gonella^a,

A. Gozzelino^a, K. Kanishchev^{a,c}, S. Lacaprara^a, M. Margoni^{a,b}, F. Montecassiano^a, M. Passaseo^a, J. Pazzini^{a,b}, M. Pegoraro^a, N. Pozzobon^{a,b}, P. Ronchese^{a,b}, F. Simonetto^{a,b}, E. Torassa^a, M. Tosi^{a,b}, P. Zotto^{a,b}, A. Zucchetta^{a,b}

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

S.P. Ratti^{a,b}, C. Riccardi^{a,b}, P. Salvini^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}, M. Menichelli^a, F. Romeo^{a,b}, A. Saha^a, A. Santocchia^{a,b}, A. Spiezia^{a,b,2}

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

K. Androsov^{a,28}, P. Azzurri^a, G. Bagliesi^a, J. Bernardini^a, T. Boccali^a, G. Broccolo^{a,c}, R. Castaldi^a, M.A. Ciocci^{a,28}, R. Dell'Orso^a, S. Donato^{a,c}, F. Fiori^{a,c}, L. Foà^{a,c}, A. Giassi^a, M.T. Grippo^{a,28}, F. Ligabue^{a,c}, T. Lomtadze^a, L. Martini^{a,b}, A. Messineo^{a,b}, C.S. Moon^{a,29}, F. Palla^{a,2}, A. Rizzi^{a,b}, A. Savoy-Navarro^{a,30}, A.T. Serban^a, P. Spagnolo^a, P. Squillacioti^{a,28}, R. Tenchini^a, G. Tonelli^{a,b}, A. Venturi^a, P.G. Verdini^a, C. Vernieri^{a,c,2}

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

L. Barone^{a,b}, F. Cavallari^a, D. Del Re^{a,b}, M. Diemoz^a, M. Grassi^{a,b}, C. Jorda^a, E. Longo^{a,b}, F. Margaroli^{a,b}, P. Meridiani^a, F. Micheli^{a,b,2}, S. Nourbakhsh^{a,b}, G. Organtini^{a,b}, R. Paramatti^a, S. Rahatlou^{a,b}, C. Rovelli^a, F. Santanastasio^{a,b}, L. Soffi^{a,b,2}, P. Traczyk^{a,b}

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

N. Amapane^{a,b}, R. Arcidiacono^{a,c}, S. Argiro^{a,b,2}, M. Arneodo^{a,c}, R. Bellan^{a,b}, C. Biino^a, N. Cartiglia^a, S. Casasso^{a,b,2}, M. Costa^{a,b}, A. Degano^{a,b}, N. Demaria^a, L. Finco^{a,b}, C. Mariotti^a, S. Maselli^a, E. Migliore^{a,b}, V. Monaco^{a,b}, M. Musich^a, M.M. Obertino^{a,c,2}, G. Ortona^{a,b}, L. Pacher^{a,b}, N. Pastrone^a, M. Pelliccioni^a, G.L. Pinna Angioni^{a,b}, A. Potenza^{a,b}, A. Romero^{a,b}, M. Ruspa^{a,c}, R. Sacchi^{a,b}, A. Solano^{a,b}, A. Staiano^a, U. Tamponi^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}, B. Gobbo^a, C. La Licata^{a,b}, M. Marone^{a,b}, D. Montanino^{a,b}, A. Schizzi^{a,b,2}, T. Umer^{a,b}, A. Zanetti^a

Kangwon National University, Chunchon, Korea

S. Chang, A. Kropivnitskaya, S.K. Nam

Kyungpook National University, Daegu, Korea

D.H. Kim, G.N. Kim, M.S. Kim, D.J. Kong, S. Lee, Y.D. Oh, H. Park, A. Sakharov, D.C. Son

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

J.Y. Kim, S. Song

Korea University, Seoul, Korea

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

University of Seoul, Seoul, Korea

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

Sungkyunkwan University, Suwon, Korea

Y. Choi, Y.K. Choi, J. Goh, E. Kwon, J. Lee, H. Seo, I. Yu

Vilnius University, Vilnius, Lithuania

A. Juodagalvis

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia

J.R. Komaragiri

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, MexicoH. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-de La Cruz³¹, R. Lopez-Fernandez, A. Sanchez-Hernandez**Universidad Iberoamericana, Mexico City, Mexico**

