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Author(s):
CMS Collaboration; Khachatryan, Vardan; Bachmair, Felix; Bäni, Lukas; Bianchini, Lorenzo; Casal, Bruno; Dissertori, Günther; Dittmar, Michael; Donegà, Mauro; Eller, Philipp; Grab, Christoph; Heidegger, Constantin; Hits, Dmitry; Hoss, Jan; Kasieczka, Gregor; Lecomte, Pierre; Lustermann, Werner; Mangano, Boris; Marionneau, Matthieu; Martinez Ruiz del Arbol, Pablo; Masciovecchio, Mario; Meinhard, Maren T.; Meister, Daniel; Micheli, Francesco; Musella, Pasquale; Nessi-Tedaldi, Francesca; Pandolfi, Francesco; Pata, Joosep; Pauss, Felicitas; Perrin, Gaël; Perrozzi, Luca; Quittnat, Milena; Rossini, Marco; Schönenberger, Myriam; Starodumov, Andrey; Takahashi, Maiko; Tavolaro, Vittorio R.; Theofilatos, Konstantinos; Wallny, Rainer; et al.

Studies of inclusive four-jet production with two *b*-tagged jets in proton-proton collisions at 7 TeV

V. Khachatryan *et al.*[*]

(CMS Collaboration)

Measurements are presented of the cross section for the production of at least four jets, of which at least two originate from *b* quarks, in proton-proton collisions. Data collected with the CMS detector at the LHC at a center-of-mass energy of 7 TeV are used, corresponding to an integrated luminosity of 3 pb^{-1}. The cross section is measured as a function of the jet transverse momentum for $p_T > 20$ GeV, and of the jet pseudorapidity for $|\eta| < 2.4$ (*b* jets), 4.7 (untagged jets). The correlations in azimuthal angle and p_T between the jets are also studied. The inclusive cross section is measured to be $\sigma(pp \rightarrow 2b + 2j + X) = 69 \pm 3(\text{stat}) \pm 24(\text{syst})$ nb. The η and p_T distributions of the four jets and the correlations between them are well reproduced by event generators that combine perturbative QCD calculations at next-to-leading-order accuracy with contributions from parton showers and multiparton interactions.

I. INTRODUCTION

The production of jets with large transverse momenta (p_T) in high-energy proton-proton (pp) collisions originates from parton-parton scattering, a process well described by quantum chromodynamics (QCD), the theory of the strong interaction. The cross section is evaluated as the convolution of the partonic cross sections and the parton distribution functions (PDF) in the proton. At the CERN LHC, the inclusive cross section measured for high-p_T jet production [1–3] is in good agreement with the predictions of perturbative QCD (pQCD) calculations at next-to-leading order (NLO) accuracy.

Multijet final states allow studies of further features of pQCD. While at leading order (LO) a parton pair (dijet) is produced in a single parton scattering (SPS); additional jets at lower momenta can originate from two other sources. Either they arise from additional gluon radiation from SPS, or they result from double parton scattering (DPS) processes where two different pairs of partons from the two protons collide independently. The SPS processes provide tests of higher-order pQCD calculations as well as of the parton shower evolution. The contributions from DPS processes increase with center-of-mass energies as the gluon density becomes large at low values of longitudinal momentum fraction in the protons. Experimentally, SPS and DPS contributions can be separated by exploiting the different final-state topology of the two processes. Final states arising from SPS exhibit strong azimuthal and p_T

correlations among all final jets, while DPS final states predominantly have a back-to-back topology only for each of the independently produced jet pairs. Measurements of DPS signals have been performed at different collision energies and for different channels [4–10]. At 7 TeV, exclusive four-jet final states have been measured by CMS [11], and *W*+dijet production has been studied by ATLAS [12] and CMS [13]. Various DPS-sensitive final states have also been measured without a direct extraction of the DPS signal by CMS [14,15] and ATLAS [16,17]. The present study complements the four-jet measurement [11] by selecting events with jets originating from bottom quarks (denoted as "*b* jets"). In a four-jet sample, the SPS and DPS contributions can be disentangled by exploiting the differences expected in the angular and momentum correlations of the measured jets, as discussed in Refs. [18–20]. The requirement of *b* jets allows grouping the four jets into two pairs according to their flavor, and selecting them with lower p_T thresholds than in the untagged case, thereby facilitating the identification of DPS contributions present in the data sample.

This paper presents a measurement of DPS-sensitive observables in heavy-flavor multijet final states. The results are compared to the predictions of various Monte Carlo (MC) event generators using fixed-order NLO matrix elements, and including the contributions of parton showers and multiple parton interactions (MPI). The latter processes are needed, in particular, to describe the softer hadronic production coming from the "underlying event" (UE). The MC generators used implement the DPS component as a high-p_T extension of the modeling of MPI at p_T values of the order of 3–5 GeV [21]. The parameters that control the simulation of softer MPI are assumed to be the same for the generation of MPI at higher-p_T scales, i.e., of DPS processes. This assumption is used for the predictions

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[*]Full author list given at the end of the article.

based on either LO or NLO matrix element calculations. The MC event generators generally simulate MPI starting from the scale corresponding to the hardest parton-parton scattering provided by the matrix element calculation. In LO event generators, such as PYTHIA and HERWIG++, such a scale is the p_T of the partons participating in the hard scattering, while in NLO dijet generators, e.g., POWHEG, or multijet generators (without NLO virtual corrections), such as MADGRAPH, the p_T of the additional outgoing partons in the matrix element calculation is also relevant for the definition of the MPI scale. Comparing the predictions of these generators with DPS-sensitive observables in data is an important step to validate the extrapolation from soft to hard MPI, and thereby the matching of the matrix element calculations to the simulation of the UE.

The paper is organized as follows. In Sec. II, a brief detector description is presented along with details of the MC simulations. In Sec. III, the event selection and analysis strategy are described, while Sec. IV illustrates the corrections applied to the data and the systematic uncertainties that affect the measurement. Section V presents the results, which are then summarized in Sec. VI.

II. THE CMS DETECTOR AND MONTE CARLO SIMULATION

The central feature of the CMS apparatus is a super-conducting solenoid, of 6 m internal diameter and 15 m in length, which provides a magnetic field of 3.8 T. Charged-particle trajectories are measured using silicon pixel and strip trackers that cover the pseudorapidity region $|\eta| < 2.5$. An electromagnetic crystal calorimeter (ECAL), and a brass/scintillator hadron calorimeter (HCAL) surround the tracking volume and cover the region $|\eta| < 3.0$. A forward quartz-fiber Cherenkov hadron calorimeter extends the coverage to $|\eta| \leq 5.2$. Muons are measured in the range $|\eta| < 2.4$ in gas-ionization detectors embedded in the steel flux-return yoke of the magnet. The CMS experiment uses a two-level trigger system consisting of a level-1 trigger based on custom hardware using signals from the muon detectors and the calorimeters, and a high level trigger (HLT) based on a farm of computers that have access to the full data for each event. A more detailed description of the CMS detector can be found elsewhere [22].

Samples of multijet events are produced with the following MC event generators:

(i) PYTHIA 6.426 [23], PYTHIA 8.185 [24], and HERWIG++ 2.5.0 [25]. All of them use LO $2 \to 2$ matrix elements. The PYTHIA 6 and PYTHIA 8 event generators simulate parton showers ordered in p_T and use the Lund string model [26] for hadronization, while HERWIG++ assumes parton showers with radiated gluons ordered in emission angle (angular ordering), and uses a cluster fragmentation model [27] for hadronization. The PYTHIA and HERWIG++ samples are generated with transverse momentum of

the outgoing partons $\hat{p}_T > 15$ GeV. The contribution of MPI is also simulated in PYTHIA and HERWIG++. The PYTHIA 6 event generator with tune Z2* [28] uses a model [29] where MPI are interleaved with parton showering. Predictions obtained with PYTHIA 6 and PYTHIA 8 with the CUETS1 tunes [21] are also considered. These use the CTEQ6L1 PDF set [30] and include an improved set of UE parameters [21]. The HERWIG++ event generator with two tunes to LHC data, UE-EE-3 [31] with the MRST LO** PDF set [32,33] and UE-EE-5-CTEQ6L1 [34] with the CTEQ6L1 PDF set, is also used for comparison. The parameters of the hadronization model are determined from LEP data for both PYTHIA [35] and HERWIG++ [31].

(ii) POWHEG 1.0 [36,37] matched to the PYTHIA 8 parton showers including a simulation of MPI. The POWHEG event generator uses NLO dijet matrix elements implemented via $2 \to 2$ and $2 \to 3$ diagrams. These matrix elements include only LO effects for the four-jet configuration of the present analysis. For the hard-scattering process, the HERAPDF1.5NLO [38] PDF set is used with a minimum $\hat{p}_T$ of 5 GeV. The b quarks are treated as massless in the matrix element calculation. The UE provided by PYTHIA 8 is simulated with the CUETS1 tune, which uses the HERAPDF1.5LO [38] PDF set and reproduces with very high precision UE and jet observables at various collision energies. Since the POWHEG predictions contain both real and virtual corrections for the dijet matrix elements, they are used as the reference baseline in the present analysis. Therefore, the full theoretical uncertainty is provided for the POWHEG simulation, while only the central predictions are provided for the other MC simulations.

(iii) MADGRAPH 5.1.5 [39] interfaced with PYTHIA 8. The MADGRAPH predictions use a LO multijet matrix element with up to four final-state partons, calculated with the CTEQ6L1 PDF, and a simulation of the UE provided by PYTHIA 8 tune CUETM1 [21], which uses the NNPDF2.3LO PDF set [40,41]. The p_T sum of the four partons, H_T, is required to be $H_T > 50$ GeV, and the b quarks are treated as massless. The matching scale between the matrix element calculations and the parton shower simulation is taken to be 10 GeV, within the k_T-MLM scheme [42]. Underlying event data are well described by this combination of matrix elements plus parton showers with a proper UE tune [21].

