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

The CMS Collaboration

Abstract

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 LHC, 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 non-perturbative corrections are found to over-predict 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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1 Introduction

Heavy ion collisions at the CERN 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 [4], and is indirectly confirmed by measurements of spectra and correlations of high transverse momenta ($p_T$) hadrons at 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 non-perturbative 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,

$$R_{AA} = \frac{d^2N_{jets}^{AA}}{T_{AA}} \frac{d\sigma_{jets}^{pp}/dp_T d\eta}{d\sigma_{jets}^{pp}/dp_T d\eta},$$

where $N_{jets}^{AA}$ is the jet spectrum measured in PbPb, $\sigma_{jets}^{pp}$ is the jet cross section from pp collisions,
and \( \langle T_{AA} \rangle \) is the nuclear 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 \( \langle N_{\text{coll}} \rangle \), and \( \sigma_{\text{NN}}^{\text{inel}} \), the nucleon-nucleon inelastic cross section, through \( \langle N_{\text{coll}} \rangle = \langle T_{AA} \rangle \sigma_{\text{NN}}^{\text{inel}} \), and is calculated with a Monte Carlo Glauber model description of the nuclear collision geometry (for a review see Ref. \[32\]).

2 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 \( \sim 15 \mu \text{m} \) and a \( \pT \) resolution of \( \sim 1.5\% \) for particles with \( \pT = 100 \text{ GeV}/c \). A 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 \( \mu \text{s} \). 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 \( \pT > 55, 65, \) and \( 80 \text{ GeV}/c \). 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-\( \pT \) single-jet triggers are combined together in both pp and PbPb. To reach lower jet \( \pT \) in the PbPb data set, the minimum bias triggered events are added.

This analysis uses 166 \( \mu \text{b}^{-1} \) of PbPb collisions at \( \sqrt{s_{\text{NN}}} = 2.76 \text{ TeV} \) recorded by CMS during the 2011 heavy ion run, as well as 5.43 \( \text{pb}^{-1} \) 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, ultra-peripheral and HCAL noise events. The primary reconstructed vertex of selected events in the \( z \) direction (beam axis) is constrained to be within \( \pm 15 \text{ cm} \) 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 \( \pT > 50 \text{ GeV}/c \) 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 \textsc{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 $\langle N_{part} \rangle$, the average number of nucleons in the nuclei that participate in the collision, using MC Glauber model calculations [32].

3 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 $\eta$ and $p_T$ dependent energy correction 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 $R^{\text{jet}}$, 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 $\Delta R$ is defined as the distance of the PF candidate from the reconstructed jet axis in the $\eta$-$\phi$ plane:

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

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.
Figure 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 $70 < \text{jet } p_T < 80$ [GeV/c] (top panels) and $110 < \text{jet } p_T < 130$ [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.

3.1 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.

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 ($p_{T}^{\text{min1}}$) and another for the subleading jet ($p_{T}^{\text{min2}}$) 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 $p_{T} > p_{T}^{\text{min1}}$ and $\Delta \phi_{1,2} > 2\pi/3$ and subleading jet $p_{T} > p_{T}^{\text{min2}}$. 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: $p_{T}^{\text{min1}} = 3$ RMS for the leading jet, and $p_{T}^{\text{min2}} = 1.8$ 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. 4.

### 3.2 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 [42–45]. Results presented here are based on the SVD technique, while the others are used as a cross-check, giving consistent results within their uncertainties.
Figure 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.

The systematic uncertainty is calculated from a number of sources and is shown in Table 1. For $R = 0.3$ jets, in the low $p_T < 80$ 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. 3.1) 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. Thejet 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 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 \[46\]. 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 1.

Table 1: 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. $70 < jet p_T < 80 \text{[GeV/c]}$ and $250 < jet p_T < 300 \text{[GeV/c]}$. 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               | $70 < jet p_T < 80 \text{[GeV/c]}$ | $250 < jet p_T < 300 \text{[GeV/c]}$ |
|----------------------|-----------------------------------|-------------------------------------|
|                      | $R = 0.2$                         | $R = 0.3$                           | $R = 0.4$                           |
|                      | $R = 0.2$                         | $R = 0.3$                           | $R = 0.4$                           |
| PbPb: (0-5%) JES & unfolding | 13% 20% 27%                       | ---  ---                            | ---  ---                            |
| JER                  | 3% 3% 3%                          | 3% 3% 3%                           | 3% 3% 3%                           |
| Underlying event     | 5% 5% 5%                          | ---  ---                            | ---  ---                            |
| PbPb: (70-90%) JES & unfolding | 8% 10% 12%                        | ---  ---                            | ---  ---                            |
| JER                  | 3% 3% 3%                          | ---  ---                            | ---  ---                            |
| Underlying event     | 5% 5% 5%                          | ---  ---                            | ---  ---                            |
| pp: JES & unfolding  | 7% 7% 6%                          | 5% 4% 5%                           | ---  ---                            |
| JER                  | 3% 3% 3%                          | 5% 5% 5%                           | ---  ---                            |
| Integrated luminosity| 3.7% 3.7% 3.7%                    | 3.7% 3.7% 3.7%                     | 3.7% 3.7% 3.7%                     |

5 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) \[47\] calculations of quantum chromodynamics. These calculations are shown for two parton distribution functions (PDF) sets: NNPDF 2.1 \[48\] (red stars), and CT10N \[49\] (purple triangles) including non-perturbative (NP) contributions such as multi-parton 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) + multi-parton interactions + hadronization to LO+PS \[47\]. 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. \[50\] 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
Figure 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.
Figure 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.

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 [51] for a review. ALICE requires the leading track constituent of the jet to have $p_T > 5$ 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 $p_T > 7$ GeV/c or a calorimeter cluster with $p_T > 8$ GeV/c within $\Delta R = 0.2$. While ALICE doesn’t 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[3.1], a data-driven background subtraction is introduced and all jets which are using tracks down to a $p_T$ of 0.15 GeV/c and calorimeter deposits down to a $E_T$ of 1 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.

6 Summary

The cross section of anti-$k_T$ particle-flow jets has been measured in pp and PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV for distance parameters $R = 0.2$, 0.3, and 0.4 in $|\eta| < 2$ and for jet $p_T$ above 70 GeV/c. It is found that next-to-leading order calculations with non-perturbative 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.
Figure 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.
Figure 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.

