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Measurement of inclusive jet cross sections in pp and PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV

V. Khachatryan *et al.*[*]
(CMS Collaboration)

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Inclusive jet spectra from pp and PbPb collisions at a nucleon-nucleon center-of-mass energy of 2.76 TeV, collected with the CMS detector at the CERN Large Hadron Collider, are presented. Jets are reconstructed with three different distance parameters ($R = 0.2$, 0.3, and 0.4) for transverse momentum (p_{T}) greater than 70 GeV/c and pseudorapidity $|\eta| < 2$. Next-to-leading-order quantum chromodynamic calculations with nonperturbative corrections are found to overpredict jet production cross sections in pp for small distance parameters. The jet nuclear modification factors for PbPb compared to pp collisions, show a steady decrease from peripheral to central events, along with a weak dependence on the jet p_{T}. They are found to be independent of the distance parameter in the measured kinematic range.

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I. INTRODUCTION

Heavy ion collisions at the CERN Large Hadron Collider (LHC) can generate a hot and dense deconfined state of matter, also known as the quark-gluon plasma (QGP). In these collisions, hard scattered partons are expected to be attenuated due to elastic and inelastic interactions with the produced medium [1–3]. This phenomenon is also known as "jet quenching", originally proposed in Ref. [4], and is indirectly confirmed by measurements of spectra and correlations of high transverse momenta (p_{T}) hadrons at the BNL Relativistic Heavy Ion Collider (RHIC) [5–8] and LHC [9–11]. In these measurements, jet quenching is observed to have a dependence on event multiplicity and hadron p_{T}, and has provided significant insights, including the color opaqueness of the QGP. However, these findings are limited by intrinsic biases. For example, the leading hadron measurements are preferentially from the population of jets that have the least interaction with the medium. These measurements are also not sufficient to discriminate quantitatively between partonic energy loss formalisms or to extract key parameters such as the transport coefficient of the hot medium to precisely measure the stopping-power of the QGP (see Refs. [12,13] for reviews). As jet quenching is intrinsically a partonic process, studies using hadronic observables blur essential physics due to the complexity of the theoretical description of hadronization and the sensitivity to nonperturbative effects. The measurement of jet structure and its modification in terms of energy flow rather than hadronic distributions promises a much closer connection to the underlying theory. Therefore a quantitative picture of jet quenching with respect to theoretical assumptions can be obtained through a full reconstruction of underlying parton kinematics, i.e., jet reconstruction [14,15].

Complementary and robust jet measurements in heavy ion collisions became feasible with the beginning of the LHC heavy ion program. For example, measurements showed that the p_{T} of back-to-back dijet pairs becomes increasingly unbalanced as the centrality of the event increases (smaller impact parameters) [16–18]. In these collisions jet pairs are also observed to be undeflected, i.e., their azimuthal angular correlations are independent of the collision centrality. Furthermore, measurements of jet shape, fragmentation functions, jet-track correlations, and missing p_{T} find that a significant fraction of the "lost" jet energy is observed to be radiated via low-p_{T} particles far outside the jet cone [17,19–22]. The comparison of inclusive jets in heavy ion collisions with those in pp collisions can differentiate between competing models of parton energy loss mechanisms [23–25]. Initial measurements of jet yields in central heavy ion collisions were compared to a pp baseline, and they are found to have a weak dependence on the jet p_{T}, with the low p_{T} region suffering slightly larger modification compared to the high p_{T} region [26,27]. However the interpretation of the jet modification results in nucleus-nucleus collisions and the understanding of their relation to the properties of the QGP requires detailed knowledge of all nuclear effects that could influence the comparisons with the pp system. The shape of the jet spectrum in proton-lead collisions is similar to that observed in pp collisions [28–30]. This suggests the modification of the jet spectra observed in PbPb collisions is indeed an effect of the hot medium produced in these collisions.

For this analysis, the jet measurements are performed as a function of three experimental observables: the jet reconstruction distance parameter [31], the jet p_{T}, and the event centrality (related to the impact parameter of the incoming nuclei) of the collisions. The reference pp jet cross section is also measured and is compared to perturbative quantum chromodynamic (pQCD) calculations. The observable of interest is the jet nuclear modification factor (R_{AA}), defined as

$$R_{AA} = \frac{d^2N^{AA}_{\mathrm{jets}}/dp_{\mathrm{T}}\,d\eta}{\langle T_{AA}\rangle d^2\sigma^{pp}_{\mathrm{jets}}/dp_{\mathrm{T}}\,d\eta}, \tag{1}$$

where N^{AA}_{jets} is the jet spectrum measured in PbPb, $\sigma^{pp}_{\mathrm{jets}}$ is the jet cross section from pp collisions, and $\langle T_{AA}\rangle$ is the nuclear

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

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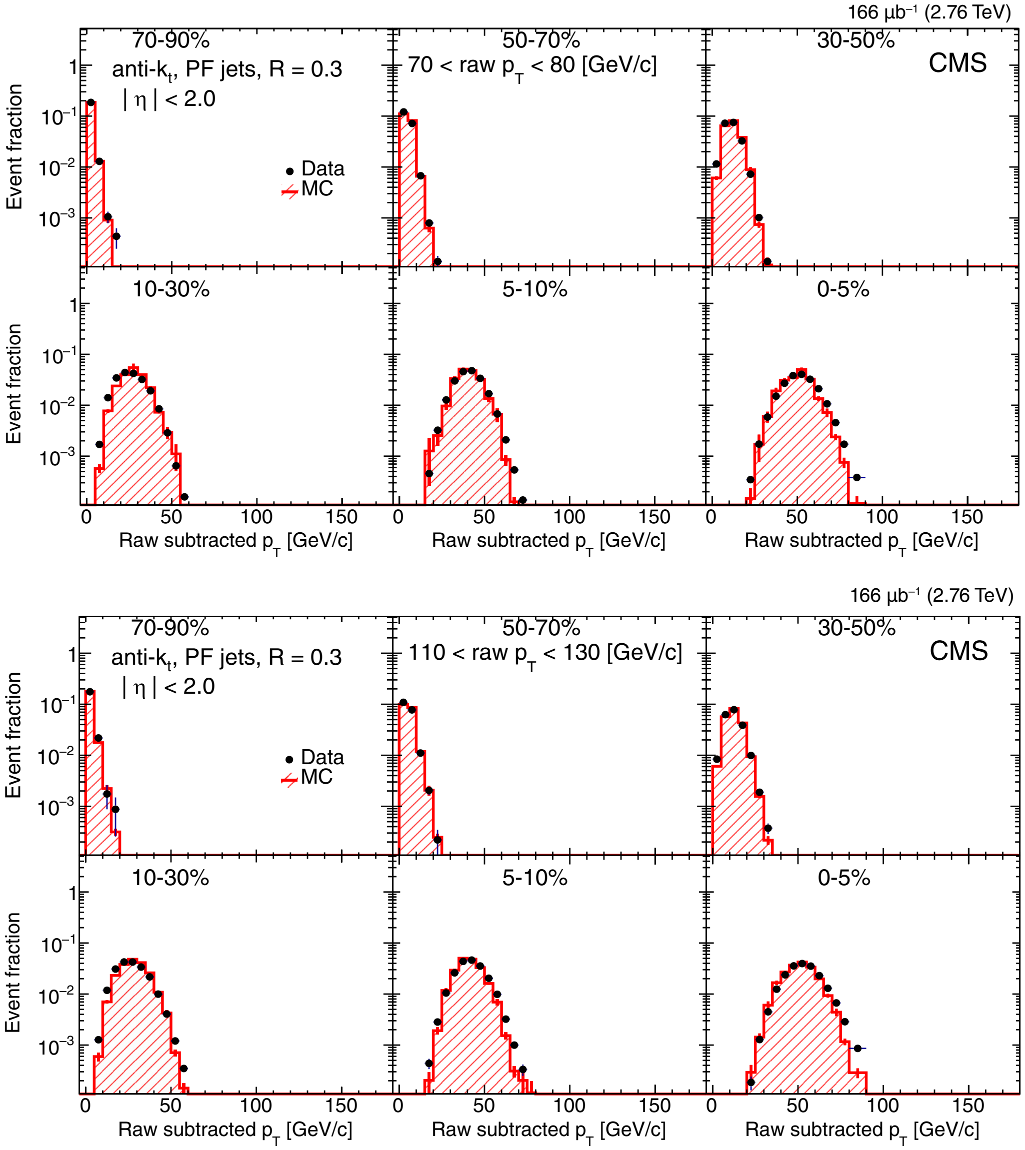

FIG. 1. Raw subtracted p_T for jets reconstructed with the anti-k_T algorithm and a distance parameter of $R = 0.3$, in the ranges $70 <$ jet $p_T < 80\,[\mathrm{GeV}/c\,]$ (top panels) and $110 <$ jet $p_T < 130\,[\mathrm{GeV}/c\,]$ (bottom panels). This quantity is found by taking the difference of the sum of PF candidates within the jet cone and raw jet p_T. Solid symbols show data, and the histogram is from PYTHIA + HYDJET generated events.

overlap function averaged over the event class studied. The quantity $\langle T_{AA}\rangle$ is related to the mean number of nucleon-nucleon (NN) collisions $\langle N_{\mathrm{coll}}\rangle$, and $\sigma_{\mathrm{inel}}^{NN}$, the nucleon-nucleon inelastic cross section, through $\langle N_{\mathrm{coll}}\rangle = \langle T_{AA}\rangle\,\sigma_{\mathrm{inel}}^{NN}$, and is calculated with a Monte Carlo Glauber model description of the nuclear collision geometry (for a review see Ref. [32]).

II. THE CMS DETECTOR AND EVENT SELECTION

The central feature of the CMS apparatus is a superconducting solenoid providing a magnetic field of 3.8 T. Charged-particle trajectories are measured with the silicon tracker that allows a transverse impact parameter resolution of $\sim$15 μm and a p_T resolution of $\sim$1.5% for particles with $p_T = 100\,\mathrm{GeV/c}$. A $\mathrm{PbWO_4}$ crystal electromagnetic calorimeter (ECAL) and a brass and scintillator hadron calorimeter (HCAL) surround the tracking volume. The forward regions are instrumented with iron and quartz-fiber hadron forward calorimeters (HF). A set of beam scintillator counters (BSC), used for triggering and beam halo rejection, is mounted on the inner side of the HF calorimeters. The very forward angles are covered at both ends by zero-degree calorimeters (ZDC). A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [33].

The first level of the CMS trigger system, composed of custom hardware processors, uses information from the calorimeters to select the most interesting events in a fixed time interval of less than 4 μs. The high-level trigger (HLT) processor farm further decreases the event rate, from around 100 kHz to less than 1 kHz, before data storage. The PbPb analysis uses minimum bias triggered and single-jet HLT data sets. The minimum bias events are characterized by the coincidence of signals in the two HF detectors or the forward and backward BSCs. The triggers used in the analysis are constructed from ECAL and HCAL energies requiring a single jet with $p_T > 55$, 65, and 80 GeV/c. For pp collisions, the triggers require at least one jet with $p_T > 40$, 60, and 80 GeV/c. The objects used in the HLT are jets reconstructed using the iterative-cone algorithm [34] with distance parameter $R = 0.5$. The soft background in PbPb collisions is removed with the iterative pileup subtraction technique [35]. In order to extend the reach of the jet spectra, data sets from the high-p_T single-jet triggers are combined together in both pp and PbPb. To reach lower jet p_T in the PbPb data set, the minimum bias triggered events are added.

This analysis uses 166 μb^{-1} of PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV recorded by CMS during the 2011 heavy ion run, as well as 5.43 pb^{-1} of pp collisions at the same collision energy recorded in early 2013. The event selection techniques developed for Ref. [20] are employed. These include the identification of a primary vertex and the removal of contamination from beam background, ultraperipheral and HCAL noise events. The primary reconstructed vertex of selected events in the z direction (beam axis) is constrained to be within ±15 cm of the center of the detector. After these selections, events with more than one PbPb collision occurring in the same beam crossing remain and are later referred to as pileup. Utilizing the sensitivity of the ZDC to spectator nucleons and of the HF to particles produced in the collisions, these pileup events (0.2%) are removed by comparing the energy deposited in the ZDC to the HF. This is further substantiated by counting the number of fully reconstructed jets with $p_T > 50$ GeV/c and comparing this to the number of tracker pixel hit counts, since pileup events tend to have large pixel counts for the same number of jets. The selection for pileup events in data does not remove any events from the simulation. This procedure was checked by individually studying a representative sample of the rejected events.

Simulated dijet events are generated using PYTHIA 6.4.23 Tune Z2 [36] for pp collisions at 2.76 TeV center-of-mass energy. For comparison to PbPb data, these PYTHIA events are embedded into a simulated PbPb event, generated by HYDJET (version 1.8) [37]. The HYDJET simulations are generated with jet quenching enabled in order to match the distribution of high-p_T jets in a minimum-bias data set. The HYDJET simulations are tuned to represent a minimum bias background measured in CMS collisions of PbPb at $\sqrt{s_{NN}} = 2.76$ TeV. Collision centrality is classified with the standard CMS heavy ion technique [20] using the total sum of the transverse energy in the HF towers, divided in percentiles according to the minimum bias samples. This distribution is divided into centrality bins, each representing 0.5% of the total nucleus-nucleus interaction cross section. For this analysis, the results are collected in six bins corresponding to the most central (i.e., smallest impact parameter) 5% of the events, denoted 0%–5%, as well as bins of 5%–10%, 10%–30%, 30%–50%, 50%–70%, and 70%–90%. The centrality of an event can be correlated with the impact parameter, as well as with $\langle N_{\text{part}} \rangle$, the average number of nucleons in the nuclei that participate in the collision, using MC Glauber model calculations [32].