The detector response is simulated in detail with the GEANT4 package [43]. All simulated samples are processed and reconstructed in the same manner as collision data. The multijet final state can be mimicked by various background sources, such as Drell-Yan and W boson production associated to jets, and top-antitop events. The size of these

backgrounds is estimated with PYTHIA 8 and found to be negligible, with a cross section in the measured phase space less than 0.5% of that for pure QCD multijet events. Therefore, these background sources are neglected in the following.

III. EVENT SELECTION

This analysis uses data from pp collisions at $\sqrt{s} = 7$ TeV recorded with the CMS apparatus in 2010 corresponding to an integrated luminosity of 3 pb^{-1}. The data were collected at low luminosity ($< 0.2 \times 10^{33}$ cm^{-2} s^{-1}), and consequently with low probability of multiple pp interactions in the same bunch crossing (pileup). These running conditions correspond to a fraction of the total integrated luminosity of 36 pb^{-1} collected in 2010. The mean number of interactions per bunch crossing is around 1.6 for this sample, which results in small pileup effects in the measured distributions. The MC samples are reweighted to the number of interactions in the data in order to match the multiplicity of reconstructed primary vertices.

For the present study, three HLT single-jet trigger sets are analyzed: one with jet p_T threshold of 15 GeV is used for leading jets with $20 < p_T < 50$ GeV, a second with p_T threshold of 30 GeV for leading jets with $50 < p_T < 140$ GeV, and a third with p_T threshold of 50 GeV for leading jets with p_T above 140 GeV. In the region $20 < p_T < 80$ GeV, the trigger efficiency is less than 100%, increasing from 45% for leading jets with $p_T \approx 20$ GeV. A correction is thus applied as a function of the leading jet p_T and η. For leading jet $p_T > 80$ GeV, the trigger is fully efficient. The choice of such regions is a compromise between statistics and reliability of the trigger efficiency correction.

The physics objects used in this analysis are particle flow (PF) jets [44]. The PF algorithm [45] combines information from all relevant CMS subdetectors to identify and reconstruct all particle candidates in the event, namely leptons, photons, and charged and neutral hadrons. The energy of the muons is obtained from the corresponding track momentum. Charged hadrons are reconstructed from tracks in the tracker. The energy of the electrons is determined from a combination of the track momentum at the main interaction vertex, the corresponding ECAL cluster energy, and the energy sum of all bremsstrahlung photons attached to the track. Photons and neutral hadrons are reconstructed from energy clusters in the ECAL and HCAL, respectively; only clusters far away from the extrapolated position of any track are used. Jets are reconstructed from the four-momenta of the PF candidates with the anti-k_T algorithm [46] with a distance parameter of 0.5. A tight quality selection [47] is applied to suppress unphysical jets, i.e., jets resulting from noise in the ECAL and/or HCAL. Each jet is required to contain at least two PF candidates, one of which has to be a charged hadron. The jet energy fraction

carried by neutral hadrons, photons, muons, and electrons must be less than 90%. With these criteria, jets are selected with an efficiency greater than 99% and a misidentification rate (i.e., the probability of selecting fake jets, like e.g., those originating from leptons or calorimeter noise) smaller than 0.5% for jet $p_T > 20$ GeV. A jet p_T correction is applied to both data and simulation to account for the nonlinear response of the calorimeters and other instrumental effects. These corrections are based on *in situ* measurements using dijet, $\gamma + $ jet, and $Z + $ jet data samples [48].

A primary vertex (PV) is identified by a collection of tracks measured in the tracker. If more than one PV is present, the vertex with the highest sum of the squared p_T of the tracks associated to it is selected. The selected vertex is required to be reconstructed from at least five charged-particle tracks and must satisfy a set of quality requirements, including $|z_{PV}| < 24$ cm and $\rho_{PV} < 2$ cm, where z_{PV} and ρ_{PV} are the longitudinal and transverse distances of the PV from the nominal interaction point in the CMS detector.

The b jets are identified by using information on the secondary decay vertex of the b hadrons, the impact parameter significance, i.e., the three-dimensional impact parameter divided by its resolution, and the tracks and jet kinematics [49], through the so-called "combined secondary vertex" (CSV) discriminant. A loose selection [49] is used in the b-tagging algorithm, which gives a b-tagging efficiency on single jets larger than 75% for jet $p_T > 20$ GeV, with a maximum of 85% at $p_T \approx 150$ GeV, as estimated by simulation studies with the PYTHIA 6 sample. The light-flavor (u, d, s quark or gluon) mistag probability is 20%, 10% and 15% for $p_T \approx 20$, 75 and 300 GeV, respectively, for $|\eta| < 2$, increasing to 35% for jets in the region $2.0 < |\eta| < 2.4$. This loose selection provides a high-statistics sample, though with relatively few genuine b jets. After requiring the two b tags, the b jet purity, i.e. the percentage of selected events where both tagged jets originate from b quarks, is about 12% for this loose selection. The highest-p_T (leading) b-tagged jet is a genuine b jet in 18% of the selected events, while the fraction of events where the second-highest-p_T (subleading) b-tagged jet originates from a b quark is about 14%. There is a high degree of correlation between the purities of the leading and the subleading jets. From simulation studies, about 65% of the selected events with a true leading b jet also contain a true subleading b jet. The b jet purity of the medium selection for the b-tagging algorithm [49] is 58% for the current analysis. Since the results obtained with the medium selection are consistent with those obtained with the loose selection within the systematic uncertainties, we use the latter results, which have higher statistical accuracy.

The correction for the events with four jets that pass the selection criteria but for which the two b-tagged jets

are not genuine b jets is performed through the unfolding procedure employed to obtain stable-particle level distributions (Sec. IV). The amount of this type of background is estimated from the purity of the measured distributions. The measurement of the b jet purity is based on fits of the track counting high efficiency (TCHE) distributions [49] of each b-tagged jet with three different shape templates obtained from MC simulation, corresponding to the TCHE values for light-quark and gluon, charm, and bottom jet flavors. The TCHE discriminant corresponds to the second-highest

impact parameter significance among all selected tracks belonging to the considered jet. The b jet purities measured in the data and those in the simulation differ by 2%–7%. Scale factors ($\mathrm{SF}_{b\text{-purity}}$), depending on jet p_T and η, are applied to the simulation to correct for this difference. By applying $\mathrm{SF}_{b\text{-purity}}$ to the simulated events, the b jet purity of the data sample passing the analysis criteria is consistent with that of the MC simulation. Compatible results are obtained if the CSV discriminant of the b-tagged jets is used in the fitting procedure, instead of TCHE distributions. The b jet purity of the
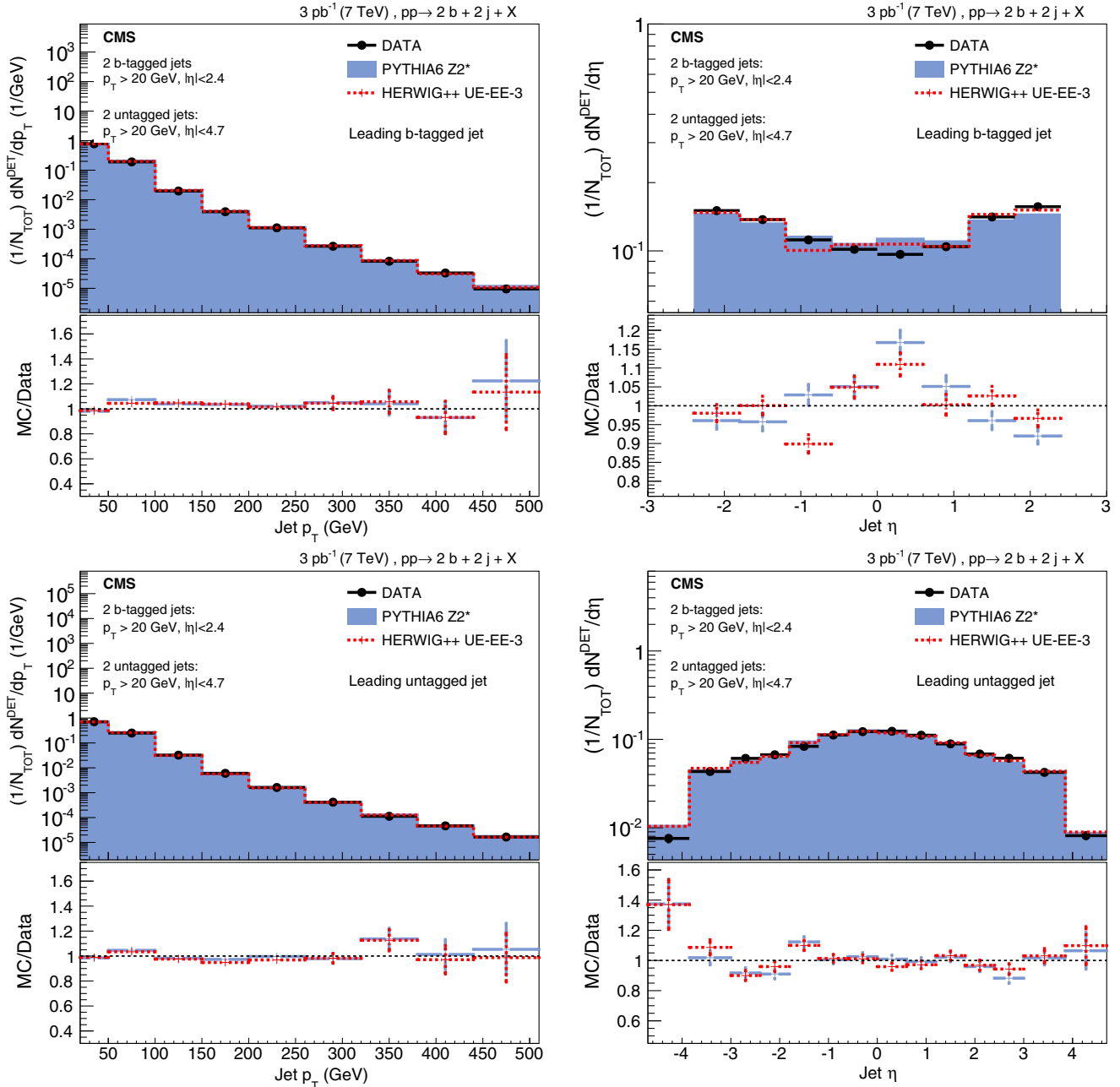

FIG. 1. Uncorrected transverse momentum (left) and pseudorapidity (right) distributions of data and simulations (PYTHIA 6 and HERWIG++) for the leading b-tagged (top) and leading untagged (bottom) jets. Only statistical uncertainties are shown.

selection is estimated in the data separately for leading and subleading b-tagged jets in different bins of p_T and η.