Figure 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 $N_{\text{part}}$ for each collision centrality, for jets of $80 < p_T < 90$ and $130 < p_T < 150$ [GeV/$c$], in the left and right 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.
Figure 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.
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A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia
V. Khachatryan, A.M. Sirunyan, A. Tumasyan

Institut für Höchenergiephysik, Wien, Austria
W. Adam, E. Asilar, T. Bergauer, J. Brandstetter, E. Brondolin, M. Dragicevic, J. Êrò, M. Flechl,
M. Friedl, R. Frühwirth\textsuperscript{1}, V.M. Ghete, C. Hartl, N. Hörmann, J. Hrubec, M. Jeitler\textsuperscript{1}, A. König,
I. Krätschmer, D. Liko, T. Matsushita, I. Mikulec, D. Rabady, N. Rad, B. Rahbaran, H. Rohringer,
J. Schieck\textsuperscript{1}, J. Strauss, W. Waltenberger, C.-E. Wulz\textsuperscript{1}

National Centre for Particle and High Energy Physics, Minsk, Belarus
V. Mossolov, N. Shumeiko, J. Suarez Gonzalez

Universiteit Antwerpen, Antwerpen, Belgium
S. Alderweireldt, E.A. De Wolf, X. Janssen, J. Lauwers, M. Van De Klundert, H. Van Haevermaeta, P. Van Mechelen, N. Van Remortela, A. Van Spilbeeka

Vrije Universiteit Brussel, Brussel, Belgium
S. Abu Zeid, F. Blekman, J. D’Hondt, N. Daci, I. De Bruyn, K. Deroover, N. Heracleous,
S. Lowette, S. Moortgat, L. Moreels, A. Olbrechts, Q. Python, S. Tavernier, W. Van Donincka,
P. Van Mulders, I. Van Parijs

Université Libre de Bruxelles, Bruxelles, Belgium
H. Brun, C. Caillol, B. Clerbaux, G. De Lentdecker, H. Delannoy, G. Fasanella, L. Favart,
R. Goldouzian, A. Grebenyuk, G. Karapostoli, T. Lenzi, A. Léonard, J. Luetic, T. Maerschalk,
A. Marinov, A. Randle-conde, T. Seva, C. Vander Velde, P. Vanlaer, R. Yonamine, F. Zenoni,
F. Zhang\textsuperscript{2}

Ghent University, Ghent, Belgium
A. Cimmino, T. Cornelis, D. Dobur, A. Fagot, G. Garcia, M. Gul, D. Poyraz, S. Salva,
R. Schöbeck, A. Sharma, M. Tytgat, W. Van Driessche, E. Yazgan, N. Zaganidis

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
H. Bakhshiansohi, C. Beluffi\textsuperscript{3}, O. Bondu, S. Brochet, G. Bruno, A. Caudron, S. De Visscher,
C. Delaere, M. Delcourt, B. Francois, A. Giammanco, A. Jafari, P. Jez, M. Komm, V. Lemaître,
A. Magitteri, A. Mertens, M. Musich, C. Nuttens, K. Piotrzkowski, L. Quertenmont,
M. Selvaggi, M. Vidal Marono, S. Wertz

Université de Mons, Mons, Belgium
N. Belly

Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil
W.L. Aldá Júnior, F.L. Alves, G.A. Alves, L. Brito, C. Hensel, A. Moraes, M.E. Pol, P. Rebello Teles

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato\textsuperscript{4}, A. Custódio, E.M. Da Costa,
G.G. Da Silveira\textsuperscript{5}, D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza,
L.M. Huertas Guativa, H. Malbouisson, D. Matos Figueiredo, C. Mora Herrera, L. Mundim,
H. Nogima, W.L. Prado Da Silva, A. Santoro, A. Szajder, E.J. Tonelli Manganote\textsuperscript{4}, A. Vilela Pereira

Universidade Estadual Paulista a, Universidade Federal do ABC b, São Paulo, Brazil
S. Ahuja\textsuperscript{a}, C.A. Bernardes\textsuperscript{b}, S. Dogra\textsuperscript{a}, T.R. Fernandez Perez Tomei\textsuperscript{a}, E.M. Gregores\textsuperscript{b},
P.G. Mercadante, C.S. Moon, S.F. Novaes, Sandra S. Padula, D. Romero Abad, J.C. Ruiz Vargas

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria
A. Aleksandrov, R. Hadjiiska, P. Iaydjiev, M. Rodozov, S. Stoykova, G. Sultanov, M. Vutova

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

Beihang University, Beijing, China
W. Fang

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

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

Universidad de Los Andes, Bogota, Colombia
C. Avila, A. Cabrera, L.F. Chaparro Sierra, C. Florez, J.P. Gomez, C.F. González Hernández, J.D. Ruiz Alvarez, J.C. Sanabria

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia
N. Godinovic, D. Lelas, I. Puljak, P.M. Ribeiro Cipriano, T. Sculac

University of Split, Faculty of Science, Split, Croatia
Z. Antunovic, M. Kovac

Institute Rudjer Boskovic, Zagreb, Croatia
V. Brigljevic, D. Ferencek, K. Kadija, S. Micanovic, L. Sudic, T. Susa

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

Charles University, Prague, Czech Republic
M. Finger, M. Finger Jr.

Universidad San Francisco de Quito, Quito, Ecuador
E. Carrera Jarrin

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
E. El-khateeb, S. Elgammal, A. Mohamed

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
B. Calpas, M. Kadastik, M. Murumaa, L. Perrini, M. Raidal, A. Tiko, C. Veelken

Department of Physics, University of Helsinki, Helsinki, Finland
P. Eerola, J. Pekkanen, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland
J. Härkönen, V. Karimäki, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, P. Luukka, J. Tuomineni, E. Tuovinen, L. Wendland
J. Garay Garcia, A. Geiser, A. Gizhko, J.M. Grados Luyando, P. Gunnellini, A. Harb, J. Hauk, M. Hempel, H. Jung, A. Kalogeropoulos, O. Karacheban, M. Kasemann, J. Keaveney, C. Kleinwort, I. Korol, D. Krücker, W. Lange, A. Lelek, J. Leonard, K. Lipka, A. Lobanov, W. Lohmann, R. Mankel, I.-A. Melzer-Pellmann, A.B. Meyer, G. Mittag, J. Mnich, A. Mussgiller, E. Ntomari, D. Pitzl, R. Placakyte, A. Raspereza, B. Roland, M.O. Sahin, P. Saxena, T. Schoerner-Sadenius, C. Seitz, S. Spannagel, N. Stefaniuk, G.P. Van Onsem, R. Walsh, C. Wissing

**University of Hamburg, Hamburg, Germany**

V. Blobel, M. Centis Vignali, A.R. Draeger, T. Dreyer, E. Garutti, D. Gonzalez, J. Haller, M. Hoffmann, A. Junkes, R. Klanner, R. Kogler, N. Kovalchuk, T. Lapsien, T. Lenz, I. Marchesini, D. Marconi, M. Meyer, M. Niedziela, D. Nowatschin, F. Pantaleo, T. Peiffer, A. Perieanu, J. Poehlsen, C. Sander, C. Scharf, P. Schleper, A. Schmidt, S. Schumann, J. Schwandt, H. Stadie, G. Steinbrück, F.M. Stober, M. Stöver, H. Tholen, D. Troendle, E. Usai, L. Vanelderen, A. Vanhoefer, B. Vormwald