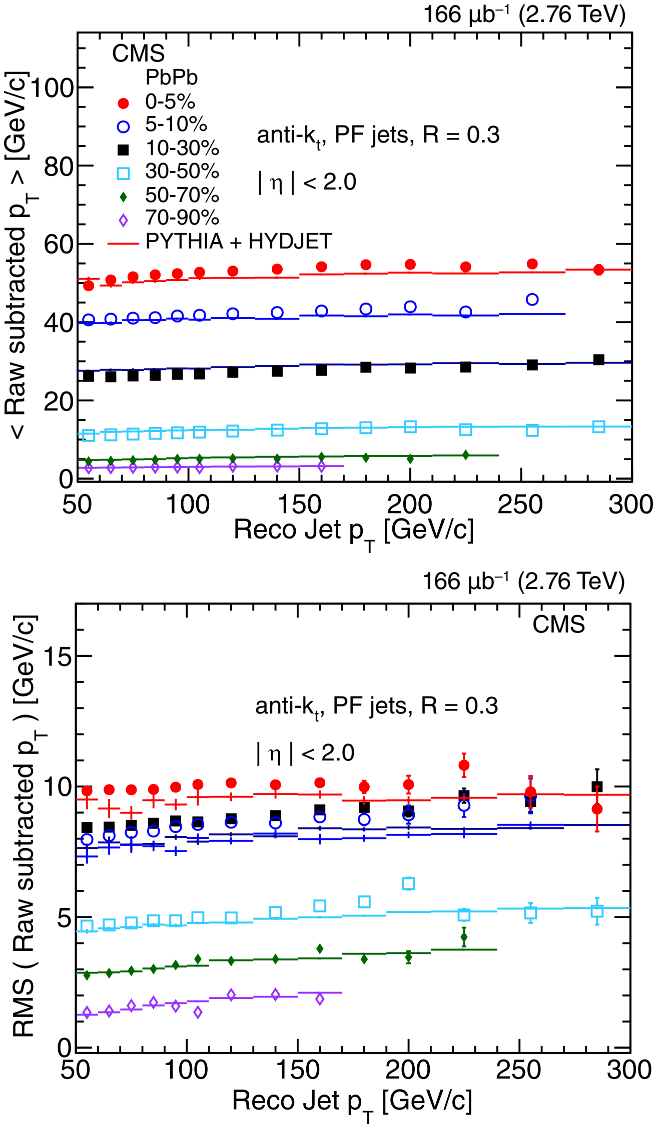

FIG. 2. Average raw subtracted p_T (top) and its rms (bottom) for PF jets reconstructed with the anti-k_T algorithm, with a distance parameter $R = 0.3$. Symbols represent data, and lines show PYTHIA + HYDJET simulated events.

III. JET RECONSTRUCTION AND SELECTION

Similar to Refs. [17,18,20,38], jet reconstruction in heavy ion collisions in CMS is performed with the sequential anti-k_T clustering algorithm via the FASTJET framework [31]. The jet clustering is performed using particle-flow (PF) [39,40] candidates that combine information from the individual CMS detector systems. Different particle types (charged and neutral hadrons, electrons, muons, and photons) are reconstructed. The anti-k_T distance parameters used are $R = 0.2, 0.3$, and 0.4.

For PbPb collisions, the soft underlying event (background) is removed from the jets with an iterative subtraction technique described in Ref. [35]. In this procedure, the PF candidates are grouped in towers that correspond to the calorimeter geometry. Jets are selected with $|\eta| < 2$ to ensure that they are fully contained within the CMS tracker up to a distance parameter of 0.4. Detector-based η and p_T dependent energy correction

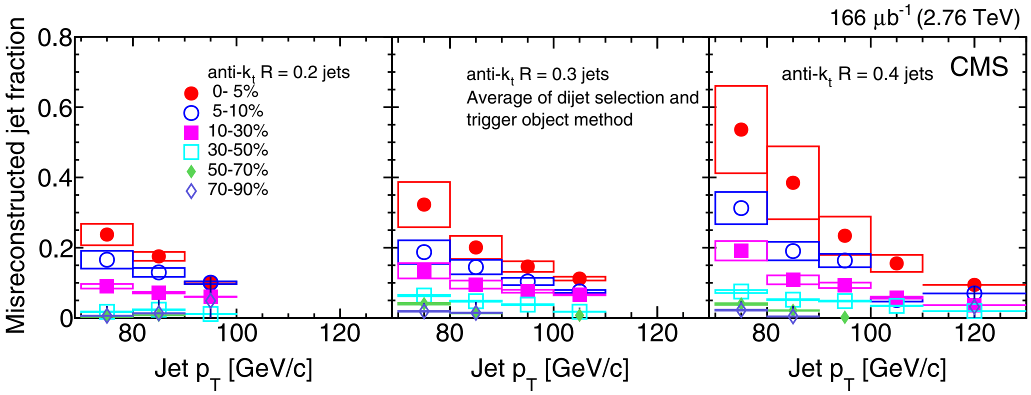

FIG. 3. Misreconstructed jet fraction of the inclusive jet spectra, derived from the minimum bias sample, as a function of reconstructed jet p_T, for various centralities and three different distance parameters (left: $R = 0.2$, center: $R = 0.3$, and right: $R = 0.4$). The correction factor is the average of the dijet selection and trigger object methods discussed in the text.

factors [41] are applied to the jets. The raw jet p_T of a jet is the p_T before any of the detector-based corrections are applied. To study the background in PbPb events, data and PYTHIA + HYDJET simulations are compared. The correction to the jet p_T obtained from this iterative subtraction technique (called "raw subtracted p_T"), for a jet with distance parameter R^{jet} is estimated by taking the difference between the sum of all the PF candidate p_T in a $\Delta R < R^{\text{jet}}$ cone and the raw jet p_T. The ΔR is defined as the distance of the PF candidate from the reconstructed jet axis in the η-ϕ plane:

$$\Delta R = \sqrt{(\Delta\phi_{\text{candidate, jet}})^2 + (\Delta\eta_{\text{candidate, jet}})^2}. \qquad (2)$$

The distributions of raw subtracted p_T for $R = 0.3$ jets, from peripheral to central collisions are shown in Fig. 1 for two different reconstructed jet p_T selections. Data are shown with filled circles and simulations with histograms. There is a good agreement between the two in all centralities and jet p_T bins. A similar level of agreement is also seen for $R = 0.2$ and $R = 0.4$.

The average raw subtracted p_T and its root mean square (rms) values are shown in Fig. 2 as a function of the reconstructed jet p_T, from central to the most peripheral collisions. Data are shown with markers and are compared with the PYTHIA + HYDJET generated events shown as histograms. The average raw subtracted p_T decreases, from the most central to peripheral events, as expected, and distributions show reasonable agreement between data and PYTHIA + HYDJET.

A. Data driven correction

Although the soft background is primarily removed with the iterative-pileup subtraction, fluctuations in this background can result in misreconstructed jets that do not originate from hard scattering. A method to remove this contamination, used in other experiments [26,27], is to select jets with a requirement on the leading charged-particle track or calorimeter energy deposit among the constituents of the jet. However, this method can bias to preferentially select jets with hard fragmentation, distorting the low-p_T region. In CMS, tracks are reconstructed with a minimum p_T of 0.15 GeV/c, thus removing any such potential bias.

TABLE I. Summary of the systematic uncertainties in the PbPb jet yield for the central (0–5%), peripheral (70–90%) bins, and the pp jet cross section. Each column showcases the total systematic uncertainties for the corresponding source for the different R and two jet p_T ranges, i.e., $70 <$ jet $p_T < 80$ [GeV/c] and $250 <$ jet $p_T < 300$ [GeV/c]). The T_{AA} uncertainties are not shown in the table. Other sources mentioned in the text that are smaller than 1% are not listed explicitly below.

	Source	$70 <$ jet $p_T < 80$ [GeV/c]			$250 <$ jet $p_T < 300$ [GeV/c]		
		$R = 0.2$	$R = 0.3$	$R = 0.4$	$R = 0.2$	$R = 0.3$	$R = 0.4$
PbPb:	Data driven correction	13%	20%	27%	…	…	…
(0–5%)	JES & unfolding	32%	32%	48%	19%	19%	21%
	JER	3%	3%	3%	3%	3%	3%
	Underlying event	5%	5%	5%	…	…	…
PbPb:	Data driven correction	8%	10%	12%	…	…	…
(70–90%)	JES & unfolding	16%	16%	18%	…	…	…
	JER	3%	3%	3%	…	…	…
	Underlying event	5%	5%	5%	…	…	…
pp:	JES & unfolding	7%	7%	6%	5%	4%	5%
	JER	3%	3%	3%	2%	2%	2%
	Integrated luminosity	3.7%	3.7%	3.7%	3.7%	3.7%	3.7%

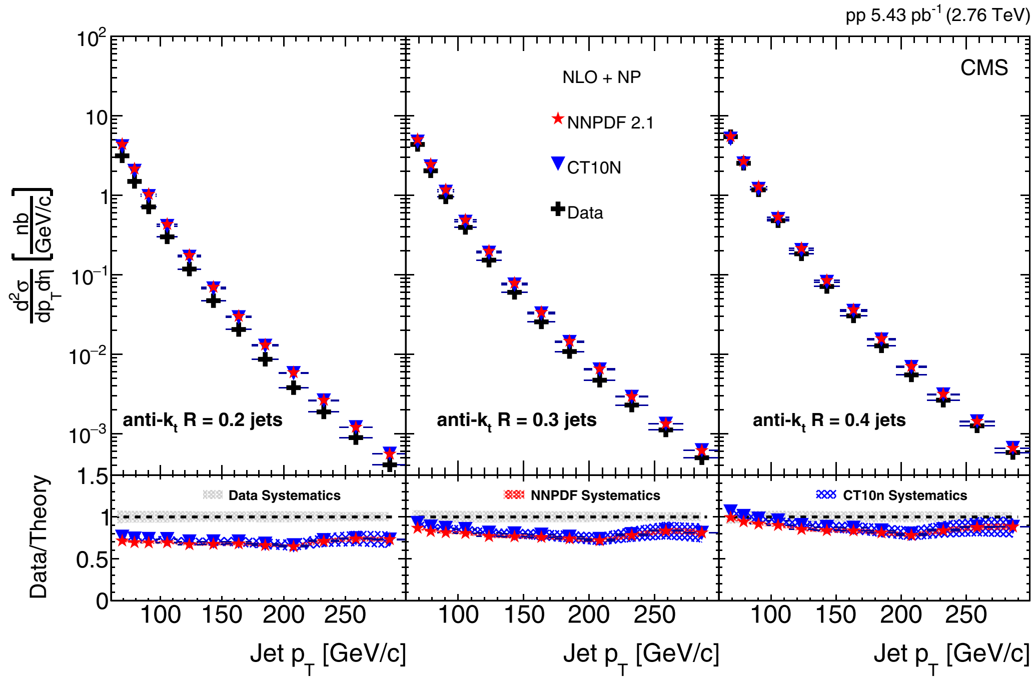

FIG. 4. Comparison of the inclusive jet cross section for anti-k_T jets with distance parameters of $R = 0.2$ (left), 0.3 (middle), and 0.4 (right), measured for *pp* collisions at 2.76 TeV (black plus markers), and NLO calculations, at the same collision energy, with NNPDF 2.1 (red star) and CT10N (blue triangle), with their respective NP corrections added. The bottom panels show the ratio of measured cross section to theory calculations. The systematic uncertainties for data are shown in the gray shaded band, while the systematic uncertainties in the NLO calculations are shown with the respective color shaded bands.

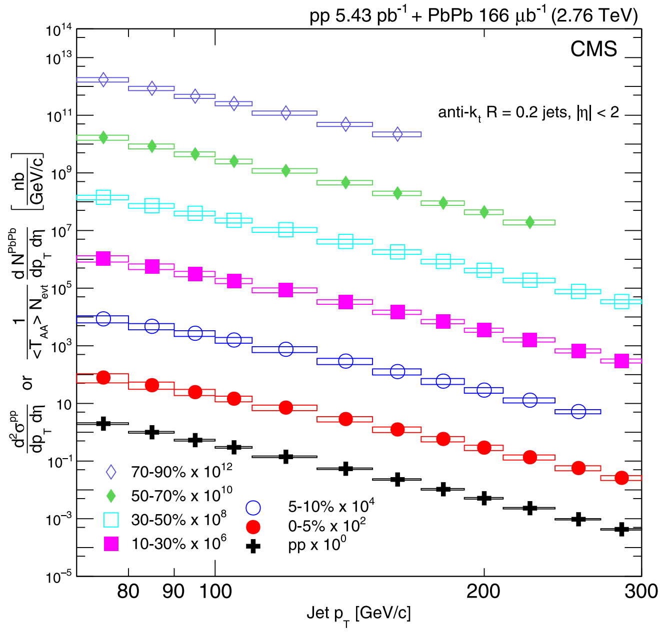

FIG. 5. Inclusive jet spectra for PbPb jets of distance parameter $R = 0.2$, in different centrality bins, and *pp* reference data. The PbPb jet spectra for different centrality classes are scaled by $\langle T_{AA} \rangle$ and multiplied by a different factor for better visualization. Vertical bars represent statistical uncertainty (too small to see on this scale) with the systematical uncertainty in the colored boxes around the data points.

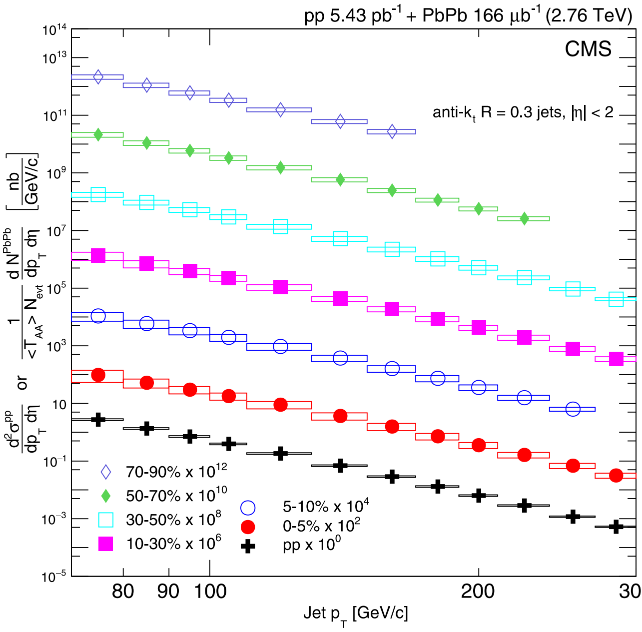

FIG. 6. Inclusive jet spectra for PbPb jets of distance parameter $R = 0.3$, in different centrality bins, and *pp* reference data. The PbPb jet spectra for different centrality classes are scaled by $\langle T_{AA} \rangle$ and multiplied by a different factor for better visualization. Vertical bars represent statistical uncertainty (too small to see on this scale) with the systematical uncertainty in the colored boxes around the data points.

