

Measurement of jet fragmentation into charged particles in pp and PbPb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV

The CMS collaboration

ABSTRACT: Jet fragmentation in pp and PbPb collisions at a centre-of-mass energy of 2.76 TeV per nucleon pair was studied using data collected with the CMS detector at the LHC. Fragmentation functions are constructed using charged-particle tracks with transverse momenta $p_T > 4$ GeV/c for dijet events with a leading jet of $p_T > 100$ GeV/c. The fragmentation functions in PbPb events are compared to those in pp data as a function of collision centrality, as well as dijet- p_T imbalance. Special emphasis is placed on the most central PbPb events including dijets with unbalanced momentum, indicative of energy loss of the hard scattered parent partons. The fragmentation patterns for both the leading and subleading jets in PbPb collisions agree with those seen in pp data at 2.76 TeV. The results provide evidence that, despite the large parton energy loss observed in PbPb collisions, the partition of the remaining momentum within the jet cone into high- p_T particles is not strongly modified in comparison to that observed for jets in vacuum.

KEYWORDS: Hadron-Hadron Scattering

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1 Introduction

When colliding lead nuclei (PbPb) at a nucleon-nucleon centre-of-mass energy of $\sqrt{s_{\text{NN}}} = 2.76$ TeV, one expects to form a system of hot and dense matter at energy densities that have not been explored before. One of the early proposed experimental signatures of the formation of a dense system in such collisions was “jet quenching”, i.e. the suppression or disappearance of the spray of hadrons resulting from the fragmentation of a hard scattered parton having suffered energy loss in the medium [1]. The energy lost by a parton in the produced medium provides fundamental information on its thermodynamical and transport properties [2, 3]. Results on the suppression of inclusive hadron production at high transverse momenta (p_{T}), as well as on the modified high- p_{T} dihadron angular correlations obtained from nucleus-nucleus collisions at $\sqrt{s_{\text{NN}}} = 200$ GeV at the Relativistic Heavy Ion Collider (RHIC) [4–7] have shown the existence of partonic energy loss in dense strongly interacting matter. Similar observations have been made at the Large Hadron Collider (LHC) [8–14].

At LHC energies, high- p_{T} jets have been fully reconstructed in heavy-ion collisions. A significant dijet transverse momentum imbalance is observed, when comparing to a reference distribution corresponding to pp collisions at the same nucleon-nucleon centre-of-mass energy [15–17]. Such an observation is consistent with energy loss of the hard scattered partons in the dense medium produced in central PbPb collisions. In the same set of results, the redistribution of the lost jet energy is studied using jet-track correlations [16]. It is found that the missing p_{T} opposite to the leading jet can be recovered only by summing up the contributions of particles down to a low p_{T} of 500 MeV/ c with respect to the beam axis and out to large radii in pseudorapidity and azimuthal angle, $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} > 0.8$, with respect to the jet axis [16]. Since these results show that the quenched energy is transferred out of the jet cone, the jet clustering algorithm reconstructs jets with a reduced energy from the fragments of the partons after they have lost

energy in the medium. The study presented here investigates to what extent the fragmentation pattern of partons that have traversed the medium resembles vacuum fragmentation, by constructing fragmentation functions in PbPb collisions and comparing them to those from unquenched jets, as measured in pp collisions. Fragmentation functions encode the probability for a parton to fragment into particles carrying a given fraction of the parton energy. Colour-charged partons undergo showering processes into partons of successively lower energy which hadronise into colour-neutral final-state particles. The evolution of such a parton radiation and splitting process leads to a characteristic shape of the fragmentation function [18]. Theoretical models of jet quenching predict an effective change of the shape of the fragmentation function due to the change of the parton radiation pattern in the medium [19–22]. Experimentally, fragmentation functions are constructed by correlating the reconstructed jet momentum with the momenta of charged particles projected onto the jet axis. The jets are defined using the final-state particles produced in the collision, clustered with the anti- k_T jet algorithm [23]. In this Letter, we present a measurement of fragmentation functions in pp and PbPb collisions and a detailed comparison of their shapes measured in the two systems. The measurement is restricted to the high- p_T component of the fragmentation function, using charged particles of $p_T > 4 \text{ GeV}/c$ that lie within $\Delta R < 0.3$ around the reconstructed jets.

2 Experimental setup

The Compact Muon Solenoid (CMS) detector is described in ref. [24]. Only the detector systems used in this analysis are discussed hereafter. The central part of the CMS detector contains a superconducting solenoid that provides a homogeneous magnetic field of 3.8 T parallel to the beam axis. Charged-particle trajectories are measured using silicon pixel and strip trackers that cover the pseudorapidity region $|\eta| < 2.5$, where η is defined as $\eta = -\log[\tan(\theta/2)]$ and θ is the polar angle with respect to the anticlockwise beam direction. An electromagnetic crystal calorimeter (ECAL) and a brass/scintillator hadron calorimeter (HCAL) surround the tracking volume and cover $|\eta| < 3.0$. The ECAL calorimeter is segmented in quasi-projective cells of a granularity in pseudorapidity and azimuthal angle of $\Delta\eta \times \Delta\phi = 0.0174 \times 0.0174$ in the barrel ($|\eta| < 1.5$), increasing across the endcap ($1.5 < |\eta| < 3.0$) to 0.09×0.09 at $|\eta| = 3.0$. The HCAL has a cell granularity of $\Delta\eta \times \Delta\phi = 0.087 \times 0.087$ in the barrel region and a variable cell granularity, changing as a function of η , in the endcap region [24]. A forward steel/quartz-fibre Cherenkov hadron calorimeter (HF) extends the coverage to $|\eta| = 5.2$. The CMS trigger system is composed of a first level made of custom hardware processors, which use information from the calorimeters and muon detectors to select events, and the High-Level Trigger (HLT) processor farm, that further decreases the event rate, before data storage.

3 Data selection

The PbPb and pp data analysed in this Letter were collected with the CMS detector in 2010 and 2011, respectively, at a centre-of-mass energy of 2.76 TeV per nucleon pair. The integrated luminosities for the PbPb and pp data samples used for this analysis are

$L_{\text{int}} \approx 6.8 \mu\text{b}^{-1}$ and $L_{\text{int}} \approx 231 \text{nb}^{-1}$, respectively. The HLT system is used to select events containing high- p_{T} jets reconstructed from calorimeter towers. In PbPb collisions, the trigger threshold is $p_{\text{T}} = 35 \text{ GeV}/c$, applied on the raw calorimetric jet energy. For pp collisions, events are selected if they pass a jet trigger threshold of $p_{\text{T}} = 40 \text{ GeV}/c$ on the calorimetric jet energy. As found in ref. [16], for the jet selection used in this analysis, requiring a $100 \text{ GeV}/c$ jet in $|\eta| < 2$, the triggers are more than 99% efficient. In addition to the trigger decision, standard event selection criteria are applied [16], including a rejection of beam related backgrounds, a selection of inelastic hadronic collisions by requiring a two-sided coincidence of signals in the HF and a well-reconstructed event vertex.

For the analysis of PbPb data, it is important to determine the degree of overlap between the two colliding nuclei in each event, termed collision centrality. Centrality is determined using the sum of transverse energy reconstructed in the HF. The distribution of the HF energy is used to divide the event sample into percentiles of the total nucleus-nucleus interaction cross section. For the purpose of this analysis, the data set is split into two centrality bins, the 0–30% most central events (i.e. those which have the largest overlap between the two colliding Pb nuclei) and the remaining peripheral events in the 30–100% centrality range. A detailed description of the centrality determination can be found in [16].

4 Jet and track reconstruction

For both pp and PbPb collisions, the analysis is based on jets reconstructed using the anti- k_{T} jet algorithm, with a radius parameter (R) of 0.3, utilizing particle-flow (PF) objects that combine tracking and calorimetric information [25, 26]. In the PbPb data, the contribution of the underlying heavy-ion event is removed using an iterative pileup subtraction method [27]. Since this procedure determines the underlying-event background using data outside the jet, the result is insensitive to the fragmentation properties of the jet. The jet-finding efficiency is above 95% for jets of $p_{\text{T}} > 40 \text{ GeV}/c$, and above 99% for jets of $p_{\text{T}} > 50 \text{ GeV}/c$ [25]. The relative jet momentum resolution in pp collisions is found to be 19 (13)% at $p_{\text{T}} = 40$ (100) GeV/c , improving with jet momentum. In central PbPb collisions, the momentum resolution deteriorates to 24 (16)% at $p_{\text{T}} = 40$ (100) GeV/c [25] due to fluctuations in the underlying event. For both pp and PbPb events, the jet momentum response has little or no deviations from a Gaussian shape.

In all cases the reconstructed jet momenta are corrected to final-state stable particle (lifetime τ with $c\tau > 10 \text{ mm}$) level using factors derived from PYTHIA 6.422 [28] (tune D6T [29, 30], CTEQ6L1 PDFs [31]) pp simulations at $\sqrt{s} = 2.76 \text{ TeV}$ [32]. The uncertainty in the corrected jet energy scale is about 3% for pp events, resulting in a per-bin jet-yield uncertainty of $\pm 15\%$. In the case of PbPb events, due to the influence of the underlying event, the uncertainty in the jet energy scale increases to about 4% for peripheral events (30–100% centrality) and 5% for central events (0–30% centrality) which results in per-bin jet-yield uncertainties of $\pm 20\%$ and $\pm 25\%$, respectively.