Additional scale factors ($SF_{b\text{-tag}}$) are applied to the simulation in order to match the b-tagging efficiencies measured in data [49]. They depend on the jet p_T, η, and flavor, and range between 0.9 and 1.1.

A further reweighting as a function of $\hat{p}_T$ is applied to the LO generators used for data correction, in order to improve their description of the measured distributions.

Events with at least one PV and at least four jets with $p_T > 20$ GeV are selected for the analysis: two of the four jets are the two b-tagged jets with highest p_T within $|\eta| < 2.4$, while the other two are the remaining highest-p_T jets selected within $|\eta| < 4.7$ without any b-tagging requirement. If two or more b-tagged jets are present, the two with the highest p_T are taken as the "b quark jet pair" (referred to as bottom hereafter). The "untagged jet pair" (referred to as light hereafter) is taken as the remaining two leading jets. The two different η ranges are chosen because the absence of the tracker in the forward region does not allow b jets to be identified for $|\eta| > 2.4$.

About 60 000 events are left in the data after the offline selection described above. In Fig. 1, the shapes of the p_T and η distributions of the leading b-tagged and the leading untagged jet are compared to predictions of PYTHIA 6 and

HERWIG++, before unfolding to the stable-particle level. These shapes are well described by both MC simulations in the central region and over the whole range of p_T, while there are differences of up to 20%–40% for the most forward pseudorapidities ($|\eta| > 3$).

Differential cross sections (referred to as "absolute cross sections" hereafter) as a function of p_T and η of each of the four jets are measured in this analysis. In addition, differential distributions normalized to the total number of selected events (referred to as "normalized cross sections") are measured as a function of jet correlation variables very similar to those used in the four-jet analysis of Ref. [11],

(i) the difference in azimuthal angle (in the plane transverse to the beam axis, in radians) between the jets belonging to the light-jet pair,

$$\Delta\phi_{\text{light}} = |\phi_{\text{light}_1} - \phi_{\text{light}_2}|; \qquad (1)$$

(ii) the balance in p_T of the two light jets,

$$\Delta_{\text{light}}^{\text{rel}} p_T = \frac{|\vec{p}_T^{\,\text{light}_1} + \vec{p}_T^{\,\text{light}_2}|}{|\vec{p}_T^{\,\text{light}_1}| + |\vec{p}_T^{\,\text{light}_2}|}; \qquad (2)$$

(iii) the azimuthal angle ΔS between the two dijet pairs, defined as

$$\Delta S = \arccos\left[\frac{\vec{p}_T(\text{bottom}_1, \text{bottom}_2) \cdot \vec{p}_T(\text{light}_1, \text{light}_2)}{|\vec{p}_T(\text{bottom}_1, \text{bottom}_2)| \cdot |\vec{p}_T(\text{light}_1, \text{light}_2)|}\right], \qquad (3)$$

where bottom$_1$ (bottom$_2$) and light$_1$ (light$_2$) are the leading (subleading) jets of the bottom and light-jet pairs, respectively, and $\vec{p}_T(\text{bottom}_1, \text{bottom}_2)$ and $\vec{p}_T(\text{light}_1, \text{light}_2)$ the momentum vectors of each pair, obtained as the vectorial sum of the momenta of the bottom and light jets, respectively.

Results of the jet correlation observables are presented as distributions normalized to the number of events measured in the selected kinematic region. Such normalized distributions are affected by smaller systematic uncertainties than the absolute cross section measurements.

IV. CORRECTIONS AND SYSTEMATIC UNCERTAINTIES

Particle-level distributions are inferred from the reconstructed data by correcting for selection efficiencies and detector effects. The results are corrected to particle level by applying an iterative unfolding [50] as implemented in the ROOUNFOLD package [51]. Particles are considered stable if their mean path length $c\tau$ is greater than 10 mm. MC jets are identified as b jets at the particle level if a b quark is found within a cone of radius

$R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.3$ around the jet axis. The background consisting of events with four jets that pass the selection criteria but for which the b-tagged jets are not genuine b jets is corrected for with PYTHIA 6 tune Z2*, after applying the $SF_{b\text{-tag}}$ and $SF_{b\text{-purity}}$ scale factors. The correlation between events selected at the reconstructed and particle levels is then studied by constructing the response matrix. The response matrix quantifies the migration probability between the particle-level and reconstructed quantities, as well as the overall reconstruction efficiency. It is obtained for each observable with the PYTHIA 6 tune Z2* sample. Diagonal terms in the response matrix correspond to particle-level quantities that are reconstructed in the same bin after detector simulation. Off-diagonal terms represent the probability of migration between bins at the particle level and bins at the reconstructed level. As an example, Fig. 2 shows the response matrices for the p_T and the η of the leading b-tagged and the leading untagged jet. They exhibit a diagonal structure, with off-diagonal terms less than 30%–40%. The bin widths are larger than the detector resolution at each bin.

The response matrix obtained with PYTHIA 6 is used for the data unfolding. As a cross-check, a sample of events generated with HERWIG++ tune UE-EE-3 is unfolded with
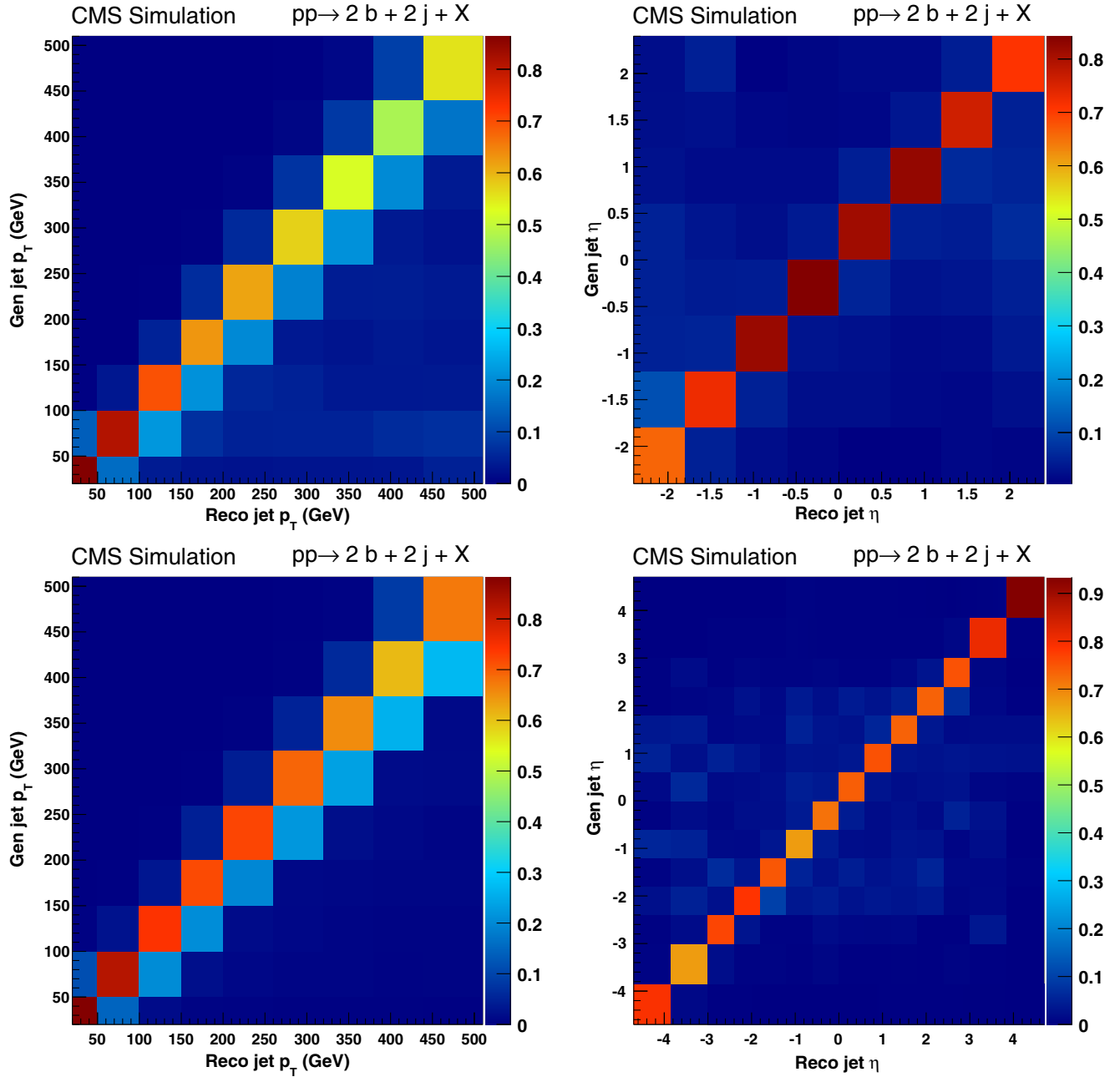
FIG. 2.   Response matrices obtained with the PYTHIA 6 tune Z2* simulation for the transverse momentum (left) and pseudorapidity (right) of the leading *b*-tagged (top) and leading untagged (bottom) jets.

the PYTHIA 6 response matrix. All distributions agree with the generated ones within 9%–20%. The iterative unfolding procedure is regularized by limiting the number of iterations to a certain value for each measured distribution. The optimal number of iterations is determined by minimizing the difference between the distributions measured in the data and the ones obtained by applying backwards the detector effects to the unfolded distributions. The number of iterations ranges between 2 and 4 depending on the observable. As expected, the statistical uncertainties of the unfolded distributions are larger than those of the

reconstructed data. The unfolding to particle level includes corrections for jet resolution, flavor misidentification, and pileup effects. The results are presented in the kinematic region defined in Table I.