S. Carrillo Moreno, F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

I. Pedraza, H.A. Salazar Ibarquen

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

E. Casimiro Linares, A. Morelos Pineda

University of Auckland, Auckland, New Zealand

D. Krofcheck

University of Canterbury, Christchurch, New Zealand

P.H. Butler, S. Reucroft

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

A. Ahmad, M. Ahmad, Q. Hassan, H.R. Hoorani, S. Khalid, W.A. Khan, T. Khurshid, M.A. Shah, M. Shoaib

National Centre for Nuclear Research, Swierk, Poland

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

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

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

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

P. Bargassa, C. Beirão Da Cruz E Silva, P. Faccioli, P.G. Ferreira Parracho, M. Gallinaro, F. Nguyen, J. Rodrigues Antunes, J. Seixas, J. Varela, P. Vischia

Joint Institute for Nuclear Research, Dubna, Russia

I. Golutvin, V. Karjavin, V. Konoplyanikov, V. Korenkov, G. Kozlov, A. Lanev, A. Malakhov, V. Matveev³², V.V. Mitsyn, P. Moisenz, V. Palichik, V. Perelygin, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, E. Tikhonenko, A. Zarubin

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

V. Golovtsov, Y. Ivanov, V. Kim³³, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev, An. Vorobyev

Institute for Nuclear Research, Moscow, Russia

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

Institute for Theoretical and Experimental Physics, Moscow, Russia

V. Epshteyn, V. Gavrilov, N. Lychkovskaya, V. Popov, G. Safronov, S. Semenov, A. Spiridonov, V. Stolin, E. Vlasov, A. Zhokin

P.N. Lebedev Physical Institute, Moscow, Russia

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

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

A. Belyaev, E. Boos, M. Dubinin⁷, L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev

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

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

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

P. Adzic³⁴, M. Dordevic, M. Ekmedzic, J. Milosevic

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

J. Alcaraz Maestre, C. Battilana, E. Calvo, M. Cerrada, M. Chamizo Llatas², N. Colino, B. De La Cruz, A. Delgado Peris, D. Domínguez Vázquez, A. Escalante Del Valle, C. Fernandez Bedoya, J.P. Fernández Ramos, J. Flix, M.C. Fouz, P. Garcia-Abia, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, G. Merino, E. Navarro De Martino,

A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, A. Quintario Olmeda, I. Redondo, L. Romero, M.S. Soares

Universidad Autónoma de Madrid, Madrid, Spain

C. Albajar, J.F. de Trocóniz, M. Missiroli

Universidad de Oviedo, Oviedo, Spain

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

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

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

CERN, European Organization for Nuclear Research, Geneva, Switzerland

D. Abbaneo, E. Auffray, G. Auzinger, M. Bachtis, P. Baillon, A.H. Ball, D. Barney, A. Benaglia, J. Bendavid, L. Benhabib, J.F. Benitez, C. Bernet⁸, G. Bianchi, P. Bloch, A. Bocci, A. Bonato, O. Bondu, C. Botta, H. Breuker, T. Camporesi, G. Cerminara, S. Colafranceschi³⁵, M. D'Alfonso, D. d'Enterria, A. Dabrowski, A. David, F. De Guio, A. De Roeck, S. De Visscher, M. Dobson, N. Dupont-Sagorin, A. Elliott-Peisert, J. Eugster, G. Franzoni, W. Funk, D. Gigi, K. Gill, D. Giordano, M. Girone, F. Glege, R. Guida, S. Gundacker, M. Guthoff, J. Hammer, M. Hansen, P. Harris, J. Hegeman, V. Innocente, P. Janot, K. Kousouris, K. Krajczar, P. Lecoq, C. Lourenço, N. Magini, L. Malgeri, M. Mannelli, J. Marrouche, L. Masetti, F. Meijers, S. Mersi, E. Meschi, F. Moortgat, S. Morovic, M. Mulders, P. Musella, L. Orsini, L. Pape, E. Perez, L. Perrozzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, M. Pimiä, D. Piparo, M. Plagge, A. Racz, G. Rolandi³⁶, M. Rovere, H. Sakulin, C. Schäfer, C. Schwick, S. Sekmen, A. Sharma, P. Siegrist, P. Silva, M. Simon, P. Sphicas³⁷, D. Spiga, J. Steggemann, B. Stieger, M. Stoye, D. Treille, A. Tsirou, G.I. Veres¹⁹, J.R. Vlimant, N. Wardle, H.K. Wöhri, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland

