

Event shape variables measured using multijet final states in proton-proton collisions at $\sqrt{s} = 13$ TeV



The CMS collaboration

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

ABSTRACT: The study of global event shape variables can provide sensitive tests of predictions for multijet production in proton-proton collisions. This paper presents a study of several event shape variables calculated using jet four momenta in proton-proton collisions at a centre-of-mass energy of 13 TeV and uses data recorded with the CMS detector at the LHC corresponding to an integrated luminosity of 2.2 fb^{-1} . After correcting for detector effects, the resulting distributions are compared with several theoretical predictions. The agreement generally improves as the energy, represented by the average transverse momentum of the two leading jets, increases.

KEYWORDS: Hadron-Hadron scattering (experiments), Jet physics, Jets

ARXIV EPRINT: [1811.00588](https://arxiv.org/abs/1811.00588)

Contents

1	Introduction	1
2	Event shape variables	2
3	The CMS detector	3
4	Jet reconstruction	4
5	Data set and event selection	4
5.1	Collision data	4
5.2	Simulated events	5
6	Unfolding of distributions	5
7	Systematic uncertainties	6
8	Results	7
9	Summary	19
	The CMS collaboration	23

1 Introduction

The production of quarks and gluons in hadron collisions and the process of hadron formation are subject to in-depth theoretical and experimental studies. The experiments at the CERN LHC have studied production of hadronic jets by measuring differential cross-sections, ratios of numbers of jets, angular distributions, etc., to deepen the understanding of quantum chromodynamics (QCD). While the production of quarks and gluons with large transverse momentum (p_T) is well described by calculations based on perturbative QCD, the hadronization process probes energy scales where perturbative calculations are not applicable. Instead, phenomenological models inspired by QCD are used to predict the experimental results.

Event shape variables (ESVs) are sensitive to the flow of energy in hadronic final states. These variables are safe from collinear and infrared divergences and have reduced experimental uncertainties [1]. Some distributions of ESVs are sensitive to the details of the hadronization process [2–4], so they can be used to tune parameters of Monte Carlo (MC) event generators, determine the strong coupling α_S [5–7], and to search for new physics phenomena [8–10].

Various ESVs have been studied in electron-positron collisions at the CERN LEP collider to determine α_S [11–15]. ESVs have also been studied in electron-proton collisions at the DESY HERA collider [16] and in proton-antiproton collisions at the FNAL Tevatron collider [17], where they were compared with next-to-leading-order (NLO) calculations and with various tunes of the PYTHIA6 event generator [18]. At the CERN LHC collider studies by the ALICE, ATLAS, and CMS Collaborations have exploited proton-proton collisions at centre-of-mass energies of $\sqrt{s} = 0.9, 2.76, \text{ and } 7 \text{ TeV}$ to evaluate ESVs [19–26].

This paper reports a measurement of ESVs by the CMS Collaboration using hadronic jets in pp collisions at $\sqrt{s} = 13 \text{ TeV}$ corresponding to an integrated luminosity (\mathcal{L}_{int}) of 2.2 fb^{-1} . The following variables are studied: the complement of transverse thrust, total jet broadening, total jet mass, and total transverse jet mass. The theoretical uncertainties in the predictions of these ESVs can be reduced by careful choice of the quantity used to classify the energy scale of the events. Following ref. [4], we use $H_{T,2} = (p_{T,\text{jet1}} + p_{T,\text{jet2}})/2$, where $p_{T,\text{jet1}}$ and $p_{T,\text{jet2}}$ refer to the transverse momenta of the highest and second highest p_T jets. The measured distributions are corrected for detector effects and compared with the predictions of QCD models implemented in the PYTHIA8 [27], MADGRAPH5_aMC@NLO+PYTHIA8 [28], and HERWIG++ [29] event generators.

The paper is organized as follows. The ESVs are discussed in section 2. After briefly describing the elements of the CMS detector in section 3, the jet reconstruction relevant to this analysis is described in section 4. The data sample and event selection criteria are described in section 5. Sections 6 and 7 present the unfolding technique and the systematic uncertainties, respectively. Section 8 contains comparisons between CMS data and theoretical predictions, and the results are summarized in section 9.

2 Event shape variables

The four ESVs studied in this analysis are defined using the four-momenta of hadronic jets.

The complement of transverse thrust: the complement of thrust is defined as:

$$\tau_{\perp} \equiv 1 - T_{\perp}, \tag{2.1}$$

where the thrust in the transverse plane is:

$$T_{\perp} \equiv \max_{\hat{n}_T} \frac{\sum_i |\vec{p}_{T,i} \cdot \hat{n}_T|}{\sum_i p_{T,i}}. \tag{2.2}$$

Here, $\vec{p}_{T,i}$ is the component of momentum of the i^{th} jet perpendicular to the beam direction and thrust direction \hat{n}_T is the unit vector that maximizes the projection and defines the transverse thrust axis. The τ_{\perp} is zero for a perfectly balanced two-jet event and is $1 - 2/\pi$ for an isotropic multijet event.

Total jet broadening: for each event, the transverse thrust axis is used to divide the event into upper (U) and lower (L) regions. The jets in U satisfy $\vec{p}_{T,i} \cdot \hat{n}_T > 0$ and those in L have $\vec{p}_{T,i} \cdot \hat{n}_T < 0$. For these two regions, the p_T -weighted pseudorapidities and azimuthal angles are

$$\eta_X \equiv \frac{\sum_{i \in X} p_{T,i} \eta_i}{\sum_{i \in X} p_{T,i}}, \phi_X \equiv \frac{\sum_{i \in X} p_{T,i} \phi_i}{\sum_{i \in X} p_{T,i}}, \tag{2.3}$$

where X refers to the U or L regions. The jet broadening variable in each region is defined as

$$B_X \equiv \frac{1}{2 P_T} \sum_{i \in X} p_{T,i} \sqrt{(\eta_i - \eta_X)^2 + (\phi_i - \phi_X)^2}, \quad (2.4)$$

where P_T is the scalar p_T sum of all the jets in the event. The total jet broadening is then defined as

$$B_{\text{Tot}} \equiv B_U + B_L. \quad (2.5)$$

Total jet mass: the normalized squared invariant mass of the jets in the U and L regions of the event is defined by

$$\rho_X \equiv \frac{M_X^2}{P^2}, \quad (2.6)$$

where M_X is the invariant mass of the jets in the region X, and P is the scalar sum of the momenta of all central jets. The total jet mass is defined as the sum of the masses in the U and L regions,

$$\rho_{\text{Tot}} \equiv \rho_U + \rho_L. \quad (2.7)$$

Total transverse jet mass: the quantity corresponding to ρ_{Tot} in the transverse plane, the total transverse jet mass (ρ_{Tot}^T), is similarly calculated using $\vec{p}_{T,i}$ of jets.

These four ESVs probe different aspects of QCD [2] and are designed to have higher values for multijet, spherical events and lower values for back-to-back dijet events. While τ_{\perp} is sensitive to the hard-scattering process, the jet masses and jet broadening depend more on the nonperturbative aspects of QCD, responsible for hadronisation process.

3 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. The solenoid volume holds 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. Steel and quartz-fibre Cherenkov hadron forward calorimeters extend the pseudorapidity (η) coverage provided by the barrel and endcap detectors to the region $3.0 < |\eta| < 5.2$. Muons are measured in gas-ionisation detectors embedded in the steel flux-return yoke outside the solenoid. In the region $|\eta| < 1.74$, the HCAL cells have widths of 0.087 in η and 0.087 radians in azimuthal angle (ϕ). For $|\eta| < 1.48$, the HCAL cells map onto 5×5 ECAL crystals arrays in the η - ϕ plane to form calorimeter towers projecting radially outwards from close to the nominal interaction point. At larger values of η , the size in η of the towers increases and the matching ECAL arrays contain fewer crystals. CMS uses a two stage online trigger to select events for offline analysis. In the first stage, a hardware-based level-1 (L1) trigger uses information from calorimeter and muon subsystems and selects event at a rate of about 100 kHz. In the second stage, a software-based high-level trigger (HLT), running on computer farms, uses full event information and reduces the event rate to about 1 KHz before data storage. A more detailed description of the CMS detector can be found in ref. [30].

4 Jet reconstruction

The particle-flow (PF) event algorithm [31] reconstructs photons, electrons, charged and neutral hadrons, and muons with an optimised combination of information from the various elements of the CMS detector. The energy of a photon is directly obtained from the ECAL measurement. The energy of an electron is determined from a combination of the electron momentum at the primary interaction vertex as determined by the tracker, the energy of the corresponding ECAL cluster, and the energy sum of all bremsstrahlung photons spatially compatible with originating from the electron track. The momentum of a muon is obtained from the curvature of the corresponding track. The energy of a charged hadron is determined from a combination of its momentum measured in the tracker and the matching ECAL and HCAL energy deposits, corrected for zero-suppression effects and for the response function of the calorimeters to hadronic showers. Finally, the energy of a neutral hadron is obtained from the corresponding energy deposits in ECAL and HCAL.

Jets are reconstructed from photons, electrons, charged and neutral hadrons, and muons using the anti- k_T clustering algorithm [32, 33] with a distance parameter $R = 0.4$. Measurement of jet energy is affected by contamination from additional pp interactions in the same bunch crossing (pileup), as well as by the nonuniform and nonlinear response of the CMS calorimeters. The technique of charged-hadron subtraction [31] is used to reduce the contribution of particles that originate from pileup interactions to the jet energy measurement. The jet four-momentum is corrected for the difference observed in simulation between jets built from reconstructed particles and generator-level particles. The jet mass and direction are kept constant for the corrections, which are functions of the η and p_T of the jet, as well as the energy density and jet area quantities defined in ref. [34]. The latter are used to correct the energy offset introduced by the pileup interactions. The energy of the jets is further corrected using dijet, Z +jet, and γ +jet events, where the p_T -balance of the event is exploited. The jet energy resolution typically amounts to 15% at 10 GeV, 8% at 100 GeV, and 4% at 1 TeV.

5 Data set and event selection

5.1 Collision data

This analysis uses pp collision data collected in 2015 at $\sqrt{s} = 13$ TeV, corresponding to $\mathcal{L}_{\text{int}} = 2.2 \text{ fb}^{-1}$. Events are selected at L1 and HLT that have jet p_T or $H_{T,2}$ thresholds, respectively, as shown in table 1. The turn-on point for each trigger, offline $H_{T,2}$ at which the trigger is 99% efficient, is used to define the $H_{T,2}$ ranges for events.

Collision and simulated events are required to have at least three jets with $p_T > 30$ GeV within the coverage of the tracker $|\eta| < 2.4$. For each event, three jets are used for the calculation of the ESVs. The jets with the highest and the second-highest p_T are selected. From the remaining jets, the one with the highest recoil term is selected as the third jet. The recoil term for jet k is

$$\mathcal{R}_{\perp,k} = \frac{|\vec{p}_{T,\text{jet}1} + \vec{p}_{T,\text{jet}2} + \vec{p}_{T,\text{jet}k}|}{|\vec{p}_{T,\text{jet}1}| + |\vec{p}_{T,\text{jet}2}| + |\vec{p}_{T,\text{jet}k}|}.$$

L1 threshold for $p_{T,\text{jet}}$ (GeV)	HLT threshold for $H_{T,2}$ (GeV)	$H_{T,2}$ range (GeV)	Number of events	
ZeroBias		60	73–93	222 184
52		80	93–165	36 452
92		140	165–225	81 932
128		200	225–298	363 294
128 or 176		260	298–365	134 320
128 or 176		320	365–452	354 140
128 or 176		400	452–557	443 361
128 or 176		500	>557	295 578

Table 1. L1 trigger thresholds, HLT thresholds, $H_{T,2}$ range and number of events used in the analysis.

The data sample is divided into eight $H_{T,2}$ ranges such that the uncertainty due to the trigger inefficiency is negligible. The ranges (in GeV) are: 73–93, 93–165, 165–225, 225–298, 298–365, 365–452, 452–557 and >557, as shown in table 1, with the number of events in each range.

5.2 Simulated events

Events are simulated using PYTHIA v8.212, MADGRAPH5_aMC@NLO V5 2.2.2+PYTHIA8, and HERWIG++ v2.7.1. The NNPDF3.0 [35] parton distribution function (PDF) set is used. The PYTHIA8 and HERWIG++ event generators use leading order 2→2 matrix element (ME) calculations and parton shower (PS) for generation of multijet topologies. The PYTHIA8 event generator uses a p_T -ordered PS, and the underlying event description is based on the multiple parton interaction (MPI) model. Events are generated with two PYTHIA8 tunes: CUETP8M1 [36] and Monash [37]. Minimum bias data collected by the CMS experiment were used to derive the PYTHIA8 CUETP8M1 tune, which is based on the Monash tune. The MADGRAPH5_aMC@NLO generator uses ME calculations to generate hard-scattering events with two to four partons and PYTHIA8 CUETP8M1 for subsequent fragmentation and hadronization. The MLM [38] matching procedure is used to avoid double counting of jets between the ME calculation and the PS description. The HERWIG++ generator uses an angular-ordered PS. For simulated events, particle-level jets are obtained by applying the anti- k_T clustering algorithm to all generated stable particles, excluding neutrinos, with $R = 0.4$.