TABLE I.   Phase space for the cross section measurement.

At least four jets	$p_T > 20$ GeV
Two leading *b* jets	$|\eta| < 2.4$
Two leading other jets	$|\eta| < 4.7$

TABLE II.   Systematic and statistical uncertainties affecting the absolute and the normalized cross sections for each measured observable: each source of uncertainty is specified and the value is the average over all the bins of the observable. The 4% uncertainty from the integrated luminosity is included in the total uncertainty affecting the absolute cross sections. The total uncertainty is obtained by summing the individual experimental uncertainties quadratically. The theoretical uncertainties, listed in the last two columns, affect all the predictions. The systematic uncertainties in the normalized cross sections are smaller than those for the absolute cross sections, since, among others, they are not affected by the migration effects from outside the selected phase space.

Measured observable	Model	JES	JER	$SF_{b\text{-tag}}$	$SF_{b\text{-purity}}$	Trigger efficiency	Stat	Total incl. int. lumi,	PDF	Scale
					Absolute cross sections					
b-tagged jet p_T	20%	25%	4%	15%	12%	6%	4%	38%	10%	10%
Untagged jet p_T	10%	25%	4%	15%	12%	6%	4%	34%	10%	10%
Jet $|\eta| \leq 3$	10%	25%	4%	15%	12%	5%	4%	34%	15%	10%
Jet $|\eta| > 3$	20%	35%	4%	15%	12%	5%	4%	45%	50%	15%
					Normalized cross sections					
$\Delta\phi^{\text{light}}$	13%	5%	1%	2%	1%	1%	4%	15%	5%	2%
$\Delta^{\text{rel}}_{\text{light}}p_T$	13%	5%	7%	2%	1%	1%	4%	16%	5%	2%
ΔS	20%	5%	10%	2%	2%	1%	4%	23%	10%	2%

All significant sources of systematic uncertainties are investigated and the corresponding uncertainty is calculated for each distribution. The total uncertainty is obtained by summing up the individual contributions in quadrature. The following systematic effects are considered:

(i) *Model dependence.* The response matrix obtained with PYTHIA 6 is used for the final correction, and the difference between this and that obtained with HERWIG++ is taken as a measure of the model dependence of the unfolding, resulting in an uncertainty ranging from 9% to 20%.

(ii) *Jet energy scale (JES).* The momentum of the jets is varied according to the uncertainty associated with the reconstructed p_T [48]. The resulting uncertainty is of the order of 20%–25% (5%) for the absolute (normalized) cross sections.

(iii) *Jet energy resolution (JER).* The JER differs for data and simulation by 6%–19% [48] depending on the η range, and introduces a systematic uncertainty of 4%–8% in all results.

(iv) *Pileup reweighting.* The effect of the pileup reweighting procedure is evaluated and found to be negligible ($< 0.1\%$).

(v) *B-tagging scale factor* ($SF_{b\text{-tag}}$). The values of the scale factors are varied by 10% for each jet flavor [49]. This variation results in an uncertainty of 15%–18% for absolute cross sections and of 1%–2% for the normalized ones.

(vi) *B jet purity.* The b jet purity of the sample is evaluated by fitting separately the TCHE distribution of the leading and of the subleading b-tagged jet in bins of p_T, η and ΔS. The difference between the unfolded results when using the $SF_{b\text{-purity}}$ obtained from the two fits is used as a systematic uncertainty, resulting in values of 10%–12% for the absolute cross sections and 1%–2% for the normalized distributions.

(vii) *Trigger efficiency.* The trigger efficiency correction is varied within its uncertainty and the resulting corrections are applied to the data. These variations result in an uncertainty ranging from 1% to 6%.

(viii) *Integrated luminosity.* The systematic uncertainty on the luminosity of the 2010 data, affecting the absolute cross sections, is 4% [52].

The dominant source of uncertainty is the JES, which is considered as correlated among the measured bins. The

TABLE III.   Inclusive cross section for $pp \to 2b + 2j + X$ for jet $p_T > 20$ GeV, with b jets within $|\eta| < 2.4$, and the other jets within $|\eta| < 4.7$. The measurements are compared to the MC predictions.

Sample	PDF	Cross section (nb)
Data	…	$69 \pm 3(\text{stat}) \pm 24(\text{syst})$
POWHEG+PYTHIA 8 tune CUETS1	HERAPDF1.5	65 ± 12
POWHEG+PYTHIA 8 tune CUETS1 MPI off	HERAPDF1.5	31 ± 6
PYTHIA 6 tune Z2*	CTEQ6L1	77 ± 15
PYTHIA 6 tune CUETS1	CTEQ6L1	77 ± 15
HERWIG++ tune UE-EE-3	MRST LO**	44 ± 8
HERWIG++ tune UE-EE-5C	CTEQ6L1	47 ± 9
PYTHIA 8 tune CUETS1	CTEQ6L1	96 ± 18
MADGRAPH+PYTHIA 8 tune CUETM1	CTEQ6L1	39 ± 7

following aspects of the theoretical uncertainty affecting the POWHEG predictions are also evaluated:

(i) *PDF uncertainty.* The choice of the PDF set influences the theoretical predictions. The uncertainty related to the PDF is determined by generating predictions with various PDF eigenvectors. As the central PDF set, the HERAPDF1.5NLO together with the PYTHIA 6 tune CUETS1 is used.

(ii) *Scale uncertainty.* The default renormalization and the factorization scales (μ_R and μ_F) in the matrix element calculations are chosen to be equal to the leading jet p_T value. The uncertainty related to the μ_R and μ_F choices is estimated by using POWHEG interfaced to the UE simulation provided by PYTHIA 8 tune CUETS1-HERAPDF. Six combinations of the (μ_R/p_T, μ_F/p_T) scales, (0.5, 0.5), (0.5, 1), (1, 0.5), (1, 2), (2, 1), and (2, 2), are used. The scale uncertainties are evaluated by taking the

FIG. 3. Differential cross sections unfolded to the particle level as a function of the jet transverse momenta p_T (left) and pseudorapidity η (right) compared to predictions of POWHEG +PYTHIA 8 tune CUETS1. Scale factors of 10^8, 10^6, and 10^2 are applied (for clarity) to the measurement of the leading, subleading, and third jet, respectively. The error bars on the data represent the total uncertainties, i.e., statistical and systematic added quadratically. The band represents the theoretical uncertainty due to the choice of the scales and PDFs.
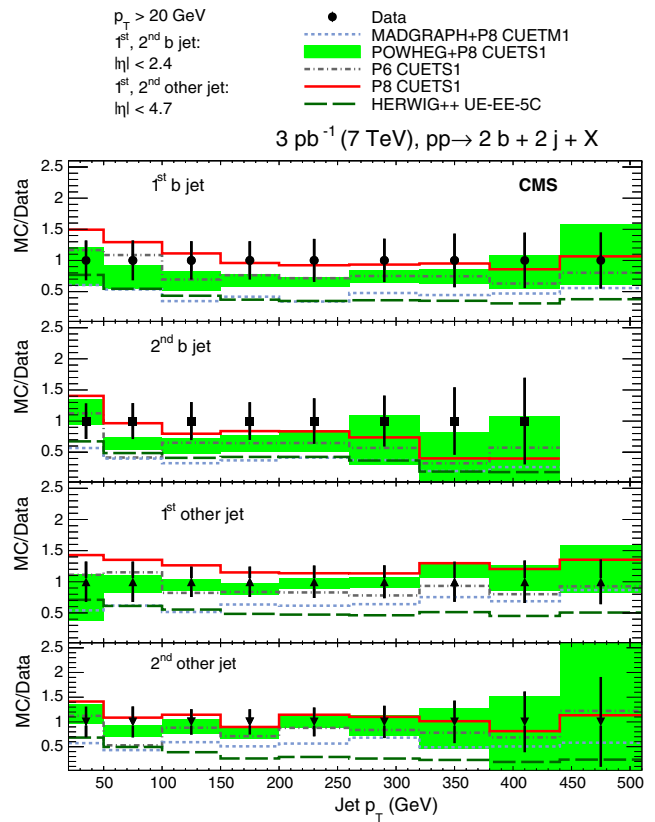
FIG. 4. Ratios of the absolute cross section predictions of POWHEG, MADGRAPH, PYTHIA 6 (P6), PYTHIA 8 (P8), and HERWIG++ over data (unfolded to the particle level) as a function of the jet transverse momenta p_T for each jet. The error bars on the data represent the total uncertainties, i.e., statistical and systematic added quadratically. Data are shown with markers at unity. The band represents the theoretical uncertainty due to the choice of the scales and PDFs (shown only around the POWHEG ratio for clarity, but affecting all predictions in the same way).

envelope of the predictions obtained with the listed scale choices.

A summary of all the systematic effects is given in Table II.