The dijets selected for this analysis consist of a leading jet (denoted by subscript 1) with $p_{\text{T},1} > 100 \text{ GeV}/c$ and a subleading jet (subscript 2) of $p_{\text{T},2} > 40 \text{ GeV}/c$, with axes that

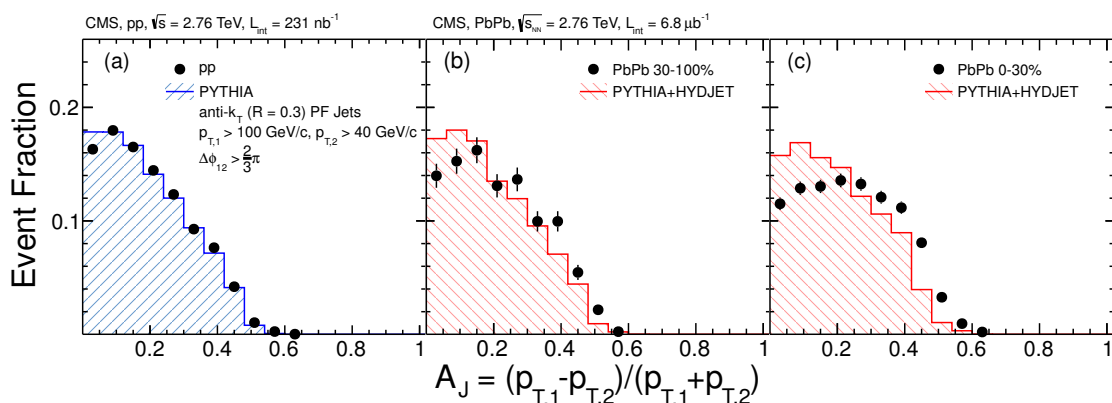


Figure 1. Dijet asymmetry, A_J , distributions in (a) pp collisions, (b) peripheral (30–100%) PbPb, and (c) central (0–30%) PbPb collisions. Data are shown as black points while the histograms show PYTHIA dijets, which when compared to PbPb data have been embedded into HYDJET events. Error bars represent the statistical uncertainty.

lie within $|\eta| < 2$. The p_T thresholds are chosen to ensure high reconstruction efficiency for the leading and, especially, the subleading jet. In addition, the azimuthal opening angle $\Delta\phi_{1,2}$ between the leading and subleading jet is required to be larger than $2\pi/3$. No explicit requirement is made on the presence or absence of a third jet in the event.

A detailed description of the charged-particle reconstruction algorithm and its performance can be found in ref. [9]. The track-finding efficiency in the kinematic range of this study is (60–70)% and the corresponding correction is applied as a function of track p_T , jet p_T , and event centrality by reweighting the found tracks with the inverse of the reconstruction efficiency. The track reconstruction efficiency correction is derived from a GEANT4 [33] simulation of the CMS detector applied to PYTHIA events, which are embedded into PbPb collisions simulated using HYDJET [34] in order to include the effect of the underlying PbPb event. The momentum resolution of the track reconstruction is $\sigma(p_T)/p_T \approx 1\text{--}3\%$.

The dijet momentum balance is studied in terms of the dijet asymmetry ratio [15–17],

$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}, \quad (4.1)$$

which is positive by construction. Figure 1 shows the A_J distributions in (a) pp and in (b,c) PbPb for two bins in event centrality. Central PbPb events (0–30%) show a significant excess of unbalanced pairs when compared to both peripheral PbPb collisions (30–100%) and pp data. This can be interpreted as a direct observation of parton energy loss in central PbPb collisions.

5 Fragmentation functions

The fragmentation functions are measured by correlating reconstructed charged-particle tracks falling within the jet cones, with the axis of the respective jet [35]. As done in previous measurements at hadron colliders [36], the fragmentation function is presented as

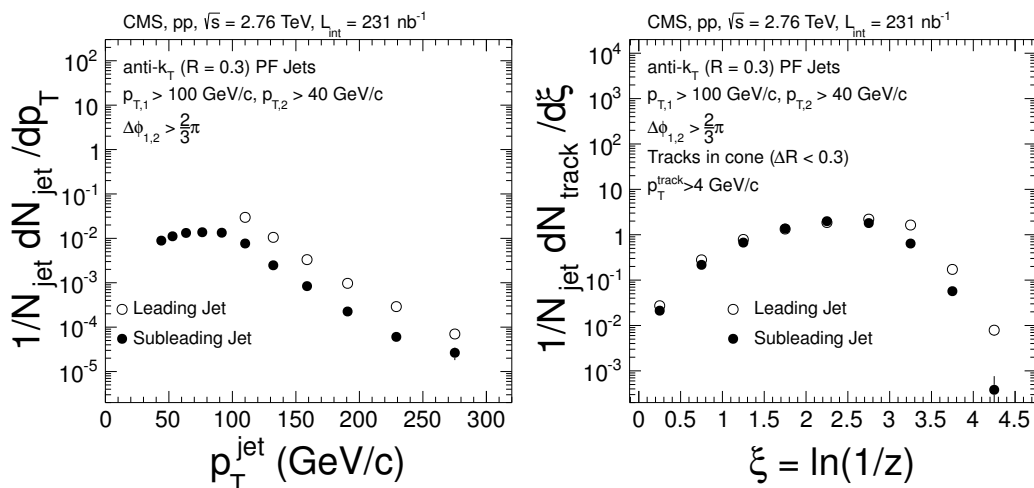


Figure 2. Data from pp collisions. Left: Leading and subleading jet p_T distributions (not corrected for jet-finding efficiency and not unfolded for the jet energy resolution). Right: Fragmentation functions reconstructed for the leading (open circles) and subleading (solid points) jets. The statistical uncertainties, shown as error bars, are smaller than the symbols in most cases.

a function of the variable

$$\xi = \ln \frac{1}{z} \quad ; \quad z = \frac{p_{\parallel}^{\text{track}}}{p_{\text{jet}}}, \quad (5.1)$$

where $p_{\parallel}^{\text{track}}$ is the momentum component of the track along the jet axis, and p_{jet} is the magnitude of the jet momentum within the jet cone. The momentum components and the angle between the charged-particle and the jet axis are calculated in the dijet centre-of-mass frame, obtained by an approximate Lorentz transformation along the beam axis in the form of a pseudorapidity shift, defined as $\eta_{\text{dijet}} = (\eta_1 + \eta_2)/2$. The tracks are selected to lie within a cone of $\Delta R < 0.3$ around the jet axis. The fragmentation functions, defined as $1/N_{\text{jet}} dN_{\text{track}}/d\xi$, are normalised to the total number of selected leading or subleading jets, N_{jet} , respectively. To minimise the contribution of tracks from the underlying event, only tracks with $p_T^{\text{track}} > 4 \text{ GeV}/c$ are selected. This restricts the measurement of the fragmentation function to the region of $\xi \lesssim 4.5$. The remaining underlying event contribution, not associated with the jet, is estimated by selecting tracks that lie in a background cone, obtained by reflecting the original jet cone about $\eta = 0$, while keeping the same ϕ coordinate. The background contribution is accumulated jet-by-jet over the full event sample and subtracted to obtain the final $dN_{\text{track}}/d\xi$ distribution. Due to this procedure, jets in the region $|\eta| < 0.3$ are excluded from the analysis, to avoid overlap between the signal jet region and the region used for background estimation.

Figure 2 shows the reconstructed leading and subleading jet fragmentation functions in pp collisions (right panel) and the corresponding jet p_T distributions (left panel), to illustrate the kinematic range in which the fragmentation functions are measured. Note that the higher jet momentum of the leading jet compared to the subleading jet, leads to an increased number of particles passing the $p_T^{\text{track}} > 4 \text{ GeV}/c$ selection for the fragmentation function measurement. This results in the observed excess of $dN_{\text{track}}/d\xi$ at high values