**Institut für Experimentelle Kernphysik, Karlsruhe, Germany**

C. Barth, C. Baus, J. Berger, E. Butz, T. Chwalek, F. Colombo, W. De Boer, A. Dierlamm, S. Fink, R. Friese, M. Giffels, A. Gilbert, P. Goldenzweig, D. Haitz, F. Hartmann, S.M. Heindl, U. Husemann, I. Katkov, P. Lobelle Pardo, B. Maier, H. Mildner, M.U. Mozer, Th. Müller, M. Plagge, G. Quast, K. Rabbertz, S. Röcker, F. Roscher, M. Schröder, I. Shvetsov, G. Sieber, H.J. Simonis, R. Ulrich, J. Wagner-Kuhr, S. Wayand, M. Weber, T. Weiler, S. Williamson, C. Wöhrmann, R. Wolf

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

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

**National and Kapodistrian University of Athens, Athens, Greece**

S. Kesisoglou, A. Panagiotou, N. Saoulidou, E. Tziaferi

**University of Ioánnina, Ioánnina, Greece**

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

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

N. Filipovic

**Wigner Research Centre for Physics, Budapest, Hungary**

G. Benčze, C. Hajdu, P. Hidas, D. Horváth, F. Sikler, V. Veszprémi, G. Vesztergombi, A.J. Zsigmond

**Institute of Nuclear Research ATOMKI, Debrecen, Hungary**

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

**University of Debrecen, Debrecen, Hungary**

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

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

S. Bahinipati, S. Choudhury, P. Mal, K. Mandal, A. Nayak, D.K. Sahoo, N. Sahoo, S.K. Swain
Panjab University, Chandigarh, India
S. Bansal, S.B. Beri, V. Bhatnagar, R. Chawla, U.Bhawandeep, A.K. Kalsi, A. Kaur, M. Kaur,
R. Kumar, P. Kumari, A. Mehta, M. Mittal, J.B. Singh, G. Walia

University of Delhi, Delhi, India
Ashok Kumar, A. Bhardwaj, B.C. Choudhary, R.B. Garg, S. Keshri, S. Malhotra, M. Naimuddin,
N. Nishu, K. Ranjan, R. Sharma, V. Sharma

Saha Institute of Nuclear Physics, Kolkata, India
R. Bhattacharyya, S. Bhattacharya, K. Chatterjee, S. Dey, S. Dutt, S. Dutta, S. Ghosh,
N. Majumdar, A. Modak, K. Mondal, S. Mukhopadhyay, S. Nandan, A. Purohit, A. Roy, D. Roy,
S. Roy Chowdhury, S. Sarkar, M. Sharan, S. Thakur

Indian Institute of Technology Madras, Madras, India
P.K. Behera

Bhabha Atomic Research Centre, Mumbai, India
R. Chudasama, D. Dutta, V. Jha, V. Kumar, A.K. Mohanty, P.K. Netrakanti, L.M. Pant,
P. Shukla, A. Topkar

Tata Institute of Fundamental Research-A, Mumbai, India
T. Aziz, S. Dugad, G. Kole, B. Mahakud, S. Mitra, G.B. Mohanty, B. Parida, N. Sur, B. Sutar

Tata Institute of Fundamental Research-B, Mumbai, India
S. Banerjee, S. Bhowmik, R.K. Dewanjee, S. Ganguly, M. Guchait, S. Jain, S. Kumar,
M. Maity, G. Majumder, K. Mazumdar, T. Sarkar, N. Wickramage

Indian Institute of Science Education and Research (IISER), Pune, India
S. Chauhan, S. Dube, V. Hegde, A. Kapoor, K. Kothekar, A. Rane, S. Sharma

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
H. Behnamian, S. Chenarani, E. Eskandari Tadavani, S.M. Etesami, A. Fahim, M. Khakzad,
M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi, G. Selvaggi, B. Sutar

University College Dublin, Dublin, Ireland
M. Felcini, M. Grunewald

INFN Sezione di Bari, Università di Bari, Politecnico di Bari, Bari, Italy
M. Abbrescia, C. Calabria, C. Caputo, A. Colaleo, D. Creanza, L. Cristella, N. De Filippis,
M. De Palma, L. Fiore, G. Iaselli, G. Maggi, G. Miniello, S. My, A. Nuzzo, A. Pompili,
P. Pugliese, R. Radogna, A. Ranieri, L. Silvestris, R. Venditti, P. Verwilligen

INFN Sezione di Bologna, Università di Bologna, Bologna, Italy
G. Abbiendi, C. Battilana, D. Bonacorsi, S. Braibant-Giacomelli, L. Brigliadori, R. Campanini,
P. Capiluppi, A. Castro, F.R. Cavallo, S.S. Chhibra, G. Codispoti, M. Cuffiani, G. Dallavalle,
F. Fabbri, A. Fanfani, D. Fasanella, P. Giacomelli, C. Grandi, L. Guiducci, S. Marcellini,
G. Masetti, A. Montanari, F.L. Navarria, A. Perrotta, A.M. Rossi, T. Rovelli, C. Tuve

INFN Sezione di Catania, Università di Catania, Catania, Italy
S. Albergo, M. Chiorello, S. Costa, A. Di Mattia, F. Giordano, R. Potenza, A. Tricomi, C. Tuve
INFN Sezione di Firenze, Università di Firenze, Firenze, Italy
G. Barbargli, A. Ciulli, C. Civinini, R. D’Alessandro, E. Focardi, V. Gori, P. Lenzi, M. Meschini, S. Paolletti, G. Sguazzoni, L. Viliani

INFN Laboratori Nazionali di Frascati, Frascati, Italy
L. Benussi, S. Bianco, F. Fabbri, D. Piccolo, F. Primavera

INFN Sezione di Genova, Università di Genova, Genova, Italy
V. Calvelli, F. Ferro, M. Lo Vetere, M.R. Monge, E. Robutti, S. Tosi

INFN Sezione di Milano-Bicocca, Università di Milano-Bicocca, Milano, Italy
L. Bionanza, M.E. Dinardo, S. Fiorendi, S. Gennai, A. Ghezzi, P. Govoni, M. Malberti, S. Malvezzi, R.A. Manzoni, D. Menasce, L. Moroni, M. Paganoni, D. Pedrini, S. Pigazzini, S. Ragazzi, T. Tabarelli de Fatis

INFN Sezione di Napoli, Università di Napoli ‘Federico II’, Napoli, Italy, Università della Basilicata
S. Buontempo, N. Cavallo, G. De Nardo, S. Di Guida, M. Esposito, F. Fabozzi, F. Fienga, A.M. Iorio, G. Lanza, L. Lista, S. Meola, P. Paolucci, C. Sciaccà, F. Thyssen