The simulation events are passed through a complete and detailed reconstruction in the CMS detector using the same reconstruction as the collision events.

6 Unfolding of distributions

A reconstructed collision event differs from the true event because of finite resolution of the detector, detector acceptances, and uncertainties and efficiencies of measurement. Hence, the detector-level distributions obtained from data are unfolded to estimate the underlying

particle-level distributions, which can be compared with predictions from theoretical models as well as with results obtained by other experiments.

Simulated events passing through the complete detector simulation, event reconstruction, and selection chain are used to construct the response matrix for an ESV, which relates its particle-level distribution with that at detector level. The response matrix incorporates all the experimental effects and is subsequently used as input for the unfolding of the observed distribution in data. Some events that satisfy the selection criteria at the particle level might not at the detector level, leading to an inefficiency. The reverse may also happen, leading to misidentification. Further, an event may migrate from one $H_{T,2}$ range to another. The corresponding efficiency and misidentification rates are also incorporated in the unfolding process, and they contribute to the related uncertainty of the unfolding process.

To investigate possible bias due to the choice of an MC generator to construct the response matrices, we generate event samples from three different generators: PYTHIA8 CUETP8M1, MADGRAPH5_aMC@NLO, and HERWIG++. Each detector level distribution is unfolded using these three response matrices and the corresponding particle-level distributions are compared. No evidence for significant bias is observed.

Two different methods, which are implemented in RooUnfold [39], are used for unfolding the observed distributions: D’Agostini iteration with early stopping [40], and Singular Value Decomposition (SVD) [41]. The difference between the unfolded distributions produced with these two methods is much smaller than 1%. Our unfolding is done using the D’Agostini iteration and PYTHIA8 CUETP8M1 is used for constructing the response matrix. The SVD method is used as a cross-check.

7 Systematic uncertainties

There are multiple sources of uncertainties in the unfolding process, and the contributions from each individual source are added in quadrature to obtain the total uncertainty. Figure 1 shows the total uncertainty and the contributions from various sources as a function of each ESV for the specific range $225 < H_{T,2} < 298$ GeV.

- *Jet energy scale (JES)*: CMS considers 26 different sources of uncertainties in the JES [42]. To estimate the effect of each source, the four-momentum of each jet is scaled up and down by the corresponding uncertainty, the ESV is calculated, and the response matrix obtained with the nominal JES is used to unfold the distributions obtained with the nominal, scaled up, and scaled down JES values. For each bin of the unfolded distribution, the larger of the differences between the nominal, and the varied ones is taken as the systematic uncertainty. The systematic uncertainties due to different sources are then added in quadrature. For most bins in the distribution of an ESV, the uncertainty is 4–6%. However, it reaches about 12% for the highest and lowest bins of ρ_{Tot} , lowest bins of ρ_{Tot}^T , and about 8% for the highest bins of B_{Tot} . Typically JES is the largest source of systematic uncertainty in the ESVs.
- *Jet energy resolution (JER)*: the JER is obtained from the ratio of p_T of the two jets in dijet events as a function of p_T and η [42]. It has been observed that the JER is worse in data compared to simulation. Hence, extra smearing is applied to the simulated

events, and different response matrices are constructed. The detector-level distribution of an ESV is unfolded with the different response matrices incorporating the uncertainty due to JER. The estimated uncertainties in the ESVs are of the order of 1%.

- *Unfolding*: the detector-level distribution of an ESV obtained from simulated events of PYTHIA8 CUETP8M1 is unfolded with two response matrices derived from MADGRAPH5_aMC@NLO and HERWIG++, and compared with the corresponding particle-level distribution in the same sample. Similar exercises are carried out for the MADGRAPH5_aMC@NLO sample using PYTHIA8 CUETP8M1 and HERWIG++ response matrices, and for the HERWIG++ sample using PYTHIA8 CUETP8M1 and MADGRAPH5_aMC@NLO response matrices. Out of these six differences for each bin, the largest is taken as the systematic uncertainty. In the closure tests of the individual response matrices, if, for a particular bin, the difference in the unfolded and generated values is larger than the uncertainty already assigned, the larger one is taken as the uncertainty due to the unfolding for that bin. The bias inherent in the D’Agostini method is estimated by using different generators. The difference in the unfolded results is included as an unfolding uncertainty. The uncertainty due to unfolding is of the order of 2%, except for a few lowest, and highest bins where it dominates the total uncertainty.
- *Parton distribution function*: the uncertainty due to the PDFs in the particle-level distribution of an ESV is estimated using the 100 sets of NNPDF3.0 replicas. The standard deviation of the 100 values thus obtained for a bin is taken as the uncertainty due to PDFs for that bin. For most bins, the uncertainty due to the PDFs is less than 1%, but increases for higher values of the variables. For B_{Tot} the uncertainty due to the PDFs increases very rapidly (>20%) and dominates for the last few bins.

The contribution of other sources of systematic uncertainty, i.e., pileup, and trigger efficiency are negligible.

8 Results

The modelling of initial-state radiation (ISR), final-state radiation (FSR) of gluons, and MPI in PYTHIA8 CUETP8M1 is tested by studying each aspect individually, via the comparison of simulated ESV distributions with data, as shown in figure 2. This study shows that the effect of disabling ISR results in a very large shift of the ESVs to lower values, i.e., reducing the spherical nature of the multijet events. The effect of disabling the FSR is small compared to the ISR, and the effect of MPI is even smaller.

The unfolded distributions for the ESVs obtained from data are compared with the particle-level predictions of various MC generators, as shown in figures 3–10 for various $H_{T,2}$ ranges. Comparisons are made to the central predictions of the event generators only. Each figure presents the variables τ_{\perp} (upper left), B_{Tot} (upper right), ρ_{Tot} (lower left), and $\rho_{\text{Tot}}^{\text{T}}$ (lower right) for a range of $H_{T,2}$. The ratios of individual MC predictions to that of data are shown in the lower panel of each plot.

The MPI parameters in the PYTHIA8 Monash and CUETP8M1 tunes are very similar. The predictions of these two tunes agree well for the four ESVs studied. In general, the

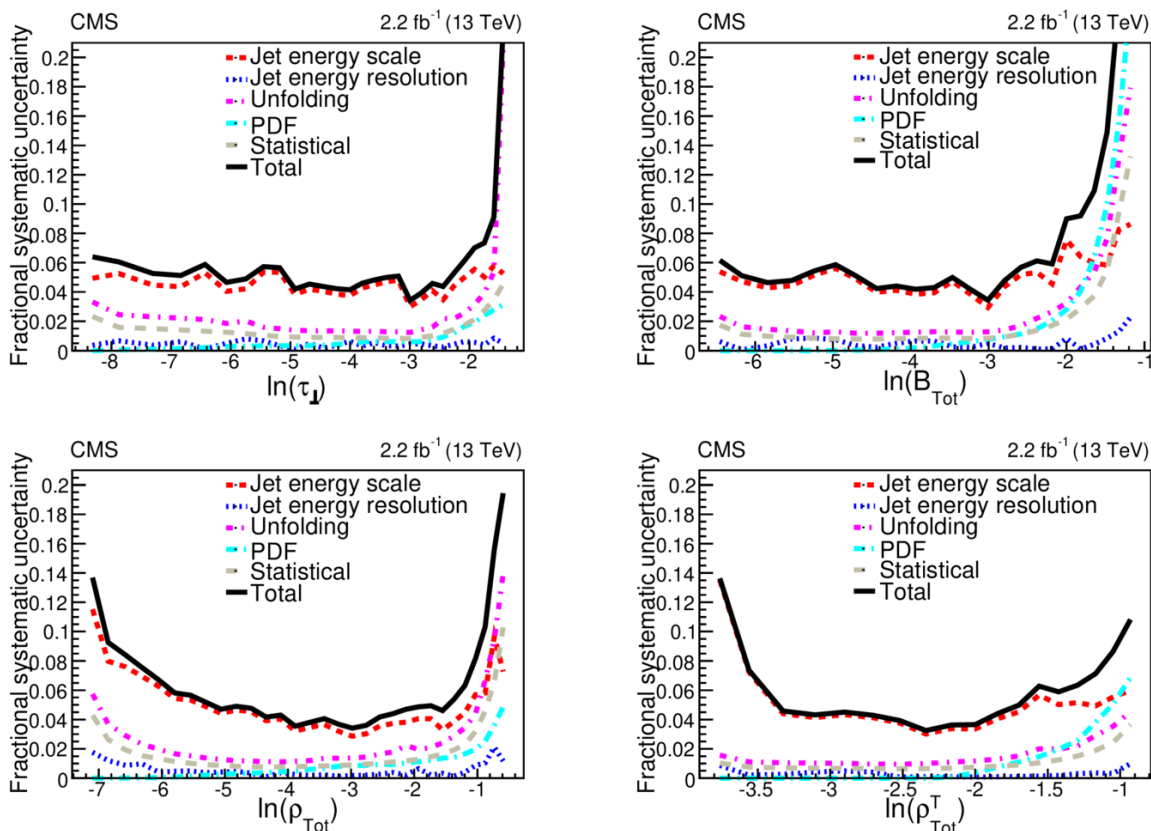


Figure 1. Total uncertainty (black line) for the four event shape variables: the complement of transverse thrust (τ_{\perp}) (upper left), total jet broadening (B_{Tot}) (upper right), total jet mass (ρ_{Tot}) (lower left) and total transverse jet mass (ρ_{Tot}^T) (lower right) evaluated with jets for $225 < H_{T,2} < 298 \text{ GeV}$. The contributions from different sources are also shown in each plot: JES (red dashed line), JER (blue dotted line), unfolding (pink dash-dotted line), PDF (light-blue dash-dotted line) and statistics (grey dashed line).

agreement between them improves with increasing $H_{T,2}$. Both tunes show good agreement with data for the τ_{\perp} and ρ_{Tot}^T variables, except for the two lowest ranges of $H_{T,2}$, and both overestimate the multijet contribution to ρ_{Tot} and B_{Tot} . We note that τ_{\perp} and ρ_{Tot}^T variables are evaluated in the transverse plane, whereas B_{Tot} and ρ_{Tot} are evaluated using both longitudinal and transverse components of the jets. This indicates that the treatment of the energy flow in the transverse plane is modelled well in the Monash and CUETP8M1 tunes of PYTHIA8, whereas the energy flow out of the transverse plane is not.

The HERWIG++ generator shows good agreement with data for all four ESVs studied, and it is better than the CUETP8M1 and Monash tunes of PYTHIA8 in predicting ρ_{Tot} and B_{Tot} . This implies its better treatment of energy flow out of the transverse plane. Although both PYTHIA8 and HERWIG++ use a PS approach to generate multijet events and hadronization, the former uses string fragmentation and a p_T -ordered shower, whereas the latter uses cluster fragmentation and angular-ordered shower.

The MADGRAPH5_aMC@NLO generator shows good agreement with data for τ_{\perp} and ρ_{Tot}^T and its agreement with data for ρ_{Tot} and B_{Tot} is much better compared to the CUETP8M1 and Monash tunes of PYTHIA8. The ME approach for generating multi-