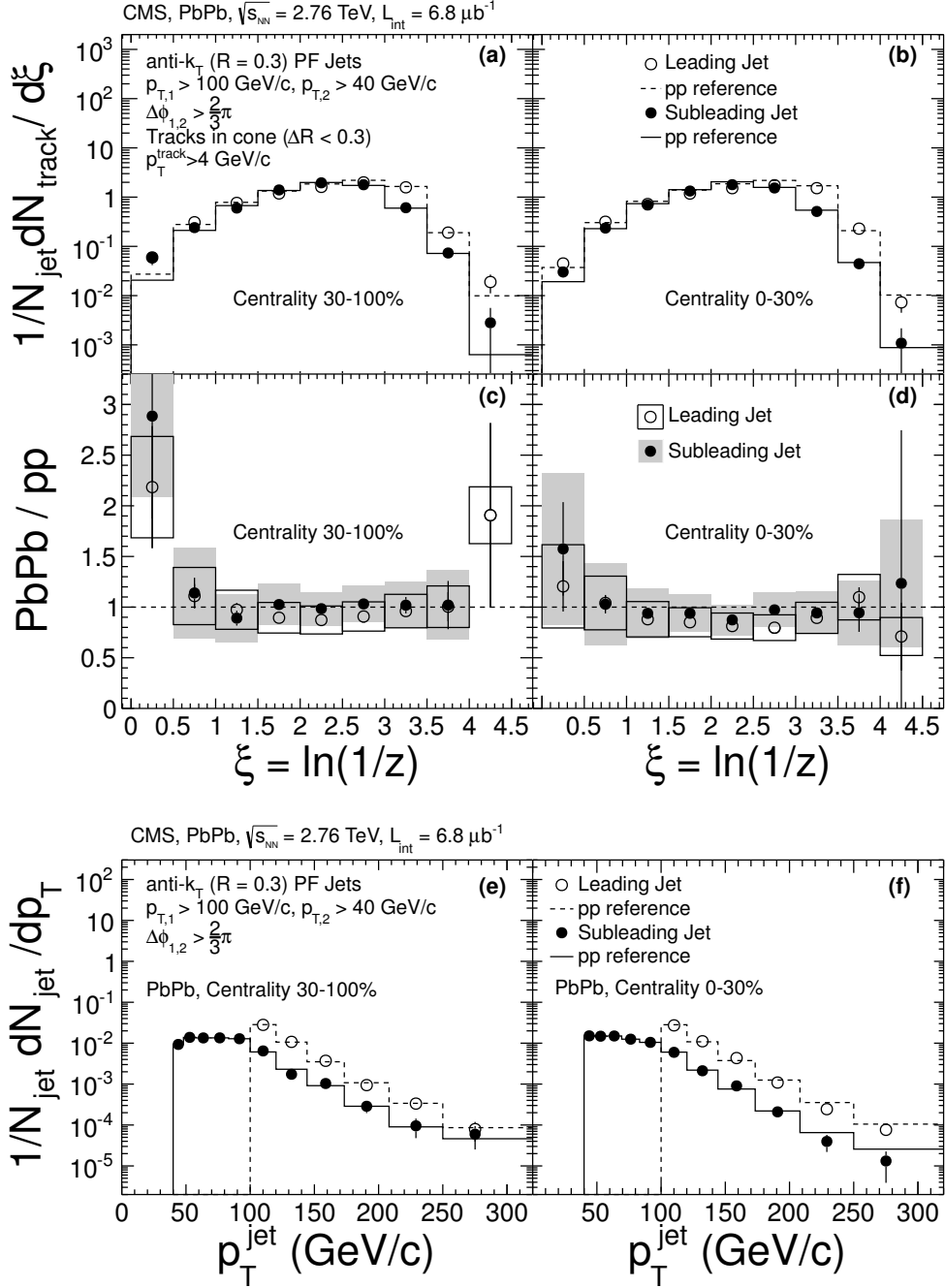


Figure 3. (a,b) Fragmentation functions reconstructed in peripheral and central PbPb data for the leading (open circles) and subleading (solid points) jets. (c,d) Ratio of each PbPb fragmentation function to its pp-based reference. Error bars are statistical, the hollow boxes represent the systematic uncertainty for the leading jet, and gray boxes show the systematic uncertainty for the subleading jet. (e,f) Jet p_T distributions in PbPb data (not corrected for efficiency and not unfolded for p_T resolution) compared to the pp-based reference (see text). Only statistical uncertainties are shown in panels a, b, e and f.

of ξ for the leading jet over the corresponding distribution for the subleading jet. The p_T^{track} threshold on the tracks introduces a jet- p_T -dependent kinematic limit in the high ξ part of the spectrum. For a direct comparison between pp and PbPb collisions, the jet momentum resolution deterioration in PbPb events has to be taken into account. For this purpose, the reconstructed p_T of every jet in the pp data is smeared by the quadratic difference of the underlying event fluctuations in PbPb and pp. Furthermore, in order to keep the kinematic constraints consistent, a jet- p_T -dependent reweighting is applied to the pp data, after fluctuation smearing, so that the resulting jet p_T distribution matches that in PbPb. The reweighting factor is applied to each jet when generating the fragmentation function for pp. The *pp-based reference* distributions obtained this way ensure that the jet fragmentation functions in PbPb and pp are compared for matching jet p_T spectra.

Figure 3 shows the fragmentation functions for (a) peripheral and (b) central PbPb collisions, for both the leading and subleading jets, compared to the pp-based reference. The ratios between the PbPb fragmentation functions and the pp-based reference distributions are shown in panels (c) and (d). The corresponding jet p_T distributions illustrating the kinematic range of the measurement are shown in panels (e) and (f). The overlaid histograms in the same set of figures show the pp-based reference distributions. The systematic uncertainty, represented by the boxes at each point in panels (c) and (d), is obtained from the propagated jet and track reconstruction uncertainties. These comparison plots show that the shape of the fragmentation functions in pp and PbPb collisions agrees within uncertainties at all centralities for the leading, as well as for the subleading, jets.

The uncertainties in the jet response may affect the results in different ways: smearing of jet energy due to fluctuations distorts the observed fragmentation functions, a miscalibration of the overall energy scale shifts the fragmentation function along the ξ axis, and a residual offset in the jet energy introduces a tilt of the shape of the distribution. These effects are studied using a Monte Carlo (MC) simulation, by varying the corresponding generator-level jet properties within the limits of the jet response uncertainty. The systematic uncertainties are determined by comparing the resulting fragmentation functions in the modified sample to the original MC reference.

The systematic uncertainty due to the charged-particle reconstruction efficiency is obtained by comparing fragmentation functions based on efficiency-corrected tracks, with the fragmentation functions using the MC generator information. Since the particle-flow event reconstruction algorithm uses reconstructed charged-particles for the jet p_T determination, a failure to reconstruct a high- p_T charged-particle can lead to an underestimation of the jet momentum, resulting in an artificially high A_J measurement. The modification of the fragmentation function measurement due to this effect is studied in PYTHIA + HYDJET events. Since the A_J distributions in data and simulation are different, the magnitude of the corresponding effect in the PbPb data is estimated based on the reconstructed A_J distributions, and is accounted for in the combined systematic uncertainty. The effect of momentum resolution on reconstructed charged-particle tracks is estimated by smearing PYTHIA + HYDJET generator-level information. This is found to have little effect on the fragmentation function, in comparison to the unsmearing generator level information. The above uncertainties are combined in quadrature to give the total systematic uncertainty.

Another potential source of systematic uncertainty comes from the response of the PF technique to jets with very different fragmentation functions. Since one component of the jet energy correction accounts for the loss of low- p_T particles, a large change in the contribution of such tracks will result in an incorrect reconstructed jet energy. To study this effect, we have compared the response to separate quark and gluon jets from PYTHIA, whose fragmentation functions differ by 20-40% in the region $2 < \xi < 4$ and by larger factors for $\xi < 1$. These dramatic differences in fragmentation pattern do result in systematic differences in the jet momentum but the effect is only at the few percent level [25]. The change in the reconstructed fragmentation function resulting from the tiny shifts in the ξ parameter caused by these jet momentum offsets are negligible.

To study in more detail the potential effect of medium-induced energy loss on the fragmentation properties of partons, the data sample of central events (0–30% centrality), where a large average dijet imbalance is observed, is divided into classes of dijet imbalance. Four A_J selections are chosen, which split the central PbPb data sample into approximately equal number of dijets: $0 < A_J < 0.13$, $0.13 < A_J < 0.24$, $0.24 < A_J < 0.35$, and $A_J > 0.35$. For each of these event classes, the fragmentation functions are constructed separately for the leading and subleading jets. In figure 4(a–d) the fragmentation functions are shown in bins of increasing dijet imbalance, from left to right. The corresponding jet p_T distributions used in the fragmentation functions are shown in Fig 4(i–l), illustrating the kinematic range of the measurement and the energy imbalance between leading and subleading jets, as selected by the A_J interval. The overlaid histogram in the same set of figures shows the pp-based reference distributions. Ratios of PbPb data to the pp-based reference are shown in figure 4(e–h). In the ξ range of 0.5–4.0 the PbPb and the pp distributions typically agree to within (10–20)% which is smaller than the systematic uncertainty in the PbPb measurement, as indicated by the size of the shaded area and open boxes for the leading and subleading jet, respectively. Within uncertainties, the PbPb data and pp-based reference show the same fragmentation properties, for different jet imbalance in leading, as well as subleading, jets.

6 Conclusions

The CMS detector has been used to study jet fragmentation properties in pp and PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV in data samples corresponding to integrated luminosities of about 231 nb^{-1} and $6.8 \mu\text{b}^{-1}$, respectively. Jets were reconstructed based on particle-flow objects using the anti- k_T sequential clustering algorithm, with a radius parameter of 0.3. The reconstructed jet momenta were corrected to final-state particle level. Dijets were selected consisting of a leading jet with $p_{T,1} > 100 \text{ GeV}/c$ and a subleading jet of $p_{T,2} > 40 \text{ GeV}/c$, with axes that lie within $|\eta| < 2$. The azimuthal opening angle $\Delta\phi_{1,2}$ between the leading and subleading jet was required to be larger than $2\pi/3$. The selected jets were used to construct the high- p_T component of the fragmentation functions by correlating their momentum with the momenta of tracks of $p_T > 4 \text{ GeV}/c$ within a cone of $\Delta R < 0.3$ around the jet axis. The PbPb results were compared to those in a pp-based reference taking into account the different jet momentum distribution and the effect of