W. Bertl, K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, S. König, D. Kotlinski, U. Langenegger, D. Renker, T. Rohe

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland

F. Bachmair, L. Bäni, L. Bianchini, P. Bortignon, M.A. Buchmann, B. Casal, N. Chanon, A. Deisher, G. Dissertori, M. Dittmar, M. Donegà, M. Dünser, P. Eller, C. Grab, D. Hits, W. Lustermann, B. Mangano, A.C. Marini, P. Martinez Ruiz del Arbol, D. Meister, N. Mohr, C. Nägeli³⁸, P. Nef, F. Nessi-Tedaldi, F. Pandolfi, F. Pauss, M. Peruzzi, M. Quitnat, L. Rebane, F.J. Ronga, M. Rossini, A. Starodumov³⁹, M. Takahashi, K. Theofilatos, R. Wallny, H.A. Weber

Universität Zürich, Zurich, Switzerland

C. Amsler⁴⁰, M.F. Canelli, V. Chiochia, A. De Cosa, A. Hinzmann, T. Hreus, M. Ivova Rikova, B. Kilminster, B. Millan Mejias, J. Ngadiuba, P. Robmann, H. Snoek, S. Taroni, M. Verzetti, Y. Yang

National Central University, Chung-Li, Taiwan

M. Cardaci, K.H. Chen, C. Ferro, C.M. Kuo, W. Lin, Y.J. Lu, R. Volpe, S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan

P. Chang, Y.H. Chang, Y.W. Chang, Y. Chao, K.F. Chen, P.H. Chen, C. Dietz, U. Grundler, W.-S. Hou, K.Y. Kao, Y.J. Lei, Y.F. Liu, R.-S. Lu, D. Majumder, E. Petrakou, Y.M. Tzeng, R. Wilken

Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand

B. Asavapibhop, N. Srimanobhas, N. Suwonjandee

Cukurova University, Adana, Turkey

A. Adiguzel, M.N. Bakirci⁴¹, S. Cerci⁴², C. Dozen, I. Dumanoglu, E. Eskut, S. Girgis, G. Gokbulut, E. Gurpinar, I. Hos, E.E. Kangal, A. Kayis Topaksu, G. Onengut⁴³, K. Ozdemir, S. Ozturk⁴¹, A. Polatoz, K. Sogut⁴⁴, D. Sunar Cerci⁴², B. Tali⁴², H. Topakli⁴¹, M. Vergili

Middle East Technical University, Physics Department, Ankara, Turkey

I.V. Akin, B. Bilin, S. Bilmis, H. Gamsizkan, G. Karapinar⁴⁵, K. Ocalan, U.E. Surat, M. Yalvac, M. Zeyrek

Bogazici University, Istanbul, Turkey

E. Gülmez, B. Isildak⁴⁶, M. Kaya⁴⁷, O. Kaya⁴⁷

Istanbul Technical University, Istanbul, Turkey

H. Bahtiyar⁴⁸, E. Barlas, K. Cankocak, F.I. Vardarli, M. Yücel

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

L. Levchuk, P. Sorokin

University of Bristol, Bristol, United Kingdom

J.J. Brooke, E. Clement, D. Cussans, H. Flacher, R. Frazier, J. Goldstein, M. Grimes, G.P. Heath, H.F. Heath, J. Jacob, L. Kreczko, C. Lucas, Z. Meng, D.M. Newbold⁴⁹, S. Paramesvaran, A. Poll, S. Senkin, V.J. Smith, T. Williams