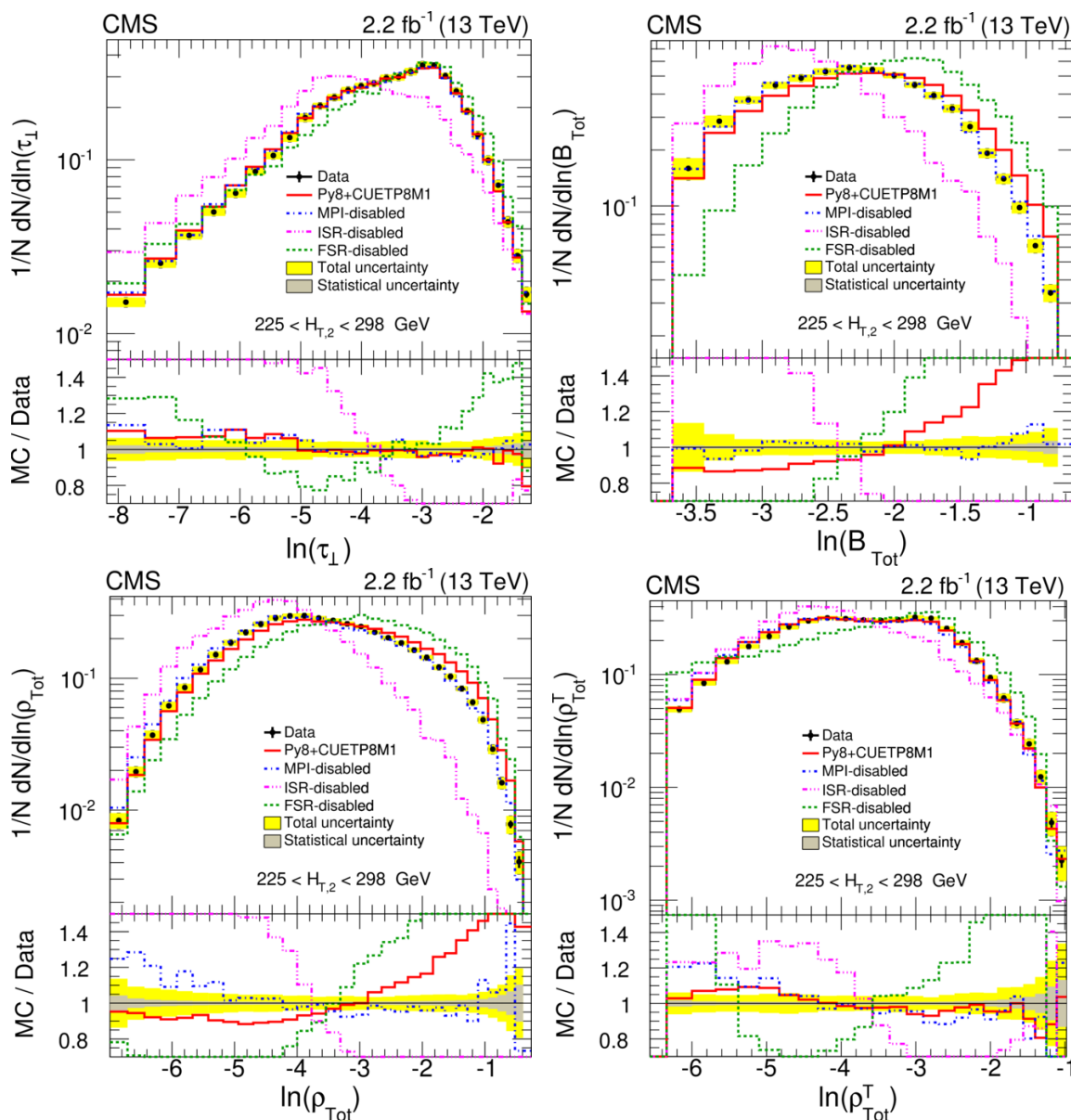


Figure 2. The effects of MPI, ISR, and FSR in PYTHIA8 CUETP8M1 on τ_{\perp} (upper left), B_{Tot} (upper right), ρ_{Tot} (lower left) and ρ_{Tot}^T (lower right) for a typical range $225 < H_{T,2} < 298$ GeV. The ratio plots for simulation (MC) with respect to data are shown in the lower panel of each plot. The inner gray band represents the statistical uncertainty and the yellow band represents the total uncertainty (systematic + statistical) in each plot.

parton hard scattering processes models the transverse as well as longitudinal flows of energy better than PYTHIA8.

The following features emerge from the comparison plots of the four ESVs. Agreement between data and benchmark event generators improves with $H_{T,2}$. Figure 11 shows the evolution of the mean value of each ESV with $H_{T,2}$ and confirms the above observations. With higher $H_{T,2}$, the initial partons are more boosted, and hence the event tends to be

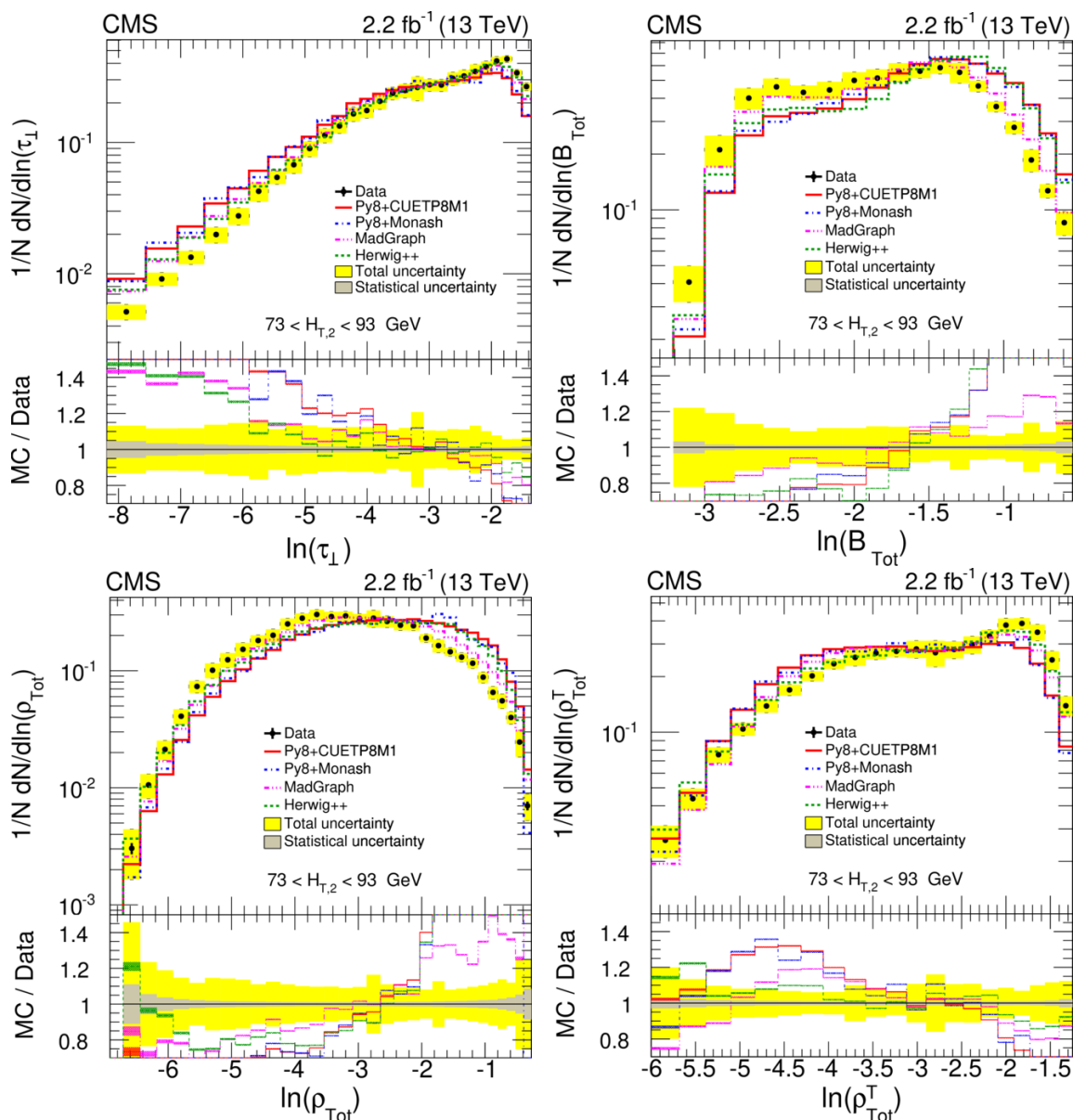


Figure 3. Normalized differential distributions of unfolded data compared with theoretical (MC) predictions of PYTHIA8 CUETP8M1 (red line), PYTHIA8 Monash (blue dash-dotted line), MADGRAPH5_aMC@NLO (pink dash-dot-dotted line) and HERWIG++ (brown dash-dot-dotted line) as a function of ESV: complement of transverse thrust (τ_{\perp}) (upper left), total jet broadening (B_{Tot}) (upper right), total jet mass (ρ_{Tot}) (lower left) and total transverse jet mass (ρ_{Tot}^T) (lower right) for $73 < H_{T,2} < 93$ GeV. In each ratio plot, the inner gray band represents statistical uncertainty and the yellow band represents the total uncertainty (systematic and statistical components added in quadrature) on data and the MC predictions include only statistical uncertainty.

less spherical. Also, α_S decreases with $H_{T,2}$, resulting in less emission of hard gluons, which further spoils the multijet, spherical nature of the event. Thus, the mean value of each ESV decreases with increasing $H_{T,2}$.

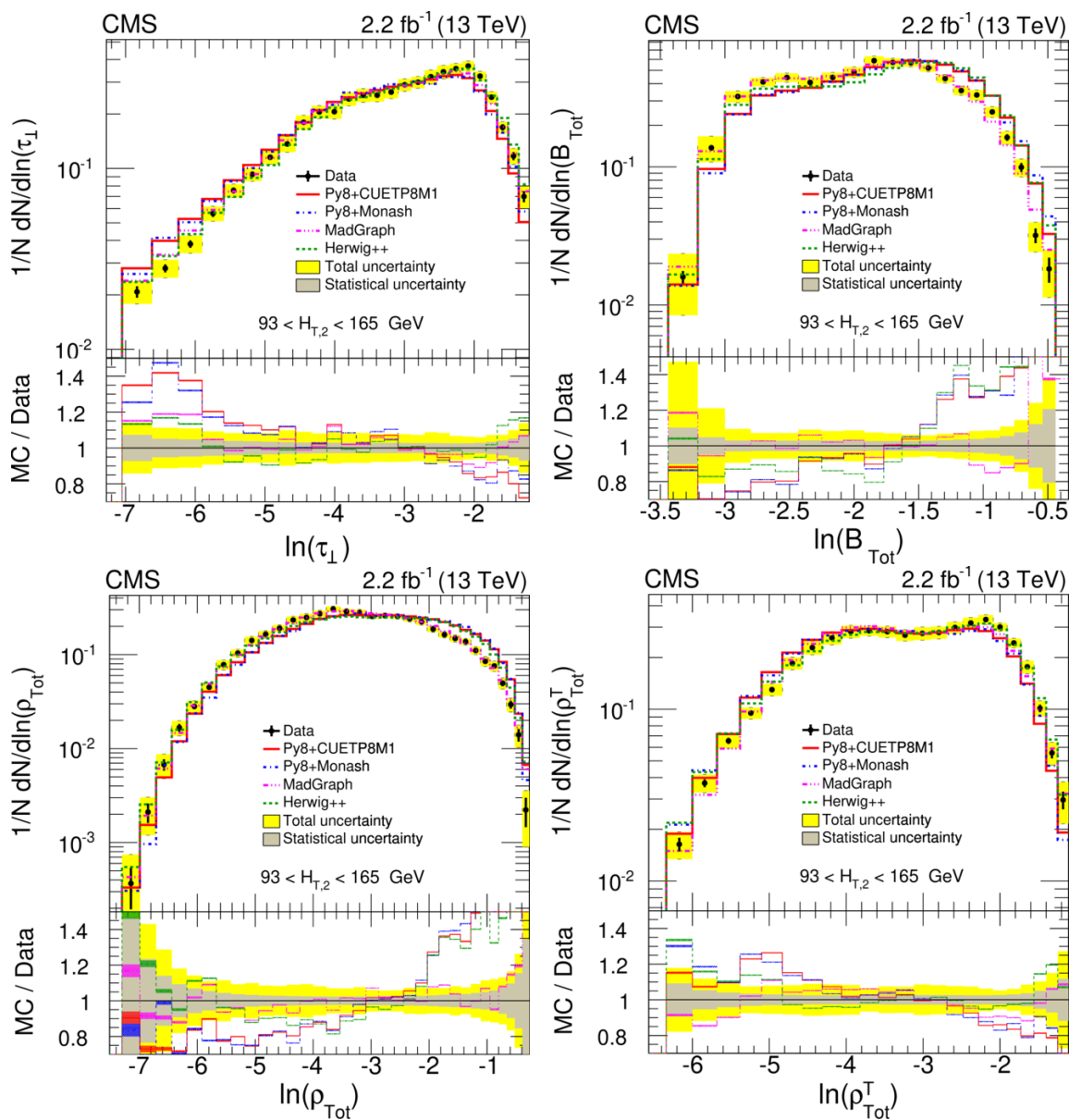


Figure 4. Normalized differential distributions of unfolded data compared with theoretical (MC) predictions of PYTHIA8 CUETP8M1 (red line), PYTHIA8 Monash (blue dash-dotted line), MADGRAPH5_amc@NLO (pink dash-dot-dotted line) and HERWIG++ (brown dash-dot-dotted line) as a function of ESV: complement of transverse thrust (τ_{\perp}) (upper left), total jet broadening (B_{Tot}) (upper right), total jet mass (ρ_{Tot}) (lower left) and total transverse jet mass (ρ_{Tot}^T) (lower right) for $93 < H_{T,2} < 165$ GeV. In each ratio plot, the inner gray band represents statistical uncertainty and the yellow band represents the total uncertainty (systematic and statistical components added in quadrature) on data and the MC predictions include only statistical uncertainty.