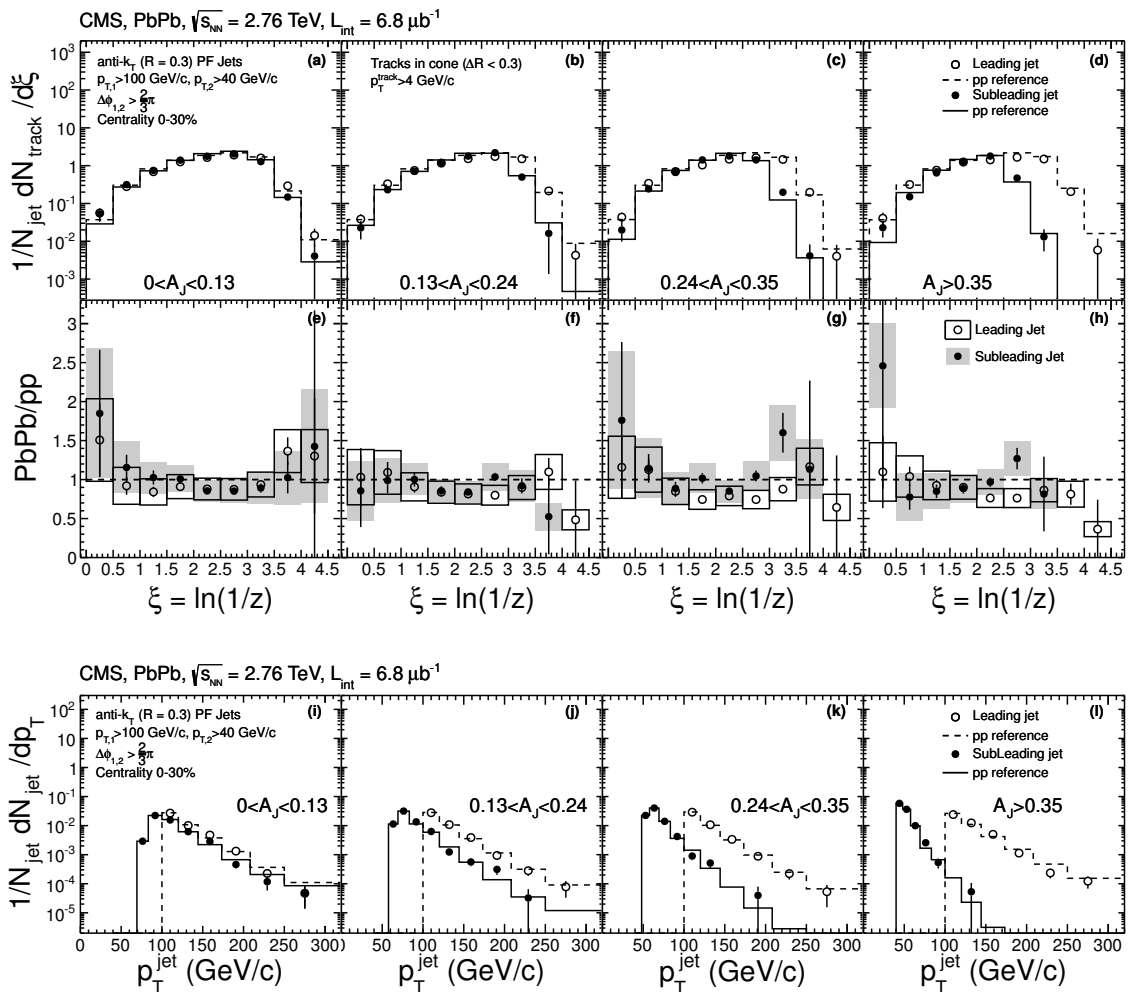


Figure 4. (a–d) Fragmentation functions for the leading (open circles) and subleading (solid points) jets in four regions of A_J in central PbPb collisions compared to the pp reference. (e–h) Ratio of each fragmentation function to its pp-based reference. Error bars shown are statistical. The systematic uncertainty is represented by hollow boxes (leading jet) or gray boxes (subleading jet). (i–l) Jet p_T distributions in PbPb collisions in four regions of A_J (not corrected for efficiency and not unfolded for p_T resolution) compared to the pp-based reference (see text). Only statistical uncertainties are shown.

fluctuations in the underlying PbPb event on the jet momentum reconstruction. The jet properties were studied as a function of the collision centrality and the dijet transverse momentum imbalance. Central PbPb events show a significant excess of unbalanced jet pairs. Nevertheless, the fragmentation functions reconstructed in PbPb collisions for different event centrality and dijet- p_T imbalance agree within the measurement uncertainty with the pp-based reference for jets of the same reconstructed momentum. This shows that, after traversing the dense strongly interacting medium, partons produced in PbPb collisions are reconstructed as jets with a significantly reduced momentum. However, the partition of the smaller momentum that remains within the jet cone into high- p_T particles corresponds to that observed for jets fragmenting in vacuum, as seen in pp collisions.

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The CMS collaboration

Yerevan Physics Institute, Yerevan, Armenia

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

Institut für Hochenergiephysik der OeAW, Wien, Austria

W. Adam, T. Bergauer, M. Dragicevic, J. Erö, C. Fabjan¹, M. Friedl, R. Frühwirth¹, V.M. Ghete, J. Hammer, N. Hörmann, J. Hrubec, M. Jeitler¹, W. Kiesenhofer, V. Knünz, M. Krammer¹, D. Liko, I. Mikulec, M. Pernicka[†], B. Rahbaran, C. Rohringer, H. Rohringer, R. Schöfbeck, J. Strauss, A. Taurok, P. Wagner, W. Waltenberger, G. Walzel, E. Widl, C.-E. Wulz¹

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

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

Universiteit Antwerpen, Antwerpen, Belgium

S. Bansal, T. Cornelis, E.A. De Wolf, X. Janssen, S. Luyckx, T. Maes, L. Mucibello, S. Ochesanu, B. Roland, R. Rougny, M. Selvaggi, Z. Staykova, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel, A. Van Spilbeeck

Vrije Universiteit Brussel, Brussel, Belgium

F. Blekman, S. Blyweert, J. D'Hondt, R. Gonzalez Suarez, A. Kalogeropoulos, M. Maes, A. Olbrechts, W. Van Doninck, P. Van Mulders, G.P. Van Onsem, I. Villella

Université Libre de Bruxelles, Bruxelles, Belgium

O. Charaf, B. Clerbaux, G. De Lentdecker, V. Dero, A.P.R. Gay, T. Hreus, A. Léonard, P.E. Marage, T. Reis, L. Thomas, C. Vander Velde, P. Vanlaer, J. Wang

Ghent University, Ghent, Belgium

V. Adler, K. Beernaert, A. Cimmino, S. Costantini, G. Garcia, M. Grunewald, B. Klein, J. Lellouch, A. Marinov, J. McCartin, A.A. Ocampo Rios, D. Ryckbosch, N. Strobbe, F. Thyssen, M. Tytgat, L. Vanelderen, P. Verwilligen, S. Walsh, E. Yazgan, N. Zaganidis

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

S. Basesmez, G. Bruno, R. Castello, A. Caudron, L. Ceard, C. Delaere, T. du Pree, D. Favart, L. Forthomme, A. Giammanco², J. Hollar, V. Lemaitre, J. Liao, O. Militarú, C. Nuttens, D. Pagano, L. Perrini, A. Pin, K. Piotrkowski, N. Schul, J.M. Vizan Garcia

Université de Mons, Mons, Belgium

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

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

G.A. Alves, M. Correa Martins Junior, D. De Jesus Damiao, T. Martins, M.E. Pol, M.H.G. Souza

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

W.L. Aldá Júnior, W. Carvalho, A. Custódio, E.M. Da Costa, C. De Oliveira Martins, S. Fonseca De Souza, D. Matos Figueiredo, L. Mundim, H. Nogima, V. Oguri, W.L. Prado Da Silva, A. Santoro, L. Soares Jorge, A. Sznajder

Instituto de Fisica Teorica, Universidade Estadual Paulista, Sao Paulo, Brazil

C.A. Bernardes³, F.A. Dias⁴, T.R. Fernandez Perez Tomei, E. M. Gregores³, C. Lagana, F. Marinho, P.G. Mercadante³, S.F. Novaes, Sandra S. Padula

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria

V. Genchev⁵, P. Iaydjiev⁵, S. Piperov, M. Rodozov, S. Stoykova, G. Sultanov, V. Tcholakov, R. Trayanov, M. Vutova

University of Sofia, Sofia, Bulgaria

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

Institute of High Energy Physics, Beijing, China

J.G. Bian, G.M. Chen, H.S. Chen, C.H. Jiang, D. Liang, S. Liang, X. Meng, J. Tao, J. Wang, X. Wang, Z. Wang, H. Xiao, M. Xu, J. Zang, Z. Zhang

State Key Lab. of Nucl. Phys. and Tech., Peking University, Beijing, China

C. Asawatangtrakuldee, Y. Ban, S. Guo, Y. Guo, W. Li, S. Liu, Y. Mao, S.J. Qian, H. Teng, S. Wang, B. Zhu, W. Zou

Universidad de Los Andes, Bogota, Colombia

C. Avila, J.P. Gomez, B. Gomez Moreno, A.F. Osorio Oliveros, J.C. Sanabria

Technical University of Split, Split, Croatia

N. Godinovic, D. Lelas, R. Plestina⁶, D. Polic, I. Puljak⁵

University of Split, Split, Croatia

Z. Antunovic, M. Kovac

Institute Rudjer Boskovic, Zagreb, Croatia

V. Brigljevic, S. Duric, K. Kadija, J. Luetic, S. Morovic

University of Cyprus, Nicosia, Cyprus

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

Charles University, Prague, Czech Republic

M. Finger, M. Finger Jr.

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

Y. Assran⁷, S. Elgammal⁸, A. Ellithi Kamel⁹, S. Khalil⁸, M.A. Mahmoud¹⁰, A. Radi^{11,12}

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

M. Kadastik, M. Müntel, M. Raidal, L. Rebane, A. Tiko

Department of Physics, University of Helsinki, Helsinki, Finland

V. Azzolini, P. Eerola, G. Fedi, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland

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

Lappeenranta University of Technology, Lappeenranta, Finland

K. Banzuzi, A. Korpela, T. Tuuva

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

M. Besancon, S. Choudhury, M. Dejardin, D. Denegri, B. Fabbro, J.L. Faure, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, E. Locci, J. Malcles, L. Millischer, A. Nayak, J. Rander, A. Rosowsky, I. Shreyber, M. Titov

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

S. Baffioni, F. Beaudette, L. Benhabib, L. Bianchini, M. Bluj¹³, C. Broutin, P. Busson, C. Charlot, N. Daci, T. Dahms, L. Dobrzynski, R. Granier de Cassagnac, M. Haguenaer, P. Miné, C. Mironov, M. Nguyen, C. Ochando, P. Paganini, D. Sabes, R. Salerno, Y. Sirois, C. Veelken, A. Zabi

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

J.-L. Agram¹⁴, J. Andrea, D. Bloch, D. Bodin, J.-M. Brom, M. Cardaci, E.C. Chabert, C. Collard, E. Conte¹⁴, F. Drouhin¹⁴, C. Ferro, J.-C. Fontaine¹⁴, D. Gelé, U. Goerlach, P. Juillot, M. Karim¹⁴, A.-C. Le Bihan, P. Van Hove

Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules (IN2P3), Villeurbanne, France

F. Fassi, D. Mercier

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France

S. Beauceron, N. Beaupere, O. Bondu, G. Boudoul, H. Brun, J. Chasserat, R. Chierici⁵, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, T. Kurca, M. Lethuillier, L. Mirabito, S. Perries, V. Sordini, S. Tosi, Y. Tschudi, P. Verdier, S. Viret

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

Z. Tsamalaidze¹⁵

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

G. Anagnostou, S. Beranek, M. Edelhoff, L. Feld, N. Heracleous, O. Hindrichs, R. Jussen, K. Klein, J. Merz, A. Ostapchuk, A. Perieanu, F. Raupach, J. Sammet, S. Schael, D. Sprenger, H. Weber, B. Wittmer, V. Zhukov¹⁶