Rutherford Appleton Laboratory, Didcot, United Kingdom

K.W. Bell, A. Belyaev⁵⁰, C. Brew, R.M. Brown, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, E. Olaiya, D. Petyt, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, W.J. Womersley, S.D. Worm

Imperial College, London, United Kingdom

M. Baber, R. Bainbridge, O. Buchmuller, D. Burton, D. Colling, N. Cripps, M. Cutajar, P. Dauncey, G. Davies, M. Della Negra, P. Dunne, W. Ferguson, J. Fulcher, D. Futyan, A. Gilbert, G. Hall, G. Iles, M. Jarvis, G. Karapostoli, M. Kenzie, R. Lane, R. Lucas⁴⁹, L. Lyons, A.-M. Magnan, S. Malik, B. Mathias, J. Nash, A. Nikitenko³⁹, J. Pela, M. Pesaresi, K. Petridis, D.M. Raymond, S. Rogerson, A. Rose, C. Seez, P. Sharp[†], A. Tapper, M. Vazquez Acosta, T. Virdee

Brunel University, Uxbridge, United Kingdom

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

Baylor University, Waco, USA

J. Dittmann, K. Hatakeyama, A. Kasmi, H. Liu, T. Scarborough

The University of Alabama, Tuscaloosa, USA

O. Charaf, S.I. Cooper, C. Henderson, P. Rumerio

Boston University, Boston, USA

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

Brown University, Providence, USA

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

University of California, Davis, Davis, USA

R. Breedon, G. Breto, M. Calderon De La Barca Sanchez, S. Chauhan, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, M. Gardner, W. Ko, R. Lander, T. Miceli, M. Mulhearn, D. Pellett, J. Pilot, F. Ricci-Tam, M. Searle, S. Shalhout, J. Smith, M. Squires, D. Stolp, M. Tripathi, S. Wilbur, R. Yohay

University of California, Los Angeles, USA

R. Cousins, P. Everaerts, C. Farrell, J. Hauser, M. Ignatenko, G. Rakness, E. Takasugi, V. Valuev, M. Weber

University of California, Riverside, Riverside, USA

J. Babb, R. Clare, J. Ellison, J.W. Gary, G. Hanson, J. Heilman, P. Jandir, E. Kennedy, F. Lacroix, H. Liu, O.R. Long, A. Luthra, M. Malberti, H. Nguyen, A. Shrinivas, S. Sumowidagdo, S. Wimpenny

University of California, San Diego, La Jolla, USA

W. Andrews, J.G. Branson, G.B. Cerati, S. Cittolin, R.T. D'Agnolo, D. Evans, A. Holzner, R. Kelley, D. Klein, M. Lebourgeois, J. Letts, I. Macneill, D. Olivito, S. Padhi, C. Palmer, M. Pieri, M. Sani, V. Sharma, S. Simon, E. Sudano, M. Tadel, Y. Tu, A. Vartak, C. Welke, F. Würthwein, A. Yagil, J. Yoo

University of California, Santa Barbara, Santa Barbara, USA

D. Barge, J. Bradmiller-Feld, C. Campagnari, T. Danielson, A. Dishaw, K. Flowers, M. Franco Sevilla, P. Geffert, C. George, F. Golf, L. Gouskos, J. Incandela, C. Justus, N. Mccoll, J. Richman, D. Stuart, W. To, C. West

California Institute of Technology, Pasadena, USA

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

Carnegie Mellon University, Pittsburgh, USA

V. Azzolini, A. Calamba, T. Ferguson, Y. Iiyama, M. Paulini, J. Russ, H. Vogel, I. Vorobiev

University of Colorado at Boulder, Boulder, USA

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

Cornell University, Ithaca, USA

J. Alexander, A. Chatterjee, J. Chu, S. Dittmer, N. Eggert, W. Hopkins, N. Mirman, G. Nicolas Kaufman, J.R. Patterson, A. Ryd, E. Salvati, L. Skinnari, W. Sun, W.D. Teo, J. Thom, J. Thompson, J. Tucker, Y. Weng, L. Winstrom, P. Wittich