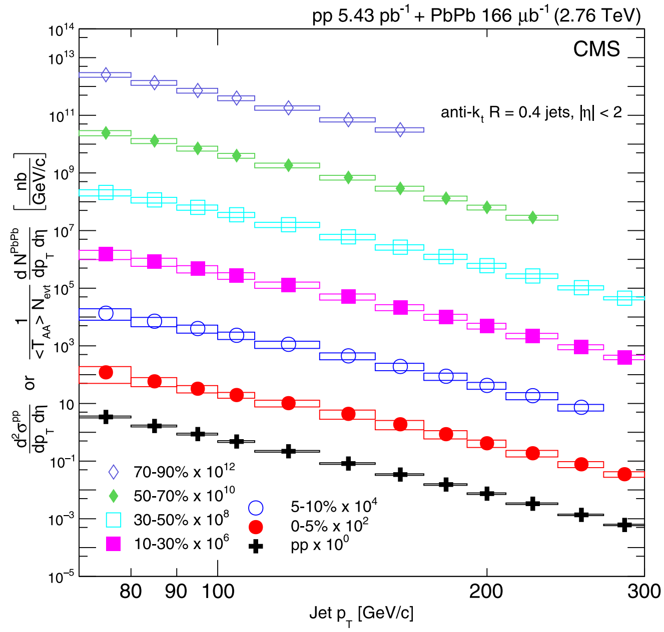

FIG. 7. Inclusive jet spectra for PbPb jets of distance parameter $R = 0.4$, in different centrality bins, and *pp* reference data. The PbPb jet spectra for different centrality classes are scaled by $\langle T_{AA}\rangle$ and multiplied by a different factor for better visualization. Vertical bars represent statistical uncertainty (too small to see on this scale) with the systematical uncertainty in the colored boxes around the data points.

In this analysis, a novel data-driven technique, based on control regions in data, is introduced to derive the spectrum of misreconstructed jets from the minimum bias sample. This spectrum is then subtracted from the jet-triggered sample. Two methods, operating in different kinematic regimes, are combined to get a correction factor. The first method (labeled the trigger object method) selects all events with a leading HLT jet p_T of less than 60 GeV/c as a control sample potentially containing misreconstructed jets. This p_T threshold is chosen based on analysis of random cones in minimum bias events, with the leading and subleading jets removed. The second method (labeled the dijet method), performed in parallel with the first method, selects minimum bias events with dijets, which can originate either from a hard scattering or fluctuating background. There are two thresholds defined in this method, one for the leading jet (p_T^{min1}) and another for the subleading jet (p_T^{min2}) in the reconstructed event. If an event fails any of the following selections, it is tagged as a background event. An event is tagged as a signal if it passes all of the criteria: Leading jet $p_T > p_T^{\mathrm{min1}}$ and $\Delta\phi_{j1,j2} > 2\pi/3$ and subleading jet $p_T > p_T^{\mathrm{min2}}$. To choose the thresholds for the dijet selection, the mean and rms of the subtraction step in the iterative subtraction algorithm are mimicked by applying a cutoff on the transverse energies of the PF towers used in the random cone study. The rms of the background subtracted event energy distribution is used as an estimate of the fluctuation. The thresholds are set as follows: $p_T^{\mathrm{min1}} = 3\,\mathrm{rms}$ for the leading

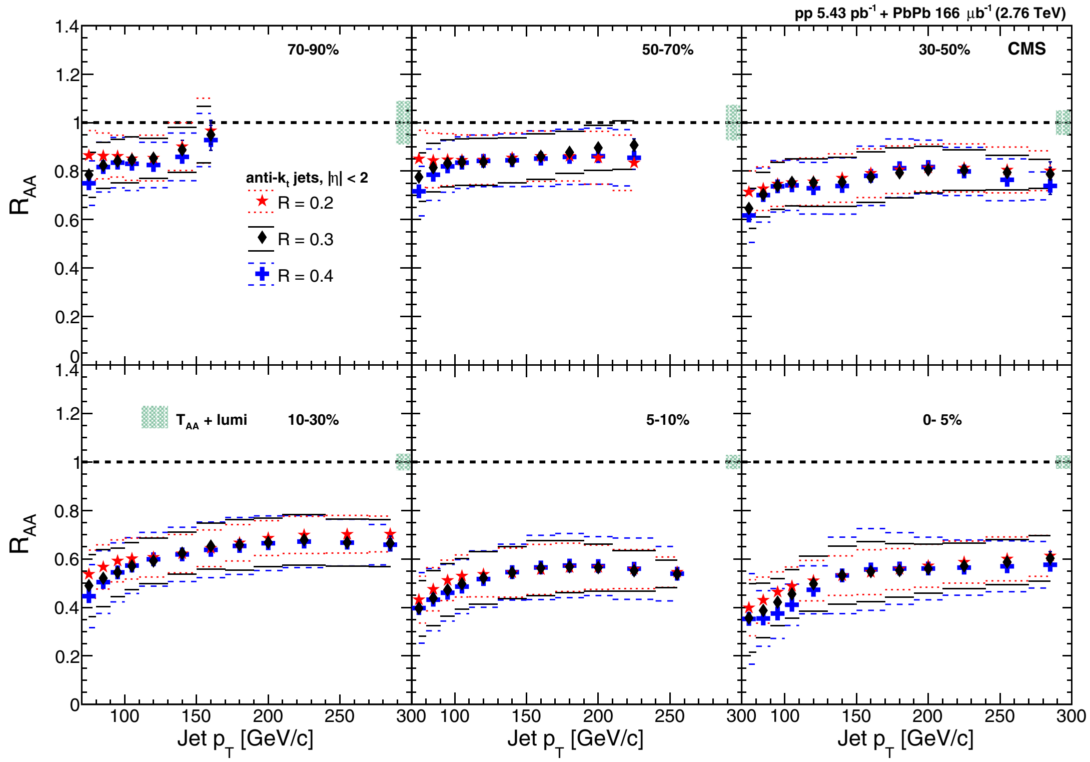

FIG. 8. Inclusive jet R_{AA} as a function of the jet p_T, for anti-k_T jets with distance parameters $R = 0.2$ (red stars), 0.3 (black diamonds), and 0.4 (blue crosses) for different centrality bins. The vertical bars (smaller than the markers) indicate the statistical uncertainty and the systematic uncertainty is represented by the bounds of the dotted, solid, and dashed horizontal lines. The uncertainty boxes at unity represent the T_{AA} and luminosity uncertainty.

jet, and $p_{\mathrm{T}}^{\mathrm{min2}} = 1.8$ rms for the subleading jet, to allow for jet modification in the medium.

Since these two methods operate in different kinematic regimes, the average of the two is used to estimate the data driven correction factor for misreconstructed jet rates as can be seen in Fig. 3, as a function of the jet p_{T}. These rates for different distance parameters are shown in the different panels (left: $R = 0.2$, center: $R = 0.3$, and right: $R = 0.4$). The symbols correspond to the centrality bins in the analysis. The minimum bias background jet spectra are then normalized to a per-event yield and the background is removed from the measured jet spectra, resulting in an inclusive jet spectrum without fragmentation bias. The correction, estimated in a similar way from PYTHIA dijet events, where one does not expect any background, is added as an additional systematic uncertainty, ranging from 6% at 70 GeV to 1% at 100 GeV. The data driven method was also applied to PYTHIA+HYDJET simulations without quenching and, using the same p_{T} threshold, this yielded a recovery efficiency of greater than 98% for signal jets, which is well within systematic uncertainties as described in Sec. IV.

B. Unfolding studies

An unfolding method is required to remove the smearing and bin migration in jet p_{T} due to detector resolution, and to extract the jet cross section measurement. Three different techniques are used to determine the final jet p_{T} spectra: Single value decomposition (SVD), Bayesian, and a bin-by-bin unfolding technique [42–46]. Results presented here are based on the SVD technique, while the others are used as a crosscheck, giving consistent results within their respective uncertainties. The three aforementioned procedures use a response matrix from PYTHIA + HYDJET of reconstructed jets, matched to generator-level jets in the η-ϕ space, that originate from the PYTHIA QCD hard scattering.

The SVD unfolding is performed with a regularization parameter, which is optimized for each centrality class and each jet resolution. The simulation and data used in unfolding have a reconstructed jet p_{T} larger than $50\,\mathrm{GeV}/c$ for all distance parameters, with unfolded results reported for jets larger than $70\,\mathrm{GeV}/c$.

IV. SYSTEMATIC UNCERTAINTIES

The systematic uncertainty is calculated from a number of sources and is shown in Table I. For $R = 0.3$ jets, in the low $p_{\mathrm{T}} < 80\,\mathrm{GeV}/c$ region, a large contribution to the jet yield uncertainty in PbPb collisions is from the data driven corrections (20%). The data driven systematic uncertainty is estimated from the overlap of the two different methods (trigger object and dijet methods as described in Sec. III A) along with an additional uncertainty of 1–6% across all jet p_{T}, centrality ranges, and jet distance parameters determined from its application on a PYTHIA sample. The jet energy scale (JES) uncertainty ranges from 6–32% (from peripheral to central events), varying due to the uncertainty in the heavy ion tracking and the quark/gluon fragmentation. The fragmentation difference is included in the JES uncertainty for pp, but is extended for PbPb jets due to expected asymmetric jet quenching effects for quark and gluon jets. The jet response matrix is smeared by 1%, at both the generator and reconstructed levels to account for variations in the simulations. Separately the regularization parameter used for the unfolding is varied between 4 and 8 resulting in at most 8% systematic uncertainty for the PbPb jet yield and at most 2% for the pp jet cross section.

A residual jet energy correction, using the dijet balance method [41], is derived and applied to the jets from pp collisions. It corresponds to less than 1% correction to the jet p_{T}. The jet energy resolution (JER) uncertainty is estimated for each p_{T} bin in the analysis and is found to be at most 3%, for both pp and PbPb. Studies of the underlying event fluctuations

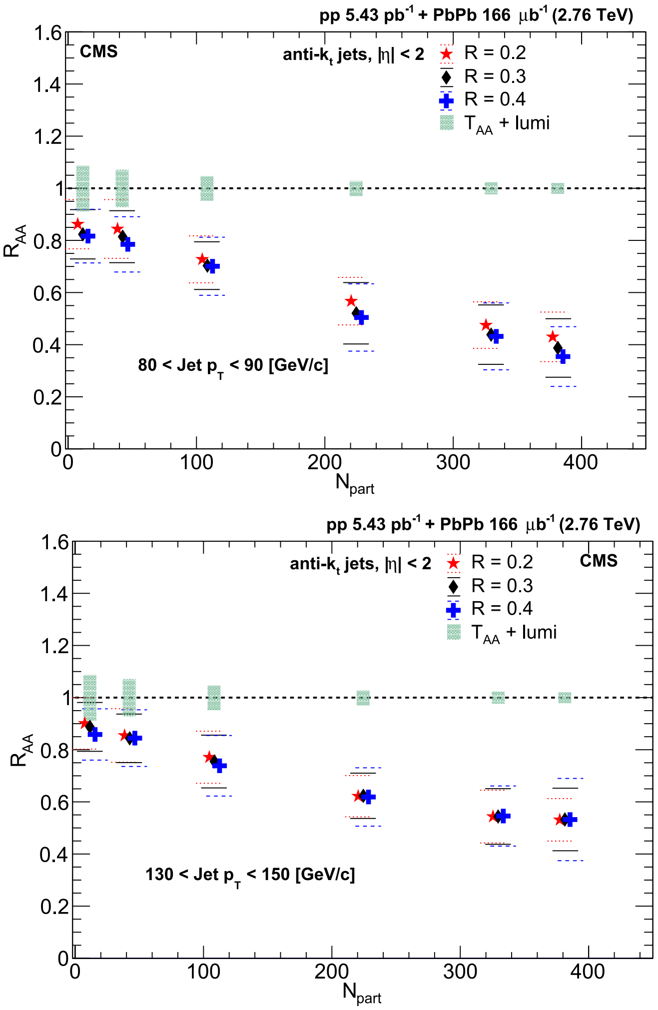

FIG. 9. Inclusive jet R_{AA} for anti-k_{T} jets with distance parameters $R = 0.2$ (red stars), 0.3 (black diamonds), and 0.4 (blue crosses), as a function of the average N_{part} for each collision centrality, for jets of $80 < p_{\mathrm{T}} < 90$ and $130 < p_{\mathrm{T}} < 150\,[\mathrm{GeV}/c]$, in the top and bottom panels, respectively. Points are shifted to the left ($R = 0.2$) and right ($R = 0.4$) for clarity. The statistical uncertainty is indicated by colored vertical lines (smaller than the markers). The systematic uncertainty is represented by the bounds of the dotted, solid, and dashed horizontal lines for the corresponding distance parameters. The uncertainty boxes at unity represent the T_{AA} and luminosity uncertainty.

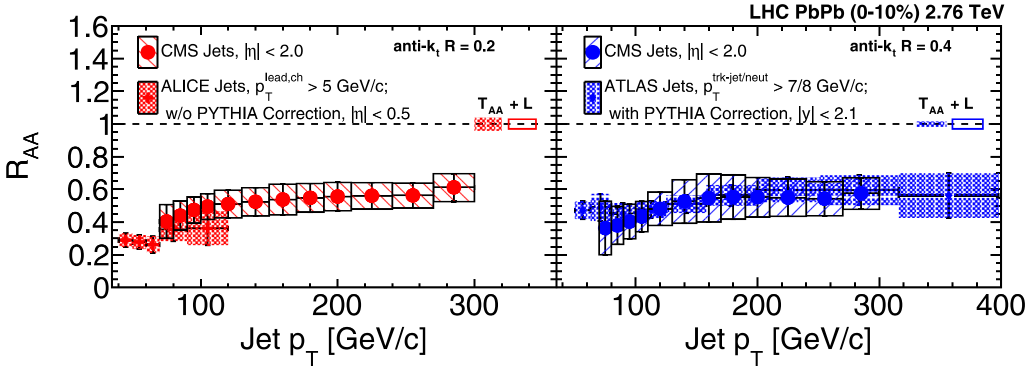

FIG. 10. Left panel: Inclusive jet R_{AA} as a function of the jet p_T, for anti-k_T jets with distance parameter $R = 0.2$ in the 0%–10% centrality bin for CMS (closed circles) and ALICE (pluses) [27]. Right panel: Inclusive jet R_{AA} as a function of the jet p_T, for anti-k_T jets with distance parameter $R = 0.4$ in the 0%–10% centrality bin for CMS (closed circles) and ATLAS (diamonds) [26]. The vertical bars indicate the statistical uncertainty. The systematic uncertainty is represented by the bounds of the boxes. The uncertainty boxes at unity represent the T_{AA} and luminosity uncertainty, open for CMS and shaded for ALICE and ATLAS. See text for a further discussion of differences in the analyses used by the three collaborations.

in jet-triggered and minimum bias events show a contribution of up to 5% to the uncertainty of reconstructed jet yields based on differences between data and PYTHIA + HYDJET quantified in the right side of Fig. 2. The contributions due to jet reconstruction efficiency, detector noise, and unfolding response matrix smearing are about 1% each.