V. RESULTS

The absolute differential cross sections are measured as a function of the jet p_T and η, along with the normalized cross sections as a function of the jet correlation variables. In Table III, the cross section is given, and compared to predictions from different event generators at the particle level. The POWHEG event generator interfaced with PYTHIA 8 tune CUETS1, referred to in the following as POWHEG, reproduces the measured cross section best. However, if the MPI simulation is switched off, the same POWHEG predictions, referred to in the following as "POWHEG MPI-off," underestimate the value of the measured cross section. All predictions are consistent with the data within uncertainties, although MADGRAPH+PYTHIA 8 tune CUETM1
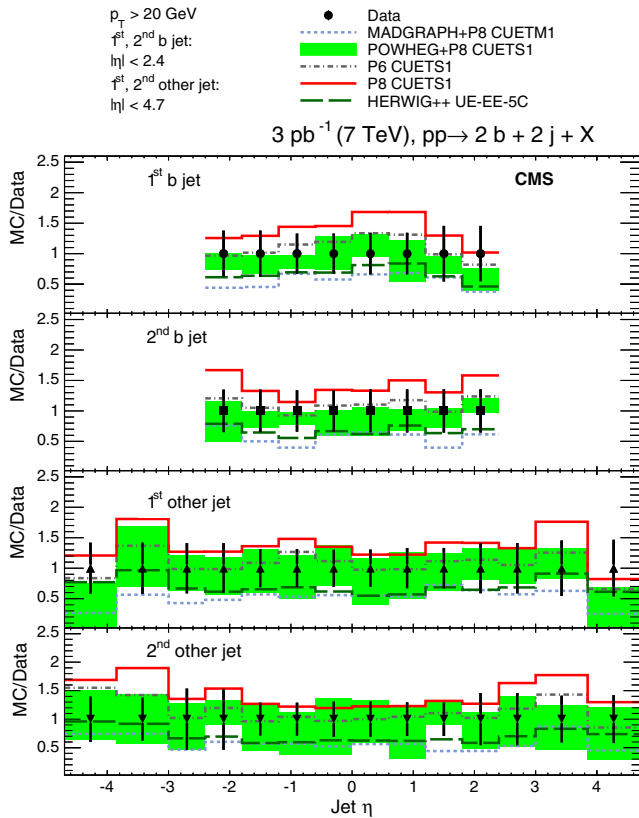

FIG. 5. Ratios of the absolute cross section predictions of POWHEG, MADGRAPH, PYTHIA 6 (P6), PYTHIA 8 (P8), and HERWIG++ over data (unfolded to the particle level) as a function of the jet pseudorapidity η for each jet. The error bars on the data represent the total uncertainties, i.e., statistical and systematic added quadratically. Data are shown with markers at unity. The band represents the theoretical uncertainty due to the choice of the scales and PDFs (shown only around the POWHEG ratio for clarity, but affecting all predictions in the same way).
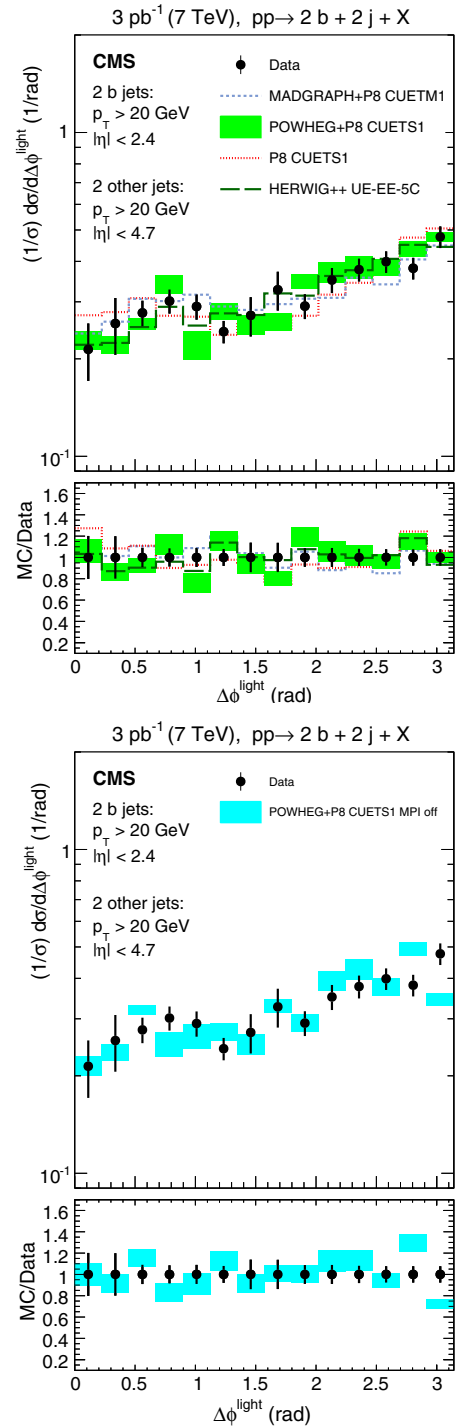

FIG. 6. Normalized cross sections unfolded to the particle level as a function of $\Delta\phi^{\text{light}}$, compared to predictions of POWHEG, MADGRAPH, PYTHIA 8 (P8), and HERWIG++ (left), and of the POWHEG+PYTHIA 8 tune CUETS1 without MPI (right). The lower panels show the ratios of the MC predictions over the data. The error bars on the data represent the total uncertainties, i.e., statistical and systematic added quadratically. Data are shown with markers at unity. The band represents the theoretical uncertainty due to the choice of the scales and PDFs (shown only around the POWHEG line for clarity, but affecting all predictions in the same way).

FIG. 7. Normalized cross sections unfolded to the particle level as a function of $\Delta_{\text{light}}^{\text{rel}} p_{\text{T}}$, compared to predictions of POWHEG, MADGRAPH, PYTHIA 8 (P8), and HERWIG++ (left), and of the POWHEG+PYTHIA 8 tune CUETS1 without MPI (right). The lower panels show the ratios of the MC predictions over the data. The error bars on the data represent the total uncertainties, i.e., statistical and systematic added quadratically. Data are shown with markers at unity. The band represents the theoretical uncertainty due to the choice of the scales and PDFs (shown only around the POWHEG line for clarity, but affecting all predictions in the same way).
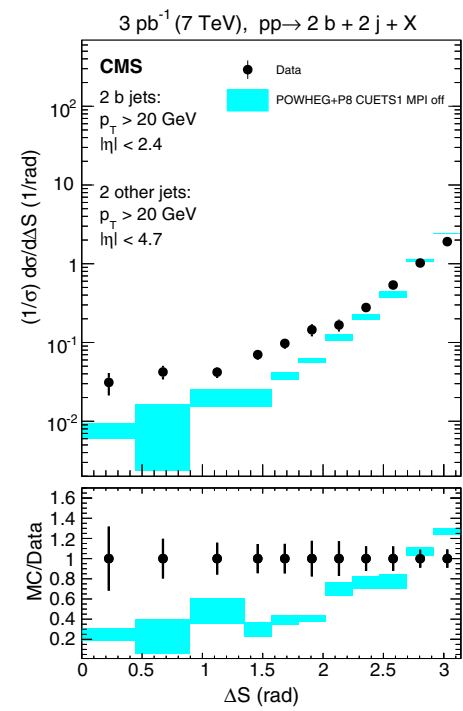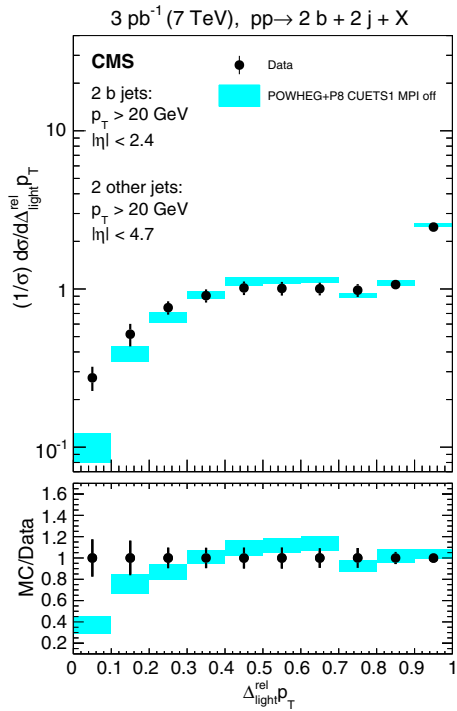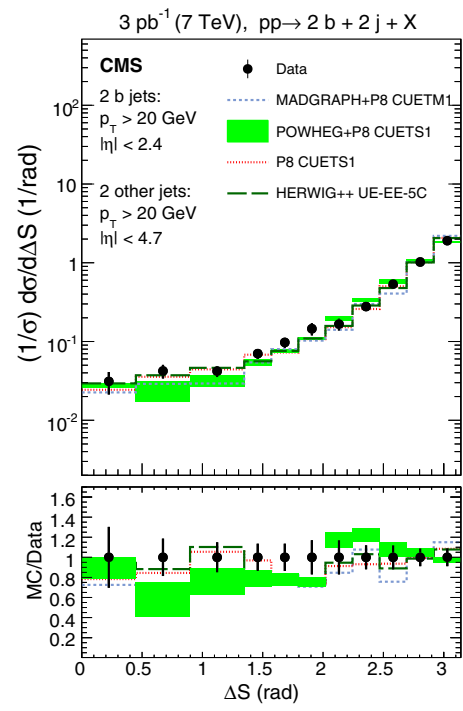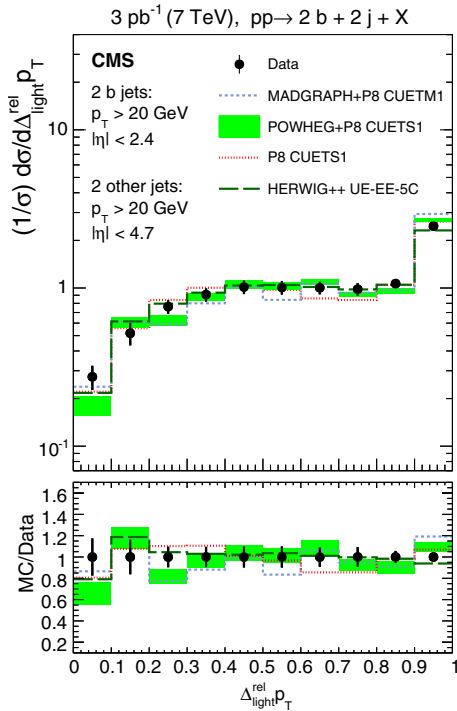
FIG. 8. Normalized cross sections unfolded to the particle level as a function of ΔS, compared to predictions of POWHEG, MADGRAPH, PYTHIA 8 (P8), and HERWIG++ (left), and of the POWHEG+PYTHIA 8 tune CUETS1 without MPI (right). The lower panels show the ratios of the MC predictions over the data. The error bars on the data represent the total uncertainties, i.e., statistical and systematic added quadratically. Data are shown with markers at unity. The band represents the theoretical uncertainty due to the choice of the scales and PDFs (shown only around the POWHEG line for clarity, but affecting all predictions in the same way).