INFN Sezione di Padova, Università di Padova, Padova, Università di Trento, Trento, Italy
P. Azzi, N. Bacchetta, L. Benaté, D. Bisello, A. Boletti, R. Carlin, A. Carvalho Antunes De Oliveira, P. Checchia, M. Dall’Osso, P. De Castro Manzano, T. Dorigo, U. Dosselli, F. Gasparini, U. Gasparini, A. Gozzelino, S. Lacapra, M. Margoni, A.T. Meneguzzo, J. Pazzini, N. Pozzobon, P. Ronchese, F. Simonetto, E. Torassa, M. Zanetti, P. Zotto, G. Zumerle

INFN Sezione di Pavia, Università di Pavia, Pavia, Italy
A. Braghieri, A. Magnani, P. Montagna, S.P. Ratti, V. Re, C. Riccardi, P. Salvini, I. Vai, P. Vitulo

INFN Sezione di Perugia, Università di Perugia, Perugia, Italy
L. Alunni Solestiz, G.M. Bilei, D. Ciangottini, L. Fanò, P. Lariccia, R. Leonardì, G. Mantovani, M. Menichelli, A. Saha, A. Santocchia

INFN Sezione di Pisa, Scuola Normale Superiore di Pisa, Pisa, Italy
K. Androsov, P. Azzurri, G. Bagliesi, J. Bernardini, T. Boccali, R. Castaldi, M.A. Ciocci, R. Dell’Orso, S. Donato, G. Fedi, A. Giassi, M.T. Grippo, F. Ligabue, T. Lomtadze, L. Martinì, A. Messineo, F. Palla, A. Rizzi, A. Savoy-Narrollo, P. Spagnolo, R. Tenchini, G. Tonelli, A. Ventura, P.G. Verdini

INFN Sezione di Roma, Università di Roma, Roma, Italy
L. Barone, F. Cavallari, M. Cipriani, G. D’imperio, D. Del Re, M. Diemoz, S. Gelli, E. Longo, F. Margaroli, B. Marzocchi, P. Meridiani, G. Organtini, R. Paramatti, F. Preiato, S. Rahatlou, C. Rotelli, F. Santanastasio

INFN Sezione di Torino, Università di Torino, Torino, Italy, Università del Piemonte Orientale, Novara, Italy
N. Amapane, R. Arcidiacono, S. Argiro, M. Arneodo, N. Bartosik, R. Bellan, C. Biino, N. Cartiglia, F. Cenna, M. Costa, R. Covarelli, A. Degano, N. Demaria, L. Finco, B. Kiani, C. Mariotti, S. Maselli, E. Migliore, V. Monaco, E. Monteil, M.M. Obertino, L. Pacher, N. Pastrone, M. Pelliccioni, G.L. Pinna Angioni, F. Ravera,
A. Romero\textsuperscript{a,b}, M. Ruspa\textsuperscript{a,c}, R. Sacchi\textsuperscript{a,b}, K. Shchelina\textsuperscript{a,b}, V. Sola\textsuperscript{a}, A. Solano\textsuperscript{a,b}, A. Staiano\textsuperscript{a},

P. Traczyk\textsuperscript{a,b}

\textbf{INFN Sezione di Trieste}\textsuperscript{a}, \textbf{Università di Trieste}\textsuperscript{b}, \textbf{Trieste, Italy}

S. Belforte\textsuperscript{a}, M. Casarsa\textsuperscript{a}, F. Cossutti\textsuperscript{a}, G. Della Ricca\textsuperscript{a,b}, A. Zanetti\textsuperscript{e}

\textbf{Kyungpook National University, Daegu, Korea}

D.H. Kim, G.N. Kim, M.S. Kim, S. Lee, S.W. Lee, Y.D. Oh, S. Sekmen, D.C. Son, Y.C. Yang

\textbf{Chonbuk National University, Jeonju, Korea}

A. Lee

\textbf{Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea}

H. Kim

\textbf{Hanyang University, Seoul, Korea}

J.A. Brochero Cifuentes, T.J. Kim

\textbf{Korea University, Seoul, Korea}

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

\textbf{Seoul National University, Seoul, Korea}

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

\textbf{University of Seoul, Seoul, Korea}

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

\textbf{Sungkyunkwan University, Suwon, Korea}

Y. Choi, J. Goh, C. Hwang, J. Lee, I. Yu

\textbf{Vilnius University, Vilnius, Lithuania}

V. Dudenas, A. Juodagalvis, J. Vaitkus

\textbf{National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia}

I. Ahmed, Z.A. Ibrahim, J.R. Komaragiri, M.A.B. Md Ali\textsuperscript{31}, F. Mohamad Idris\textsuperscript{32}, W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

\textbf{Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico}

H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz\textsuperscript{33}, A. Hernandez-Almada, R. Lopez-Fernandez, R. Magaña Villalba, J. Mejia Guisao, A. Sanchez-Hernandez

\textbf{Universidad Iberoamericana, Mexico City, Mexico}

S. Carrillo Moreno, C. Oropeza Barrera, F. Vazquez Valencia

\textbf{Benemerita Universidad Autonoma de Puebla, Puebla, Mexico}

S. Carpinteyro, I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

\textbf{Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico}

A. Morelos Pineda

\textbf{University of Auckland, Auckland, New Zealand}

D. Krofcheck

\textbf{University of Canterbury, Christchurch, New Zealand}

P.H. Butler
National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
A. Ahmad, M. Ahmad, Q. Hassan, H.R. Hoorani, W.A. Khan, A. Saddique, M.A. Shah, M. Shoaib, M. Waqas

National Centre for Nuclear Research, Swierk, Poland
H. Bialkowska, M. Bluji, B. Boimska, T. Frueboes, M. Górski, M. Kazana, K. Nawrocki, K. Romanowska-Rybinska, M. Szleper, P. Zalewski

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

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
P. Bargassa, C. Beirão Da Cruz E Silva, A. Di Francesco, P. Faccioli, P.G. Ferreira Parracho, M. Gallinaro, J. Hollar, N. Leonardo, L. Lloret Iglesias, M.V. Nemallapudi, J. Rodrigues Antunes, J. Seixas, O. Toldaiev, D. Vadrucio, J. Varela, P. Vischia

Joint Institute for Nuclear Research, Dubna, Russia
S. Afanasiev, M. Gavrilenko, I. Golotvin, A. Kamenev, V. Karjavin, V. Korenkov, A. Lanev, A. Malakhov, V. Matveev, V.V. Mitsyn, V. Palichik, V. Perelygin, S. Shmatov, N. Skatchkov, V. Smirnov, E. Tikhonenko, B.S. Yuldashev, A. Zarubin

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia
L. Chchipounov, V. Golovtsov, Y. Ivanov, V. Kim, E. Kuznetsova, V. Murzin, V. Oreshkin, V. Sulimov, A. Vorobyev