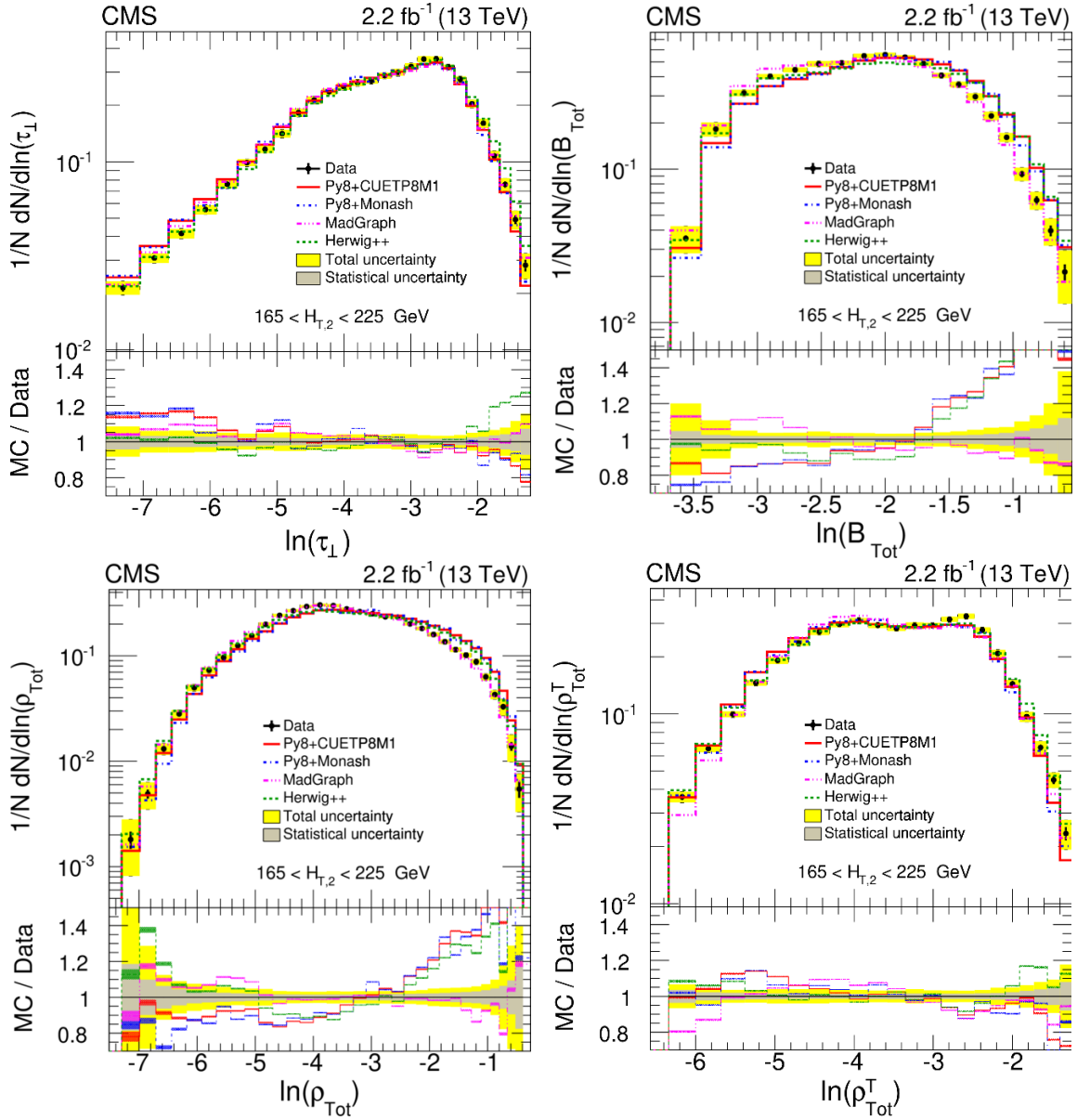


Figure 5. Normalized differential distributions of unfolded data compared with theoretical (MC) predictions of PYTHIA8 CUETP8M1 (red line), PYTHIA8 Monash (blue dash-dotted line), MADGRAPH5_aMC@NLO (pink dash-dot-dotted line) and HERWIG++ (brown dash-dot-dotted line) as a function of ESV: complement of transverse thrust (τ_{\perp}) (upper left), total jet broadening (B_{Tot}) (upper right), total jet mass (ρ_{Tot}) (lower left) and total transverse jet mass ($\rho_{\text{Tot}}^{\text{T}}$) (lower right) for $165 < H_{\text{T},2} < 225$ GeV. In each ratio plot, the inner gray band represents statistical uncertainty and the yellow band represents the total uncertainty (systematic and statistical components added in quadrature) on data and the MC predictions include only statistical uncertainty.

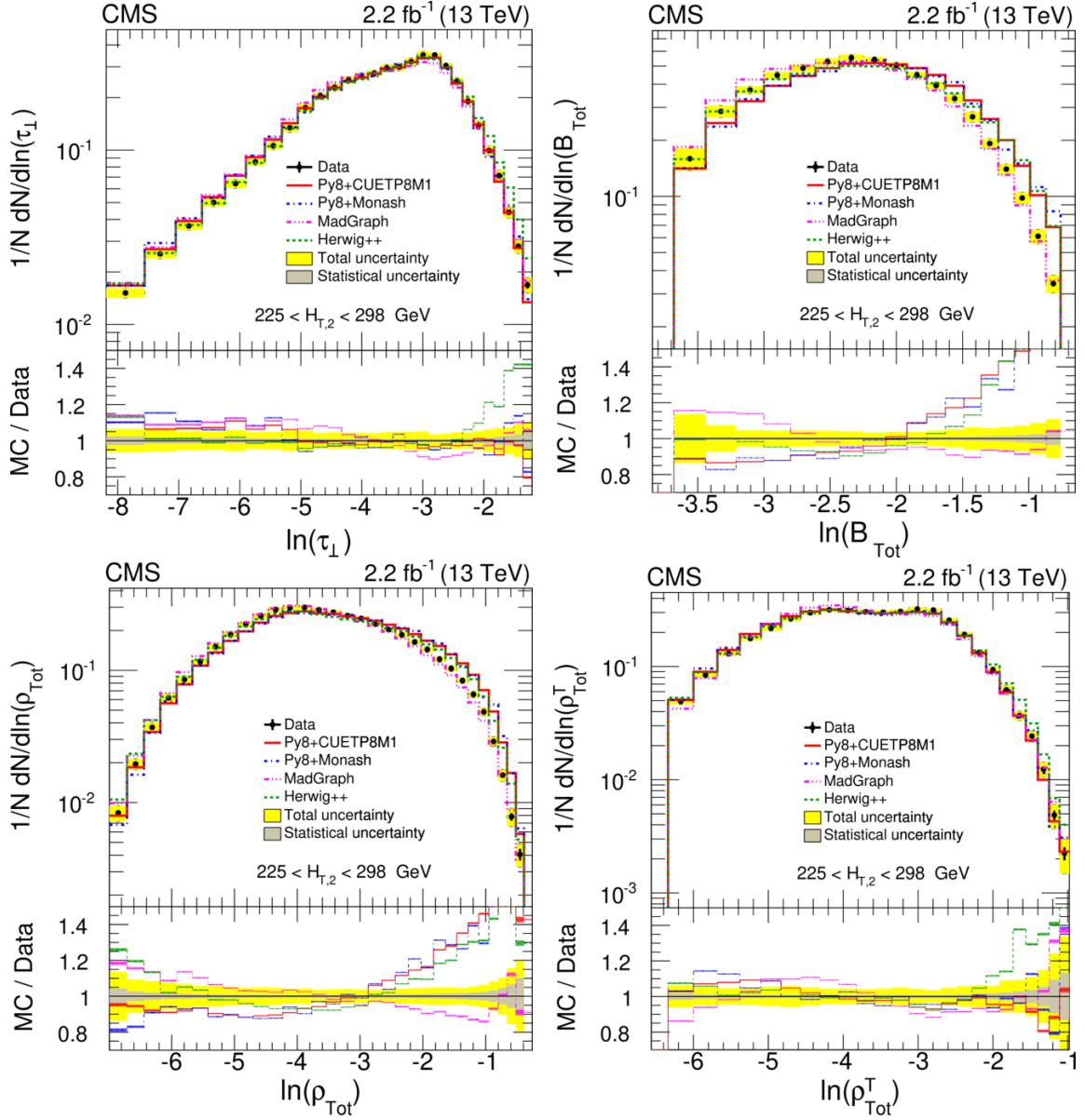


Figure 6. Normalized differential distributions of unfolded data compared with theoretical (MC) predictions of PYTHIA8 CUETP8M1 (red line), PYTHIA8 Monash (blue dash-dotted line), MADGRAPH5_aMC@NLO (pink dash-dot-dotted line) and HERWIG++ (brown dash-dot-dotted line) as a function of ESV: complement of transverse thrust (τ_{\perp}) (upper left), total jet broadening (B_{Tot}) (upper right), total jet mass (ρ_{Tot}) (lower left) and total transverse jet mass ($\rho_{\text{Tot}}^{\text{T}}$) (lower right) for $225 < H_{\text{T},2} < 298$ GeV. In each ratio plot, the inner gray band represents statistical uncertainty and the yellow band represents the total uncertainty (systematic and statistical components added in quadrature) on data and the MC predictions include only statistical uncertainty.

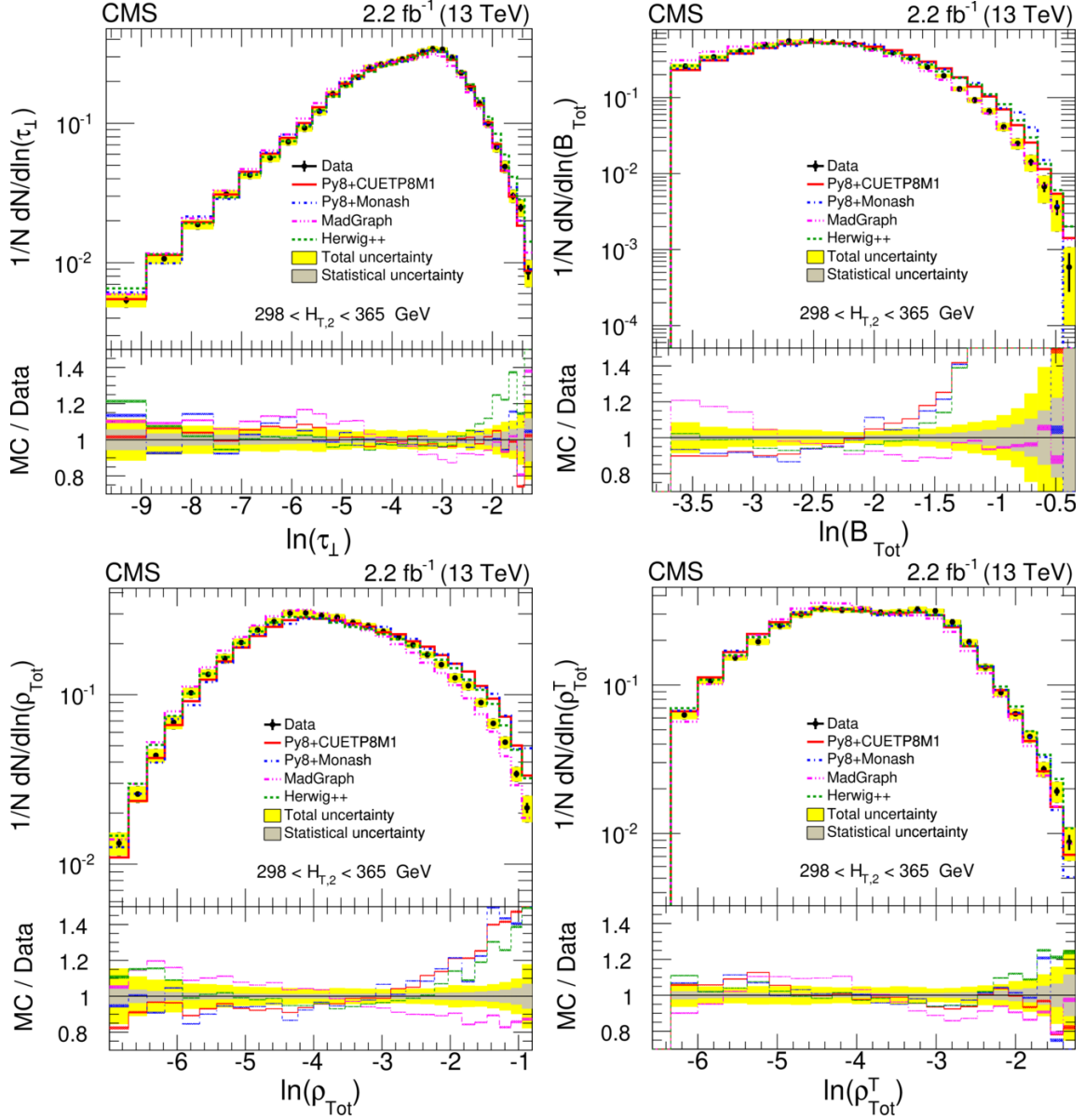


Figure 7. Normalized differential distributions of unfolded data compared with theoretical (MC) predictions of PYTHIA8 CUETP8M1 (red line), PYTHIA8 Monash (blue dash-dotted line), MADGRAPH5_aMC@NLO (pink dash-dot-dotted line) and HERWIG++ (brown dash-dot-dotted line) as a function of ESV: complement of transverse thrust (τ_{\perp}) (upper left), total jet broadening (B_{Tot}) (upper right), total jet mass (ρ_{Tot}) (lower left) and total transverse jet mass ($\rho_{\text{Tot}}^{\text{T}}$) (lower right) for $298 < H_{\text{T},2} < 365$ GeV. In each ratio plot, the inner gray band represents statistical uncertainty and the yellow band represents the total uncertainty (systematic and statistical components added in quadrature) on data and the MC predictions include only statistical uncertainty.