(MADGRAPH in the following) tends to underestimate the data, and PYTHIA 8 to overestimate them.

In Fig. 3, the absolute differential cross sections as a function of the p_T and η of the selected jets are shown compared to predictions from POWHEG. Figures 4 and 5 present the same differential cross sections as ratios of theoretical predictions from various MC event generators to the data. The POWHEG predictions reproduce very well the measurements as a function of p_T and η of each jet, in both the central and forward regions. The other MC simulations also describe the data satisfactorily, although HERWIG++ tune UE-EE-5C and MADGRAPH are systematically lower than the data. Similar conclusions about HERWIG++ and MADGRAPH have been already drawn for inclusive [21] and exclusive four-jet [11] final states.

Figures 6–8 show the normalized differential cross sections as a function of the correlation observables, $\Delta\phi^{\text{light}}$, $\Delta_{\text{light}}^{\text{rel}}p_T$, and ΔS. The data are compared to the MC simulations considered previously. In addition, predictions from POWHEG MPI-off are also shown. All MC simulations that include MPI contributions describe the data well. This is remarkable given that the predictions are based on MPI models tuned to data at softer scales ($p_T \approx 3$–5 GeV). Conversely, POWHEG MPI-off is ruled out by the data, especially at low values of $\Delta_{\text{light}}^{\text{rel}}p_T$ (<0.1) and for values of ΔS smaller than 2. This is a clear indication for the need of MPI contributions. The discrepancy between the measurement and the POWHEG MPI-off predictions goes up to 60% in the low ΔS region, while for the four-jet events of Ref. [11] the disagreement is of about 40%. This shows that heavy-flavor multijet production with common jet threshold is more sensitive to a DPS contribution than an untagged four-jet sample with asymmetric p_T thresholds. The fact that the normalized distribution as a function of $\Delta\phi^{\text{light}}$ is also described reasonably well by POWHEG MPI-off reflects the limited DPS sensitivity of this observable, as already observed for exclusive four-jet final states [11].

In summary, predictions using LO or NLO dijet matrix elements matched to the simulation of MPI effects reproduce the measured normalized cross sections, whereas those without MPI fail to describe them. This study demonstrates the presence of DPS in the data and confirms the sensitivity to such contributions of the jet correlation variables ΔS and $\Delta_{\text{light}}^{\text{rel}}p_T$.

VI. SUMMARY

A study of events with at least four jets, at least two of which are b jets, in proton-proton collisions at 7 TeV is presented. The data, corresponding to an integrated luminosity of 3 pb^{-1}, were collected with the CMS experiment in 2010. The two b jets must be within pseudorapidity $|\eta| < 2.4$, and the two other jets must be within $|\eta| < 4.7$. The transverse momenta of all the jets are required to be greater than 20 GeV. The cross section is measured to be $\sigma(pp \rightarrow 2b + 2j + X) = 69 \pm 3(\text{stat}) \pm 24(\text{syst})$ nb. The differential cross sections as a function of the p_T and η of each of the four jets are presented, along with the cross sections as a function of kinematic jet correlation variables. The results are compared to several theoretical predictions with and without contributions from double parton scattering. The models based on leading order or next-to-leading-order dijet matrix element calculations, matched to parton shower and including MPI contributions, describe well the differential cross sections as a function of p_T and η in the whole measured region. The differential cross sections as a function of the jet correlation variables are poorly reproduced by models that do not include contributions from MPI. Specifically, the predictions of POWHEG interfaced with PYTHIA 8 without the simulation of multiple parton interactions underestimate the cross sections as a function of ΔS and $\Delta_{\text{light}}^{\text{rel}}p_T$ in the regions of the phase space where a DPS signal is expected. These results demonstrate, for the first time, the sensitivity of kinematic jet correlation variables, such as ΔS and $\Delta_{\text{light}}^{\text{rel}}p_T$, to DPS processes in multijet final states with heavy quarks.

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Mcbrayer,[147] M. Murray,[147] S. Sanders,[147] R. Stringer,[147] J. D. Tapia Takaki,[147] Q. Wang,[147] A. Ivanov,[148] K. Kaadze,[148] S. Khalil,[148] M. Makouski,[148] Y. Maravin,[148] A. Mohammadi,[148] L. K. Saini,[148] N. Skhirtladze,[148] S. Toda,[148] D. Lange,[149] F. Rebassoo,[149] D. Wright,[149] C. Anelli,[150] A. Baden,[150] O. Baron,[150] A. Belloni,[150] B. Calvert,[150] S. C. Eno,[150] C. Ferraioli,[150] J. A. Gomez,[150] N. J. Hadley,[150] S. Jabeen,[150] R. G. Kellogg,[150] T. Kolberg,[150] J. Kunkle,[150] Y. Lu,[150] A. C. Mignerey,[150] Y. H. Shin,[150] A. Skuja,[150] M. B. Tonjes,[150] S. C. Tonwar,[150]