Institute for Nuclear Research, Moscow, Russia
Yu. Andreev, A. Dermenev, S. Grinenko, N. Golubev, A. Karneyeu, M. Kirsanov, N. Krasnikov, A. Pashenkov, D. Tlisov, A. Toropin

Institute for Theoretical and Experimental Physics, Moscow, Russia
V. Epshtein, V. Gavrilov, N. Lychkovskaya, V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, M. Toms, E. Vlasov, A. Zhokin

Moscow Institute of Physics and Technology
A. Bylinkin

National Research Nuclear University ‘Moscow Engineering Physics Institute’ (MEPhI), Moscow, Russia
R. Chistov, M. Danilov, V. Rusinov

P.N. Lebedev Physical Institute, Moscow, Russia
V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, A. Leonidov, S.V. Rusakov, A. Terkulov

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
A. Baskakov, A. Belyaev, E. Boos, A. Ershov, A. Gribushin, A. Kaminskiy, O. Kodolova, V. Korotkich, I. Lokhtin, I. Miagkov, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev, I. Vardanyan

Novosibirsk State University (NSU), Novosibirsk, Russia
V. Blinov, Y. Skovpen
State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia
I. Azhgirey, I. Bayshev, S. Bitioukov, D. Elumakhov, V. Kachanov, A. Kalinin, D. Konstantinov, V. Krychkine, V. Petrov, R. Ryutin, A. Sobol, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
P. Adzic, P. Cirkovic, D. Devetak, M. Dordevic, J. Milosevic, V. Rekovic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
J. Alcaraz Maestre, M. Barrio Luna, E. Calvo, M. Cerrada, M. Chamizo Llatas, N. Colino, B. De La Cruz, A. Delgado Peris, A. Escalante Del Valle, C. Fernandez Bedoya, J.P. Fernandez Ramos, J. Flix, M.C. Fouz, P. Garcia-Abia, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, E. Navarro De Martin, A. Perez-Calero Yzquierdo, J. Puerta Pelayo, A. Quintario Olmeda, I. Redondo, L. Romero, M.S. Soares

Universidad Autónoma de Madrid, Madrid, Spain
J.F. de Trocóniz, M. Missiroli, D. Moran

Universidad de Oviedo, Oviedo, Spain
J. Cuevas, J. Fernandez Menendez, I. Gonzalez Caballero, J.R. González Fernández, E. Palencia Cortezon, S. Sanchez Cruz, I. Suárez Andrés, J.M. Vizan Garcia

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
I.J. Cabrillo, A. Calderon, J.R. Castañeiras De Saa, E. Currais, M. Fernandez, J. Garcia-Ferrero, G. Gomez, A. Lopez Virto, J. Marco, C. Martinez Rivero, F. Matorras, J. Pedro Gomez, T. Rodrigo, A. Ruiz-Jimeno, L. Scodellaro, N. Trevisani, I. Vila, R. Vilar Cortabitarte

CERN, European Organization for Nuclear Research, Geneva, Switzerland
D. Abbaneo, E. Auffray, G. Auzinger, M. Bachtis, P. Bailly, A.H. Ball, D. Barney, P. Bloch, A. Bocci, A. Bonato, C. Botta, T. Camporesi, R. Castello, M. Cepeda, G. Cerminara, M. D’Alfonso, D. d’Enterria, A. Dabrowski, V. Daponte, A. David, M. De Gruttola, A. De Roeck, E. Di Marco, M. Dobson, B. Dorney, T. du Pree, D. Duggan, M. Düren, N. Dupont, A. Elliott-Peisert, S. Fartoukh, G. Franzoni, J. Fulcher, W. Funk, D. Gigi, K. Gill, M. Girone, F. Glege, D. Gulhan, S. Gunther, M. Guther, J. Hammer, P. Harris, J. Hegeman, V. Innocente, P. Janot, J. Kieseler, H. Kirschenmann, V. Knünz, A. Kornmayer, M.J. Kortelainen, K. Kousouris, M. Kramer, C. Lange, P. Lecoq, C. Lourenço, M.T. Lucchini, L. Malgeri, M. Mannelli, A. Martelli, F. Meijers, J.A. Merlin, S. Mersi, E. Meschi, F. Moortgat, S. Morovic, M. Mulders, H. Neugebauer, S. Orfanelli, L. Orsini, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, A. Racz, T. Reis, G. Rolandi, M. Rovere, M. Ruan, H. Sakulin, J.B. Sauvan, C. Schäfer, C. Schwik, M. Seidel, A. Sharma, P. Silva, P. Spichas, J. Steggemann, M. Stoye, Y. Takahashi, M. Tosi, D. Treille, A. Triossi, A. Tsirou, V. Veckalns, G.I. Veres, N. Wardle, H.K. Wöhri, A. Zagorodniitska, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland
W. Bertl, K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland
F. Bachmair, L. Bäni, L. Bianchini, B. Casal, G. Dissertori, M. Dittmar, M. Donegà, C. Grab, C. Heidegger, D. Hits, J. Hoss, G. Kasieczka, P. Lecomte, W. Lustermann, B. Mangano, M. Marionneau, P. Martineau Ruiz del Arbol, M. Masciovecchio, M.T. Meinhard, D. Meister,
F. Micheli, P. Musella, F. Nessi-Tedaldi, F. Pandolfi, J. Pata, F. Pauss, G. Perrin, L. Perrozzi, M. Quittnat, M. Rossini, M. Schönenberger, A. Starodumov, V.R. Tavolaro, K. Theoﬁlatos, R. Wallny

Universität Zürich, Zurich, Switzerland
T.K. Aarrestad, C. Amsler, L. Caminada, M.F. Canelli, A. De Cosa, C. Galloni, A. Hinzmann, T. Hreus, B. Kilminster, J. Ngadiuba, D. Pinna, G. Rauco, P. Robmann, D. Salermo, Y. Yang, A. Zucchetta

National Central University, Chung-Li, Taiwan
V. Candelise, T.H. Doan, Sh. Jain, R. Khurana, M. Konyushikhin, C.M. Kuo, W. Lin, Y.J. Lu, A. Pozdnyakov, S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan
Arun Kumar, P. Chang, Y.H. Chang, Y.W. Chang, Y. Chao, K.F. Chen, P.H. Chen, C. Dietz, F. Fiori, W.-S. Hou, Y. Hsiung, Y.F. Liu, R.-S. Lu, M. Miñano Moya, E. Paganis, A. Psallidas, J.f. Tsai, Y.M. Tzeng

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

Cukurova University, Adana, Turkey
A. Adiguzel, S. Cerci, S. Damarseckin, Z.S. Demiroglu, C. Dozen, I. Dumanoglu, S. Girgis, G. Gokbulut, Y. Guler, I. Hos, E.E. Kangal, O. Kara, U. Kiminsu, M. Oglakci, G. Onengut, K. Ozdemir, D. Sunar Cerci, B. Tali, H. Topakli, S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