Fairfield University, Fairfield, USA

D. Winn

Fermi National Accelerator Laboratory, Batavia, USA

S. Abdullin, M. Albrow, J. Anderson, G. Apollinari, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, K. Burkett, J.N. Butler, H.W.K. Cheung, F. Chlebana, S. Cihangir, V.D. Elvira, I. Fisk, J. Freeman, Y. Gao, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, J. Hanlon, D. Hare, R.M. Harris, J. Hirschauer, B. Hooberman, S. Jindariani, M. Johnson, U. Joshi, K. Kaadze, B. Klima, B. Kreis, S. Kwan, J. Linacre, D. Lincoln, R. Lipton, T. Liu, J. Lykken, K. Maeshima, J.M. Marraffino, V.I. Martinez Outschoorn, S. Maruyama, D. Mason, P. McBride, K. Mishra, S. Mrenna, Y. Musienko³², S. Nahn, C. Newman-Holmes, V. O'Dell, O. Prokofyev, E. Sexton-Kennedy, S. Sharma, A. Soha, W.J. Spalding, L. Spiegel, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, R. Vidal, A. Whitbeck, J. Whitmore, F. Yang

University of Florida, Gainesville, USA

D. Acosta, P. Avery, D. Bourilkov, M. Carver, T. Cheng, D. Curry, S. Das, M. De Gruttola, G.P. Di Giovanni, R.D. Field, M. Fisher, I.K. Furic, J. Hugon, J. Konigsberg, A. Korytov, T. Kypreos, J.F. Low, K. Matchev, P. Milenovic⁵¹, G. Mitselmakher, L. Muniz, A. Rinkevicius, L. Shchutska, N. Skhirtladze, M. Snowball, J. Yelton, M. Zakaria

Florida International University, Miami, USA

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

Florida State University, Tallahassee, USA

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

Florida Institute of Technology, Melbourne, USA

M.M. Baarmand, M. Hohlmann, H. Kalakhety, F. Yumiceva

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

M.R. Adams, L. Apanasevich, V.E. Bazterra, D. Berry, R.R. Betts, I. Bucinskaite, R. Cavanaugh, O. Evdokimov, L. Gauthier, C.E. Gerber, D.J. Hofman, S. Khalatyan, P. Kurt, D.H. Moon, C. O'Brien, C. Silkworth, P. Turner, N. Varelas

The University of Iowa, Iowa City, USA

E.A. Albayrak⁴⁸, B. Bilki⁵², W. Clarida, K. Dilsiz, F. Duru, M. Haytmyradov, J.-P. Merlo, H. Mermerkaya⁵³, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul, Y. Onel, F. Ozok⁴⁸, A. Penzo, R. Rahmat, S. Sen, P. Tan, E. Tiras, J. Wetzel, T. Yetkin⁵⁴, K. Yi

Johns Hopkins University, Baltimore, USA

B.A. Barnett, B. Blumenfeld, S. Bolognesi, D. Fehling, A.V. Gritsan, P. Maksimovic, C. Martin, M. Swartz

The University of Kansas, Lawrence, USA

P. Baringer, A. Bean, G. Benelli, C. Bruner, J. Gray, R.P. Kenny III, M. Murray, D. Noonan, S. Sanders, J. Sekaric, R. Stringer, Q. Wang, J.S. Wood

Kansas State University, Manhattan, USA

A.F. Barfuss, I. Chakaberia, A. Ivanov, S. Khalil, M. Makouski, Y. Maravin, L.K. Saini, S. Shrestha, I. Svintradze

Lawrence Livermore National Laboratory, Livermore, USA

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

University of Maryland, College Park, USA

A. Baden, B. Calvert, S.C. Eno, J.A. Gomez, N.J. Hadley, R.G. Kellogg, T. Kolberg, Y. Lu, M. Marionneau, A.C. Mignerey, K. Pedro, A. Skuja, M.B. Tonjes, S.C. Tonwar

Massachusetts Institute of Technology, Cambridge, USA

A. Apyan, R. Barbieri, G. Bauer, W. Busza, I.A. Cali, M. Chan, L. Di Matteo, V. Dutta, G. Gomez Ceballos, M. Goncharov, D. Gulhan, M. Klute, Y.S. Lai, Y.-J. Lee, A. Levin, P.D. Luckey, T. Ma, C. Paus, D. Ralph, C. Roland, G. Roland, G.S.F. Stephans, F. Stöckli, K. Sumorok, D. Velicanu, J. Veverka, B. Wyslouch, M. Yang, M. Zanetti, V. Zhukova