D. Abercrombie,[151] B. Allen,[151] A. Apyan,[151] R. Barbieri,[151] A. Baty,[151] R. Bi,[151] K. Bierwagen,[151] S. Brandt,[151] W. Busza,[151] I. A. Cali,[151] Z. Demiragli,[151] L. Di Matteo,[151] G. Gomez Ceballos,[151] M. Goncharov,[151] D. Hsu,[151] Y. Iiyama,[151] G. M. Innocenti,[151] M. Klute,[151] D. Kovalskyi,[151] K. Krajczar,[151] Y. S. Lai,[151] Y.-J. Lee,[151] A. Levin,[151] P. D. Luckey,[151] A. C. Marini,[151] C. Mcginn,[151] C. Mironov,[151] S. Narayanan,[151] X. Niu,[151] C. Paus,[151] C. Roland,[151] G. Roland,[151] J. Salfeld-Nebgen,[151] G. S. F. Stephans,[151] K. Sumorok,[151] K. Tatar,[151] M. Varma,[151] D. Veliclanu,[151] J. Veverka,[151] J. Wang,[151] T. W. Wang,[151] B. Wyslouch,[151] M. Yang,[151] V. Zhukova,[151] A. C. Benvenuti,[152] R. M. Chatterjee,[152] A. Evans,[152] A. Finkel,[152] A. Gude,[152] P. Hansen,[152] S. Kalafut,[152] S. C. Kao,[152] Y. Kubota,[152] Z. Lesko,[152] J. Mans,[152] S. Nourbakhsh,[152] N. Ruckstuhl,[152] R. Rusack,[152] N. Tambe,[152] J. Turkewitz,[152] J. G. Acosta,[153] S. Oliveros,[153] E. Avdeeva,[154] R. Bartek,[154] K. Bloom,[154] S. Bose,[154] D. R. Claes,[154] A. Dominguez,[154] C. Fangmeier,[154] R. Gonzalez Suarez,[154] R. Kamalieddin,[154] D. Knowlton,[154] I. Kravchenko,[154] A. Malta Rodrigues,[154] F. Meier,[154] J. Monroy,[154] J. E. Siado,[154] G. R. Snow,[154] B. Stieger,[154] M. Alyari,[155] J. Dolen,[155] J. George,[155] A. Godshalk,[155] C. Harrington,[155] I. Iashvili,[155] J. Kaisen,[155] A. Kharchilava,[155] A. Kumar,[155] A. Parker,[155] S. Rappoccio,[155] B. Roozbahani,[155] G. Alverson,[156] E. Barberis,[156] D. Baumgartel,[156] A. Hortiangtham,[156] A. Massironi,[156] D. M. Morse,[156] D. Nash,[156] T. Orimoto,[156] R. Teixeira De Lima,[156] D. Trocino,[156] R.-J. Wang,[156] D. Wood,[156] S. Bhattacharya,[157] K. A. Hahn,[157] A. Kubik,[157] J. F. Low,[157] N. Mucia,[157] N. Odell,[157] B. Pollack,[157] M. H. Schmitt,[157] K. Sung,[157] M. Trovato,[157] M. Velasco,[157] N. Dev,[158] M. Hildreth,[158] K. Hurtado Anampa,[158] C. Jessop,[158] D. J. Karmgard,[158] N. Kellams,[158] K. Lannon,[158] N. Marinelli,[158] F. Meng,[158] C. Mueller,[158] Y. Musienko,[158,kk] M. Planer,[158] A. Reinsvold,[158] R. Ruchti,[158] G. Smith,[158] S. Taroni,[158] N. Valls,[158] M. Wayne,[158] M. Wolf,[158] A. Woodard,[158] J. Alimena,[159] L. Antonelli,[159] J. Brinson,[159] B. Bylsma,[159] L. S. Durkin,[159] S. Flowers,[159] B. Francis,[159] A. Hart,[159] C. Hill,[159] R. Hughes,[159] W. Ji,[159] B. Liu,[159] W. Luo,[159] D. Puigh,[159] B. L. Winer,[159] H. W. Wulsin,[159] S. Cooperstein,[160] O. Driga,[160] P. Elmer,[160] J. Hardenbrook,[160] P. Hebda,[160] J. Luo,[160] D. Marlow,[160] T. Medvedeva,[160] M. Mooney,[160] J. Olsen,[160] C. Palmer,[160] P. Piroué,[160] D. Stickland,[160] C. Tully,[160] A. Zuranski,[160] S. Malik,[161] A. Barker,[162] V. E. Barnes,[162] D. Benedetti,[162] S. Folgueras,[162] L. Gutay,[162] M. K. Jha,[162] M. Jones,[162] A. W. Jung,[162] K. Jung,[162] D. H. Miller,[162] N. Neumeister,[162] B. C. Radburn-Smith,[162] X. Shi,[162] J. Sun,[162] A. Svyatkovskiy,[162] F. Wang,[162] W. Xie,[162] L. Xu,[162] N. Parashar,[163] J. Stupak,[163] A. Adair,[164] B. Akgun,[164] Z. Chen,[164] K. M. Ecklund,[164] F. J. M. Geurts,[164] M. Guilbaud,[164] W. Li,[164] B. Michlin,[164] M. Northup,[164] B. P. Padley,[164] R. Redjimi,[164] J. Roberts,[164] J. Rorie,[164] Z. Tu,[164] J. Zabel,[164] B. Betchart,[165] A. Bodek,[165] P. de Barbaro,[165] R. Demina,[165] Y. t. Duh,[165] T. Ferbel,[165] M. Galanti,[165] A. Garcia-Bellido,[165] J. Han,[165] O. Hindrichs,[165] A. Khukhunaishvili,[165] K. H. Lo,[165] P. Tan,[165] M. Verzetti,[165] J. P. Chou,[166] E. Contreras-Campana,[166] Y. Gershtein,[166] T. A. Gómez Espinosa,[166] E. Halkiadakis,[166] M. Heindl,[166] D. Hidas,[166] E. Hughes,[166] S. Kaplan,[166] R. Kunnawalkam Elayavalli,[166] S. Kyriacou,[166] A. Lath,[166] K. Nash,[166] H. Saka,[166] S. Salur,[166] S. Schnetzer,[166] D. Sheffield,[166] S. Somalwar,[166] R. Stone,[166] S. Thomas,[166] P. Thomassen,[166] M. Walker,[166] M. Foerster,[167] J. Heideman,[167] G. Riley,[167] K. Rose,[167] S. Spanier,[167] K. Thapa,[167] O. Bouhali,[168,ttt] A. Celik,[168] M. Dalchenko,[168] M. De Mattia,[168] A. Delgado,[168] S. Dildick,[168] R. Eusebi,[168] J. Gilmore,[168] T. Huang,[168] E. Juska,[168] T. Kamon,[168,uuu] R. Mueller,[168] Y. Pakhotin,[168] R. Patel,[168] A. Perloff,[168] L. Perniè,[168] D. Rathjens,[168] A. Rose,[168] A. Safonov,[168] A. Tatarinov,[168] K. A. Ulmer,[168] N. Akchurin,[169] C. Cowden,[169] J. Damgov,[169] C. Dragoiu,[169] P. R. Dudero,[169] J. Faulkner,[169] S. Kunori,[169] K. Lamichhane,[169] S. W. Lee,[169] T. Libeiro,[169] S. Undleeb,[169] I. Volobouev,[169] Z. Wang,[169] A. G. Delannoy,[170] S. Greene,[170] A. Gurrola,[170] R. Janjam,[170] W. Johns,[170] C. Maguire,[170] A. Melo,[170] H. Ni,[170] P. Sheldon,[170] S. Tuo,[170] J. Velkovska,[170] Q. Xu,[170] M. W. Arenton,[171] P. Barria,[171] B. Cox,[171] J. Goodell,[171] R. Hirosky,[171] A. Ledovskoy,[171] H. Li,[171] C. Neu,[171] T. Sinthuprasith,[171] X. Sun,[171] Y. Wang,[171] E. Wolfe,[171] F. Xia,[171] C. Clarke,[172] R. Harr,[172] P. E. Karchin,[172] P. Lamichhane,[172] J. Sturdy,[172] D. A. Belknap,[173] S. Dasu,[173] L. Dodd,[173] S. Duric,[173] B. Gomber,[173] M. Grothe,[173] M. Herndon,[173] A. Hervé,[173] P. Klabbers,[173] A. Lanaro,[173] A. Levine,[173] K. Long,[173] R. Loveless,[173] I. Ojalvo,[173] T. Perry,[173] G. A. Pierro,[173] G. Polese,[173] T. Ruggles,[173] A. Savin,[173] A. Sharma,[173] N. Smith,[173] W. H. Smith,[173] D. Taylor,[173] and N. Woods[173]

(CMS Collaboration)

[1]*Yerevan Physics Institute, Yerevan, Armenia*
[2]*Institut für Hochenergiephysik der OeAW, Wien, Austria*
[3]*National Centre for Particle and High Energy Physics, Minsk, Belarus*

[4]*Universiteit Antwerpen, Antwerpen, Belgium*

[5]*Vrije Universiteit Brussel, Brussel, Belgium*

[6]*Université Libre de Bruxelles, Bruxelles, Belgium*

[7]*Ghent University, Ghent, Belgium*

[8]*Université Catholique de Louvain, Louvain-la-Neuve, Belgium*

[9]*Université de Mons, Mons, Belgium*

[10]*Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil*

[11]*Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil*

[12a]*Universidade Estadual Paulista, São Paulo, Brazil*

[12b]*Universidade Federal do ABC, São Paulo, Brazil*

[13]*Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria*

[14]*University of Sofia, Sofia, Bulgaria*

[15]*Beihang University, Beijing, China*

[16]*Institute of High Energy Physics, Beijing, China*

[17]*State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China*

[18]*Universidad de Los Andes, Bogota, Colombia*

[19]*University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture,
Split, Croatia*

[20]*University of Split, Faculty of Science, Split, Croatia*

[21]*Institute Rudjer Boskovic, Zagreb, Croatia*

[22]*University of Cyprus, Nicosia, Cyprus*

[23]*Charles University, Prague, Czech Republic*

[24]*Universidad San Francisco de Quito, Quito, Ecuador*

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

[26]*National Institute of Chemical Physics and Biophysics, Tallinn, Estonia*

[27]*Department of Physics, University of Helsinki, Helsinki, Finland*

[28]*Helsinki Institute of Physics, Helsinki, Finland*

[29]*Lappeenranta University of Technology, Lappeenranta, Finland*

[30]*IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France*

[31]*Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France*

[32]*Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace
Mulhouse, CNRS/IN2P3, Strasbourg, France*

[33]*Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules,
CNRS/IN2P3, Villeurbanne, France*

[34]*Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3,
Institut de Physique Nucléaire de Lyon, Villeurbanne, France*

[35]*Georgian Technical University, Tbilisi, Georgia*

[36]*Tbilisi State University, Tbilisi, Georgia*

[37]*RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany*

[38]*RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany*

[39]*RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany*

[40]*Deutsches Elektronen-Synchrotron, Hamburg, Germany*

[41]*University of Hamburg, Hamburg, Germany*

[42]*Institut für Experimentelle Kernphysik, Karlsruhe, Germany*

[43]*Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece*

[44]*National and Kapodistrian University of Athens, Athens, Greece*

[45]*University of Ioánnina, Ioánnina, Greece*

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

[47]*Wigner Research Centre for Physics, Budapest, Hungary*

[48]*Institute of Nuclear Research ATOMKI, Debrecen, Hungary*

[49]*University of Debrecen, Debrecen, Hungary*

[50]*National Institute of Science Education and Research, Bhubaneswar, India*

[51]*Panjab University, Chandigarh, India*

[52]*University of Delhi, Delhi, India*

[53]*Saha Institute of Nuclear Physics, Kolkata, India*

[54]*Indian Institute of Technology Madras, India*

[55]*Bhabha Atomic Research Centre, Mumbai, India*

[56]*Tata Institute of Fundamental Research-A, Mumbai, India*

[57]Tata Institute of Fundamental Research-B, Mumbai, India

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

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

[60]University College Dublin, Dublin, Ireland

[61a]INFN Sezione di Bari, Politecnico di Bari, Bari, Italy

[61b]Università di Bari, Politecnico di Bari, Bari, Italy

[61c]Politecnico di Bari, Politecnico di Bari, Bari, Italy

[62a]INFN Sezione di Bologna, Bologna, Italy

[62b]Università di Bologna, Bologna, Italy

[63a]INFN Sezione di Catania, Catania, Italy

[63b]Università di Catania, Catania, Italy

[64a]INFN Sezione di Firenze, Firenze, Italy

[64b]Università di Firenze, Firenze, Italy

[65]INFN Laboratori Nazionali di Frascati, Frascati, Italy

[66a]INFN Sezione di Genova, Genova, Italy

[66b]Università di Genova, Genova, Italy

[67a]INFN Sezione di Milano-Bicocca, Milano, Italy

[67b]Università di Milano-Bicocca, Milano, Italy

[68a]INFN Sezione di Napoli, Napoli, Italy

[68b]Università di Napoli 'Federico II', Napoli, Italy

[68c]Università della Basilicata, Potenza, Italy, Università G. Marconi, Roma, Italy