Since in PbPb, the per-event jet yield is being measured, there is a 3% uncertainty on the number of minimum bias events and there is no uncertainty quoted for the luminosity. For the pp cross section, there is a 3.7% uncertainty in the integrated luminosity [47]. Systematic uncertainties, from different contributions to the jet R_{AA}, are summed in quadrature with an overall uncertainty of 19–40%, from peripheral to central collisions for $R = 0.3$ jets. Detailed systematic uncertainties for different R and two representative jet p_T ranges are shown in Table I.

V. RESULTS

The inclusive jet cross sections in *pp* collisions at 2.76 TeV are shown in Fig. 4 for three different distance parameters. A comparison is made to next-to-leading-order (NLO) [48] calculations of quantum chromodynamics. These calculations are shown for two parton distribution functions (PDF) sets: NNPDF 2.1 [49] (red stars), and CT10N [50] (purple triangles) including nonperturbative (NP) contributions such as multiparton interactions and hadronization. Contributions to the jet cross section from NP effects are not inherently included in pQCD calculations due to a lower scale cutoff of a few GeV/c. Thus, the NP correction factors need to be added and are computed as the ratio of cross sections calculated with leading order (LO) + parton shower (PS) + multiparton interactions + hadronization to LO+PS [48]. The bottom panel of Fig. 4 shows the ratio of the data for jet cross sections in *pp* collisions to theoretical calculations, with the measured jet cross section from *pp* collisions for different distance parameters. The agreement with data gets better at larger distance parameters. In Ref. [51] the ratio tends closer to unity for jets with $R = 0.7$. The theoretical uncertainties shown are due to variations of the strong coupling constant and the parton shower, factorization scales involved in the NLO calculations for the different PDF sets.

The unfolded jet cross sections for PbPb and *pp* events are shown in Figs. 5–7 for different distance parameters. The PbPb spectra are normalized by the number of minimum bias events, and are scaled by $\langle T_{AA} \rangle$, with each centrality multiplied by a different factor, to separate the spectra for better visualization. The *pp* reference data are normalized to the integrated luminosity of the analyzed data set. The high p_T cutoffs for the spectra (hence also the R_{AA}) are dictated by statistical limitations.

The jet R_{AA}, found from the PbPb and *pp* spectra after all corrections including SVD unfolding, are shown for different distance parameters in Fig. 8. The jet R_{AA} decreases with increasing collision centrality in the range of the measured jet p_T. Within the systematic uncertainty, the jet R_{AA} shows the same level of suppression for the three distance parameters. Uncorrelated uncertainties remain too large to further elucidate the hierarchy of the jet distance parameter dependence of this R_{AA} measurement.

To focus on the centrality dependence of the jet R_{AA}, two ranges of jet p_T are selected and the corresponding jet R_{AA} values are plotted as a function of the average number of participants $\langle N_{\text{part}} \rangle$ in Fig. 9, for jets of $80 < p_T < 90$ and $130 < p_T < 150\,\text{GeV}/c$. The systematic uncertainty is shown in the three bounds of lines for $R = 0.2$ (dotted), 0.3 (solid), and 0.4 (dashed) jets. The jet R_{AA} shows a clear trend of increasing suppression as the number of participants in the PbPb collision increases. Overall, in the kinematic range explored, the R_{AA} show the same level of suppression across the three distance parameters.

An experimental comparison of inclusive anti-k_T jet R_{AA} for 0–10% centrality is shown in Fig. 10 (left panel for anti-k_T jets with distance parameter $R = 0.2$ for ALICE [27] and the right panel with $R = 0.4$ for ATLAS [26]). Uncertainties are represented by the vertical bars for the statistical and boxes for the systematic uncertainties. The T_{AA} and luminosity uncertainty are shown by the boxes at unity. The collection of jets for the jet R_{AA} calculation in these experiments differ, especially for lower jet p_{T}, due to the techniques employed to remove or correct the jets that did not originate in a hard scattering but that are purely due to the fluctuations in the heavy-ion underlying event. Some, but not all of the key differences are described here, for more, see ALICE [27], ATLAS [26], and [52] for a review. ALICE requires the leading track constituent of the jet to have $p_{\mathrm{T}} > 5\,\mathrm{GeV}/c$ and constrains $R = 0.2$ jets to be within $|\eta| < 0.9$. ATLAS requires its $R = 0.4$ jets in $|y| < 2.1$ to have a track jet with $p_{\mathrm{T}} > 7\,\mathrm{GeV}/c$ or a calorimeter cluster with $p_{\mathrm{T}} > 8\,\mathrm{GeV}/c$ within $\Delta R = 0.2$. While ALICE does not apply any correction on this constituent selection, ATLAS corrects for the missing jets due to this selection with correction factors estimated by PYTHIA. In this analysis, as described in Sec. III A, a data-driven background subtraction is introduced and all jets which are using tracks down to a p_{T} of $0.15\,\mathrm{GeV}/c$ and calorimeter deposits down to a E_{T} of $1\,\mathrm{GeV}$ are included in the jet R_{AA} calculation. Within the current precision of jet R_{AA} measurements, there is a good agreement in the overlapping p_{T} ranges despite the fact that the measured jet collections differ between experiments.

VI. SUMMARY

The cross section of anti-k_{T} particle-flow jets has been measured in pp and PbPb collisions at $\sqrt{s_{NN}} = 2.76\,\mathrm{TeV}$ for distance parameters $R = 0.2$, 0.3, and 0.4 in $|\eta| < 2$ and for jet p_{T} above $70\,\mathrm{GeV}/c$. It is found that next-to-leading order calculations with nonperturbative corrections over predict the pp cross sections, with a smaller discrepancy for larger distance parameters. The PbPb inclusive jet nuclear modification factors show a steady decrease from peripheral to central events, with a slight rise with jet p_{T}. No significant dependence of the jet nuclear modification factor on the distance parameter is found for the jets in the kinematic range measured in this analysis.

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G. Grenier,[34] B. Ille,[34] F. Lagarde,[34] I. B. Laktineh,[34] M. Lethuillier,[34] L. Mirabito,[34] A. L. Pequegnot,[34] S. Perries,[34]

A. Popov,[34,m] D. Sabes,[34] V. Sordini,[34] M. Vander Donckt,[34] P. Verdier,[34] S. Viret,[34] A. Khvedelidze,[35,h] Z. Tsamalaidze,[36,h] C. Autermann,[37] S. Beranek,[37] L. Feld,[37] A. Heister,[37] M. K. Kiesel,[37] K. Klein,[37] M. Lipinski,[37] A. Ostapchuk,[37] M. Preuten,[37] F. Raupach,[37] S. Schael,[37] C. Schomakers,[37] J. Schulz,[37] T. Verlage,[37] H. Weber,[37] V. Zhukov,[37,m] A. Albert,[38] M. Brodski,[38] E. Dietz-Laursonn,[38] D. Duchardt,[38] M. Endres,[38] M. Erdmann,[38] S. Erdweg,[38] T. Esch,[38] R. Fischer,[38] A. Güth,[38] M. Hamer,[38] T. Hebbeker,[38] C. Heidemann,[38] K. Hoepfner,[38] S. Knutzen,[38] M. Merschmeyer,[38] A. Meyer,[38] P. Millet,[38] S. Mukherjee,[38] M. Olschewski,[38] K. Padeken,[38] T. Pook,[38] M. Radziej,[38] H. Reithler,[38] M. Rieger,[38] F. Scheuch,[38] L. Sonnenschein,[38] D. Teyssier,[38] S. Thüer,[38] V. Cherepanov,[39] G. Flügge,[39] F. Hoehle,[39] B. Kargoll,[39] T. Kress,[39] A. Künsken,[39] J. Lingemann,[39] T. Müller,[39] A. Nehrkorn,[39] A. Nowack,[39] I. M. Nugent,[39] C. Pistone,[39] O. Pooth,[39] A. Stahl,[39,n] M. Aldaya Martin,[40] T. Arndt,[40] C. Asawatangtrakuldee,[40] K. Beernaert,[40] O. Behnke,[40] U. Behrens,[40] A. A. Bin Anuar,[40] K. Borras,[40,o] A. Campbell,[40] P. Connor,[40] C. Contreras-Campana,[40] F. Costanza,[40] C. Diez Pardos,[40] G. Dolinska,[40] G. Eckerlin,[40] D. Eckstein,[40] T. Eichhorn,[40] E. Eren,[40] E. Gallo,[40,p] J. Garay Garcia,[40] A. Geiser,[40] A. Gizhko,[40] J. M. Grados Luyando,[40] P. Gunnellini,[40] A. Harb,[40] J. Hauk,[40] M. Hempel,[40,q] H. Jung,[40] A. Kalogeropoulos,[40] O. Karacheban,[40,q] M. Kasemann,[40] J. Keaveney,[40] C. Kleinwort,[40] I. Korol,[40] D. Krücker,[40] W. Lange,[40] A. Lelek,[40] J. Leonard,[40] K. Lipka,[40] A. Lobanov,[40] W. Lohmann,[40,q] R. Mankel,[40] I.-A. Melzer-Pellmann,[40] A. B. Meyer,[40] G. Mittag,[40] J. Mnich,[40] A. Mussgiller,[40] E. Ntomari,[40] D. Pitzl,[40] R. Placakyte,[40] A. Raspereza,[40] B. Roland,[40] M. Ö. Sahin,[40] P. Saxena,[40] T. Schoerner-Sadenius,[40] C. Seitz,[40] S. Spannagel,[40] N. Stefaniuk,[40] G. P. Van Onsem,[40] R. Walsh,[40] C. Wissing,[40] V. Blobel,[41] M. Centis Vignali,[41] A. R. Draeger,[41] T. Dreyer,[41] E. Garutti,[41] D. Gonzalez,[41] J. Haller,[41] M. Hoffmann,[41] A. Junkes,[41] R. Klanner,[41] R. Kogler,[41] N. Kovalchuk,[41] T. Lapsien,[41] T. Lenz,[41] I. Marchesini,[41] D. Marconi,[41] M. Meyer,[41] M. Niedziela,[41] D. Nowatschin,[41] F. Pantaleo,[41,n] T. Peiffer,[41] A. Perieanu,[41] J. Poehlsen,[41] C. Sander,[41] C. Scharf,[41] P. Schleper,[41] A. Schmidt,[41] S. Schumann,[41] J. Schwandt,[41] H. Stadie,[41] G. Steinbrück,[41] F. M. Stober,[41] M. Stöver,[41] H. Tholen,[41] D. Troendle,[41] E. Usai,[41] L. Vanelderen,[41] A. Vanhoefer,[41] B. Vormwald,[41] C. Barth,[42] C. Baus,[42] J. Berger,[42] E. Butz,[42] T. Chwalek,[42] F. Colombo,[42] W. De Boer,[42] A. Dierlamm,[42] S. Fink,[42] R. Friese,[42] M. Giffels,[42] A. Gilbert,[42] P. Goldenzweig,[42] D. Haitz,[42] F. Hartmann,[42,n] S. M. Heindl,[42] U. Husemann,[42] I. Katkov,[42,m] P. Lobelle Pardo,[42] B. Maier,[42] H. Mildner,[42] M. U. Mozer,[42] Th. Müller,[42] M. Plagge,[42] G. Quast,[42] K. Rabbertz,[42] S. Röcker,[42] F. Roscher,[42] M. Schröder,[42] I. Shvetsov,[42] G. Sieber,[42] H. J. Simonis,[42] R. Ulrich,[42] J. Wagner-Kuhr,[42] S. Wayand,[42] M. Weber,[42] T. Weiler,[42] S. Williamson,[42] C. Wöhrmann,[42] R. Wolf,[42] G. Anagnostou,[43] G. Daskalakis,[43] T. Geralis,[43] V. A. Giakoumopoulou,[43] A. Kyriakis,[43] D. Loukas,[43] I. Topsis-Giotis,[43] S. Kesisoglou,[44] A. Panagiotou,[44] N. Saoulidou,[44] E. Tziaferi,[44] I. Evangelou,[45] G. Flouris,[45] C. Foudas,[45] P. Kokkas,[45] N. Loukas,[45] N. Manthos,[45] I. Papadopoulos,[45] E. Paradas,[45] N. Filipovic,[46] G. Bencze,[47] C. Hajdu,[47] P. Hidas,[47] D. Horvath,[47,r] F. Sikler,[47] V. Veszpremi,[47] G. Vesztergombi,[47,s] A. J. Zsigmond,[47] N. Beni,[48] S. Czellar,[48] J. Karancsi,[48,t] A. Makovec,[48] J. Molnar,[48] Z. Szillasi,[48] M. Bartók,[49,s] P. Raics,[49] Z. L. Trocsanyi,[49] B. Ujvari,[49] S. Bahinipati,[50] S. Choudhury,[50,u] P. Mal,[50] K. Mandal,[50] A. Nayak,[50,v] D. K. Sahoo,[50] N. Sahoo,[50] S. K. Swain,[50] S. Bansal,[51] S. B. Beri,[51] V. Bhatnagar,[51] R. Chawla,[51] U. Bhawandeep,[51] A. K. Kalsi,[51] A. Kaur,[51] M. Kaur,[51] R. Kumar,[51] P. Kumari,[51] A. Mehta,[51] M. Mittal,[51] J. B. Singh,[51] G. Walia,[51] Ashok Kumar,[52] A. Bhardwaj,[52] B. C. Choudhary,[52] R. B. Garg,[52] S. Keshri,[52] S. Malhotra,[52] M. Naimuddin,[52] N. Nishu,[52] K. Ranjan,[52] R. Sharma,[52] V. Sharma,[52] R. Bhattacharya,[53] S. Bhattacharya,[53] K. Chatterjee,[53] S. Dey,[53] S. Dutt,[53] S. Dutta,[53] S. Ghosh,[53] N. Majumdar,[53] A. Modak,[53] K. Mondal,[53] S. Mukhopadhyay,[53] S. Nandan,[53] A. Purohit,[53] A. Roy,[53] D. Roy,[53] S. Roy Chowdhury,[53] S. Sarkar,[53] M. Sharan,[53] S. Thakur,[53] P. K. Behera,[54] R. Chudasama,[55] D. Dutta,[55] V. Jha,[55] V. Kumar,[55] A. K. Mohanty,[55,n] P. K. Netrakanti,[55] L. M. Pant,[55] P. Shukla,[55] A. Topkar,[55] T. Aziz,[56] S. Dugad,[56] G. Kole,[56] B. Mahakud,[56] S. Mitra,[56] G. B. Mohanty,[56] B. Parida,[56] N. Sur,[56] B. Sutar,[56] S. Banerjee,[57] S. Bhowmik,[57,w] R. K. Dewanjee,[57] S. Ganguly,[57] M. Guchait,[57] Sa. Jain,[57] S. Kumar,[57] M. Maity,[57,w] G. Majumder,[57] K. Mazumdar,[57] T. Sarkar,[57,w] N. Wickramage,[57,x] S. Chauhan,[58] S. Dube,[58] V. Hegde,[58] A. Kapoor,[58] K. Kothekar,[58] A. Rane,[58] S. Sharma,[58] H. Behnamian,[59] S. Chenarani,[59,y] E. Eskandari Tadavani,[59] S. M. Etesami,[59,y] A. Fahim,[59,z] M. Khakzad,[59] M. Mohammadi Najafabadi,[59] M. Naseri,[59] S. Paktinat Mehdiabadi,[59,aa] F. Rezaei Hosseinabadi,[59] B. Safarzadeh,[59,ab] M. Zeinali,[59] M. Felcini,[60] M. Grunewald,[60] M. Abbrescia,[61a,61b] C. Calabria,[61a,61b] C. Caputo,[61a,61b] A. Colaleo,[61a] D. Creanza,[61a,61c] L. Cristella,[61a,61b] N. De Filippis,[61a,61c] M. De Palma,[61a,61b] L. Fiore,[61a] G. Iaselli,[61a,61c] G. Maggi,[61a,61c] M. Maggi,[61a] G. Miniello,[61a,61b] S. My,[61a,61b] S. Nuzzo,[61a,61b] A. Pompili,[61a,61b] G. Pugliese,[61a,61c] R. Radogna,[61a,61b] A. Ranieri,[61a] G. Selvaggi,[61a,61b] L. Silvestris,[61a,n] R. Venditti,[61a,61b] P. Verwilligen,[61a] G. Abbiendi,[62a] C. Battilana,[62a] D. Bonacorsi,[62a,62b] S. Braibant-Giacomelli,[62a,62b] L. Brigliadori,[62a,62b] R. Campanini,[62a,62b] P. Capiluppi,[62a,62b] A. Castro,[62a,62b] F. R. Cavallo,[62a] S. S. Chhibra,[62a,62b] G. Codispoti,[62a,62b] M. Cuffiani,[62a,62b] G. M. Dallavalle,[62a] F. Fabbri,[62a] A. Fanfani,[62a,62b] D. Fasanella,[62a,62b] P. Giacomelli,[62a] C. Grandi,[62a] L. Guiducci,[62a,62b] S. Marcellini,[62a] G. Masetti,[62a] A. Montanari,[62a] F. L. Navarria,[62a,62b] A. Perrotta,[62a] A. M. Rossi,[62a,62b] T. Rovelli,[62a,62b] G. P. Siroli,[62a,62b] N. Tosi,[62a,62b,n] S. Albergo,[63a,63b] M. Chiorboli,[63a,63b] S. Costa,[63a,63b] A. Di Mattia,[63a] F. Giordano,[63a,63b] R. Potenza,[63a,63b] A. Tricomi,[63a,63b] C. Tuve,[63a,63b] G. Barbagli,[64a] V. Ciulli,[64a,64b] C. Civinini,[64a] R. D'Alessandro,[64a,64b] E. Focardi,[64a,64b] V. Gori,[64a,64b] P. Lenzi,[64a,64b] M. Meschini,[64a] S. Paoletti,[64a] G. Sguazzoni,[64a] L. Viliani,[64a,64b,n] L. Benussi,[65] S. Bianco,[65] F. Fabbri,[65] D. Piccolo,[65] F. Primavera,[65,n] V. Calvelli,[66a,66b] F. Ferro,[66a] M. Lo Vetere,[66a,66b] M. R. Monge,[66a,66b] E. Robutti,[66a] S. Tosi,[66a,66b] L. Brianza,[67a,n] M. E. Dinardo,[67a,67b] S. Fiorendi,[67a,67b] S. Gennai,[67a] A. Ghezzi,[67a,67b] P. Govoni,[67a,67b] M. Malberti,[67a] S. Malvezzi,[67a] R. A. Manzoni,[67a,67b,n] D. Menasce,[67a] L. Moroni,[67a] M. Paganoni,[67a,67b] D. Pedrini,[67a] S. Pigazzini,[67a] S. Ragazzi,[67a,67b] T. Tabarelli de Fatis,[67a,67b] S. Buontempo,[68a] N. Cavallo,[68a,68c] G. De Nardo,[68a] S. Di Guida,[68a,68d,n]