Middle East Technical University, Physics Department, Ankara, Turkey
B. Bilin, S. Bilmis, B. Isildak, G. Karapinar, M. Yalvac, M. Zeyrek

Bogazici University, Istanbul, Turkey
E. Gülmek, M. Kaya, O. Kaya, E.A. Yetkin, T. Yetkin

Istanbul Technical University, Istanbul, Turkey
A. Cakir, K. Cankocak, S. Sen

Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine
B. Grynyov

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine
L. Levchuk, P. Sorokin

University of Bristol, Bristol, United Kingdom
R. Aggleton, F. Ball, L. Beck, J.J. Brooke, D. Burns, E. Clement, D. Cussans, H. Flacher, J. Goldstein, M. Grimes, G.P. Heath, H.F. Heath, J. Jacob, L. Kreczko, C. Lucas, D.M. Newbold, S. Paramesvaran, A. Poll, T. Sakuma, S. Seif El Nasr-storey, D. Smith, V.J. Smith

Rutherford Appleton Laboratory, Didcot, United Kingdom
A. Belyaev, C. Brew, R.M. Brown, L. Calligaris, D. Cieri, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, E. Olaiya, D. Petyt, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams

Imperial College, London, United Kingdom
M. Baber, R. Bainbridge, O. Buchmuller, A. Bundock, D. Burton, S. Casasso, M. Citron, D. Colling, L. Corpe, P. Dauncey, G. Davies, A. De Wit, M. Della Negra, R. Di Maria, P. Dunne, A. Elwood, D. Fuytan, Y. Haddad, G. Hall, G. Iles, T. James, R. Lane, C. Laner, R. Lucas,
L. Lyons, A.-M. Magnan, S. Malik, L. Mastrolorenzo, J. Nash, A. Nikitenko, J. Pela, B. Penning, M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, C. Seez, S. Summers, A. Tapper, K. Uchida, M. Vazquez Acosta, T. Virdee, J. Wright, S.C. Zenz

Brunel University, Uxbridge, United Kingdom
J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, D. Leslie, I.D. Reid, P. Symonds, L. Teodorescu, M. Turner

Baylor University, Waco, USA
A. Borzou, K. Call, J. Dittmann, K. Hatakeyama, H. Liu, N. Pastika

The University of Alabama, Tuscaloosa, USA
O. Charaf, S.I. Cooper, C. Henderson, P. Rumerio, C. West

Boston University, Boston, USA
D. Arcaro, A. Avetisyan, T. Bose, D. Gastler, D. Rankin, C. Richardson, J. Rohlf, L. Sulak, D. Zou

Brown University, Providence, USA
G. Benelli, E. Berry, D. Cutts, A. Garabedian, J. Hakala, U. Heintz, J.M. Hogan, O. Jesus, K.H.M. Kwok, E. Laird, G. Landsberg, Z. Mao, M. Narain, S. Piperov, S. Sagir, E. Spencer, R. Syarif

University of California, Davis, Davis, USA
R. Breedon, G. Breto, D. Burns, M. Calderon De La Barca Sanchez, S. Chauhan, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, C. Flores, G. Funk, M. Gardner, W. Ko, R. Lander, C. Mclean, M. Mulhearn, D. Pellett, J. Pilot, S. Shalhout, J. Smith, M. Squires, D. Stolp, M. Tripathi, S. Wilbur, R. Yohay

University of California, Los Angeles, USA
R. Cousins, P. Everaerts, A. Florent, J. Hauser, M. Ignatenko, D. Saltzberg, E. Takasugi, V. Valuev, M. Weber

University of California, Riverside, Riverside, USA
K. Burt, R. Clare, J. Ellison, J.W. Gary, S.M.A. Ghiasi Shirazi, G. Hanson, J. Heilman, P. Jandir, E. Kennedy, F. Lacroix, O.R. Long, M. Olmedo Negrete, M.I. Paneva, A. Shrinivas, W. Si, H. Wei, S. Wimpenny, B. R. Yates

University of California, San Diego, La Jolla, USA
J.G. Branson, G.B. Cerati, S. Cittolin, M. Derdzinski, R. Gerosa, A. Holzner, D. Klein, V. Krutelyov, J. Letts, I. Macneill, D. Olivito, S. Padhi, M. Pieri, M. Sani, V. Sharma, S. Simon, M. Tadel, A. Vartak, S. Wasserbaech, C. Welke, J. Wood, F. Würthwein, A. Yagil, G. Zevi Della Porta

University of California, Santa Barbara - Department of Physics, Santa Barbara, USA
R. Bhandari, J. Bradmiller-Feld, C. Campagnari, A. Dishaw, V. Dutta, K. Flowers, M. Franco Sevilla, P. Geffert, C. George, F. Golf, L. Gouskos, J. Gran, R. Heller, J. Incandela, N. Mccoll, S.D. Mullin, A. Ovcharova, J. Richman, D. Stuart, I. Suarez, J. Yoo

California Institute of Technology, Pasadena, USA
D. Anderson, A. Apresyan, J. Bendavid, A. Bornheim, J. Bunn, Y. Chen, J. Duarte, J.M. Lawhorn, A. Mott, H.B. Newman, C. Pena, M. Spiropulu, J.R. Vlimant, S. Xie, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, USA
M.B. Andrews, V. Azzolini, T. Ferguson, M. Paulini, J. Russ, M. Sun, H. Vogel, I. Vorobiev
University of Colorado Boulder, Boulder, USA
J.P. Cumalat, W.T. Ford, F. Jensen, A. Johnson, M. Krohn, T. Mulholland, K. Stenson, S.R. Wagner

Cornell University, Ithaca, USA
J. Alexander, J. Chaves, J. Chu, S. Dittmer, K. Mcdermott, N. Mirman, G. Nicolas Kaufman, J.R. Patterson, A. Rinkevicius, A. Ryd, L. Skinnari, L. Soffi, S.M. Tan, Z. Tao, J. Thom, J. Tucker, P. Wittich, M. Zientek

Fairfield University, Fairfield, USA
D. Winn

Fermi National Accelerator Laboratory, Batavia, USA
S. Abdullin, M. Albrow, G. Apollinari, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, G. Bolla, K. Burkett, J.N. Butler, H.W.K. Cheung, F. Chlebana, S. Cihangir†, M. Cremonesi, V.D. Elvira, I. Fisk, J. Freeman, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, D. Hare, R.M. Harris, S. Hasegawa, J. Hirschauer, Z. Hu, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, B. Klima, B. Kreis, S. Lammel, J. Linacre, D. Lincoln, R. Lipton, T. Liu, R. Lopes De Sá, J. Lykken, K. Maeshima, N. Magini, J.M. Marraffino, S. Maruyama, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahm, C. Newman-Holmes†, V. O’Dell, K. Pedro, O. Prokofyev, G. Rakness, L. Ristori, E. Sexton-Kennedy, A. Soha, W.J. Spalding, L. Spiegel, S. Stoynev, N. Strobbe, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, C. Vernieri, M. Verzocchi, R. Vidal, M. Wang, H.A. Weber, A. Whitbeck