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

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

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

M. Bontenackels, V. Cherepanov, M. Davids, G. Flügge, H. Geenen, M. Geisler, W. Haj Ahmad, F. Hoehle, B. Kargoll, T. Kress, Y. Kuessel, A. Linn, A. Nowack, L. Perchalla, O. Pooth, J. Rennefeld, P. Sauerland, A. Stahl

Deutsches Elektronen-Synchrotron, Hamburg, Germany

M. Aldaya Martin, J. Behr, W. Behrenhoff, U. Behrens, M. Bergholz¹⁷, A. Bethani, K. Borras, A. Burgmeier, A. Cakir, L. Calligaris, A. Campbell, E. Castro, F. Costanza, D. Dammann, G. Eckerlin, D. Eckstein, D. Fischer, G. Flucke, A. Geiser, I. Glushkov, P. Gunnellini, S. Habib, J. Hauk, G. Hellwig, H. Jung⁵, M. Kasemann, P. Katsas, C. Kleinwort, H. Kluge, A. Knutsson, M. Krämer, D. Krücker, E. Kuznetsova, W. Lange, W. Lohmann¹⁷, B. Lutz, R. Mankel, I. Marfin, M. Marienfeld, I.-A. Melzer-Pellmann, A.B. Meyer, J. Mnich, A. Mussgiller, S. Naumann-Emme, J. Olzem, H. Perrey, A. Petrukhin, D. Pitzl, A. Raspereza, P.M. Ribeiro Cipriano, C. Riedl, M. Rosin, J. Salfeld-Nebgen, R. Schmidt¹⁷, T. Schoerner-Sadenius, N. Sen, A. Spiridonov, M. Stein, R. Walsh, C. Wissing

University of Hamburg, Hamburg, Germany

C. Autermann, V. Blobel, S. Bobrovskiy, J. Draeger, H. Enderle, J. Erfle, U. Gebbert, M. Görner, T. Hermanns, R.S. Höing, K. Kaschube, G. Kaussen, H. Kirschenmann, R. Klanner, J. Lange, B. Mura, F. Nowak, T. Peiffer, N. Pietsch, D. Rathjens, C. Sander, H. Schettler, P. Schleper, E. Schlieckau, A. Schmidt, M. Schröder, T. Schum, M. Seidel, H. Stadie, G. Steinbrück, J. Thomsen

Institut für Experimentelle Kernphysik, Karlsruhe, Germany

C. Barth, J. Berger, C. Böser, T. Chwalek, W. De Boer, A. Descroix, A. Dierlamm, M. Feindt, M. Guthoff⁵, C. Hackstein, F. Hartmann, T. Hauth⁵, M. Heinrich, H. Held, K.H. Hoffmann, S. Honc, I. Katkov¹⁶, J.R. Komaragiri, D. Martschei, S. Mueller, Th. Müller, M. Niegel, A. Nürnberg, O. Oberst, A. Oehler, J. Ott, G. Quast, K. Rabbertz, F. Ratnikov, N. Ratnikova, S. Röcker, A. Scheurer, F.-P. Schilling, G. Schott, H.J. Simonis, F.M. Stober, D. Troendle, R. Ulrich, J. Wagner-Kuhr, S. Wayand, T. Weiler, M. Zeise

Institute of Nuclear Physics "Demokritos", Aghia Paraskevi, Greece

G. Daskalakis, T. Geralis, S. Kesisoglou, A. Kyriakis, D. Loukas, I. Manolakos, A. Markou, C. Markou, C. Mavrommatis, E. Ntomari

University of Athens, Athens, Greece

L. Gouskos, T.J. Mertzimekis, A. Panagiotou, N. Saoulidou

University of Ioánnina, Ioánnina, Greece

I. Evangelou, C. Foudas⁵, P. Kokkas, N. Manthos, I. Papadopoulos, V. Patras

KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary

G. Bencze, C. Hajdu⁵, P. Hidas, D. Horvath¹⁸, K. Krajczar¹⁹, B. Radics, F. Sikler⁵, V. Veszpremi, G. Vesztergombi¹⁹

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

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

University of Debrecen, Debrecen, Hungary

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

Panjab University, Chandigarh, India

S.B. Beri, V. Bhatnagar, N. Dhingra, R. Gupta, M. Jindal, M. Kaur, J.M. Kohli, M.Z. Mehta, N. Nishu, L.K. Saini, A. Sharma, J. Singh

University of Delhi, Delhi, India

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

Saha Institute of Nuclear Physics, Kolkata, India

S. Banerjee, S. Bhattacharya, S. Dutta, B. Gomber, Sa. Jain, Sh. Jain, R. Khurana, S. Sarkar, M. Sharan

Bhabha Atomic Research Centre, Mumbai, India

A. Abdulsalam, R.K. Choudhury, D. Dutta, S. Kailas, V. Kumar, P. Mehta, A.K. Mohanty⁵, L.M. Pant, P. Shukla

Tata Institute of Fundamental Research - EHEP, Mumbai, India

T. Aziz, S. Ganguly, M. Guchait²⁰, M. Maity²¹, G. Majumder, K. Mazumdar, G.B. Mohanty, B. Parida, K. Sudhakar, N. Wickramage

Tata Institute of Fundamental Research - HECR, Mumbai, India

S. Banerjee, S. Dugad

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

H. Arfaei, H. Bakhshiansohi²², S.M. Etesami²³, A. Fahim²², M. Hashemi, H. Hesari, A. Jafari²², M. Khakzad, A. Mohammadi²⁴, M. Mohammadi Najafabadi, S. Paktinat Mehdiabadi, B. Safarzadeh²⁵, M. Zeinali²³

INFN Sezione di Bari ^a, Università di Bari ^b, Politecnico di Bari ^c, Bari, Italy

M. Abbrescia^{a,b}, L. Barbone^{a,b}, C. Calabria^{a,b,5}, S.S. Chhibra^{a,b}, A. Colaleo^a, D. Creanza^{a,c}, N. De Filippis^{a,c,5}, M. De Palma^{a,b}, L. Fiore^a, G. Iaselli^{a,c}, L. Lusito^{a,b}, G. Maggi^{a,c}, M. Maggi^a, B. Marangelli^{a,b}, S. My^{a,c}, S. Nuzzo^{a,b}, N. Pacifico^{a,b}, A. Pompili^{a,b}, G. Pugliese^{a,c}, G. Selvaggi^{a,b}, L. Silvestris^a, G. Singh^{a,b}, R. Venditti, G. Zito^a

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

G. Abbiendi^a, A.C. Benvenuti^a, D. Bonacorsi^{a,b}, S. Braibant-Giacomelli^{a,b}, L. Brigliadori^{a,b}, P. Capiluppi^{a,b}, A. Castro^{a,b}, F.R. Cavallo^a, M. Cuffiani^{a,b}, G.M. Dallavalle^a, F. Fabbri^a, A. Fanfani^{a,b}, D. Fasanella^{a,b,5}, P. Giacomelli^a, C. Grandi^a, L. Guiducci, S. Marcellini^a, G. Masetti^a, M. Meneghelli^{a,b,5}, A. Montanari^a, F.L. Navarria^{a,b}, F. Odorici^a, A. Perrotta^a, F. Primavera^{a,b}, A.M. Rossi^{a,b}, T. Rovelli^{a,b}, G. Siroli^{a,b}, R. Travaglini^{a,b}

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

S. Albergo^{a,b}, G. Cappello^{a,b}, M. Chiorboli^{a,b}, S. Costa^{a,b}, R. Potenza^{a,b}, A. Tricomi^{a,b}, C. Tuve^{a,b}

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

G. Barbagli^a, V. Ciulli^{a,b}, C. Civinini^a, R. D'Alessandro^{a,b}, E. Focardi^{a,b}, S. Frosali^{a,b}, E. Gallo^a, S. Gonzi^{a,b}, M. Meschini^a, S. Paoletti^a, G. Sguazzoni^a, A. Tropiano^{a,5}

INFN Laboratori Nazionali di Frascati, Frascati, Italy

L. Benussi, S. Bianco, S. Colafranceschi²⁶, F. Fabbri, D. Piccolo

INFN Sezione di Genova, Genova, Italy

P. Fabbriatore, R. Musenich

INFN Sezione di Milano-Bicocca ^a, Università di Milano-Bicocca ^b, Milano, Italy

A. Benaglia^{a,b,5}, F. De Guio^{a,b}, L. Di Matteo^{a,b,5}, S. Fiorendi^{a,b}, S. Gennai^{a,5}, A. Ghezzi^{a,b}, S. Malvezzi^a, R.A. Manzoni^{a,b}, A. Martelli^{a,b}, A. Massironi^{a,b,5}, D. Menasce^a, L. Moroni^a, M. Paganoni^{a,b}, D. Pedrini^a, S. Ragazzi^{a,b}, N. Redaelli^a, S. Sala^a, T. Tabarelli de Fatis^{a,b}

INFN Sezione di Napoli ^a, Università di Napoli "Federico II" ^b, Napoli, Italy

S. Buontempo^a, C.A. Carrillo Montoya^{a,5}, N. Cavallo^{a,27}, A. De Cosa^{a,b,5}, O. Dogangun^{a,b}, F. Fabozzi^{a,27}, A.O.M. Iorio^a, L. Lista^a, S. Meola^{a,28}, M. Merola^{a,b}, P. Paolucci^{a,5}

INFN Sezione di Padova ^a, Università di Padova ^b, Università di Trento (Trento) ^c, Padova, Italy