M. Esposito,[68a,68b] F. Fabozzi,[68a,68c] F. Fienga,[68a,68b] A. O. M. Iorio,[68a,68b] G. Lanza,[68a] L. Lista,[68a] S. Meola,[68a,68d,n] P. Paolucci,[68a,n] C. Sciacca,[68a,68b] F. Thyssen,[68a] P. Azzi,[69a,n] N. Bacchetta,[69a] L. Benato,[69a,69b] D. Bisello,[69a,69b] A. Boletti,[69a,69b] R. Carlin,[69a,69b] A. Carvalho Antunes De Oliveira,[69a,69b] P. Checchia,[69a] M. Dall'Osso,[69a,69b] P. De Castro Manzano,[69a] T. Dorigo,[69a] U. Dosselli,[69a] F. Gasparini,[69a,69b] U. Gasparini,[69a,69b] A. Gozzelino,[69a] S. Lacaprara,[69a] M. Margoni,[69a,69b] A. T. Meneguzzo,[69a,69b] J. Pazzini,[69a,69b] N. Pozzobon,[69a,69b] P. Ronchese,[69a,69b] F. Simonetto,[69a,69b] E. Torassa,[69a] M. Zanetti,[69a] P. Zotto,[69a,69b] G. Zumerle,[69a,69b] A. Braghieri,[70a] A. Magnani,[70a,70b] P. Montagna,[70a,70b] S. P. Ratti,[70a,70b] V. Re,[70a] C. Riccardi,[70a,70b] P. Salvini,[70a] I. Vai,[70a,70b] P. Vitulo,[70a,70b] L. Alunni Solestizi,[71a,71b] G. M. Bilei,[71a] D. Ciangottini,[71a,71b] L. Fanò,[71a,71b] P. Lariccia,[71a,71b] R. Leonardi,[71a,71b] G. Mantovani,[71a,71b] M. Menichelli,[71a] A. Saha,[71a] A. Santocchia,[71a,71b] K. Androsov,[72a,ac] P. Azzurri,[72a,n] G. Bagliesi,[72a] J. Bernardini,[72a] T. Boccali,[72a] R. Castaldi,[72a] M. A. Ciocci,[72a,ac] R. Dell'Orso,[72a] S. Donato,[72a,72c] G. Fedi,[72a] A. Giassi,[72a] M. T. Grippo,[72a,ac] F. Ligabue,[72a,72c] T. Lomtadze,[72a] L. Martini,[72a,72b] A. Messineo,[72a,72b] F. Palla,[72a] A. Rizzi,[72a,72b] A. Savoy-Navarro,[72a,ad] P. Spagnolo,[72a] R. Tenchini,[72a] G. Tonelli,[72a,72b] A. Venturi,[72a] P. G. Verdini,[72a] L. Barone,[73a,73b] F. Cavallari,[73a] M. Cipriani,[73a,73b] G. D'imperio,[73a,73b,n] D. Del Re,[73a,73b,n] M. Diemoz,[73a] S. Gelli,[73a,73b] E. Longo,[73a,73b] F. Margaroli,[73a,73b] B. Marzocchi,[73a,73b] P. Meridiani,[73a] G. Organtini,[73a,73b] R. Paramatti,[73a] F. Preiato,[73a,73b] S. Rahatlou,[73a,73b] C. Rovelli,[73a] F. Santanastasio,[73a,73b] N. Amapane,[74a,74b] R. Arcidiacono,[74a,74c,n] S. Argiro,[74a,74b] M. Arneodo,[74a,74c] N. Bartosik,[74a] R. Bellan,[74a,74b] C. Biino,[74a] N. Cartiglia,[74a] F. Cenna,[74a,74b] M. Costa,[74a,74b] R. Covarelli,[74a,74b] A. Degano,[74a,74b] N. Demaria,[74a] L. Finco,[74a,74b] B. Kiani,[74a,74b] C. Mariotti,[74a] S. Maselli,[74a] E. Migliore,[74a,74b] V. Monaco,[74a,74b] E. Monteil,[74a,74b] M. M. Obertino,[74a,74b] L. Pacher,[74a,74b] N. Pastrone,[74a] M. Pelliccioni,[74a] G. L. Pinna Angioni,[74a,74b] F. Ravera,[74a,74b] A. Romero,[74a,74b] M. Ruspa,[74a,74c] R. Sacchi,[74a,74b] K. Shchelina,[74a,74b] V. Sola,[74a] A. Solano,[74a,74b] A. Staiano,[74a] P. Traczyk,[74a,74b] S. Belforte,[75a] M. Casarsa,[75a] F. Cossutti,[75a] G. Della Ricca,[75a,75b] A. Zanetti,[75a] D. H. Kim,[76] G. N. Kim,[76] M. S. Kim,[76] S. Lee,[76] S. W. Lee,[76] Y. D. Oh,[76] S. Sekmen,[76] D. C. Son,[76] Y. C. Yang,[76] A. Lee,[77] H. Kim,[78] J. A. Brochero Cifuentes,[79] T. J. Kim,[79] S. Cho,[80] S. Choi,[80] Y. Go,[80] D. Gyun,[80] S. Ha,[80] B. Hong,[80] Y. Jo,[80] Y. Kim,[80] B. Lee,[80] K. Lee,[80] K. S. Lee,[80] S. Lee,[80] J. Lim,[80] S. K. Park,[80] Y. Roh,[80] J. Almond,[81] J. Kim,[81] H. Lee,[81] S. B. Oh,[81] B. C. Radburn-Smith,[81] S. h. Seo,[81] U. K. Yang,[81] H. D. Yoo,[81] G. B. Yu,[81] M. Choi,[82] H. Kim,[82] J. H. Kim,[82] J. S. H. Lee,[82] I. C. Park,[82] G. Ryu,[82] M. S. Ryu,[82] Y. Choi,[83] J. Goh,[83] C. Hwang,[83] J. Lee,[83] I. Yu,[83] V. Dudenas,[84] A. Juodagalvis,[84] J. Vaitkus,[84] I. Ahmed,[85] Z. A. Ibrahim,[85] J. R. Komaragiri,[85] M. A. B. Md Ali,[85,ae] F. Mohamad Idris,[85,af] W. A. T. Wan Abdullah,[85] M. N. Yusli,[85] Z. Zolkapli,[85] H. Castilla-Valdez,[86] E. De La Cruz-Burelo,[86] I. Heredia-De La Cruz,[86,ag] A. Hernandez-Almada,[86] R. Lopez-Fernandez,[86] R. Magaña Villalba,[86] J. Mejia Guisao,[86] A. Sanchez-Hernandez,[86] S. Carrillo Moreno,[87] C. Oropeza Barrera,[87] F. Vazquez Valencia,[87] S. Carpinteyro,[88] I. Pedraza,[88] H. A. Salazar Ibarguen,[88] C. Uribe Estrada,[88] A. Morelos Pineda,[89] D. Krofcheck,[90] P. H. Butler,[91] A. Ahmad,[92] M. Ahmad,[92] Q. Hassan,[92] H. R. Hoorani,[92] W. A. Khan,[92] A. Saddique,[92] M. A. Shah,[92] M. Shoaib,[92] M. Waqas,[92] H. Bialkowska,[93] M. Bluj,[93] B. Boimska,[93] T. Frueboes,[93] M. Górski,[93] M. Kazana,[93] K. Nawrocki,[93] K. Romanowska-Rybinska,[93] M. Szleper,[93] P. Zalewski,[93] K. Bunkowski,[94] A. Byszuk,[94,ah] K. Doroba,[94] A. Kalinowski,[94] M. Konecki,[94] J. Krolikowski,[94] M. Misiura,[94] M. Olszewski,[94] M. Walczak,[94] P. Bargassa,[95] C. Beirão Da Cruz E Silva,[95] A. Di Francesco,[95] P. Faccioli,[95] P. G. Ferreira Parracho,[95] M. Gallinaro,[95] J. Hollar,[95] N. Leonardo,[95] L. Lloret Iglesias,[95] M. V. Nemallapudi,[95] J. Rodrigues Antunes,[95] J. Seixas,[95] O. Toldaiev,[95] D. Vadruccio,[95] J. Varela,[95] P. Vischia,[95] S. Afanasiev,[96] M. Gavrilenko,[96] I. Golutvin,[96] A. Kamenev,[96] V. Karjavin,[96] V. Korenkov,[96] A. Lanev,[96] A. Malakhov,[96] V. Matveev,[96,ai] V. V. Mitsyn,[96] V. Palichik,[96] V. Perelygin,[96] S. Shmatov,[96] N. Skatchkov,[96] V. Smirnov,[96] E. Tikhonenko,[96] B. S. Yuldashev,[96,aj] A. Zarubin,[96] L. Chtchipounov,[97] V. Golovtsov,[97] Y. Ivanov,[97] V. Kim,[97,ak] E. Kuznetsova,[97,al] V. Murzin,[97] V. Oreshkin,[97] V. Sulimov,[97] A. Vorobyev,[97] Yu. Andreev,[98] A. Dermenev,[98] S. Gninenko,[98] N. Golubev,[98] A. Karneyeu,[98] M. Kirsanov,[98] N. Krasnikov,[98] A. Pashenkov,[98] D. Tlisov,[98] A. Toropin,[98] V. Epshteyn,[99] V. Gavrilov,[99] N. Lychkovskaya,[99] V. Popov,[99] I. Pozdnyakov,[99] G. Safronov,[99] A. Spiridonov,[99] M. Toms,[99] E. Vlasov,[99] A. Zhokin,[99] A. Bylinkin,[100,am] R. Chistov,[101,an] M. Danilov,[101,an] V. Rusinov,[101] V. Andreev,[102] M. Azarkin,[102,am] I. Dremin,[102,am] M. Kirakosyan,[102] A. Leonidov,[102,am] S. V. Rusakov,[102] A. Terkulov,[102] A. Baskakov,[103] A. Belyaev,[103] E. Boos,[103] A. Ershov,[103] A. Gribushin,[103] A. Kaminskiy,[103,ao] O. Kodolova,[103] V. Korotkikh,[103] I. Lokhtin,[103] I. Miagkov,[103] S. Obraztsov,[103] S. Petrushanko,[103] V. Savrin,[103] A. Snigirev,[103] I. Vardanyan,[103] V. Blinov,[104,ap] Y Skovpen,[104,ap] I. Azhgirey,[105] I. Bayshev,[105] S. Bitioukov,[105] D. Elumakhov,[105] V. Kachanov,[105] A. Kalinin,[105] D. Konstantinov,[105] V. Krychkine,[105] V. Petrov,[105] R. Ryutin,[105] A. Sobol,[105] S. Troshin,[105] N. Tyurin,[105] A. Uzunian,[105] A. Volkov,[105] P. Adzic,[106,aq] P. Cirkovic,[106] D. Devetak,[106] M. Dordevic,[106] J. Milosevic,[106] V. Rekovic,[106] J. Alcaraz Maestre,[107] M. Barrio Luna,[107] E. Calvo,[107] M. Cerrada,[107] M. Chamizo Llatas,[107] N. Colino,[107] B. De La Cruz,[107] A. Delgado Peris,[107] A. Escalante Del Valle,[107] C. Fernandez Bedoya,[107] J. P. Fernández Ramos,[107] J. Flix,[107] M. C. Fouz,[107] P. Garcia-Abia,[107] O. Gonzalez Lopez,[107] S. Goy Lopez,[107] J. M. Hernandez,[107] M. I. Josa,[107] E. Navarro De Martino,[107] A. Pérez-Calero Yzquierdo,[107] J. Puerta Pelayo,[107] A. Quintario Olmeda,[107] I. Redondo,[107] L. Romero,[107] M. S. Soares,[107] J. F. de Trocóniz,[108] M. Missiroli,[108] D. Moran,[108] J. Cuevas,[109] J. Fernandez Menendez,[109] I. Gonzalez Caballero,[109] J. R. González Fernández,[109] E. Palencia Cortezon,[109] S. Sanchez Cruz,[109] I. Suárez Andrés,[109] J. M. Vizan Garcia,[109] I. J. Cabrillo,[110] A. Calderon,[110] J. R. Castiñeiras De Saa,[110] E. Curras,[110] M. Fernandez,[110] J. Garcia-Ferrero,[110] G. Gomez,[110] A. Lopez Virto,[110] J. Marco,[110] C. Martinez Rivero,[110] F. Matorras,[110] J. Piedra Gomez,[110] T. Rodrigo,[110] A. Ruiz-Jimeno,[110] L. Scodellaro,[110] N. Trevisani,[110] I. Vila,[110] R. Vilar Cortabitarte,[110] D. Abbaneo,[111] E. Auffray,[111] G. Auzinger,[111] M. Bachtis,[111] P. Baillon,[111] A. H. Ball,[111] D. Barney,[111] P. Bloch,[111] A. Bocci,[111] A. Bonato,[111] C. Botta,[111] T. Camporesi,[111]