University of Florida, Gainesville, USA
D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, A. Brinkerhoff, A. Carnes, M. Carver, D. Curry, S. Das, R.D. Field, I.K. Furic, J. Konigsberg, A. Korytov, P. Ma, K. Matchev, H. Mei, P. Milenovic66, G. Mitselmakher, D. Rank, L. Shchutska, D. Sperka, L. Thomas, J. Wang, S. Wang, J. Yelton

Florida International University, Miami, USA
S. Linn, P. Markowitz, G. Martinez, J.L. Rodriguez

Florida State University, Tallahassee, USA
A. Ackert, J.R. Adams, T. Adams, A. Askelw, S. Bein, B. Diamond, S. Hagopian, V. Hagopian, K.F. Johnson, A. Khatiwada, H. Prosper, A. Santra, M. Weinberg

Florida Institute of Technology, Melbourne, USA
M.M. Baarmand, V. Bhopatkar, S. Colafranceschi67, M. Hohlmann, D. Noonan, T. Roy, F. Yumiceva

University of Illinois at Chicago (UIC), Chicago, USA
M.R. Adams, L. Apanasevich, D. Berry, R.R. Betts, I. Bucinskaite, R. Cavanaugh, O. Evdokimov, L. Gauthier, C.E. Gerber, D.J. Hofman, K. Jung, P. Kurt, C. O’Brien, I.D. Sandoval Gonzalez, P. Turner, N. Varelas, H. Wang, Z. Wu, M. Zakaria, J. Zhang

The University of Iowa, Iowa City, USA
B. Bilki68, W. Clarida, K. Dilsiz, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, H. Mermerkaya69, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul, Y. Onel, F. Ozok70, A. Penzo, C. Snyder, E. Tiras, J. Wetzel, K. Yi

Johns Hopkins University, Baltimore, USA
I. Anderson, B. Blumenfeld, A. Cocoros, N. Eminizer, D. Fehling, L. Feng, A.V. Gritsan, P. Maksimovic, C. Martin, M. Osherson, J. Roskes, U. Sarica, M. Swartz, M. Xiao, Y. Xin, C. You
The University of Kansas, Lawrence, USA
A. Al-bataineh, P. Baringer, A. Bean, S. Boren, J. Bowen, C. Bruner, J. Castle, L. Forthomme, R.P. Kenny III, A. Kropivnitskaya, D. Majumder, W. Mcbrayer, M. Murray, S. Sanders, R. Stringer, J.D. Tapia Takaki, Q. Wang

Kansas State University, Manhattan, USA
A. Ivanov, K. Kaadze, S. Khalil, Y. Maravin, A. Mohammadi, L.K. Saini, N. Skhirtladze, S. Toda

Lawrence Livermore National Laboratory, Livermore, USA
F. Rebassoo, D. Wright

University of Maryland, College Park, USA
C. Anelli, A. Baden, O. Baron, A. Belloni, B. Calvert, S.C. Eno, C. Ferraioli, J.A. Gomez, N.J. Hadley, S. Jabeen, R.G. Kellogg, T. Kolberg, J. Kunkle, Y. Lu, A.C. Mignerey, F. Ricci-Tam, Y.H. Shin, A. Skuja, M.B. Tonjes, S.C. Tonwar

Massachusetts Institute of Technology, Cambridge, USA
D. Abercrombie, B. Allen, A. Apyan, R. Barbieri, A. Baty, R. Bi, K. Bierwagen, S. Brandt, W. Busza, I.A. Cali, Z. Demiragli, L. Di Matteo, G. Gomez Ceballos, M. Goncharov, D. Hsu, Y. Iiyama, G.M. Innocenti, M. Klute, D. Kovalskyi, K. Krajc zar, Y.S. Lai, Y.-J. Lee, A. Levin, P.D. Luckey, A.C. Marini, C. McGinn, C. Mironov, S. Narayanan, X. Ni, C. Paus, C. Roland, G. Roland, J. Salfeld-Nebgen, G.S.F. Stephens, K. Sumorok, K. Tatar, M. Varma, D. Velicanu, J. Veverka, J. Wang, T.W. Wang, B. Wyslouch, M. Yang, V. Zhukova

University of Minnesota, Minneapolis, USA
A.C. Benvenuti, R.M. Chatterjee, A. Evans, A. Finkel, A. Gude, P. Hansen, S. Kalafut, S.C. Kao, Y. Kubota, Z. Lesko, J. Mans, S. Nourbakhsh, N. Ruckstuhl, R. Rusack, N. Tambe, J. Turkewitz

University of Mississippi, Oxford, USA
J.G. Acosta, S. Oliveros

University of Nebraska-Lincoln, Lincoln, USA
E. Avdeeva, R. Bartek, K. Bloom, D.R. Claes, A. Dominguez, C. Fangmeier, R. Gonzalez Suarez, R. Kamalieddin, I. Kravchenko, A. Malta Rodrigues, F. Meier, J. Monroy, J.E. Siado, G.R. Snow, B. Stieger

State University of New York at Buffalo, Buffalo, USA
M. Alyari, J. Dolen, J. George, A. Godshalk, C. Harrington, I. Iashvili, J. Kaisen, A. Kharchilava, A. Kumar, A. Parker, S. Rappoccio, B. Roozbahani

Northeastern University, Boston, USA
G. Al verson, E. Barberis, A. Hortiangtham, A. Massironi, D.M. Morse, D. Nash, T. Orimoto, R. Teixeira De Lima, D. Trocino, R.-J. Wang, D. Wood

Northwestern University, Evanston, USA
S. Bhattacharya, K.A. Hahn, A. Kubik, A. Kumar, J.F. Low, N. Mucia, N. Odell, B. Pollack, M.H. Schmitt, K. Sung, M. Trovato, M. Velasco

University of Notre Dame, Notre Dame, USA
N. Dev, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon, N. Marinelli, F. Meng, C. Mueller, Y. Musienko, M. Planer, A. Reinsvold, R. Ruchti, G. Smith, S. Taroni, M. Wayne, M. Wolf, A. Woodard
The Ohio State University, Columbus, USA
J. Alimena, L. Antonelli, J. Brinson, B. Bylsma, L.S. Durkin, S. Flowers, B. Francis, A. Hart, C. Hill, R. Hughes, W. Ji, B. Liu, W. Luo, D. Puigh, B.L. Winer, H.W. Wulsin

Princeton University, Princeton, USA
S. Cooperstein, O. Driga, P. Elmer, J. Hardenbrook, P. Hebda, D. Lange, J. Luo, D. Marlow, T. Medvedeva, K. Mei, M. Mooney, J. Olsen, C. Palmer, P. Piroué, D. Stickland, C. Tully, A. Zuranski