P. Azzi^a, N. Bacchetta^{a,5}, P. Bellan^{a,b}, D. Bisello^{a,b}, A. Branca^{a,5}, R. Carlin^{a,b}, P. Checchia^a, T. Dorigo^a, F. Gasparini^{a,b}, A. Gozzelino^a, K. Kanishchev^{a,c}, S. Lacaprara^a, I. Lazzizzera^{a,c}, M. Margoni^{a,b}, A.T. Meneguzzo^{a,b}, M. Nespolo^{a,5}, J. Pazzini, L. Perrozzi^a, N. Pozzobon^{a,b}, P. Ronchese^{a,b}, F. Simonetto^{a,b}, E. Torassa^a, M. Tosi^{a,b,5}, S. Vanini^{a,b}, P. Zotto^{a,b}, A. Zucchetta^a, G. Zumerle^{a,b}

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

M. Gabusi^{a,b}, S.P. Ratti^{a,b}, C. Riccardi^{a,b}, P. Torre^{a,b}, P. Vitulo^{a,b}

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

M. Biasini^{a,b}, G.M. Bilei^a, L. Fanò^{a,b}, P. Lariccia^{a,b}, A. Lucaroni^{a,b,5}, G. Mantovani^{a,b}, M. Menichelli^a, A. Nappi^{a,b}, F. Romeo^{a,b}, A. Saha, A. Santocchia^{a,b}, S. Taroni^{a,b,5}

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

P. Azzurri^{a,c}, G. Bagliesi^a, T. Boccali^a, G. Broccolo^{a,c}, R. Castaldi^a, R.T. D'Agnolo^{a,c}, R. Dell'Orso^a, F. Fiori^{a,b,5}, L. Foà^{a,c}, A. Giassi^a, A. Kraan^a, F. Ligabue^{a,c}, T. Lomtadze^a, L. Martini^{a,29}, A. Messineo^{a,b}, F. Palla^a, A. Rizzi^{a,b}, A.T. Serban^{a,30}, P. Spagnolo^a, P. Squillacioti^{a,5}, R. Tenchini^a, G. Tonelli^{a,b,5}, A. Venturi^{a,5}, P.G. Verdini^a

INFN Sezione di Roma ^a, Università di Roma "La Sapienza" ^b, Roma, Italy

L. Barone^{a,b}, F. Cavallari^a, D. Del Re^{a,b,5}, M. Diemoz^a, M. Grassi^{a,b,5}, E. Longo^{a,b}, P. Meridiani^{a,5}, F. Micheli^{a,b}, S. Nourbakhsh^{a,b}, G. Organtini^{a,b}, R. Paramatti^a, S. Rahatlou^{a,b}, M. Sigamani^a, L. Soffi^{a,b}

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

N. Amapane^{a,b}, R. Arcidiacono^{a,c}, S. Argiro^{a,b}, M. Arneodo^{a,c}, C. Biino^a, C. Botta^{a,b}, N. Cartiglia^a, M. Costa^{a,b}, N. Demaria^a, A. Graziano^{a,b}, C. Mariotti^{a,5}, S. Maselli^a, E. Migliore^{a,b}, V. Monaco^{a,b}, M. Musich^{a,5}, M.M. Obertino^{a,c}, N. Pastrone^a, M. Pelliccioni^a, A. Potenza^{a,b}, A. Romero^{a,b}, M. Ruspa^{a,c}, R. Sacchi^{a,b}, V. Sola^{a,b}, A. Solano^{a,b}, A. Staiano^a, A. Vilela Pereira^a

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

S. Belforte^a, F. Cossutti^a, G. Della Ricca^{a,b}, B. Gobbo^a, M. Marone^{a,b,5}, D. Montanino^{a,b,5}, A. Penzo^a, A. Schizzi^{a,b}

Kangwon National University, Chunchon, Korea

S.G. Heo, T.Y. Kim, S.K. Nam

Kyungpook National University, Daegu, Korea

S. Chang, J. Chung, D.H. Kim, G.N. Kim, D.J. Kong, H. Park, S.R. Ro, D.C. Son, T. Son

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

J.Y. Kim, Zero J. Kim, S. Song

Konkuk University, Seoul, Korea

H.Y. Jo

Korea University, Seoul, Korea

S. Choi, D. Gyun, B. Hong, M. Jo, H. Kim, T.J. Kim, K.S. Lee, D.H. Moon, S.K. Park, E. Seo

University of Seoul, Seoul, Korea

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

Sungkyunkwan University, Suwon, Korea

Y. Cho, Y. Choi, Y.K. Choi, J. Goh, M.S. Kim, E. Kwon, B. Lee, J. Lee, S. Lee, H. Seo, I. Yu

Vilnius University, Vilnius, Lithuania

M.J. Bilinskas, I. Grigelionis, M. Janulis, A. Juodagalvis

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, R. Lopez-Fernandez, R. Magaña Villalba, J. Martínez-Ortega, A. Sánchez-Hernández, L.M. Villasenor-Cendejas

Universidad Iberoamericana, Mexico City, Mexico

S. Carrillo Moreno, F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

H.A. Salazar Ibarguen

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

E. Casimiro Linares, A. Morelos Pineda, M.A. Reyes-Santos

University of Auckland, Auckland, New Zealand

D. Krofcheck

University of Canterbury, Christchurch, New Zealand

A.J. Bell, P.H. Butler, R. Doesburg, S. Reucroft, H. Silverwood

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

M. Ahmad, M.I. Asghar, H.R. Hoorani, S. Khalid, W.A. Khan, T. Khurshid, S. Qazi, M.A. Shah, M. Shoaib

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

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

Soltan Institute for Nuclear Studies, Warsaw, Poland

H. Bialkowska, B. Boimska, T. Frueboes, R. Gokieli, M. Górski, M. Kazana, K. Nawrocki, K. Romanowska-Rybinska, M. Szleper, G. Wrochna, P. Zalewski

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

N. Almeida, P. Bargassa, A. David, P. Faccioli, M. Fernandes, P.G. Ferreira Parracho, M. Gallinaro, J. Seixas, J. Varela, P. Vischia

Joint Institute for Nuclear Research, Dubna, Russia

S. Afanasiev, I. Belotelov, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, V. Karjavin, G. Kozlov, A. Lanev, A. Malakhov, P. Moisenz, V. Palichik, V. Perelygin, S. Shmatov, V. Smirnov, A. Volodko, A. Zarubin

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

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

Institute for Nuclear Research, Moscow, Russia

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

Institute for Theoretical and Experimental Physics, Moscow, Russia

V. Epshteyn, M. Erofeeva, V. Gavrilo, M. Kossov⁵, N. Lychkovskaya, V. Popov, G. Safronov, S. Semenov, V. Stolin, E. Vlasov, A. Zhokin

Moscow State University, Moscow, Russia

A. Belyaev, E. Boos, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, V. Korotkikh, I. Lokhtin, A. Markina, S. Obraztsov, M. Perfilov, S. Petrushanko, A. Popov, L. Sarycheva[†], V. Savrin, A. Snigirev, I. Vardanyan

P.N. Lebedev Physical Institute, Moscow, Russia

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

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

I. Azhgirey, I. Bayshev, S. Bitiukov, V. Grishin⁵, V. Kachanov, D. Konstantinov, A. Korablev, V. Krychkine, V. Petrov, R. Ryutin, A. Sobol, L. Tourtchanovitch, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

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

P. Adzic³¹, M. Djordjevic, M. Ekmedzic, D. Krpic³¹, J. Milosevic

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

M. Aguilar-Benitez, J. Alcaraz Maestre, P. Arce, C. Battilana, E. Calvo, M. Cerrada, M. Chamizo Llatas, N. Colino, B. De La Cruz, A. Delgado Peris, C. Diez Pardos, D. Domínguez Vázquez, C. Fernandez Bedoya, J.P. Fernández Ramos, A. Ferrando, J. Flix, M.C. Fouz, P. Garcia-Abia, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, G. Merino, J. Puerta Pelayo, A. Quintario Olmeda, I. Redondo, L. Romero, J. Santaolalla, M.S. Soares, C. Willmott

Universidad Autónoma de Madrid, Madrid, Spain

C. Albajar, G. Codispoti, J.F. de Trocóniz

Universidad de Oviedo, Oviedo, Spain

J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, L. Lloret Iglesias, J. Piedra Gomez³²

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

J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, S.H. Chuang, J. Duarte Campderros, M. Felcini³³, M. Fernandez, G. Gomez, J. Gonzalez Sanchez, C. Jorda, P. Lobelle Pardo, A. Lopez Virto, J. Marco, R. Marco, C. Martinez Rivero, F. Matorras, F.J. Munoz Sanchez, T. Rodrigo, A.Y. Rodríguez-Marrero, A. Ruiz-Jimeno, L. Scodellaro, M. Sobron Sanudo, I. Vila, R. Vilar Cortabitarte

CERN, European Organization for Nuclear Research, Geneva, Switzerland

D. Abbaneo, E. Auffray, G. Auzinger, P. Baillon, A.H. Ball, D. Barney, C. Bernet⁶, G. Bianchi, P. Bloch, A. Bocci, A. Bonato, H. Breuker, T. Camporesi, G. Cerminara, T. Christiansen, J.A. Coarasa Perez, D. D'Enterria, A. Dabrowski, A. De Roeck, S. Di Guida, M. Dobson, N. Dupont-Sagorin, A. Elliott-Peisert, B. Frisch, W. Funk, G. Georgiou, M. Giffels, D. Gigi, K. Gill, D. Giordano, M. Giunta, F. Glege, R. Gomez-Reino Garrido, P. Govoni, S. Gowdy, R. Guida, M. Hansen, P. Harris, C. Hartl, J. Harvey, B. Hegner, A. Hinzmann, V. Innocente, P. Janot, K. Kaadze, E. Karavakis, K. Kousouris, P. Lecoq, Y.-J. Lee, P. Lenzi, C. Lourenço, T. Mäki, M. Malberti, L. Malgeri, M. Mannelli, L. Masetti,