University of Minnesota, Minneapolis, USA

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

University of Mississippi, Oxford, USA

J.G. Acosta, S. Oliveros

University of Nebraska-Lincoln, Lincoln, USA

E. Avdeeva, K. Bloom, S. Bose, D.R. Claes, A. Dominguez, R. Gonzalez Suarez, J. Keller, D. Knowlton, I. Kravchenko, J. Lazo-Flores, S. Malik, F. Meier, G.R. Snow

State University of New York at Buffalo, Buffalo, USA

J. Dolen, A. Godshalk, I. Iashvili, A. Kharchilava, A. Kumar, S. Rappoccio

Northeastern University, Boston, USA

G. Alverson, E. Barberis, D. Baumgartel, M. Chasco, J. Haley, A. Massironi, D.M. Morse, D. Nash, T. Orimoto, D. Trocino, R.J. Wang, D. Wood, J. Zhang

Northwestern University, Evanston, USA

K.A. Hahn, A. Kubik, N. Mucia, N. Odell, B. Pollack, A. Pozdnyakov, M. Schmitt, S. Stoynev, K. Sung, M. Velasco, S. Won

University of Notre Dame, Notre Dame, USA

A. Brinkerhoff, K.M. Chan, A. Drozdetskiy, M. Hildreth, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon, W. Luo, S. Lynch, N. Marinelli, T. Pearson, M. Planer, R. Ruchti, N. Valls, M. Wayne, M. Wolf, A. Woodard

The Ohio State University, Columbus, USA

L. Antonelli, J. Brinson, B. Bylsma, L.S. Durkin, S. Flowers, C. Hill, R. Hughes, K. Kotov, T.Y. Ling, D. Puigh, M. Rodenburg, G. Smith, C. Vuosalo, B.L. Winer, H. Wolfe, H.W. Wulsin

Princeton University, Princeton, USA

E. Berry, O. Driga, P. Elmer, P. Hebda, A. Hunt, S.A. Koay, P. Lujan, D. Marlow, T. Medvedeva, M. Mooney, J. Olsen, P. Piroué, X. Quan, H. Saka, D. Stickland², C. Tully, J.S. Werner, S.C. Zenz, A. Zuranski

University of Puerto Rico, Mayaguez, USA

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

Purdue University, West Lafayette, USA

E. Alagoz, V.E. Barnes, D. Benedetti, G. Bolla, D. Bortoletto, M. De Mattia, Z. Hu, M.K. Jha, M. Jones, K. Jung, M. Kress, N. Leonardo, D. Lopes Pegna, V. Maroussov, P. Merkel, D.H. Miller, N. Neumeister, B.C. Radburn-Smith, X. Shi, I. Shipsey, D. Silvers, A. Svyatkovskiy, F. Wang, W. Xie, L. Xu, H.D. Yoo, J. Zablocki, Y. Zheng

Purdue University Calumet, Hammond, USA

N. Parashar, J. Stupak

Rice University, Houston, USA

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

University of Rochester, Rochester, USA

B. Betchart, A. Bodek, R. Covarelli, P. de Barbaro, R. Demina, Y. Eshaq, T. Ferbel, A. Garcia-Bellido, P. Goldenzweig, J. Han, A. Harel, A. Khukhunaishvili, D.C. Miner, G. Petrillo, D. Vishnevskiy

The Rockefeller University, New York, USA

R. Ciesielski, L. Demortier, K. Goulios, G. Lungu, C. Mesropian

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

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

University of Tennessee, Knoxville, USA

K. Rose, S. Spanier, A. York

Texas A&M University, College Station, USA

O. Bouhali⁵⁵, R. Eusebi, W. Flanagan, J. Gilmore, T. Kamon⁵⁶, V. Khotilovich, V. Krutelyov, R. Montalvo, I. Osipenkov, Y. Pakhotin, A. Perloff, J. Roe, A. Rose, A. Safonov, T. Sakuma, I. Suarez, A. Tatarinov