University of Puerto Rico, Mayaguez, USA
S. Malik

Purdue University, West Lafayette, USA
A. Barker, V.E. Barnes, S. Folgueras, L. Gutay, M.K. Jha, M. Jones, A.W. Jung, D.H. Miller, N. Neumeister, J.F. Schulte, X. Shi, J. Sun, A. Svyatkovskiy, F. Wang, W. Xie, L. Xu

Purdue University Calumet, Hammond, USA
N. Parashar, J. Stupak

Rice University, Houston, USA
A. Adair, B. Akgun, Z. Chen, K.M. Ecklund, F.J.M. Geurts, M. Guilbaud, W. Li, B. Michlin, M. Northup, B.P. Padley, R. Redjimi, J. Roberts, J. Rorie, Z. Tu, J. Zabel

University of Rochester, Rochester, USA
B. Betchart, A. Bodek, P. de Barbaro, R. Demina, Y.t. Duh, T. Ferbel, M. Galanti, A. Garcia-Bellido, J. Han, O. Hindrichs, A. Khukhunaishvili, K.H. Lo, P. Tan, M. Verzetti

Rutgers, The State University of New Jersey, Piscataway, USA
A. Agapitos, J.P. Chou, E. Contreras-Campana, Y. Gershtein, T.A. Gómez Espinosa, E. Halkiadakis, M. Heindl, D. Hidas, E. Hughes, S. Kaplan, R. Kunnawalkam Elayavalli, S. Kyriacou, A. Lath, K. Nash, A. Parikh, G. Pikul, H. Saka, S. Salur, S. Schnetzer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen, M. Walker

University of Tennessee, Knoxville, USA
A.G. Delannoy, M. Foerster, J. Heideman, G. Riley, K. Rose, S. Spanier, K. Thapa

Texas A&M University, College Station, USA
O. Bouhali, A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, E. Juska, T. Kamon, R. Mueller, Y. Pakhotin, R. Patel, A. Perloff, L. Permi, D. Rathjens, A. Rose, A. Safronov, A. Tatarinov, K.A. Ulmer

Texas Tech University, Lubbock, USA
N. Akchurin, C. Cowden, J. Damgov, F. De Guio, C. Dragoiu, P.R. Dudero, J. Faulkner, E. Gurpinar, S. Kunori, K. Lamicchane, S.W. Lee, T. Libeiro, T. Peltola, S. Undleeb, I. Volobouev, Z. Wang

Vanderbilt University, Nashville, USA
S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, A. Melo, H. Ni, P. Sheldon, S. Tuo, J. Velkovska, Q. Xu

University of Virginia, Charlottesville, USA
M.W. Arenton, P. Barria, B. Cox, J. Goodell, R. Hirosky, A. Ledovskoy, H. Li, C. Neu, T. Sinthuprasith, X. Sun, Y. Wang, E. Wolfe, F. Xia

Wayne State University, Detroit, USA
C. Clarke, R. Harr, P.E. Karchin, J. Sturdy
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University of Wisconsin - Madison, Madison, WI, USA
D.A. Belknap, S. Dasu, L. Dodd, S. Duric, B. Gomber, M. Grothe, M. Herndon, A. Hervé, P. Klabbers, A. Lanaro, A. Levine, K. Long, R. Loveless, I. Ojalvo, T. Perry, G.A. Pierro, G. Polese, T. Ruggles, A. Savin, N. Smith, W.H. Smith, D. Taylor, N. Woods

†: Deceased
1: Also at Vienna University of Technology, Vienna, Austria
2: Also at State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
3: Also at Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France
4: Also at Universidade Estadual de Campinas, Campinas, Brazil
5: Also at Universidade Federal de Pelotas, Pelotas, Brazil
6: Also at Université Libre de Bruxelles, Bruxelles, Belgium
7: Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany
8: Also at Joint Institute for Nuclear Research, Dubna, Russia
9: Also at Ain Shams University, Cairo, Egypt
10: Now at British University in Egypt, Cairo, Egypt
11: Also at Zewail City of Science and Technology, Zewail, Egypt
12: Also at Université de Haute Alsace, Mulhouse, France
13: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
14: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
15: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
16: Also at University of Hamburg, Hamburg, Germany
17: Also at Brandenburg University of Technology, Cottbus, Germany
18: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
19: Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
20: Also at University of Debrecen, Debrecen, Hungary
21: Also at Indian Institute of Science Education and Research, Bhopal, India
22: Also at Institute of Physics, Bhubaneswar, India
23: Also at University of Visva-Bharati, Santiniketan, India
24: Also at University of Ruhuna, Matara, Sri Lanka
25: Also at Isfahan University of Technology, Isfahan, Iran
26: Also at University of Tehran, Department of Engineering Science, Tehran, Iran
27: Also at Yazd University, Yazd, Iran
28: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
29: Also at Università degli Studi di Siena, Siena, Italy
30: Also at Purdue University, West Lafayette, USA
31: Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia
32: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia
33: Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico
34: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
35: Also at Institute for Nuclear Research, Moscow, Russia
36: Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
37: Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan
38: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
39: Also at University of Florida, Gainesville, USA
40: Also at P.N. Lebedev Physical Institute, Moscow, Russia
41: Also at INFN Sezione di Padova; Università di Padova; Università di Trento (Trento), Padova, Italy
42: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
43: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
44: Also at INFN Sezione di Roma; Università di Roma, Roma, Italy
45: Also at Scuola Normale e Sezione dell’INFN, Pisa, Italy
46: Also at National and Kapodistrian University of Athens, Athens, Greece
47: Also at Riga Technical University, Riga, Latvia
48: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
49: Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland
50: Also at Adiyaman University, Adiyaman, Turkey
51: Also at Mersin University, Mersin, Turkey
52: Also at Cag University, Mersin, Turkey
53: Also at Piri Reis University, Istanbul, Turkey
54: Also at Gaziosmanpasa University, Tokat, Turkey
55: Also at Ozyegin University, Istanbul, Turkey
56: Also at Izmir Institute of Technology, Izmir, Turkey
57: Also at Marmara University, Istanbul, Turkey
58: Also at Kafkas University, Kars, Turkey
59: Also at Istanbul Bilgi University, Istanbul, Turkey
60: Also at Yildiz Technical University, Istanbul, Turkey
61: Also at Hacettepe University, Ankara, Turkey
62: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
63: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
64: Also at Instituto de Astrofísica de Canarias, La Laguna, Spain
65: Also at Utah Valley University, Orem, USA
66: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
67: Also at Facoltà Ingegneria, Università di Roma, Roma, Italy
68: Also at Argonne National Laboratory, Argonne, USA
69: Also at Erzincan University, Erzincan, Turkey
70: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
71: Also at Texas A&M University at Qatar, Doha, Qatar
72: Also at Kyungpook National University, Daegu, Korea