F. Meijers, S. Mersi, E. Meschi, R. Moser, M.U. Mozer, M. Mulders, P. Musella, E. Nesvold, T. Orimoto, L. Orsini, E. Palencia Cortezon, E. Perez, A. Petrilli, A. Pfeiffer, M. Pierini, M. Pimiä, D. Piparo, G. Polese, L. Quertenmont, A. Racz, W. Reece, J. Rodrigues Antunes, G. Rolandi³⁴, T. Rommerskirchen, C. Rovelli³⁵, M. Rovere, H. Sakulin, F. Santanastasio, C. Schäfer, C. Schwick, I. Segoni, S. Sekmen, A. Sharma, P. Siegrist, P. Silva, M. Simon, P. Sphicas³⁶, D. Spiga, M. Spiropulu⁴, M. Stoye, A. Tsirou, G.I. Veres¹⁹, J.R. Vlimant, H.K. Wöhri, S.D. Worm³⁷, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland

W. Bertl, K. Deiters, W. Erdmann, K. Gabathuler, R. Horisberger, Q. Ingram, H.C. Kaestli, S. König, D. Kotlinski, U. Langenegger, F. Meier, D. Renker, T. Rohe, J. Sibille³⁸

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland

L. Bäni, P. Bortignon, M.A. Buchmann, B. Casal, N. Chanon, Z. Chen, A. Deisher, G. Dissertori, M. Dittmar, M. Dünser, J. Eugster, K. Freudenreich, C. Grab, D. Hits, P. Lecomte, W. Lustermann, A.C. Marini, P. Martinez Ruiz del Arbol, N. Mohr, F. Moortgat, C. Nägeli³⁹, P. Nef, F. Nessi-Tedaldi, F. Pandolfi, L. Pape, F. Pauss, M. Peruzzi, F.J. Ronga, M. Rossini, L. Sala, A.K. Sanchez, A. Starodumov⁴⁰, B. Stieger, M. Takahashi, L. Tauscher[†], A. Thea, K. Theofilatos, D. Treille, C. Urscheler, R. Wallny, H.A. Weber, L. Wehrli

Universität Zürich, Zurich, Switzerland

E. Aguilo, C. Amsler, V. Chiochia, S. De Visscher, C. Favaro, M. Ivova Rikova, B. Millan Mejias, P. Otiougova, P. Robmann, H. Snoek, S. Tupputi, M. Verzetti

National Central University, Chung-Li, Taiwan

Y.H. Chang, K.H. Chen, C.M. Kuo, S.W. Li, W. Lin, Z.K. Liu, Y.J. Lu, D. Mekterovic, A.P. Singh, R. Volpe, S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan

P. Bartalini, P. Chang, Y.H. Chang, Y.W. Chang, Y. Chao, K.F. Chen, C. Dietz, U. Grundler, W.-S. Hou, Y. Hsiung, K.Y. Kao, Y.J. Lei, R.-S. Lu, D. Majumder, E. Petrakou, X. Shi, J.G. Shiu, Y.M. Tzeng, X. Wan, M. Wang

Cukurova University, Adana, Turkey

A. Adiguzel, M.N. Bakirci⁴¹, S. Cerci⁴², C. Dozen, I. Dumanoglu, E. Eskut, S. Girgis, G. Gokbulut, E. Gurpinar, I. Hos, E.E. Kangal, G. Karapinar, A. Kayis Topaksu, G. Onengut, K. Ozdemir, S. Ozturk⁴³, A. Polatoz, K. Sogut⁴⁴, D. Sunar Cerci⁴², B. Tali⁴², H. Topakli⁴¹, L.N. Vergili, M. Vergili

Middle East Technical University, Physics Department, Ankara, Turkey

I.V. Akin, T. Aliev, B. Bilin, S. Bilmis, M. Deniz, H. Gamsizkan, A.M. Guler, K. Ocalan, A. Ozpineci, M. Serin, R. Sever, U.E. Surat, M. Yalvac, E. Yildirim, M. Zeyrek

Bogazici University, Istanbul, Turkey

E. Gülmez, B. Isildak⁴⁵, M. Kaya⁴⁶, O. Kaya⁴⁶, S. Ozkorucuklu⁴⁷, N. Sonmez⁴⁸

Istanbul Technical University, Istanbul, Turkey

K. Cankocak

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

L. Levchuk

University of Bristol, Bristol, United KingdomF. Bostock, J.J. Brooke, E. Clement, D. Cussans, H. Flacher, R. Frazier, J. Goldstein, M. Grimes, G.P. Heath, H.F. Heath, L. Kreczko, S. Metson, D.M. Newbold³⁷, K. Nirunpong, A. Poll, S. Senkin, V.J. Smith, T. Williams**Rutherford Appleton Laboratory, Didcot, United Kingdom**L. Basso⁴⁹, A. Belyaev⁴⁹, C. Brew, R.M. Brown, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, J. Jackson, B.W. Kennedy, E. Olaiya, D. Petyt, B.C. Radburn-Smith, C.H. Shepherd-Themistocleous, I.R. Tomalin, W.J. Womersley**Imperial College, London, United Kingdom**R. Bainbridge, G. Ball, R. Beuselinck, O. Buchmuller, D. Colling, N. Cripps, M. Cutajar, P. Dauncey, G. Davies, M. Della Negra, W. Ferguson, J. Fulcher, D. Futyan, A. Gilbert, A. Guneratne Bryer, G. Hall, Z. Hatherell, J. Hays, G. Iles, M. Jarvis, G. Karapostoli, L. Lyons, A.-M. Magnan, J. Marrouche, B. Mathias, R. Nandi, J. Nash, A. Nikitenko⁴⁰, A. Papageorgiou, J. Pela⁵, M. Pesaresi, K. Petridis, M. Pioppi⁵⁰, D.M. Raymond, S. Rogerson, A. Rose, M.J. Ryan, C. Seez, P. Sharp[†], A. Sparrow, A. Tapper, M. Vazquez Acosta, T. Virdee, S. Wakefield, N. Wardle, T. Whyntie**Brunel University, Uxbridge, United Kingdom**

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

Baylor University, Waco, USA

K. Hatakeyama, H. Liu, T. Scarborough

The University of Alabama, Tuscaloosa, USA

C. Henderson, P. Rumerio

Boston University, Boston, USA

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

Brown University, Providence, USA

J. Alimena, S. Bhattacharya, D. Cutts, A. Ferapontov, U. Heintz, S. Jabeen, G. Kukartsev, E. Laird, G. Landsberg, M. Luk, M. Narain, D. Nguyen, M. Segala, T. Sinthuprasith, T. Speer, K.V. Tsang

University of California, Davis, Davis, USA

R. Breedon, G. Breto, M. Calderon De La Barca Sanchez, S. Chauhan, M. Chertok, J. Conway, R. Conway, P.T. Cox, J. Dolen, R. Erbacher, M. Gardner, R. Houtz, W. Ko,

A. Kopecky, R. Lander, O. Mall, T. Miceli, R. Nelson, D. Pellett, B. Rutherford, M. Searle, J. Smith, M. Squires, M. Tripathi, R. Vasquez Sierra

University of California, Los Angeles, Los Angeles, USA

V. Andreev, D. Cline, R. Cousins, J. Duris, S. Erhan, P. Everaerts, C. Farrell, J. Hauser, M. Ignatenko, C. Jarvis, C. Plager, G. Rakness, P. Schlein[†], J. Tucker, V. Valuev, M. Weber

University of California, Riverside, Riverside, USA

J. Babb, R. Clare, M.E. Dinardo, J. Ellison, J.W. Gary, F. Giordano, G. Hanson, G.Y. Jeng⁵¹, H. Liu, O.R. Long, A. Luthra, H. Nguyen, S. Paramesvaran, J. Sturdy, S. Sumowidagdo, R. Wilken, S. Wimpenny

University of California, San Diego, La Jolla, USA

W. Andrews, J.G. Branson, G.B. Cerati, S. Cittolin, D. Evans, F. Golf, A. Holzner, R. Kelley, M. Lebourgeois, J. Letts, I. Macneill, B. Mangano, S. Padhi, C. Palmer, G. Petrucciani, M. Pieri, M. Sani, V. Sharma, S. Simon, E. Sudano, M. Tadel, Y. Tu, A. Vartak, S. Wasserbaech⁵², F. Würthwein, A. Yagil, J. Yoo

University of California, Santa Barbara, Santa Barbara, USA

D. Barge, R. Bellan, C. Campagnari, M. D'Alfonso, T. Danielson, K. Flowers, P. Geffert, J. Incandela, C. Justus, P. Kalavase, S.A. Koay, D. Kovalskyi, V. Krutelyov, S. Lowette, N. Mccoll, V. Pavlunin, F. Rebassoo, J. Ribnik, J. Richman, R. Rossin, D. Stuart, W. To, C. West

California Institute of Technology, Pasadena, USA

A. Apresyan, A. Bornheim, Y. Chen, E. Di Marco, J. Duarte, M. Gataullin, Y. Ma, A. Mott, H.B. Newman, C. Rogan, V. Timciuc, P. Traczyk, J. Veverka, R. Wilkinson, Y. Yang, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, USA

B. Akgun, R. Carroll, T. Ferguson, Y. Iiyama, D.W. Jang, Y.F. Liu, M. Paulini, H. Vogel, I. Vorobiev

University of Colorado at Boulder, Boulder, USA

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

Cornell University, Ithaca, USA

J. Alexander, A. Chatterjee, N. Eggert, L.K. Gibbons, B. Heltsley, A. Khukhunaishvili, B. Kreis, N. Mirman, G. Nicolas Kaufman, J.R. Patterson, A. Ryd, E. Salvati, W. Sun, W.D. Teo, J. Thom, J. Thompson, J. Vaughan, Y. Weng, L. Winstrom, P. Wittich

Fairfield University, Fairfield, USA

D. Winn

Fermi National Accelerator Laboratory, Batavia, USA

S. Abdullin, M. Albrow, J. Anderson, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, I. Bloch, K. Burkett, J.N. Butler, V. Chetluru, H.W.K. Cheung, F. Chlebana,