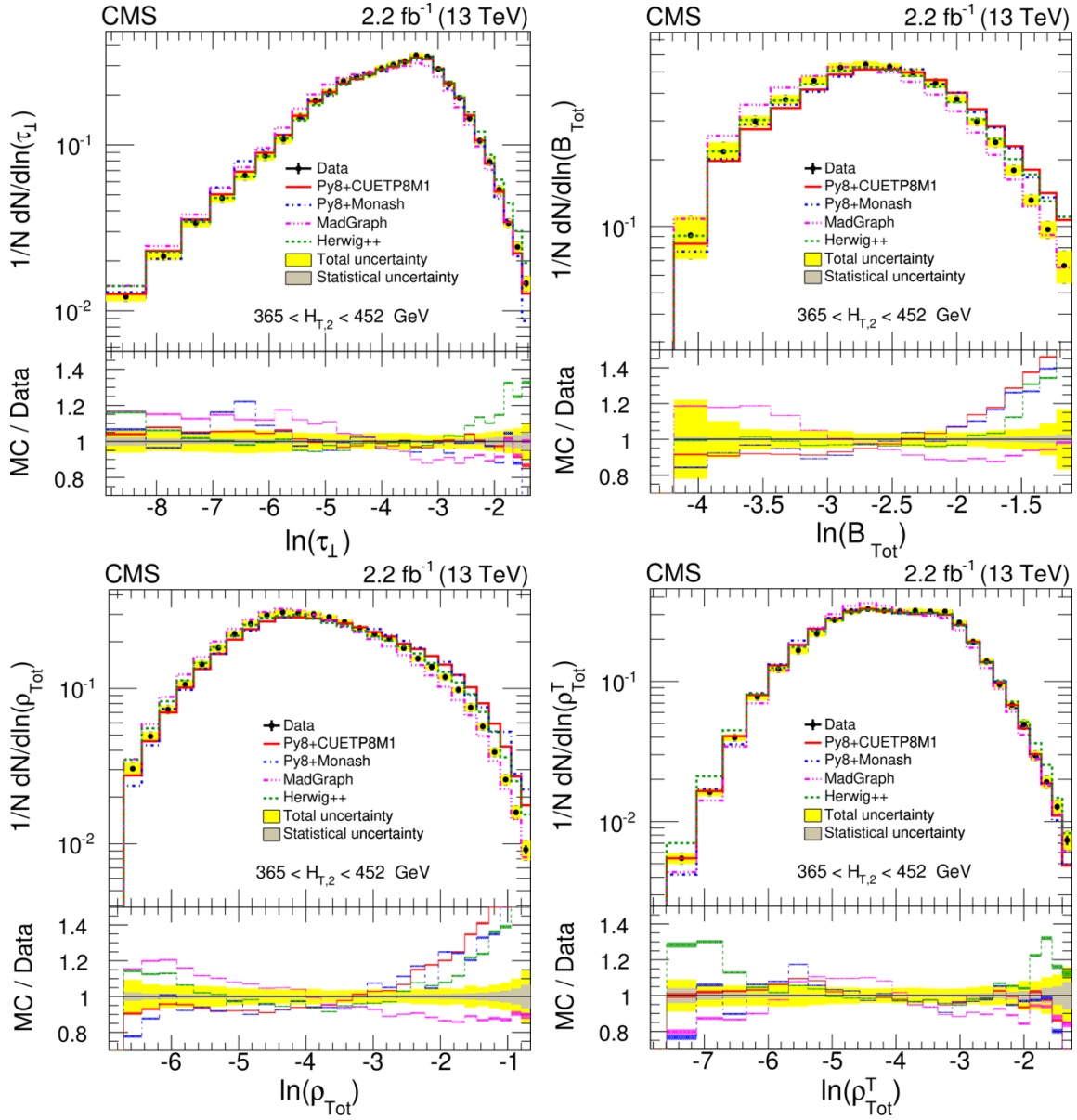


Figure 8. Normalized differential distributions of unfolded data compared with theoretical (MC) predictions of PYTHIA8 CUETP8M1 (red line), PYTHIA8 Monash (blue dash-dotted line), MADGRAPH5_amc@NLO (pink dash-dot-dotted line) and HERWIG++ (brown dash-dot-dotted line) as a function of ESV: complement of transverse thrust (τ_{\perp}) (upper left), total jet broadening (B_{Tot}) (upper right), total jet mass (ρ_{Tot}) (lower left) and total transverse jet mass ($\rho_{\text{Tot}}^{\text{T}}$) (lower right) for $365 < H_{T,2} < 452$ GeV. In each ratio plot, the inner gray band represents statistical uncertainty and the yellow band represents the total uncertainty (systematic and statistical components added in quadrature) on data and the MC predictions include only statistical uncertainty.

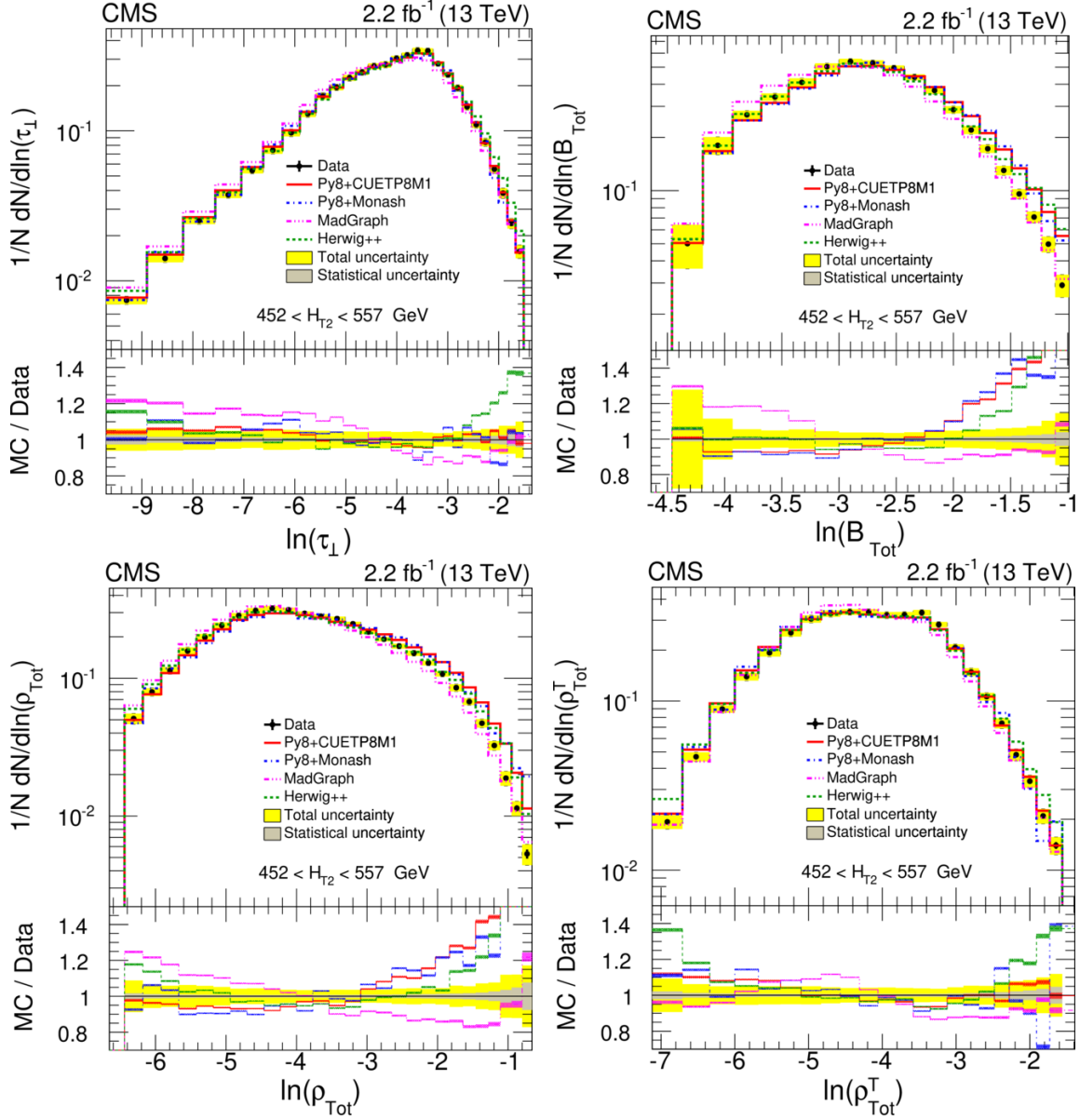


Figure 9. Normalized differential distributions of unfolded data compared with theoretical (MC) predictions of PYTHIA8 CUETP8M1 (red line), PYTHIA8 Monash (blue dash-dotted line), MADGRAPH5_amc@NLO (pink dash-dot-dotted line) and HERWIG++ (brown dash-dot-dotted line) as a function of ESV: complement of transverse thrust (τ_{\perp}) (upper left), total jet broadening (B_{Tot}) (upper right), total jet mass (ρ_{Tot}) (lower left) and total transverse jet mass ($\rho_{\text{Tot}}^{\text{T}}$) (lower right) for $452 < H_{T,2} < 557$ GeV. In each ratio plot, the inner gray band represents statistical uncertainty and the yellow band represents the total uncertainty (systematic and statistical components added in quadrature) on data and the MC predictions include only statistical uncertainty.

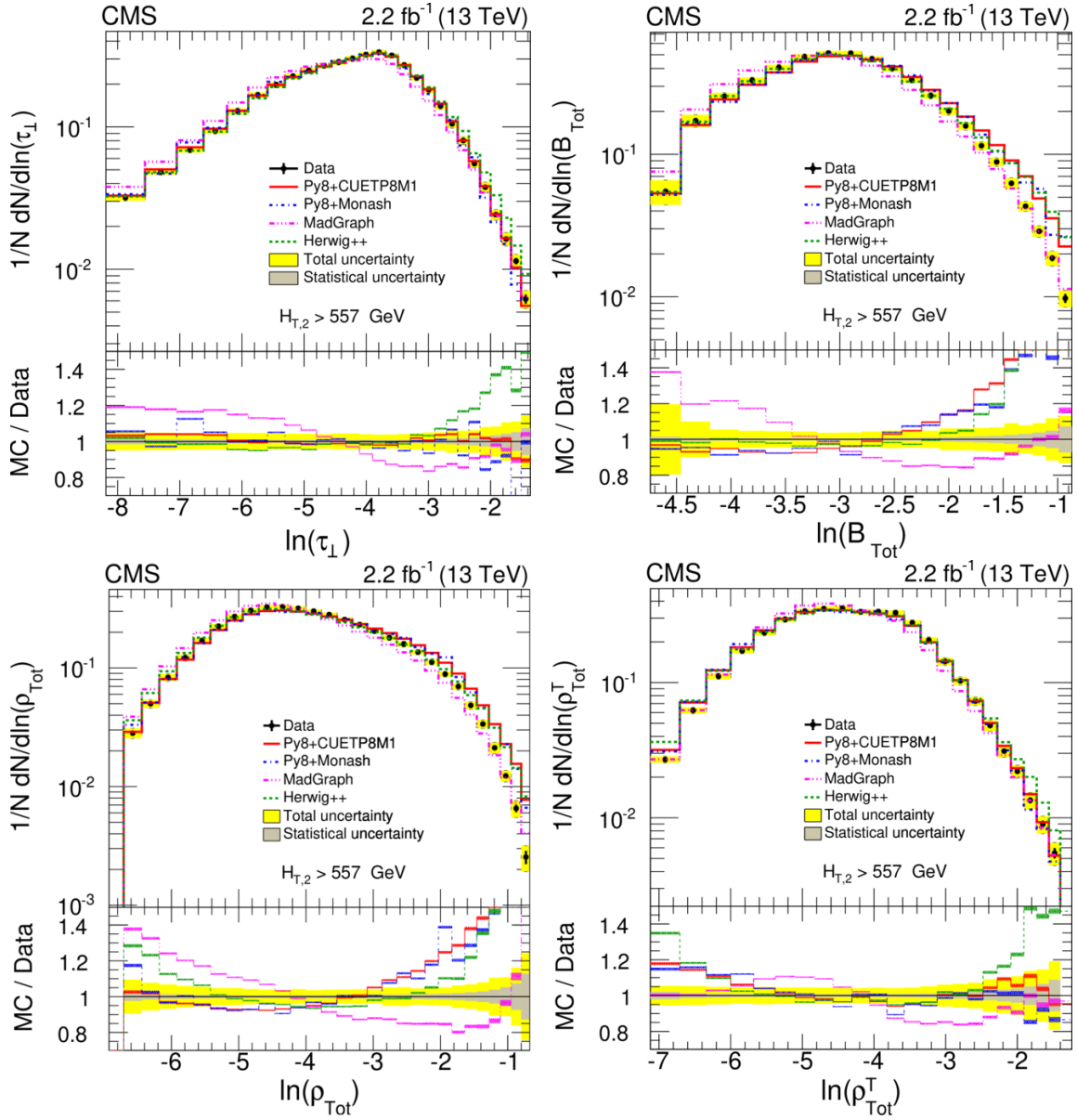


Figure 10. Normalized differential distributions of unfolded data compared with theoretical (MC) predictions of PYTHIA8 CUETP8M1 (red line), PYTHIA8 Monash (blue dash-dotted line), MADGRAPH5_aMC@NLO (pink dash-dot-dotted line) and HERWIG++ (brown dash-dot-dotted line) as a function of ESV: complement of transverse thrust (τ_{\perp}) (upper left), total jet broadening (B_{Tot}) (upper right), total jet mass (ρ_{Tot}) transverse jet mass (ρ_{Tot}^T) (lower left) and total transverse jet mass (ρ_{Tot}^T) (lower right) for $H_{T,2} > 557$ GeV. In each ratio plot, the inner gray band represents statistical uncertainty and the yellow band represents the total uncertainty (systematic and statistical components added in quadrature) on data and the MC predictions include only statistical uncertainty.