R. Castello,[111] M. Cepeda,[111] G. Cerminara,[111] M. D'Alfonso,[111] D. d'Enterria,[111] A. Dabrowski,[111] V. Daponte,[111] A. David,[111] M. De Gruttola,[111] A. De Roeck,[111] E. Di Marco,[111,ar] M. Dobson,[111] B. Dorney,[111] T. du Pree,[111] D. Duggan,[111] M. Dünser,[111] N. Dupont,[111] A. Elliott-Peisert,[111] S. Fartoukh,[111] G. Franzoni,[111] J. Fulcher,[111] W. Funk,[111] D. Gigi,[111] K. Gill,[111] M. Girone,[111] F. Glege,[111] D. Gulhan,[111] S. Gundacker,[111] M. Guthoff,[111] J. Hammer,[111] P. Harris,[111] J. Hegeman,[111] V. Innocente,[111] P. Janot,[111] J. Kieseler,[111] H. Kirschenmann,[111] V. Knünz,[111] A. Kornmayer,[111,n] M. J. Kortelainen,[111] K. Kousouris,[111] M. Krammer,[111,a] C. Lange,[111] P. Lecoq,[111] C. Lourenço,[111] M. T. Lucchini,[111] L. Malgeri,[111] M. Mannelli,[111] A. Martelli,[111] F. Meijers,[111] J. A. Merlin,[111] S. Mersi,[111] E. Meschi,[111] F. Moortgat,[111] S. Morovic,[111] M. Mulders,[111] H. Neugebauer,[111] S. Orfanelli,[111] L. Orsini,[111] L. Pape,[111] E. Perez,[111] M. Peruzzi,[111] A. Petrilli,[111] G. Petrucciani,[111] A. Pfeiffer,[111] M. Pierini,[111] A. Racz,[111] T. Reis,[111] G. Rolandi,[111,as] M. Rovere,[111] M. Ruan,[111] H. Sakulin,[111] J. B. Sauvan,[111] C. Schäfer,[111] C. Schwick,[111] M. Seidel,[111] A. Sharma,[111] P. Silva,[111] P. Sphicas,[111,at] J. Steggemann,[111] M. Stoye,[111] Y. Takahashi,[111] M. Tosi,[111] D. Treille,[111] A. Triossi,[111] A. Tsirou,[111] V. Veckalns,[111,au] G. I. Veres,[111,s] N. Wardle,[111] H. K. Wöhri,[111] A. Zagozdzinska,[111,ah] W. D. Zeuner,[111] W. Bertl,[112] K. Deiters,[112] W. Erdmann,[112] R. Horisberger,[112] Q. Ingram,[112] H. C. Kaestli,[112] D. Kotlinski,[112] U. Langenegger,[112] T. Rohe,[112] F. Bachmair,[113] L. Bäni,[113] L. Bianchini,[113] B. Casal,[113] G. Dissertori,[113] M. Dittmar,[113] M. Donegà,[113] C. Grab,[113] C. Heidegger,[113] D. Hits,[113] J. Hoss,[113] G. Kasieczka,[113] P. Lecomte,[113,av] W. Lustermann,[113] B. Mangano,[113] M. Marionneau,[113] P. Martinez Ruiz del Arbol,[113] M. Masciovecchio,[113] M. T. Meinhard,[113] D. Meister,[113] F. Micheli,[113] P. Musella,[113] F. Nessi-Tedaldi,[113] F. Pandolfi,[113] J. Pata,[113] F. Pauss,[113] G. Perrin,[113] L. Perrozzi,[113] M. Quittnat,[113] M. Rossini,[113] M. Schönenberger,[113] A. Starodumov,[113,aw] V. R. Tavolaro,[113] K. Theofilatos,[113] R. Wallny,[113] T. K. Aarrestad,[114] C. Amsler,[114,ax] L. Caminada,[114] M. F. Canelli,[114] A. De Cosa,[114] C. Galloni,[114] A. Hinzmann,[114] T. Hreus,[114] B. Kilminster,[114] J. Ngadiuba,[114] D. Pinna,[114] G. Rauco,[114] P. Robmann,[114] D. Salerno,[114] Y. Yang,[114] A. Zucchetta,[114] V. Candelise,[115] T. H. Doan,[115] Sh. Jain,[115] R. Khurana,[115] M. Konyushikhin,[115] C. M. Kuo,[115] W. Lin,[115] Y. J. Lu,[115] A. Pozdnyakov,[115] S. S. Yu,[115] Arun Kumar,[116] P. Chang,[116] Y. H. Chang,[116] Y. W. Chang,[116] Y. Chao,[116] K. F. Chen,[116] P. H. Chen,[116] C. Dietz,[116] F. Fiori,[116] W.-S. Hou,[116] Y. Hsiung,[116] Y. F. Liu,[116] R.-S. Lu,[116] M. Miñano Moya,[116] E. Paganis,[116] A. Psallidas,[116] J. f. Tsai,[116] Y. M. Tzeng,[116] B. Asavapibhop,[117] G. Singh,[117] N. Srimanobhas,[117] N. Suwonjandee,[117] A. Adiguzel,[118] S. Cerci,[118,ay] S. Damarseckin,[118] Z. S. Demiroglu,[118] C. Dozen,[118] I. Dumanoglu,[118] S. Girgis,[118] G. Gokbulut,[118] Y. Guler,[118] I. Hos,[118] E. E. Kangal,[118,az] O. Kara,[118] U. Kiminsu,[118] M. Oglakci,[118] G. Onengut,[118,ba] K. Ozdemir,[118,bb] D. Sunar Cerci,[118,ay] B. Tali,[118,ay] H. Topakli,[118,bc] S. Turkcapar,[118] I. S. Zorbakir,[118] C. Zorbilmez,[118] B. Bilin,[119] S. Bilmis,[119] B. Isildak,[119,bd] G. Karapinar,[119,be] M. Yalvac,[119] M. Zeyrek,[119] E. Gülmez,[120] M. Kaya,[120,bf] O. Kaya,[120,bg] E. A. Yetkin,[120,bh] T. Yetkin,[120,bi] A. Cakir,[121] K. Cankocak,[121] S. Sen,[121,bj] B. Grynyov,[122] L. Levchuk,[123] P. Sorokin,[123] R. Aggleton,[124] F. Ball,[124] L. Beck,[124] J. J. Brooke,[124] D. Burns,[124] E. Clement,[124] D. Cussans,[124] H. Flacher,[124] J. Goldstein,[124] M. Grimes,[124] G. P. Heath,[124] H. F. Heath,[124] J. Jacob,[124] L. Kreczko,[124] C. Lucas,[124] D. M. Newbold,[124,bk] S. Paramesvaran,[124] A. Poll,[124] T. Sakuma,[124] S. Seif El Nasr-storey,[124] D. Smith,[124] V. J. Smith,[124] A. Belyaev,[125,bl] C. Brew,[125] R. M. Brown,[125] L. Calligaris,[125] D. Cieri,[125] D. J. A. Cockerill,[125] J. A. Coughlan,[125] K. Harder,[125] S. Harper,[125] E. Olaiya,[125] D. Petyt,[125] C. H. Shepherd-Themistocleous,[125] A. Thea,[125] I. R. Tomalin,[125] T. Williams,[125] M. Baber,[126] R. Bainbridge,[126] O. Buchmuller,[126] A. Bundock,[126] D. Burton,[126] S. Casasso,[126] M. Citron,[126] D. Colling,[126] L. Corpe,[126] P. Dauncey,[126] G. Davies,[126] A. De Wit,[126] M. Della Negra,[126] R. Di Maria,[126] P. Dunne,[126] A. Elwood,[126] D. Futyan,[126] Y. Haddad,[126] G. Hall,[126] G. Iles,[126] T. James,[126] R. Lane,[126] C. Laner,[126] R. Lucas,[126,bk] L. Lyons,[126] A.-M. Magnan,[126] S. Malik,[126] L. Mastrolorenzo,[126] J. Nash,[126] A. Nikitenko,[126,aw] J. Pela,[126] B. Penning,[126] M. Pesaresi,[126] D. M. Raymond,[126] A. Richards,[126] A. Rose,[126] C. Seez,[126] S. Summers,[126] A. Tapper,[126] K. Uchida,[126] M. Vazquez Acosta,[126,bm] T. Virdee,[126,n] J. Wright,[126] S. C. Zenz,[126] J. E. Cole,[127] P. R. Hobson,[127] A. Khan,[127] P. Kyberd,[127] D. Leslie,[127] I. D. Reid,[127] P. Symonds,[127] L. Teodorescu,[127] M. Turner,[127] A. Borzou,[128] K. Call,[128] J. Dittmann,[128] K. Hatakeyama,[128] H. Liu,[128] N. Pastika,[128] O. Charaf,[129] S. I. Cooper,[129] C. Henderson,[129] P. Rumerio,[129] C. West,[129] D. Arcaro,[130] A. Avetisyan,[130] T. Bose,[130] D. Gastler,[130] D. Rankin,[130] C. Richardson,[130] J. Rohlf,[130] L. Sulak,[130] D. Zou,[130] G. Benelli,[131] E. Berry,[131] D. Cutts,[131] A. Garabedian,[131] J. Hakala,[131] U. Heintz,[131] J. M. Hogan,[131] O. Jesus,[131] K. H. M. Kwok,[131] E. Laird,[131] G. Landsberg,[131] Z. Mao,[131] M. Narain,[131] S. Piperov,[131] S. Sagir,[131] E. Spencer,[131] R. Syarif,[131] R. Breedon,[132] G. Breto,[132] D. Burns,[132] M. Calderon De La Barca Sanchez,[132] S. Chauhan,[132] M. Chertok,[132] J. Conway,[132] R. Conway,[132] P. T. Cox,[132] R. Erbacher,[132] C. Flores,[132] G. Funk,[132] M. Gardner,[132] W. Ko,[132] R. Lander,[132] C. Mclean,[132] M. Mulhearn,[132] D. Pellett,[132] J. Pilot,[132] S. Shalhout,[132] J. Smith,[132] M. Squires,[132] D. Stolp,[132] M. Tripathi,[132] S. Wilbur,[132] R. Yohay,[132] R. Cousins,[133] P. Everaerts,[133] A. Florent,[133] J. Hauser,[133] M. Ignatenko,[133] D. Saltzberg,[133] E. Takasugi,[133] V. Valuev,[133] M. Weber,[133] K. Burt,[134] R. Clare,[134] J. Ellison,[134] J. W. Gary,[134] S. M. A. Ghiasi Shirazi,[134] G. Hanson,[134] J. Heilman,[134] P. Jandir,[134] E. Kennedy,[134] F. Lacroix,[134] O. R. Long,[134] M. Olmedo Negrete,[134] M. I. Paneva,[134] A. Shrinivas,[134] W. Si,[134] H. Wei,[134] S. Wimpenny,[134] B. R. Yates,[134] J. G. Branson,[135] G. B. Cerati,[135] S. Cittolin,[135] M. Derdzinski,[135] R. Gerosa,[135] A. Holzner,[135] D. Klein,[135] V. Krutelyov,[135] J. Letts,[135] I. Macneill,[135] D. Olivito,[135] S. Padhi,[135] M. Pieri,[135] M. Sani,[135] V. Sharma,[135] S. Simon,[135] M. Tadel,[135] A. Vartak,[135] S. Wasserbaech,[135,bn] C. Welke,[135] J. Wood,[135] F. Würthwein,[135] A. Yagil,[135] G. Zevi Della Porta,[135] R. Bhandari,[136] J. Bradmiller-Feld,[136] C. Campagnari,[136] A. Dishaw,[136] V. Dutta,[136] K. Flowers,[136] M. Franco Sevilla,[136] P. Geffert,[136] C. George,[136] F. Golf,[136] L. Gouskos,[136] J. Gran,[136] R. Heller,[136] J. Incandela,[136] N. Mccoll,[136] S. D. Mullin,[136] A. Ovcharova,[136] J. Richman,[136] D. Stuart,[136] I. Suarez,[136] J. Yoo,[136] D. Anderson,[137] A. Apresyan,[137] J. Bendavid,[137] A. Bornheim,[137] J. Bunn,[137] Y. Chen,[137] J. Duarte,[137] J. M. Lawhorn,[137] A. Mott,[137] H. B. Newman,[137] C. Pena,[137] M. Spiropulu,[137] J. R. Vlimant,[137] S. Xie,[137] R. Y. Zhu,[137]