[68d]Università G. Marconi, Potenza, Italy, Università G. Marconi, Roma, Italy

[69a]INFN Sezione di Padova, Padova, Italy

[69b]Università di Padova, Padova, Italy

[69c]Università di Trento, Trento, Italy

[70a]INFN Sezione di Pavia, Pavia, Italy

[70b]Università di Pavia, Pavia, Italy

[71a]INFN Sezione di Perugia, Perugia, Italy

[71b]Università di Perugia, Perugia, Italy

[72a]INFN Sezione di Pisa, Pisa, Italy

[72b]Università di Pisa, Pisa, Italy

[72c]Scuola Normale Superiore di Pisa, Pisa, Italy

[73a]INFN Sezione di Roma, Roma, Italy

[73b]Università di Roma, Roma, Italy

[74a]INFN Sezione di Torino, Torino, Italy

[74b]Università di Torino, Torino, Italy

[74c]Università del Piemonte Orientale, Novara, Italy

[75a]INFN Sezione di Trieste, Trieste, Italy

[75b]Università di Trieste, Trieste, Italy

[76]Kyungpook National University, Daegu, Korea

[77]Chonbuk National University, Jeonju, Korea

[78]Hanyang University, Seoul, Korea

[79]Korea University, Seoul, Korea

[80]Seoul National University, Seoul, Korea

[81]University of Seoul, Seoul, Korea

[82]Sungkyunkwan University, Suwon, Korea

[83]Vilnius University, Vilnius, Lithuania

[84]National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia

[85]Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico

[86]Universidad Iberoamericana, Mexico City, Mexico

[87]Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

[88]Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico

[89]University of Auckland, Auckland, New Zealand

[90]University of Canterbury, Christchurch, New Zealand

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

[92]National Centre for Nuclear Research, Swierk, Poland

[93]Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland

[94]Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal

[95]Joint Institute for Nuclear Research, Dubna, Russia

[96]Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia

[97]Institute for Nuclear Research, Moscow, Russia

[98]Institute for Theoretical and Experimental Physics, Moscow, Russia

[99]National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI),
Moscow, Russia

[100]P. N. Lebedev Physical Institute, Moscow, Russia

[101]Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia

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

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

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

[105]Universidad Autónoma de Madrid, Madrid, Spain

[106]Universidad de Oviedo, Oviedo, Spain

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

[108]CERN, European Organization for Nuclear Research, Geneva, Switzerland

[109]Paul Scherrer Institut, Villigen, Switzerland

[110]Institute for Particle Physics, ETH Zurich, Zurich, Switzerland

[111]Universität Zürich, Zurich, Switzerland

[112]National Central University, Chung-Li, Taiwan

[113]National Taiwan University (NTU), Taipei, Taiwan

[114]Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand

[115]Cukurova University, Adana, Turkey

[116]Middle East Technical University, Physics Department, Ankara, Turkey

[117]Bogazici University, Istanbul, Turkey

[118]Istanbul Technical University, Istanbul, Turkey

[119]Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine

[120]National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine

[121]University of Bristol, Bristol, United Kingdom

[122]Rutherford Appleton Laboratory, Didcot, United Kingdom

[123]Imperial College, London, United Kingdom

[124]Brunel University, Uxbridge, United Kingdom

[125]Baylor University, Waco, Texas 76798, USA

[126]The University of Alabama, Tuscaloosa, Alabama 35487, USA

[127]Boston University, Boston, Massachusetts 02215, USA

[128]Brown University, Providence, Rhode Island 02912, USA

[129]University of California, Davis, Davis, California 95616, USA

[130]University of California, Los Angeles, California 90095, USA

[131]University of California, Riverside, Riverside, California 92521, USA

[132]University of California, San Diego, La Jolla, California 92093, USA

[133]University of California, Santa Barbara—Department of Physics, Santa Barbara,
California 93106, USA

[134]California Institute of Technology, Pasadena, California 91125, USA

[135]Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, USA

[136]University of Colorado Boulder, Boulder, Colorado 80309, USA

[137]Cornell University, Ithaca, New York 14853, USA

[138]Fairfield University, Fairfield, Connecticut 06430, USA

[139]Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA

[140]University of Florida, Gainesville, Florida 32611, USA

[141]Florida International University, Miami, Florida 33199, USA

[142]Florida State University, Tallahassee, Florida 32306, USA

[143]Florida Institute of Technology, Melbourne, Florida 32901, USA

[144]University of Illinois at Chicago (UIC), Chicago, Illinois 60607, USA

[145]The University of Iowa, Iowa City, Iowa 52242, USA

[146]Johns Hopkins University, Baltimore, Maryland 21218, USA

[147]The University of Kansas, Lawrence, Kansas 66045, USA

[148]Kansas State University, Manhattan, Kansas 66506, USA

[149]Lawrence Livermore National Laboratory, Livermore, California 94551, USA

[150]University of Maryland, College Park, Maryland 20742, USA

[151]Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

[152]University of Minnesota, Minneapolis, Minnesota 55455, USA

[153]University of Mississippi, Oxford, Mississippi 38677, USA

[154]University of Nebraska-Lincoln, Lincoln, Nebraska 68588, USA

[155]State University of New York at Buffalo, Buffalo, New York 14260, USA
[156]Northeastern University, Boston, Massachusetts 02115, USA
[157]Northwestern University, Evanston, Illinois 60208, USA
[158]University of Notre Dame, Notre Dame, Indiana 46556, USA
[159]The Ohio State University, Columbus, Ohio 43210, USA
[160]Princeton University, Princeton, New Jersey 08542, USA
[161]University of Puerto Rico, Mayaguez, Puerto Rico 00681, USA
[162]Purdue University, West Lafayette, Indiana 47907, USA
[163]Purdue University Calumet, Hammond, Indiana 46323, USA
[164]Rice University, Houston, Texas 77251, USA
[165]University of Rochester, Rochester, New York 14627, USA
[166]Rutgers, The State University of New Jersey, Piscataway, New Jersey 08854, USA
[167]University of Tennessee, Knoxville, Tennessee 37996, USA
[168]Texas A&M University, College Station, Texas 77843, USA
[169]Texas Tech University, Lubbock, Texas 79409, USA
[170]Vanderbilt University, Nashville, Tennessee 37235, USA
[171]University of Virginia, Charlottesville, Virginia 22904, USA
[172]Wayne State University, Detroit, Michigan 48202, USA
[173]University of Wisconsin—Madison, Madison, Wisconsin 53706, USA

[a]Deceased.
[b]Also at Vienna University of Technology, Vienna, Austria.
[c]Also at State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China.
[d]Also at Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France.
[e]Also at Universidade Estadual de Campinas, Campinas, Brazil.
[f]Also at Université Libre de Bruxelles, Bruxelles, Belgium.
[g]Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany.
[h]Also at Joint Institute for Nuclear Research, Dubna, Russia.
[i]Also at Helwan University, Cairo, Egypt.
[j]Also at Zewail City of Science and Technology, Zewail, Egypt.
[k]Also at Ain Shams University, Cairo, Egypt.
[l]Also at Fayoum University, El-Fayoum, Egypt.
[m]Also at British University in Egypt, Cairo, Egypt.
[n]Also at Université de Haute Alsace, Mulhouse, France.
[o]Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
[p]Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia.
[q]Also at Tbilisi State University, Tbilisi, Georgia.
[r]Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.
[s]Also at University of Hamburg, Hamburg, Germany.
[t]Also at Brandenburg University of Technology, Cottbus, Germany.
[u]Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
[v]Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary.
[w]Also at University of Debrecen, Debrecen, Hungary.
[x]Also at Indian Institute of Science Education and Research, Bhopal, India.
[y]Also at Institute of Physics, Bhubaneswar, India.
[z]Also at University of Visva-Bharati, Santiniketan, India.
[aa]Also at University of Ruhuna, Matara, Sri Lanka.
[bb]Also at Isfahan University of Technology, Isfahan, Iran.
[cc]Also at University of Tehran, Department of Engineering Science, Tehran, Iran.
[dd]Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran.
[ee]Also at Università degli Studi di Siena, Siena, Italy.
[ff]Also at Purdue University, West Lafayette, USA.
[gg]Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia.
[hh]Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia.
[ii]Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico.
[jj]Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland.
[kk]Also at Institute for Nuclear Research, Moscow, Russia.
[ll]Also at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia.
[mm]Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan.

[nn]Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia.

[oo]Also at University of Florida, Gainesville, USA.

[pp]Also at P. N. Lebedev Physical Institute, Moscow, Russia.

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

[rr]Also at INFN Sezione di Roma, Università di Roma, Roma, Italy.

[ss]Also at National Technical University of Athens, Athens, Greece.

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

[uu]Also at National and Kapodistrian University of Athens, Athens, Greece.

[vv]Also at Riga Technical University, Riga, Latvia.

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

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

[yy]Also at Mersin University, Mersin, Turkey.

[zz]Also at Cag University, Mersin, Turkey.

[aaa]Also at Piri Reis University, Istanbul, Turkey.

[bbb]Also at Gaziosmanpasa University, Tokat, Turkey.

[ccc]Also at Adiyaman University, Adiyaman, Turkey.

[ddd]Also at Ozyegin University, Istanbul, Turkey.

[eee]Also at Izmir Institute of Technology, Izmir, Turkey.

[fff]Also at Marmara University, Istanbul, Turkey.

[ggg]Also at Kafkas University, Kars, Turkey.

[hhh]Also at Istanbul Bilgi University, Istanbul, Turkey.

[iii]Also at Yildiz Technical University, Istanbul, Turkey.

[jjj]Also at Hacettepe University, Ankara, Turkey.

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

[lll]Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.

[mmm]Also at Instituto de Astrofísica de Canarias, La Laguna, Spain.

[nnn]Also at Utah Valley University, Orem, USA.

[ooo]Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.

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

[qqq]Also at Argonne National Laboratory, Argonne, USA.

[rrr]Also at Erzincan University, Erzincan, Turkey.

[sss]Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.

[ttt]Also at Texas A&M University at Qatar, Doha, Qatar.

[uuu]Also at Kyungpook National University, Daegu, Korea.