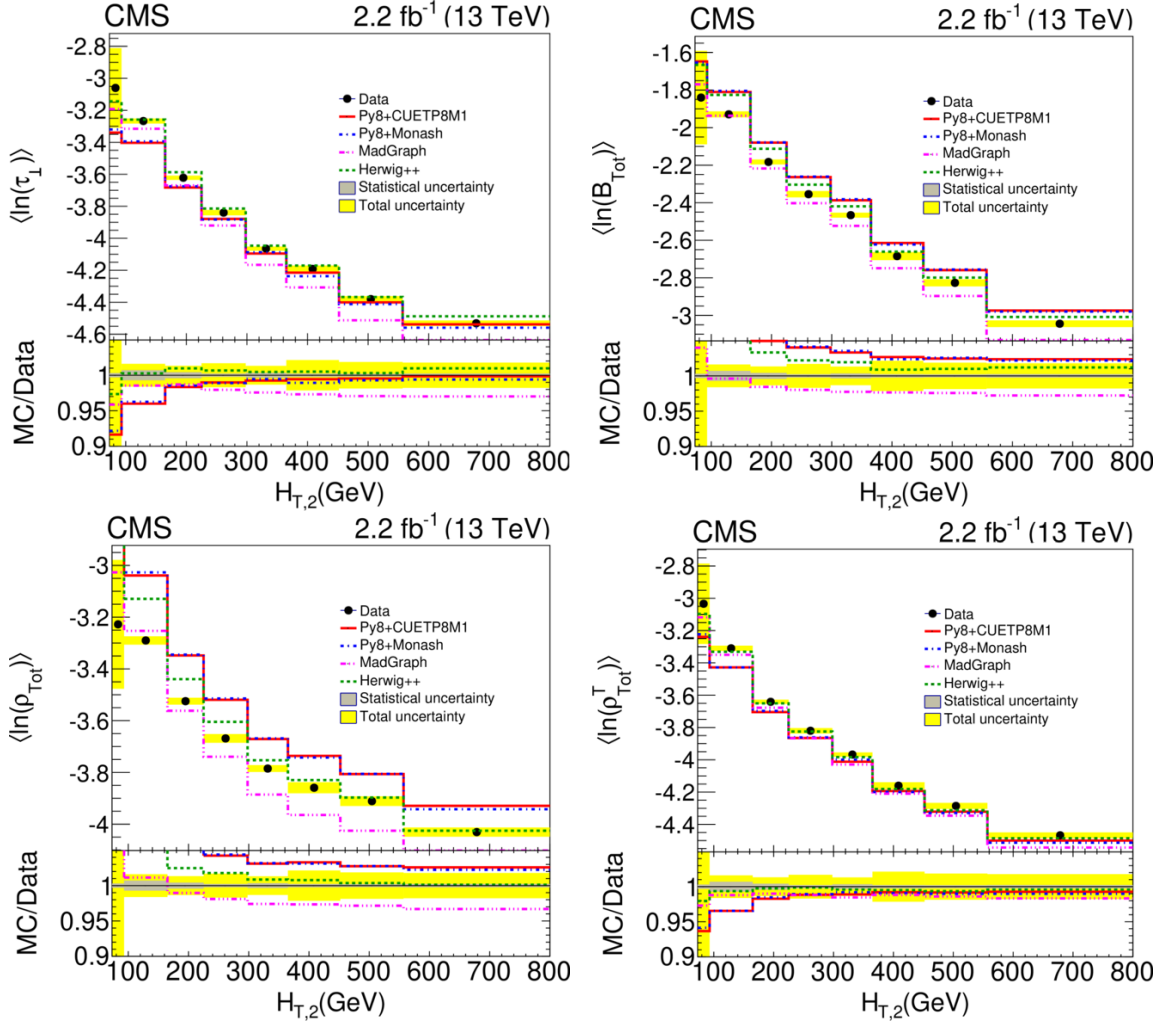


Figure 11. The evolution of the mean of τ_{\perp} (upper left), B_{Tot} (upper right), ρ_{Tot} (lower left) and ρ_{Tot}^T (lower right) and with increasing $H_{T,2}$. The ratio plots with respect to data are presented in the bottom panel to compare predictions of PYTHIA8 CUETP8M1 (red line), PYTHIA8 Monash (blue dash-dotted line), MADGRAPH5_aMC@NLO (pink dash-dot-dotted line) and HERWIG++ (brown dash-dot-dotted line). The yellow band represents the total uncertainty (systematic and statistical components added in quadrature).

9 Summary

This paper presents the first measurement at $\sqrt{s} = 13$ TeV of four event shape variables: complement of transverse thrust (τ_{\perp}), total jet broadening (B_{Tot}), total jet mass (ρ_{Tot}), and total transverse jet mass ($\rho_{\text{Tot}}^{\text{T}}$) using proton-proton collision data. It also covers a wider range of energy than the analysis at $\sqrt{s} = 7$ TeV [19, 22]. Data are compared with theoretical predictions from event generators PYTHIA8, HERWIG++, and MADGRAPH5_aMC@NLO+PYTHIA8. The PYTHIA8 generator describes the flow of energy in the transverse plane well as seen in the τ_{\perp} and $\rho_{\text{Tot}}^{\text{T}}$ distributions. HERWIG++ and MADGRAPH5_aMC@NLO show good agreement with the data for all the four event shape variables and are better than PYTHIA8 in predicting ρ_{Tot} and B_{Tot} . A study of the effects of initial state radiation, final state radiation, and multiple parton interactions in PYTHIA8 is also presented.

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: BMBWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RPF (Cyprus); SENESCYT (Ecuador); 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); NKFIA (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); MES (Latvia); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MOS (Montenegro); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS, RFBR, and NRC KI (Russia); MESTD (Serbia); SEIDI, CPAN, PCTI, and FEDER (Spain); MOSTR (Sri Lanka); 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 Horizon 2020 Grant, contract No. 675440 (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 F.R.S.-FNRS and FWO (Belgium) under

the “Excellence of Science — EOS” — be.h project n. 30820817; the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Lendület (“Momentum”) Programme and the János Bolyai Research Scholarship of the Hungarian Academy of Sciences, the New National Excellence Program ÚNKP, the NKFI research grants 123842, 123959, 124845, 124850 and 125105 (Hungary); the Council of Science and Industrial Research, India; the HOMING PLUS programme of the Foundation for Polish Science, cofinanced from European Union, Regional Development Fund, the Mobility Plus programme of the Ministry of Science and Higher Education, the National Science Center (Poland), contracts Harmonia 2014/14/M/ST2/00428, Opus 2014/13/B/ST2/02543, 2014/15/B/ST2/03998, and 2015/19/B/ST2/02861, Sonata-bis 2012/07/E/ST2/01406; the National Priorities Research Program by Qatar National Research Fund; the Programa Estatal de Fomento de la Investigación Científica y Técnica de Excelencia María de Maeztu, grant MDM-2015-0509 and the Programa Severo Ochoa del Principado de Asturias; the Thalís and Aristeia programmes cofinanced by EU-ESF and the Greek NSRF; the Rachadapisek Sompot Fund for Postdoctoral Fellowship, Chulalongkorn University and the Chulalongkorn Academic into Its 2nd Century Project Advancement Project (Thailand); the Welch Foundation, contract C-1845; and the Weston Havens Foundation (U.S.A.).

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](#)].
- [2] A. Banfi, G.P. Salam and G. Zanderighi, *Phenomenology of event shapes at hadron colliders*, *JHEP* **06** (2010) 038 [[arXiv:1001.4082](https://arxiv.org/abs/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](https://arxiv.org/abs/hep-ph/0312283)] [[INSPIRE](#)].
- [4] M. Rubin, G.P. Salam and S. Sapeta, *Giant QCD K-factors beyond NLO*, *JHEP* **09** (2010) 084 [[arXiv:1006.2144](https://arxiv.org/abs/1006.2144)] [[INSPIRE](#)].
- [5] R.W.L. Jones, M. Ford, G.P. Salam, H. Stenzel and D. Wicke, *Theoretical uncertainties on α_s from event shape variables in e^+e^- annihilations*, *JHEP* **12** (2003) 007 [[hep-ph/0312016](https://arxiv.org/abs/hep-ph/0312016)] [[INSPIRE](#)].
- [6] G. Dissertori, A. Gehrmann-De Ridder, T. Gehrmann, E.W.N. Glover, G. Heinrich and H. Stenzel, *First determination of the strong coupling constant using NNLO predictions for hadronic event shapes in e^+e^- annihilations*, *JHEP* **02** (2008) 040 [[arXiv:0712.0327](https://arxiv.org/abs/0712.0327)] [[INSPIRE](#)].
- [7] G. Dissertori et al., *Determination of the strong coupling constant using matched NNLO+NLLA predictions for hadronic event shapes in e^+e^- annihilations*, *JHEP* **08** (2009) 036 [[arXiv:0906.3436](https://arxiv.org/abs/0906.3436)] [[INSPIRE](#)].
- [8] R.M. Chatterjee, M. Guchait and D. Sengupta, *Probing supersymmetry using event shape variables at 8 TeV LHC*, *Phys. Rev. D* **86** (2012) 075014 [[arXiv:1206.5770](https://arxiv.org/abs/1206.5770)] [[INSPIRE](#)].

- [9] A. Datta, A. Datta and S. Poddar, *Enriching the exploration of the $mUED$ model with event shape variables at the CERN LHC*, *Phys. Lett. B* **712** (2012) 219 [[arXiv:1111.2912](#)] [[INSPIRE](#)].
- [10] P. Konar and P. Roy, *Event shape discrimination of supersymmetry from large extra dimensions at a linear collider*, *Phys. Lett. B* **634** (2006) 295 [[hep-ph/0509161](#)] [[INSPIRE](#)].
- [11] ALEPH collaboration, A. Heister et al., *Studies of QCD at e^+e^- centre-of-mass energies between 91 GeV and 209 GeV*, *Eur. Phys. J. C* **35** (2004) 457 [[INSPIRE](#)].
- [12] DELPHI collaboration, P. Abreu et al., *Tuning and test of fragmentation models based on identified particles and precision event shape data*, *Z. Phys. C* **73** (1996) 11 [[INSPIRE](#)].
- [13] L3 collaboration, M. Acciarri et al., *Study of hadronic events and measurements of α_s between 30 GeV and 91 GeV*, *Phys. Lett. B* **411** (1997) 339 [[INSPIRE](#)].
- [14] L3 collaboration, P. Achard et al., *Studies of hadronic event structure in e^+e^- annihilation from 30 GeV to 209 GeV with the L3 detector*, *Phys. Rept.* **399** (2004) 71 [[hep-ex/0406049](#)] [[INSPIRE](#)].
- [15] OPAL collaboration, P.D. Acton et al., *A determination of $\alpha_s(M_{Z^0})$ at LEP using resummed QCD calculations*, *Z. Phys. C* **59** (1993) 1 [[INSPIRE](#)].
- [16] 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](#)].
- [17] 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](#)].
- [18] T. Sjöstrand, S. Mrenna and P.Z. Skands, *PYTHIA 6.4 physics and manual*, *JHEP* **05** (2006) 026 [[hep-ph/0603175](#)] [[INSPIRE](#)].
- [19] 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](#)].
- [20] 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](#)].
- [21] CMS collaboration, *Jet and underlying event properties as a function of charged-particle multiplicity in proton-proton collisions at $\sqrt{s} = 7$ TeV*, *Eur. Phys. J. C* **73** (2013) 2674 [[arXiv:1310.4554](#)] [[INSPIRE](#)].
- [22] CMS collaboration, *Study of hadronic event-shape variables in multijet final states in pp collisions at $\sqrt{s} = 7$ TeV*, *JHEP* **10** (2014) 087 [[arXiv:1407.2856](#)] [[INSPIRE](#)].
- [23] 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](#)].
- [24] ATLAS collaboration, *Measurement of charged-particle event shape variables in $\sqrt{s} = 7$ TeV proton-proton interactions with the ATLAS detector*, *Phys. Rev. D* **88** (2013) 032004 [[arXiv:1207.6915](#)] [[INSPIRE](#)].
- [25] ATLAS collaboration, *Measurement of event-shape observables in $Z \rightarrow \ell^+\ell^-$ events in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector at the LHC*, *Eur. Phys. J. C* **76** (2016) 375 [[arXiv:1602.08980](#)] [[INSPIRE](#)].