M. B. Andrews,[138] V. Azzolini,[138] T. Ferguson,[138] M. Paulini,[138] J. Russ,[138] M. Sun,[138] H. Vogel,[138] I. Vorobiev,[138]
J. P. Cumalat,[139] W. T. Ford,[139] F. Jensen,[139] A. Johnson,[139] M. Krohn,[139] T. Mulholland,[139] K. Stenson,[139] S. R. Wagner,[139]
J. Alexander,[140] J. Chaves,[140] J. Chu,[140] S. Dittmer,[140] K. Mcdermott,[140] N. Mirman,[140] G. Nicolas Kaufman,[140]
J. R. Patterson,[140] A. Rinkevicius,[140] A. Ryd,[140] L. Skinnari,[140] L. Soffi,[140] S. M. Tan,[140] Z. Tao,[140] J. Thom,[140] J. Tucker,[140]
P. Wittich,[140] M. Zientek,[140] D. Winn,[141] S. Abdullin,[142] M. Albrow,[142] G. Apollinari,[142] S. Banerjee,[142] L. A. T. Bauerdick,[142]
A. Beretvas,[142] J. Berryhill,[142] P. C. Bhat,[142] G. Bolla,[142] K. Burkett,[142] J. N. Butler,[142] H. W. K. Cheung,[142] F. Chlebana,[142]
S. Cihangir,[142,av] M. Cremonesi,[142] V. D. Elvira,[142] I. Fisk,[142] J. Freeman,[142] E. Gottschalk,[142] L. Gray,[142] D. Green,[142]
S. Grünendahl,[142] O. Gutsche,[142] D. Hare,[142] R. M. Harris,[142] S. Hasegawa,[142] J. Hirschauer,[142] Z. Hu,[142] B. Jayatilaka,[142]
S. Jindariani,[142] M. Johnson,[142] U. Joshi,[142] B. Klima,[142] B. Kreis,[142] S. Lammel,[142] J. Linacre,[142] D. Lincoln,[142] R. Lipton,[142]
T. Liu,[142] R. Lopes De Sá,[142] J. Lykken,[142] K. Maeshima,[142] N. Magini,[142] J. M. Marraffino,[142] S. Maruyama,[142] D. Mason,[142]
P. McBride,[142] P. Merkel,[142] S. Mrenna,[142] S. Nahn,[142] C. Newman-Holmes,[142,av] V. O'Dell,[142] K. Pedro,[142] O. Prokofyev,[142]
G. Rakness,[142] L. Ristori,[142] E. Sexton-Kennedy,[142] A. Soha,[142] W. J. Spalding,[142] L. Spiegel,[142] S. Stoynev,[142] N. Strobbe,[142]
L. Taylor,[142] S. Tkaczyk,[142] N. V. Tran,[142] L. Uplegger,[142] E. W. Vaandering,[142] C. Vernieri,[142] M. Verzocchi,[142] R. Vidal,[142]
M. Wang,[142] H. A. Weber,[142] A. Whitbeck,[142] D. Acosta,[143] P. Avery,[143] P. Bortignon,[143] D. Bourilkov,[143] A. Brinkerhoff,[143]
A. Carnes,[143] M. Carver,[143] D. Curry,[143] S. Das,[143] R. D. Field,[143] I. K. Furic,[143] J. Konigsberg,[143] A. Korytov,[143] P. Ma,[143]
K. Matchev,[143] H. Mei,[143] P. Milenovic,[143,bo] G. Mitselmakher,[143] D. Rank,[143] L. Shchutska,[143] D. Sperka,[143] L. Thomas,[143]
J. Wang,[143] S. Wang,[143] J. Yelton,[143] S. Linn,[144] P. Markowitz,[144] G. Martinez,[144] J. L. Rodriguez,[144] A. Ackert,[145]
J. R. Adams,[145] T. Adams,[145] A. Askew,[145] S. Bein,[145] B. Diamond,[145] S. Hagopian,[145] V. Hagopian,[145] K. F. Johnson,[145]
A. Khatiwada,[145] H. Prosper,[145] A. Santra,[145] M. Weinberg,[145] M. M. Baarmand,[146] V. Bhopatkar,[146] S. Colafranceschi,[146,bp]
M. Hohlmann,[146] D. Noonan,[146] T. Roy,[146] F. Yumiceva,[146] M. R. Adams,[147] L. Apanasevich,[147] D. Berry,[147] R. R. Betts,[147]
I. Bucinskaite,[147] R. Cavanaugh,[147] O. Evdokimov,[147] L. Gauthier,[147] C. E. Gerber,[147] D. J. Hofman,[147] K. Jung,[147] P. Kurt,[147]
C. O'Brien,[147] I. D. Sandoval Gonzalez,[147] P. Turner,[147] N. Varelas,[147] H. Wang,[147] Z. Wu,[147] M. Zakaria,[147] J. Zhang,[147]
B. Bilki,[148,bq] W. Clarida,[148] K. Dilsiz,[148] S. Durgut,[148] R. P. Gandrajula,[148] M. Haytmyradov,[148] V. Khristenko,[148]
J.-P. Merlo,[148] H. Mermerkaya,[148,br] A. Mestvirishvili,[148] A. Moeller,[148] J. Nachtman,[148] H. Ogul,[148] Y. Onel,[148] F. Ozok,[148,bs]
A. Penzo,[148] C. Snyder,[148] E. Tiras,[148] J. Wetzel,[148] K. Yi,[148] I. Anderson,[149] B. Blumenfeld,[149] A. Cocoros,[149] N. Eminizer,[149]
D. Fehling,[149] L. Feng,[149] A. V. Gritsan,[149] P. Maksimovic,[149] C. Martin,[149] M. Osherson,[149] J. Roskes,[149] U. Sarica,[149]
M. Swartz,[149] M. Xiao,[149] Y. Xin,[149] C. You,[149] A. Al-bataineh,[150] P. Baringer,[150] A. Bean,[150] S. Boren,[150] J. Bowen,[150]
C. Bruner,[150] J. Castle,[150] L. Forthomme,[150] R. P. Kenny III,[150] A. Kropivnitskaya,[150] D. Majumder,[150] W. Mcbrayer,[150]
M. Murray,[150] S. Sanders,[150] R. Stringer,[150] J. D. Tapia Takaki,[150] Q. Wang,[150] A. Ivanov,[151] K. Kaadze,[151] S. Khalil,[151]
Y. Maravin,[151] A. Mohammadi,[151] L. K. Saini,[151] N. Skhirtladze,[151] S. Toda,[151] F. Rebassoo,[152] D. Wright,[152] C. Anelli,[153]
A. Baden,[153] O. Baron,[153] A. Belloni,[153] B. Calvert,[153] S. C. Eno,[153] C. Ferraioli,[153] J. A. Gomez,[153] N. J. Hadley,[153]
S. Jabeen,[153] R. G. Kellogg,[153] T. Kolberg,[153] J. Kunkle,[153] Y. Lu,[153] A. C. Mignerey,[153] F. Ricci-Tam,[153] Y. H. Shin,[153]
A. Skuja,[153] M. B. Tonjes,[153] S. C. Tonwar,[153] D. Abercrombie,[154] B. Allen,[154] A. Apyan,[154] R. Barbieri,[154] A. Baty,[154]
R. Bi,[154] K. Bierwagen,[154] S. Brandt,[154] W. Busza,[154] I. A. Cali,[154] Z. Demiragli,[154] L. Di Matteo,[154] G. Gomez Ceballos,[154]
M. Goncharov,[154] D. Hsu,[154] Y. Iiyama,[154] G. M. Innocenti,[154] M. Klute,[154] D. Kovalskyi,[154] K. Krajczar,[154] Y. S. Lai,[154]
Y.-J. Lee,[154] A. Levin,[154] P. D. Luckey,[154] A. C. Marini,[154] C. Mcginn,[154] C. Mironov,[154] S. Narayanan,[154] X. Niu,[154]
C. Paus,[154] C. Roland,[154] G. Roland,[154] J. Salfeld-Nebgen,[154] G. S. F. Stephans,[154] K. Sumorok,[154] K. Tatar,[154] M. Varma,[154]
D. Velicanu,[154] J. Veverka,[154] J. Wang,[154] T. W. Wang,[154] B. Wyslouch,[154] M. Yang,[154] V. Zhukova,[154] A. C. Benvenuti,[155]
R. M. Chatterjee,[155] A. Evans,[155] A. Finkel,[155] A. Gude,[155] P. Hansen,[155] S. Kalafut,[155] S. C. Kao,[155] Y. Kubota,[155] Z. Lesko,[155]
J. Mans,[155] S. Nourbakhsh,[155] N. Ruckstuhl,[155] R. Rusack,[155] N. Tambe,[155] J. Turkewitz,[155] J. G. Acosta,[156] S. Oliveros,[156]
E. Avdeeva,[157] R. Bartek,[157] K. Bloom,[157] D. R. Claes,[157] A. Dominguez,[157] C. Fangmeier,[157] R. Gonzalez Suarez,[157]
R. Kamalieddin,[157] I. Kravchenko,[157] A. Malta Rodrigues,[157] F. Meier,[157] J. Monroy,[157] J. E. Siado,[157] G. R. Snow,[157]
B. Stieger,[157] M. Alyari,[158] J. Dolen,[158] J. George,[158] A. Godshalk,[158] C. Harrington,[158] I. Iashvili,[158] J. Kaisen,[158]
A. Kharchilava,[158] A. Kumar,[158] A. Parker,[158] S. Rappoccio,[158] B. Roozbahani,[158] G. Alverson,[159] E. Barberis,[159]
A. Hortiangtham,[159] A. Massironi,[159] D. M. Morse,[159] D. Nash,[159] T. Orimoto,[159] R. Teixeira De Lima,[159] D. Trocino,[159]
R.-J. Wang,[159] D. Wood,[159] S. Bhattacharya,[160] K. A. Hahn,[160] A. Kubik,[160] A. Kumar,[160] J. F. Low,[160] N. Mucia,[160]
N. Odell,[160] B. Pollack,[160] M. H. Schmitt,[160] K. Sung,[160] M. Trovato,[160] M. Velasco,[160] N. Dev,[161] M. Hildreth,[161]
K. Hurtado Anampa,[161] C. Jessop,[161] D. J. Karmgard,[161] N. Kellams,[161] K. Lannon,[161] N. Marinelli,[161] F. Meng,[161]
C. Mueller,[161] Y. Musienko,[161,bt] M. Planer,[161] A. Reinsvold,[161] R. Ruchti,[161] G. Smith,[161] S. Taroni,[161] M. Wayne,[161]
M. Wolf,[161] A. Woodard,[161] J. Alimena,[162] L. Antonelli,[162] J. Brinson,[162] B. Bylsma,[162] L. S. Durkin,[162] S. Flowers,[162]
B. Francis,[162] A. Hart,[162] C. Hill,[162] R. Hughes,[162] W. Ji,[162] B. Liu,[162] W. Luo,[162] D. Puigh,[162] B. L. Winer,[162] H. W. Wulsin,[162]
S. Cooperstein,[163] O. Driga,[163] P. Elmer,[163] J. Hardenbrook,[163] P. Hebda,[163] D. Lange,[163] J. Luo,[163] D. Marlow,[163]
T. Medvedeva,[163] K. Mei,[163] M. Mooney,[163] J. Olsen,[163] C. Palmer,[163] P. Piroué,[163] D. Stickland,[163] C. Tully,[163] A. Zuranski,[163]
S. Malik,[164] A. Barker,[165] V. E. Barnes,[165] S. Folgueras,[165] L. Gutay,[165] M. K. Jha,[165] M. Jones,[165] A. W. Jung,[165]
D. H. Miller,[165] N. Neumeister,[165] J. F. Schulte,[165] X. Shi,[165] J. Sun,[165] A. Svyatkovskiy,[165] F. Wang,[165] W. Xie,[165] L. Xu,[165]
N. Parashar,[166] J. Stupak,[166] A. Adair,[167] B. Akgun,[167] Z. Chen,[167] K. M. Ecklund,[167] F. J. M. Geurts,[167] M. Guilbaud,[167]
W. Li,[167] B. Michlin,[167] M. Northup,[167] B. P. Padley,[167] R. Redjimi,[167] J. Roberts,[167] J. Rorie,[167] Z. Tu,[167] J. Zabel,[167]
B. Betchart,[168] A. Bodek,[168] P. de Barbaro,[168] R. Demina,[168] Y. t. Duh,[168] T. Ferbel,[168] M. Galanti,[168] A. Garcia-Bellido,[168]