Texas Tech University, Lubbock, USA

N. Akchurin, C. Cowden, J. Damgov, C. Dragoiu, P.R. Duderod, J. Faulkner, K. Kovitanggoon, S. Kunori, S.W. Lee, T. Libeiro, I. Volobouev

Vanderbilt University, Nashville, USA

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

University of Virginia, Charlottesville, USA

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

Wayne State University, Detroit, USA

S. Gollapinni, R. Harr, P.E. Karchin, C. Kottachchi Kankanamge Don, P. Lamichhane, J. Sturdy

University of Wisconsin, Madison, USA

D.A. Belknap, D. Carlsmith, M. Cepeda, S. Dasu, S. Duric, E. Friis, R. Hall-Wilton, M. Herndon, A. Hervé, P. Klabbbers, A. Lanaro, C. Lazaridis, A. Levine, R. Loveless, A. Mohapatra, I. Ojalvo, T. Perry, G.A. Pierro, G. Polese, I. Ross, T. Sarangi, A. Savin, W.H. Smith, N. Woods

†: Deceased

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

- 2: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
- 3: Also at Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France
- 4: Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
- 5: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
- 6: Also at Universidade Estadual de Campinas, Campinas, Brazil
- 7: Also at California Institute of Technology, Pasadena, USA
- 8: Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
- 9: Also at Joint Institute for Nuclear Research, Dubna, Russia
- 10: Also at Suez University, Suez, Egypt
- 11: Also at Cairo University, Cairo, Egypt
- 12: Also at Fayoum University, El-Fayoum, Egypt
- 13: Also at British University in Egypt, Cairo, Egypt
- 14: Now at Ain Shams University, Cairo, Egypt
- 15: Also at Université de Haute Alsace, Mulhouse, France
- 16: Also at Brandenburg University of Technology, Cottbus, Germany
- 17: Also at The University of Kansas, Lawrence, USA
- 18: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
- 19: Also at Eötvös Loránd University, Budapest, Hungary
- 20: Also at University of Debrecen, Debrecen, Hungary
- 21: Also at University of Visva-Bharati, Santiniketan, India
- 22: Now at King Abdulaziz University, Jeddah, Saudi Arabia
- 23: Also at University of Ruhuna, Matara, Sri Lanka
- 24: Also at Isfahan University of Technology, Isfahan, Iran
- 25: Also at Sharif University of Technology, Tehran, Iran
- 26: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
- 27: Also at Laboratori Nazionali di Legnaro dell'INFN, Legnaro, Italy
- 28: Also at Università degli Studi di Siena, Siena, Italy
- 29: Also at Centre National de la Recherche Scientifique (CNRS) - IN2P3, Paris, France
- 30: Also at Purdue University, West Lafayette, USA
- 31: Also at Universidad Michoacana de San Nicolas de Hidalgo, Morelia, Mexico
- 32: Also at Institute for Nuclear Research, Moscow, Russia
- 33: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
- 34: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
- 35: Also at Facoltà Ingegneria, Università di Roma, Roma, Italy
- 36: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy
- 37: Also at University of Athens, Athens, Greece
- 38: Also at Paul Scherrer Institut, Villigen, Switzerland
- 39: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
- 40: Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland
- 41: Also at Gaziosmanpasa University, Tokat, Turkey
- 42: Also at Adiyaman University, Adiyaman, Turkey
- 43: Also at Cag University, Mersin, Turkey
- 44: Also at Mersin University, Mersin, Turkey
- 45: Also at Izmir Institute of Technology, Izmir, Turkey
- 46: Also at Ozyegin University, Istanbul, Turkey

- 47: Also at Kafkas University, Kars, Turkey
- 48: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
- 49: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
- 50: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
- 51: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
- 52: Also at Argonne National Laboratory, Argonne, USA
- 53: Also at Erzincan University, Erzincan, Turkey
- 54: Also at Yildiz Technical University, Istanbul, Turkey
- 55: Also at Texas A&M University at Qatar, Doha, Qatar
- 56: Also at Kyungpook National University, Daegu, Korea