- [26] ALICE collaboration, *Transverse sphericity of primary charged particles in minimum bias proton-proton collisions at $\sqrt{s} = 0.9, 2.76$ and 7 TeV*, *Eur. Phys. J. C* **72** (2012) 2124 [[arXiv:1205.3963](#)] [[INSPIRE](#)].
- [27] T. Sjöstrand et al., *An introduction to PYTHIA 8.2*, *Comput. Phys. Commun.* **191** (2015) 159 [[arXiv:1410.3012](#)] [[INSPIRE](#)].
- [28] J. Alwall et al., *The automated computation of tree-level and next-to-leading order differential cross sections and their matching to parton shower simulations*, *JHEP* **07** (2014) 079 [[arXiv:1405.0301](#)] [[INSPIRE](#)].
- [29] J. Bellm et al., *HERWIG 7.0/HERWIG++ 3.0 release note*, *Eur. Phys. J. C* **76** (2016) 196 [[arXiv:1512.01178](#)] [[INSPIRE](#)].
- [30] CMS collaboration, *The CMS experiment at the CERN LHC*, 2008 *JINST* **3** S08004 [[INSPIRE](#)].
- [31] CMS collaboration, *Particle-flow reconstruction and global event description with the CMS detector*, 2017 *JINST* **12** P10003 [[arXiv:1706.04965](#)] [[INSPIRE](#)].
- [32] M. Cacciari, G.P. Salam and G. Soyez, *The anti- k_t jet clustering algorithm*, *JHEP* **04** (2008) 063 [[arXiv:0802.1189](#)] [[INSPIRE](#)].
- [33] M. Cacciari, G.P. Salam and G. Soyez, *FastJet user manual*, *Eur. Phys. J. C* **72** (2012) 1896 [[arXiv:1111.6097](#)] [[INSPIRE](#)].
- [34] CMS collaboration, *Determination of jet energy calibration and transverse momentum resolution in CMS*, 2011 *JINST* **6** P11002 [[arXiv:1107.4277](#)] [[INSPIRE](#)].
- [35] NNPDF collaboration, R.D. Ball et al., *Parton distributions for the LHC run II*, *JHEP* **04** (2015) 040 [[arXiv:1410.8849](#)] [[INSPIRE](#)].
- [36] CMS collaboration, *Event generator tunes obtained from underlying event and multiparton scattering measurements*, *Eur. Phys. J. C* **76** (2016) 155 [[arXiv:1512.00815](#)] [[INSPIRE](#)].
- [37] P. Skands, S. Carrazza and J. Rojo, *Tuning PYTHIA 8.1: the Monash 2013 tune*, *Eur. Phys. J. C* **74** (2014) 3024 [[arXiv:1404.5630](#)] [[INSPIRE](#)].
- [38] J. Alwall et al., *Comparative study of various algorithms for the merging of parton showers and matrix elements in hadronic collisions*, *Eur. Phys. J. C* **53** (2008) 473 [[arXiv:0706.2569](#)] [[INSPIRE](#)].
- [39] T. Auye, *Unfolding algorithms and tests using RooUnfold*, in *Proceedings, PHYSTAT 2011 workshop on statistical issues related to discovery claims in search experiments and unfolding*, CERN-2011-006, CERN, Geneva, Switzerland, 17–20 January 2011, pg. 313 [[arXiv:1105.1160](#)] [[INSPIRE](#)].
- [40] G. D’Agostini, *A multidimensional unfolding method based on Bayes’ theorem*, *Nucl. Instrum. Meth. A* **362** (1995) 487 [[INSPIRE](#)].
- [41] A. Hocker and V. Kartvelishvili, *SVD approach to data unfolding*, *Nucl. Instrum. Meth. A* **372** (1996) 469 [[hep-ph/9509307](#)] [[INSPIRE](#)].
- [42] CMS collaboration, *Jet energy scale and resolution in the CMS experiment in pp collisions at 8 TeV*, 2017 *JINST* **12** P02014 [[arXiv:1607.03663](#)] [[INSPIRE](#)].

The CMS collaboration

Yerevan Physics Institute, Yerevan, Armenia

A.M. Sirunyan, A. Tumasyan

Institut für Hochenergiephysik, Wien, Austria

W. Adam, F. Ambrogio, E. Asilar, T. Bergauer, J. Brandstetter, M. Dragicevic, J. Erö, A. Escalante Del Valle, M. Flechl, R. Frühwirth¹, V.M. Ghete, J. Hrubec, M. Jeitler¹, N. Krammer, I. Krätschmer, D. Liko, T. Madlener, I. Mikulec, N. Rad, H. Rohringer, J. Schieck¹, R. Schöffbeck, M. Spanring, D. Spitzbart, A. Taurok, W. Waltenberger, J. Wittmann, C.-E. Wulz¹, M. Zarucki

Institute for Nuclear Problems, Minsk, Belarus

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

Universiteit Antwerpen, Antwerpen, Belgium

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

Vrije Universiteit Brussel, Brussel, Belgium

S. Abu Zeid, F. Blekman, J. D'Hondt, I. De Bruyn, J. De Clercq, K. Deroover, G. Flouris, D. Lontkovskiy, 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, Bruxelles, 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. Khvastunov², 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, C. Caputo, P. David, C. Delaere, M. Delcourt, B. Francois, A. Giammanco, G. Krintiras, V. Lemaître, A. Magitteri, A. Mertens, M. Musich, K. Piotrkowski, A. Saggio, M. Vidal Marono, S. Wertz, J. Zobec

Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil

F.L. Alves, G.A. Alves, M. Correa Martins Junior, 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. Chinellato³, E. Coelho, E.M. Da Costa, G.G. Da Silveira⁴, 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 Manganote³, 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

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. Fang⁵, X. Gao⁵, 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. Shaheen⁶, A. Spiezia, J. Tao, Z. Wang, E. Yazgan, H. Zhang, S. Zhang⁶, 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. Starodumov⁷, T. Susa

University of Cyprus, Nicosia, Cyprus

M.W. Ather, A. Attikis, M. Kolosova, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski

Charles University, Prague, Czech Republic

M. Finger⁸, M. Finger Jr.⁸

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.A. Abdelalim^{9,10}, A. Mahrous⁹, A. Mohamed¹⁰

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

S. Bhowmik, A. Carvalho Antunes De Oliveira, R.K. Dewanjee, K. Ehataht, M. Kadastik,
M. Raidal, C. Veelken

Department of Physics, University of Helsinki, Helsinki, Finland

P. Eerola, 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. Abdulsalam¹¹, C. Amendola, I. Antropov, F. Beaudette, P. Busson, C. Charlot,
R. Granier de Cassagnac, I. Kucher, A. Lobanov, J. Martin Blanco, C. Martin Perez,
M. Nguyen, C. Ochando, G. Ortona, P. Paganini, P. Pigard, J. Rembser, 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. Agram¹², J. Andrea, D. Bloch, J.-M. Brom, E.C. Chabert, V. Cherepanov, C. Collard,
E. Conte¹², J.-C. Fontaine¹², 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, S. Perries, A. Popov¹³, V. Sordini, G. Touquet, M. Vander Donckt, S. Viret

Georgian Technical University, Tbilisi, Georgia

T. Toriashvili¹⁴

Tbilisi State University, Tbilisi, Georgia

Z. Tsamalaidze⁸

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. Zhukov¹³

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

A. Albert, D. Duchardt, M. Endres, M. Erdmann, S. Erdweg, T. Esch, R. Fischer, S. Ghosh, A. Güth, T. Hebbeker, C. Heidemann, K. Hoepfner, H. Keller, L. Mastrolorenzo, M. Merschmeyer, A. Meyer, P. Millet, S. Mukherjee, T. Pook, M. Radziej, H. Reithler, M. Rieger, A. Schmidt, D. Teyssier, S. Thüer

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

G. Flügge, O. Hlushchenko, T. Kress, A. Künsken, T. Müller, A. Nehr Korn, A. Nowack, C. Pistone, O. Pooth, D. Roy, H. Sert, A. Stahl¹⁵

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. Borras¹⁶, V. Botta, A. Campbell, P. Connor, C. Contreras-Campana, V. Danilov, A. De Wit, M.M. Defranchis, C. Diez Pardos, D. Domínguez Damiani, G. Eckerlin, T. Eichhorn, A. Elwood, E. Eren, E. Gallo¹⁷, A. Geiser, A. Grohsjean, 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, J. Leonard, K. Lipka, W. Lohmann¹⁸, 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, H. Tholen, O. Turkot, 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, T. Dreyer, E. Garutti, D. Gonzalez, P. Gunnellini, J. Haller, A. Hinzmann, A. Karavdina, G. Kasieczka, R. Klanner, R. Kogler, N. Kovalchuk, S. Kurz, V. Kutzner, J. Lange, D. Marconi, J. Multhaupt, M. Niedziela, C.E.N. Niemeyer, 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, A. Vanhoefer, B. Vormwald, I. Zoi

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, K. El Morabit, N. Faltermann, B. Freund, M. Giffels, M.A. Harrendorf, F. Hartmann¹⁵, S.M. Heindl, U. Husemann, F. Kassel¹⁵, I. Katkov¹³, 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. Gerasis, 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, I. Papavergou, 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. Giannelios, 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. Bartók¹⁹, 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. Horvath²⁰, Á. Hunyadi, F. Sikler, T.Á. Vámi, V. Veszpremi, G. Vesztergombi[†]

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

N. Beni, S. Czellar, J. Karancsi²¹, 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. Bahinipati²², C. Kar, P. Mal, K. Mandal, A. Nayak²³, D.K. Sahoo²², S.K. Swain

Panjab University, Chandigarh, India

S. Bansal, S.B. Beri, V. Bhatnagar, S. Chauhan, R. Chawla, N. Dhingra, R. Gupta, A. Kaur, M. Kaur, S. Kaur, R. Kumar, P. Kumari, M. Lohan, A. Mehta, K. Sandeep, S. Sharma, J.B. Singh, A.K. Viridi, 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. Bhardwaj²⁴, M. Bharti²⁴, R. Bhattacharya, S. Bhattacharya, U. Bhawandeep²⁴, D. Bhowmik, S. Dey, S. Dutt²⁴, S. Dutta, S. Ghosh, K. Mondal, S. Nandan, A. Purohit, P.K. Rout, A. Roy, S. Roy Chowdhury, G. Saha, S. Sarkar, M. Sharan, B. Singh²⁴, S. Thakur²⁴

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. Maity²⁵, G. Majumder, K. Mazumdar, N. Sahoo, T. Sarkar²⁵

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. Chenarani²⁶, E. Eskandari Tadavani, S.M. Etesami²⁶, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, F. Rezaei Hosseinabadi, B. Safarzadeh²⁷, 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}, M. Ince^{a,b}, 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, G. Selvaggi^{a,b}, A. Sharma^a, L. Silvestris^a, 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}, E. Fontanesi,

P. Giacomelli^a, C. Grandi^a, L. Guiducci^{a,b}, S. Lo Meo^a, 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, Firenze, 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, Milano, 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, F. Monti, L. Moroni^a, M. Paganoni^{a,b}, D. Pedrini^a, S. Ragazzi^{a,b}, T. Tabarelli de Fatis^{a,b}, D. Zuolo^{a,b}

INFN Sezione di Napoli ^a, Università di Napoli 'Federico II' ^b, Napoli, Italy, Università della Basilicata ^c, Potenza, Italy, Università G. Marconi ^d, Roma, Italy

S. Buontempo^a, N. Cavallo^{a,c}, A. De Iorio^{a,b}, 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.Y. Hoh, S. Lacaprara^a, P. Lujan, M. Margoni^{a,b}, A.T. Meneguzzo^{a,b}, J. Pazzini^{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

M. Biasini^{a,b}, G.M. Bilei^a, C. Cecchi^{a,b}, D. Ciangottini^{a,b}, L. Fanò^{a,b}, P. Lariccia^{a,b}, R. Leonardi^{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, F. Fiori^{a,c}, 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}, 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^a, 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,b}, 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, A. Da Rold^{a,b}, 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.I. Pak, 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. Goh²⁹, 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 Ali³⁰, F. Mohamad Idris³¹, W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