J. Han,[168] O. Hindrichs,[168] A. Khukhunaishvili,[168] K. H. Lo,[168] P. Tan,[168] M. Verzetti,[168] A. Agapitos,[169] J. P. Chou,[169] E. Contreras-Campana,[169] Y. Gershtein,[169] T. A. Gómez Espinosa,[169] E. Halkiadakis,[169] M. Heindl,[169] D. Hidas,[169] E. Hughes,[169] S. Kaplan,[169] R. Kunnawalkam Elayavalli,[169] S. Kyriacou,[169] A. Lath,[169] K. Nash,[169] A. Parikh,[169] G. Pikul,[169] H. Saka,[169] S. Salur,[169] S. Schnetzer,[169] D. Sheffield,[169] S. Somalwar,[169] R. Stone,[169] S. Thomas,[169] P. Thomassen,[169] M. Walker,[169] A. G. Delannoy,[170] M. Foerster,[170] J. Heideman,[170] G. Riley,[170] K. Rose,[170] S. Spanier,[170] K. Thapa,[170] O. Bouhali,[171,bu] A. Celik,[171] M. Dalchenko,[171] M. De Mattia,[171] A. Delgado,[171] S. Dildick,[171] R. Eusebi,[171] J. Gilmore,[171] T. Huang,[171] E. Juska,[171] T. Kamon,[171,bv] R. Mueller,[171] Y. Pakhotin,[171] R. Patel,[171] A. Perloff,[171] L. Perniè,[171] D. Rathjens,[171] A. Rose,[171] A. Safonov,[171] A. Tatarinov,[171] K. A. Ulmer,[171] N. Akchurin,[172] C. Cowden,[172] J. Damgov,[172] F. De Guio,[172] C. Dragoiu,[172] P. R. Dudero,[172] J. Faulkner,[172] E. Gurpinar,[172] S. Kunori,[172] K. Lamichhane,[172] S. W. Lee,[172] T. Libeiro,[172] T. Peltola,[172] S. Undleeb,[172] I. Volobouev,[172] Z. Wang,[172] S. Greene,[173] A. Gurrola,[173] R. Janjam,[173] W. Johns,[173] C. Maguire,[173] A. Melo,[173] H. Ni,[173] P. Sheldon,[173] S. Tuo,[173] J. Velkovska,[173] Q. Xu,[173] M. W. Arenton,[174] P. Barria,[174] B. Cox,[174] J. Goodell,[174] R. Hirosky,[174] A. Ledovskoy,[174] H. Li,[174] C. Neu,[174] T. Sinthuprasith,[174] X. Sun,[174] Y. Wang,[174] E. Wolfe,[174] F. Xia,[174] C. Clarke,[175] R. Harr,[175] P. E. Karchin,[175] J. Sturdy,[175] D. A. Belknap,[176] S. Dasu,[176] L. Dodd,[176] S. Duric,[176] B. Gomber,[176] M. Grothe,[176] M. Herndon,[176] A. Hervé,[176] P. Klabbers,[176] A. Lanaro,[176] A. Levine,[176] K. Long,[176] R. Loveless,[176] I. Ojalvo,[176] T. Perry,[176] G. A. Pierro,[176] G. Polese,[176] T. Ruggles,[176] A. Savin,[176] N. Smith,[176] W. H. Smith,[176] D. Taylor,[176] and N. Woods[176]

(CMS Collaboration)

[1] *Yerevan Physics Institute, Yerevan, Armenia*
[2] *Institut für Hochenergiephysik, 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, 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, Bari, Italy*
[61b]*Università di Bari, Bari, Italy*
[61c]*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, Roma, Italy*
[68b]*Università di Napoli 'Federico II', Roma, Italy*
[68c]*Università della Basilicata, Roma, Italy*
[68d]*Università G. Marconi, Roma, Italy*
[69a]*INFN Sezione di Padova, Trento, Italy*
[69b]*Università di Padova, 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, Novara, Italy*
[74b]*Università di Torino, Novara, 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]*Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea*

[79]*Hanyang University, Seoul, Korea*
[80]*Korea University, Seoul, Korea*
[81]*Seoul National University, Seoul, Korea*
[82]*University of Seoul, Seoul, Korea*
[83]*Sungkyunkwan University, Suwon, Korea*
[84]*Vilnius University, Vilnius, Lithuania*
[85]*National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia*
[86]*Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico*
[87]*Universidad Iberoamericana, Mexico City, Mexico*
[88]*Benemerita Universidad Autonoma de Puebla, Puebla, Mexico*
[89]*Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico*
[90]*University of Auckland, Auckland, New Zealand*
[91]*University of Canterbury, Christchurch, New Zealand*
[92]*National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan*
[93]*National Centre for Nuclear Research, Swierk, Poland*
[94]*Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland*
[95]*Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal*
[96]*Joint Institute for Nuclear Research, Dubna, Russia*
[97]*Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia*
[98]*Institute for Nuclear Research, Moscow, Russia*
[99]*Institute for Theoretical and Experimental Physics, Moscow, Russia*
[100]*Moscow Institute of Physics and Technology*
[101]*National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia*
[102]*P. N. Lebedev Physical Institute, Moscow, Russia*
[103]*Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia*
[104]*Novosibirsk State University (NSU), Novosibirsk, Russia*
[105]*State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia*
[106]*University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia*
[107]*Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain*
[108]*Universidad Autónoma de Madrid, Madrid, Spain*
[109]*Universidad de Oviedo, Oviedo, Spain*
[110]*Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain*
[111]*CERN, European Organization for Nuclear Research, Geneva, Switzerland*
[112]*Paul Scherrer Institut, Villigen, Switzerland*
[113]*Institute for Particle Physics, ETH Zurich, Zurich, Switzerland*
[114]*Universität Zürich, Zurich, Switzerland*
[115]*National Central University, Chung-Li, Taiwan*
[116]*National Taiwan University (NTU), Taipei, Taiwan*
[117]*Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand*
[118]*Cukurova University, Adana, Turkey*
[119]*Middle East Technical University, Physics Department, Ankara, Turkey*
[120]*Bogazici University, Istanbul, Turkey*
[121]*Istanbul Technical University, Istanbul, Turkey*
[122]*Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine*
[123]*National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine*
[124]*University of Bristol, Bristol, United Kingdom*
[125]*Rutherford Appleton Laboratory, Didcot, United Kingdom*
[126]*Imperial College, London, United Kingdom*
[127]*Brunel University, Uxbridge, United Kingdom*
[128]*Baylor University, Waco, USA*
[129]*The University of Alabama, Tuscaloosa, USA*
[130]*Boston University, Boston, USA*
[131]*Brown University, Providence, USA*
[132]*University of California, Davis, Davis, USA*
[133]*University of California, Los Angeles, USA*
[134]*University of California, Riverside, Riverside, USA*
[135]*University of California, San Diego, La Jolla, USA*
[136]*University of California, Santa Barbara-Department of Physics, Santa Barbara, USA*
[137]*California Institute of Technology, Pasadena, USA*

[138]*Carnegie Mellon University, Pittsburgh, USA*
[139]*University of Colorado Boulder, Boulder, USA*
[140]*Cornell University, Ithaca, USA*
[141]*Fairfield University, Fairfield, USA*
[142]*Fermi National Accelerator Laboratory, Batavia, USA*
[143]*University of Florida, Gainesville, USA*
[144]*Florida International University, Miami, USA*
[145]*Florida State University, Tallahassee, USA*
[146]*Florida Institute of Technology, Melbourne, USA*
[147]*University of Illinois at Chicago (UIC), Chicago, USA*
[148]*The University of Iowa, Iowa City, USA*
[149]*Johns Hopkins University, Baltimore, USA*
[150]*The University of Kansas, Lawrence, USA*
[151]*Kansas State University, Manhattan, USA*
[152]*Lawrence Livermore National Laboratory, Livermore, USA*
[153]*University of Maryland, College Park, USA*
[154]*Massachusetts Institute of Technology, Cambridge, USA*
[155]*University of Minnesota, Minneapolis, USA*
[156]*University of Mississippi, Oxford, USA*
[157]*University of Nebraska-Lincoln, Lincoln, USA*
[158]*State University of New York at Buffalo, Buffalo, USA*
[159]*Northeastern University, Boston, USA*
[160]*Northwestern University, Evanston, USA*
[161]*University of Notre Dame, Notre Dame, USA*
[162]*The Ohio State University, Columbus, USA*
[163]*Princeton University, Princeton, USA*
[164]*University of Puerto Rico, Mayaguez, USA*
[165]*Purdue University, West Lafayette, USA*
[166]*Purdue University Calumet, Hammond, USA*
[167]*Rice University, Houston, USA*
[168]*University of Rochester, Rochester, USA*
[169]*Rutgers, The State University of New Jersey, Piscataway, USA*
[170]*University of Tennessee, Knoxville, USA*
[171]*Texas A&M University, College Station, USA*
[172]*Texas Tech University, Lubbock, USA*
[173]*Vanderbilt University, Nashville, USA*
[174]*University of Virginia, Charlottesville, USA*
[175]*Wayne State University, Detroit, USA*
[176]*University of Wisconsin-Madison, Madison, WI, USA*

[a] Vienna University of Technology, Vienna, Austria.
[b] State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China.
[c] Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France.
[d] Universidade Estadual de Campinas, Campinas, Brazil.
[e] Universidade Federal de Pelotas, Pelotas, Brazil.
[f] Université Libre de Bruxelles, Bruxelles, Belgium.
[g] Deutsches Elektronen-Synchrotron, Hamburg, Germany.
[h] Joint Institute for Nuclear Research, Dubna, Russia.
[i] Ain Shams University, Cairo, Egypt.
[j] British University in Egypt, Cairo, Egypt.
[k] Zewail City of Science and Technology, Zewail, Egypt.
[l] Université de Haute Alsace, Mulhouse, France.
[m] Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia.
[n] CERN, European Organization for Nuclear Research, Geneva, Switzerland.
[o] RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.
[p] University of Hamburg, Hamburg, Germany.
[q] Brandenburg University of Technology, Cottbus, Germany.
[r] Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
[s] MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary.

[t] University of Debrecen, Debrecen, Hungary.
[u] Indian Institute of Science Education and Research, Bhopal, India.
[v] Institute of Physics, Bhubaneswar, India.
[w] University of Visva-Bharati, Santiniketan, India.
[x] University of Ruhuna, Matara, Sri Lanka.
[y] Isfahan University of Technology, Isfahan, Iran.
[z] University of Tehran, Department of Engineering Science, Tehran, Iran.
[aa] Yazd University, Yazd, Iran.
[ab] Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran.
[ac] Università degli Studi di Siena, Siena, Italy.
[ad] Purdue University, West Lafayette, USA.
[ae] International Islamic University of Malaysia, Kuala Lumpur, Malaysia.
[af] Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia.
[ag] Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico.
[ah] Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland.
[ai] Institute for Nuclear Research, Moscow, Russia; National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia.
[aj] Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan.
[ak] St. Petersburg State Polytechnical University, St. Petersburg, Russia.
[al] University of Florida, Gainesville, USA.
[am] National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia.
[an] P. N. Lebedev Physical Institute, Moscow, Russia.
[ao] INFN Sezione di Padova, Padova, Italy; Università di Padova, Padova, Italy; Università di Trento (Trento), Padova, Italy.
[ap] Budker Institute of Nuclear Physics, Novosibirsk, Russia.
[aq] Faculty of Physics, University of Belgrade, Belgrade, Serbia.
[ar] INFN Sezione di Roma, Roma, Italy; Università di Roma, Roma, Italy.
[as] Scuola Normale e Sezione dell'INFN, Pisa, Italy.
[at] National and Kapodistrian University of Athens, Athens, Greece.
[au] Riga Technical University, Riga, Latvia.
[av] Deceased.
[aw] Institute for Theoretical and Experimental Physics, Moscow, Russia.
[ax] Albert Einstein Center for Fundamental Physics, Bern, Switzerland.
[ay] Adiyaman University, Adiyaman, Turkey.
[az] Mersin University, Mersin, Turkey.
[ba] Cag University, Mersin, Turkey.
[bb] Piri Reis University, Istanbul, Turkey.
[bc] Gaziosmanpasa University, Tokat, Turkey.
[bd] Ozyegin University, Istanbul, Turkey.
[be] Izmir Institute of Technology, Izmir, Turkey.
[bf] Marmara University, Istanbul, Turkey.
[bg] Kafkas University, Kars, Turkey.
[bh] Istanbul Bilgi University, Istanbul, Turkey.
[bi] Yildiz Technical University, Istanbul, Turkey.
[bj] Hacettepe University, Ankara, Turkey.
[bk] Rutherford Appleton Laboratory, Didcot, United Kingdom.
[bl] School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
[bm] Instituto de Astrofísica de Canarias, La Laguna, Spain.
[bn] Utah Valley University, Orem, USA.
[bo] University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.
[bp] Facoltà Ingegneria, Università di Roma, Roma, Italy.
[bq] Argonne National Laboratory, Argonne, USA.
[br] Erzincan University, Erzincan, Turkey.
[bs] Mimar Sinan University, Istanbul, Istanbul, Turkey.
[bt] Institute for Nuclear Research, Moscow, Russia.
[bu] Texas A&M University at Qatar, Doha, Qatar.
[bv] Kyungpook National University, Daegu, Korea.