Universidad de Sonora (UNISON), Hermosillo, Mexico

J.F. Benitez, A. Castaneda Hernandez, J.A. Murillo Quijada

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 Cruz³², R. Lopez-Fernandez, J. Mejia Guisao, R.I. Rabadan-Trejo, M. Ramirez-Garcia, 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, M. Szeleper, P. Traczyk, P. Zalewski

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

K. Bunkowski, A. Byszuk³³, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, A. Pyskir, M. Walczak

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

M. Araujo, P. Bargassa, C. Beirão Da Cruz E Silva, A. Di Francesco, P. Faccioli, B. Galinhas, M. Gallinaro, J. Hollar, N. Leonardo, M.V. Nemallapudi, J. Seixas, G. Strong, O. Toldaiev, D. Vadrucchio, J. Varela

Joint Institute for Nuclear Research, Dubna, Russia

S. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavine, A. Lanev, A. Malakhov, V. Matveev^{34,35}, P. Moisezenz, V. Palichik, V. Perelygin, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, N. Voytishin, A. Zarubin

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

V. Golovtsov, Y. Ivanov, V. Kim³⁶, E. Kuznetsova³⁷, 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. Stepenov, 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. Chadeeva³⁸, P. Parygin, D. Philippov, S. Polikarpov³⁸, E. Popova, V. Rusinov

P.N. Lebedev Physical Institute, Moscow, Russia

V. Andreev, M. Azarkin, I. Dremin³⁵, M. Kirakosyan, S.V. Rusakov, A. Terkulov

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

A. Baskakov, A. Belyaev, E. Boos, M. Dubinin³⁹, 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

A. Barnyakov⁴⁰, V. Blinov⁴⁰, T. Dimova⁴⁰, L. Kardapoltsev⁴⁰, Y. Skovpen⁴⁰

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, V. Okhotnikov

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, SerbiaP. Adzic⁴¹, 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. Vizán García

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. Villar Cortabitarte

University of Ruhuna, Department of Physics, Matara, Sri Lanka

N. Wickramage

CERN, European Organization for Nuclear Research, Geneva, SwitzerlandD. Abbaneo, B. Akgun, E. Auffray, G. Auzinger, P. Baillon, A.H. Ball, D. Barney, J. Bendavid, M. Bianco, A. Bocci, C. Botta, E. Brondolin, T. Camporesi, M. Cepeda, G. Cerminara, E. Chapon, Y. Chen, G. Cucciati, D. d'Enterria, A. Dabrowski, N. Daci, V. Daponte, A. David, A. De Roeck, N. Deelen, M. Dobson, M. Dünser, N. Dupont, A. Elliott-Peisert, P. Everaerts, F. Fallavollita⁴², D. Fasanella, G. Franzoni, J. Fulcher, W. Funk, D. Gigi, A. Gilbert, K. Gill, F. Glege, M. Guilbaud, D. Gulhan, J. Hegeman, C. Heidegger, V. Innocente, A. Jafari, P. Janot, O. Karacheban¹⁸, J. Kieseler, A. Kornmayer, M. Krammer¹, C. Lange, P. Lecoq, C. Lourenço, L. Malgeri, M. Mannelli, F. Meijers, J.A. Merlin, S. Mersi, E. Meschi, P. Milenovic⁴³, F. Moortgat, M. Mulders, J. Ngadiuba, S. Nourbakhsh, S. Orfanelli, L. Orsini, F. Pantaleo¹⁵, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, F.M. Pitters, D. Rabady, A. Racz, T. Reis, G. Rolandi⁴⁴, M. Rovere, H. Sakulin, C. Schäfer, C. Schwick, M. Seidel,

M. Selvaggi, A. Sharma, P. Silva, P. Sphicas⁴⁵, A. Stakia, J. Steggemann, M. Tosi, D. Treille, A. Tsirou, V. Veckalns⁴⁶, M. Verzetti, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland

L. Caminada⁴⁷, 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, T.A. Gómez Espinosa, C. Grab, D. Hits, T. Klijsma, 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, C. Reissel, 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. Amsler⁴⁸, D. Brzhechko, M.F. Canelli, A. De Cosa, R. Del Burgo, S. Donato, C. Galloni, T. Hreus, B. Kilminster, S. Leontsinis, 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, 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.F. Liu, R.-S. Lu, E. Paganis, A. Psallidas, A. Steen

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

B. Asavapibhop, N. Srimanobhas, N. Suwonjandee

Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey

A. Bat, F. Boran, S. Cerci⁴⁹, S. Damarseckin, Z.S. Demiroglu, F. Dolek, C. Dozen, I. Dumanoglu, E. Eskut, S. Girgis, G. Gokbulut, Y. Guler, E. Gurpinar, I. Hos⁵⁰, C. Isik, E.E. Kangal⁵¹, O. Kara, A. Kayis Topaksu, U. Kiminsu, M. Oglakci, G. Onengut, K. Ozdemir⁵², S. Ozturk⁵³, A. Polatoz, U.G. Tok, S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

Middle East Technical University, Physics Department, Ankara, Turkey

B. Isildak⁵⁴, G. Karapinar⁵⁵, M. Yalvac, M. Zeyrek

Bogazici University, Istanbul, Turkey

I.O. Atakisi, E. Gülmez, M. Kaya⁵⁶, O. Kaya⁵⁷, S. Ozkorucuklu⁵⁸, S. Tekten, E.A. Yetkin⁵⁹

Istanbul Technical University, Istanbul, Turkey

M.N. Agaras, A. Cakir, K. Cankocak, Y. Komurcu, S. Sen⁶⁰

**Institute for Scintillation Materials of National Academy of Science of Ukraine,
Kharkov, Ukraine**

B. Grynyov

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

L. Levchuk

University of Bristol, Bristol, United Kingdom

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. Newbold⁶¹, S. Paramesvaran, B. Penning, T. Sakuma, D. Smith, V.J. Smith, J. Taylor, A. Titterton

Rutherford Appleton Laboratory, Didcot, United Kingdom

K.W. Bell, A. Belyaev⁶², 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, United Kingdom

R. Bainbridge, P. Bloch, J. Borg, S. Breeze, O. Buchmuller, A. Bundock, D. Colling, 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. Nash⁶³, A. Nikitenko⁷, V. Palladino, M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, G. Singh, M. Stoye, T. Strebler, S. Summers, A. Tapper, K. Uchida, T. Virdee¹⁵, N. Wardle, D. Winterbottom, J. Wright, S.C. Zenz

Brunel University, Uxbridge, United Kingdom

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, U.S.A.

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

Catholic University of America, Washington DC, U.S.A.

R. Bartek, A. Dominguez

The University of Alabama, Tuscaloosa, U.S.A.

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

Boston University, Boston, U.S.A.

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

Brown University, Providence, U.S.A.

G. Benelli, X. Coubez, D. Cutts, M. Hadley, J. Hakala, U. Heintz, J.M. Hogan⁶⁴, K.H.M. Kwok, E. Laird, G. Landsberg, J. Lee, Z. Mao, M. Narain, S. Sagir⁶⁵, R. Syarif, E. Usai, D. Yu

University of California, Davis, Davis, U.S.A.

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, M. Mulhearn, D. Pellett, J. Pilot, S. Shalhout, M. Shi, D. Stolp, D. Taylor, K. Tos, M. Tripathi, Z. Wang, F. Zhang

University of California, Los Angeles, U.S.A.

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, U.S.A.

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, U.S.A.

J.G. Branson, P. Chang, 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. Wasserbaech⁶⁶, J. Wood, F. Würthwein, A. Yagil, G. Zevi Della Porta

University of California, Santa Barbara - Department of Physics, Santa Barbara, U.S.A.

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, U.S.A.

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, U.S.A.

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

University of Colorado Boulder, Boulder, U.S.A.

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

Cornell University, Ithaca, U.S.A.

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, U.S.A.

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, 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, C. Pena, O. Prokofyev, G. Rakness, L. Ristori, A. Savoy-Navarro⁶⁷, 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, U.S.A.

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, K.H. Lo, P. Ma, K. Matchev, H. Mei, G. Mitselmakher, D. Rosenzweig, K. Shi, D. Sperka, J. Wang, S. Wang, X. Zuo

Florida International University, Miami, U.S.A.

Y.R. Joshi, S. Linn

Florida State University, Tallahassee, U.S.A.

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

Florida Institute of Technology, Melbourne, U.S.A.

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

University of Illinois at Chicago (UIC), Chicago, U.S.A.

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, H. Trauger, N. Varelas, H. Wang, X. Wang, Z. Wu, J. Zhang

The University of Iowa, Iowa City, U.S.A.

M. Alhusseini, B. Bilki⁶⁸, W. Clarida, K. Dilsiz⁶⁹, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul⁷⁰, Y. Onel, F. Ozok⁷¹, A. Penzo, C. Snyder, E. Tiras, J. Wetzel

Johns Hopkins University, Baltimore, U.S.A.

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, U.S.A.

A. Al-bataineh, P. Baringer, A. Bean, S. Boren, J. Bowen, A. Bylinkin, 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, U.S.A.

S. Duric, 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, U.S.A.

F. Rebassoo, D. Wright

University of Maryland, College Park, U.S.A.

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, S. Nabili, F. Ricci-Tam, Y.H. Shin, A. Skuja, S.C. Tonwar, K. Wong

Massachusetts Institute of Technology, Cambridge, U.S.A.

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, U.S.A.

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

University of Mississippi, Oxford, U.S.A.

J.G. Acosta, S. Oliveros

University of Nebraska-Lincoln, Lincoln, U.S.A.

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, U.S.A.

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

Northeastern University, Boston, U.S.A.

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, U.S.A.

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, U.S.A.

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. Musienko³⁴, 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, U.S.A.

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

Princeton University, Princeton, U.S.A.

S. Cooperstein, P. Elmer, J. Hardenbrook, 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, U.S.A.

S. Malik, S. Norberg

Purdue University, West Lafayette, U.S.A.

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

Purdue University Northwest, Hammond, U.S.A.

T. Cheng, J. Dolen, N. Parashar

Rice University, Houston, U.S.A.

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

University of Rochester, Rochester, U.S.A.

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, P. Tan, R. Taus

Rutgers, The State University of New Jersey, Piscataway, U.S.A.

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

University of Tennessee, Knoxville, U.S.A.

A.G. Delannoy, J. Heideman, G. Riley, S. Spanier

Texas A&M University, College Station, U.S.A.

O. Bouhali⁷², A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, T. Kamon⁷³, S. Luo, R. Mueller, A. Perloff, L. Perniè, D. Rathjens, A. Safonov

Texas Tech University, Lubbock, U.S.A.

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

Vanderbilt University, Nashville, U.S.A.

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, U.S.A.

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, U.S.A.

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

University of Wisconsin - Madison, Madison, WI, U.S.A.

M. Brodski, J. Buchanan, C. Caillol, D. Carlsmith, S. Dasu, L. Dodd, B. Gomber, M. Grothe, M. Herndon, A. Hervé, U. Hussain, P. Klabbbers, A. Lanaro, K. Long, R. Loveless, T. Ruggles, A. Savin, V. Sharma, 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 University of Chinese Academy of Sciences, Beijing, China
- 7: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
- 8: Also at Joint Institute for Nuclear Research, Dubna, Russia
- 9: Also at Helwan University, Cairo, Egypt
- 10: Now at Zewail City of Science and Technology, Zewail, Egypt
- 11: Also at Department of Physics, King Abdulaziz University, Jeddah, Saudi Arabia
- 12: Also at Université de Haute Alsace, Mulhouse, France
- 13: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
- 14: Also at Tbilisi State University, Tbilisi, Georgia
- 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 Kyunghee University, Seoul, Korea
- 30: Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia
- 31: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia
- 32: Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico
- 33: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
- 34: Also at Institute for Nuclear Research, Moscow, Russia
- 35: Now at National Research Nuclear University ‘Moscow Engineering Physics Institute’ (MEPhI), Moscow, Russia

- 36: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
- 37: Also at University of Florida, Gainesville, U.S.A.
- 38: Also at P.N. Lebedev Physical Institute, Moscow, Russia
- 39: Also at California Institute of Technology, Pasadena, U.S.A.
- 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 University, Faculty of Science, Istanbul, Turkey
- 59: Also at Istanbul Bilgi University, Istanbul, Turkey
- 60: Also at Hacettepe University, Ankara, Turkey
- 61: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
- 62: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
- 63: Also at Monash University, Faculty of Science, Clayton, Australia
- 64: Also at Bethel University, St. Paul, U.S.A.
- 65: Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
- 66: Also at Utah Valley University, Orem, U.S.A.
- 67: Also at Purdue University, West Lafayette, U.S.A.
- 68: Also at Beykent University, Istanbul, Turkey
- 69: Also at Bingol University, Bingol, Turkey
- 70: Also at Sinop University, Sinop, Turkey
- 71: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
- 72: Also at Texas A&M University at Qatar, Doha, Qatar
- 73: Also at Kyungpook National University, Daegu, Korea