V.D. Elvira, I. Fisk, J. Freeman, Y. Gao, D. Green, O. Gutsche, A. Hahn, J. Hanlon, R.M. Harris, J. Hirschauer, B. Hooberman, S. Jindariani, M. Johnson, U. Joshi, B. Kilminster, B. Klima, S. Kunori, S. Kwan, C. Leonidopoulos, D. Lincoln, R. Lipton, L. Lueking, J. Lykken, K. Maeshima, J.M. Marraffino, S. Maruyama, D. Mason, P. McBride, K. Mishra, S. Mrenna, Y. Musienko⁵³, C. Newman-Holmes, V. O'Dell, O. Prokofyev, E. Sexton-Kennedy, S. Sharma, W.J. Spalding, L. Spiegel, P. Tan, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, R. Vidal, J. Whitmore, W. Wu, F. Yang, F. Yumiceva, J.C. Yun

University of Florida, Gainesville, USA

D. Acosta, P. Avery, D. Bourilkov, M. Chen, S. Das, M. De Gruttola, G.P. Di Giovanni, D. Dobur, A. Drozdetskiy, R.D. Field, M. Fisher, Y. Fu, I.K. Furic, J. Gartner, J. Hugon, B. Kim, J. Konigsberg, A. Korytov, A. Kropivnitskaya, T. Kypreos, J.F. Low, K. Matchev, P. Milenovic⁵⁴, G. Mitselmakher, L. Muniz, R. Remington, A. Rinkevicius, P. Sellers, N. Skhirtladze, M. Snowball, J. Yelton, M. Zakaria

Florida International University, Miami, USA

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

Florida State University, Tallahassee, USA

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

Florida Institute of Technology, Melbourne, USA

M.M. Baarmand, B. Dorney, M. Hohlmann, H. Kalakhety, I. Vodopiyarov

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

M.R. Adams, I.M. Anghel, L. Apanasevich, Y. Bai, V.E. Bazterra, R.R. Betts, I. Bucinskaite, J. Callner, R. Cavanaugh, C. Dragoiu, O. Evdokimov, L. Gauthier, C.E. Gerber, S. Hamdan, D.J. Hofman, S. Khalatyan, F. Lacroix, M. Malek, C. O'Brien, C. Silkworth, D. Strom, N. Varelas

The University of Iowa, Iowa City, USA

U. Akgun, E.A. Albayrak, B. Bilki⁵⁵, W. Clarida, F. Duru, S. Griffiths, J.-P. Merlo, H. Mermerkaya⁵⁶, A. Mestvirishvili, A. Moeller, J. Nachtman, C.R. Newsom, E. Norbeck, Y. Onel, F. Ozok, S. Sen, E. Tiras, J. Wetzel, T. Yetkin, K. Yi

Johns Hopkins University, Baltimore, USA

B.A. Barnett, B. Blumenfeld, S. Bolognesi, D. Fehling, G. Giurgiu, A.V. Gritsan, Z.J. Guo, G. Hu, P. Maksimovic, S. Rappoccio, M. Swartz, A. Whitbeck

The University of Kansas, Lawrence, USA

P. Baringer, A. Bean, G. Benelli, O. Grachov, R.P. Kenny Iii, M. Murray, D. Noonan, S. Sanders, R. Stringer, G. Tinti, J.S. Wood, V. Zhukova

Kansas State University, Manhattan, USA

A.F. Barfuss, T. Bolton, I. Chakaberia, A. Ivanov, S. Khalil, M. Makouski, Y. Maravin, S. Shrestha, I. Svintradze

Lawrence Livermore National Laboratory, Livermore, USA

J. Gronberg, D. Lange, D. Wright

University of Maryland, College Park, USA

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

Massachusetts Institute of Technology, Cambridge, USA

G. Bauer, J. Bendavid, W. Busza, E. Butz, I.A. Cali, M. Chan, V. Dutta, G. Gomez Ceballos, M. Goncharov, K.A. Hahn, Y. Kim, M. Klute, W. Li, P.D. Luckey, T. Ma, S. Nahn, C. Paus, D. Ralph, C. Roland, G. Roland, M. Rudolph, G.S.F. Stephans, F. Stöckli, K. Sumorok, K. Sung, D. Velicanu, E.A. Wenger, R. Wolf, B. Wyslouch, S. Xie, M. Yang, Y. Yilmaz, A.S. Yoon, M. Zanetti

University of Minnesota, Minneapolis, USA

S.I. Cooper, P. Cushman, B. Dahmes, A. De Benedetti, G. Franzoni, A. Gude, J. Haupt, S.C. Kao, K. Klapoetke, Y. Kubota, J. Mans, N. Pastika, R. Rusack, M. Sasseville, A. Singovsky, N. Tambe, J. Turkewitz

University of Mississippi, University, USA

L.M. Cremaldi, R. Kroeger, L. Perera, R. Rahmat, D.A. Sanders

University of Nebraska-Lincoln, Lincoln, USA

E. Avdeeva, K. Bloom, S. Bose, J. Butt, D.R. Claes, A. Dominguez, M. Eads, P. Jindal, J. Keller, I. Kravchenko, J. Lazo-Flores, H. Malbouisson, S. Malik, G.R. Snow

State University of New York at Buffalo, Buffalo, USA

U. Baur, A. Godshalk, I. Iashvili, S. Jain, A. Kharchilava, A. Kumar, S.P. Shipkowski, K. Smith

Northeastern University, Boston, USA

G. Alverson, E. Barberis, D. Baumgartel, M. Chasco, J. Haley, D. Nash, D. Trocino, D. Wood, J. Zhang

Northwestern University, Evanston, USA

A. Anastassov, A. Kubik, N. Mucia, N. Odell, R.A. Ofierzynski, B. Pollack, A. Pozdnyakov, M. Schmitt, S. Stoynev, M. Velasco, S. Won

University of Notre Dame, Notre Dame, USA

L. Antonelli, D. Berry, A. Brinkerhoff, M. Hildreth, C. Jessop, D.J. Karmgard, J. Kolb, K. Lannon, W. Luo, S. Lynch, N. Marinelli, D.M. Morse, T. Pearson, R. Ruchti, J. Slaunwhite, N. Valls, M. Wayne, M. Wolf

The Ohio State University, Columbus, USA

B. Bylsma, L.S. Durkin, A. Hart, C. Hill, R. Hughes, K. Kotov, T.Y. Ling, D. Puigh, M. Rodenburg, C. Vuosalo, G. Williams, B.L. Winer

Princeton University, Princeton, USA

N. Adam, E. Berry, P. Elmer, D. Gerbaudo, V. Halyo, P. Hebda, J. Hegeman, A. Hunt, D. Lopes Pegna, P. Lujan, D. Marlow, T. Medvedeva, M. Mooney, J. Olsen, P. Piroué, X. Quan, A. Raval, H. Saka, D. Stickland, C. Tully, J.S. Werner, A. Zuranski

University of Puerto Rico, Mayaguez, USA

J.G. Acosta, E. Brownson, X.T. Huang, A. Lopez, H. Mendez, S. Oliveros, J.E. Ramirez Vargas, A. Zatserklyaniy

Purdue University, West Lafayette, USA

E. Alagoz, V.E. Barnes, D. Benedetti, G. Bolla, D. Bortoletto, M. De Mattia, A. Everett, Z. Hu, M. Jones, O. Koybasi, M. Kress, A.T. Laasanen, N. Leonardo, V. Maroussov, P. Merkel, D.H. Miller, N. Neumeister, I. Shipsey, D. Silvers, A. Svyatkovskiy, M. Vidal Marono, H.D. Yoo, J. Zablocki, Y. Zheng

Purdue University Calumet, Hammond, USA

S. Guragain, N. Parashar

Rice University, Houston, USA

A. Adair, C. Boulahouache, V. Cuplov, K.M. Ecklund, F.J.M. Geurts, B.P. Padley, R. Redjimi, J. Roberts, J. Zabel

University of Rochester, Rochester, USA

B. Betchart, A. Bodek, Y.S. Chung, R. Covarelli, P. de Barbaro, R. Demina, Y. Eshaq, A. Garcia-Bellido, P. Goldenzweig, Y. Gotra, J. Han, A. Harel, S. Korjenevski, D.C. Miner, D. Vishnevskiy, M. Zielinski

The Rockefeller University, New York, USA

A. Bhatti, R. Ciesielski, L. Demortier, K. Goulianos, G. Lungu, S. Malik, C. Mesropian

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

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

University of Tennessee, Knoxville, USA

G. Cerizza, M. Hollingsworth, S. Spanier, Z.C. Yang, A. York

Texas A&M University, College Station, USA

R. Eusebi, W. Flanagan, J. Gilmore, T. Kamon⁵⁷, V. Khotilovich, R. Montalvo, I. Osipenkov, Y. Pakhotin, A. Perloff, J. Roe, A. Safonov, T. Sakuma, S. Sengupta, I. Suarez, A. Tatarinov, D. Toback

Texas Tech University, Lubbock, USA

N. Akchurin, J. Damgov, P.R. Duderov, C. Jeong, K. Kovitanggoon, S.W. Lee, T. Libeiro, Y. Roh, I. Volobouev

Vanderbilt University, Nashville, USA

E. Appelt, D. Engh, C. Florez, S. Greene, A. Gurrola, W. Johns, C. Johnston, P. Kurt, C. Maguire, A. Melo, P. Sheldon, B. Snook, S. Tuo, J. Velkovska

University of Virginia, Charlottesville, USA

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

Wayne State University, Detroit, USA

S. Gollapinni, R. Harr, P.E. Karchin, C. Kottachchi Kankanamge Don, P. Lamichhane, A. Sakharov

University of Wisconsin, Madison, USA

M. Anderson, M. Bachtis, D. Belknap, L. Borrello, D. Carlsmith, M. Cepeda, S. Dasu, L. Gray, K.S. Grogg, M. Grothe, R. Hall-Wilton, M. Herndon, A. Hervé, P. Klabbers, J. Klukas, A. Lanaro, C. Lazaridis, J. Leonard, R. Loveless, A. Mohapatra, I. Ojalvo, F. Palmonari, G.A. Pierro, I. Ross, A. Savin, W.H. Smith, J. Swanson

†: Deceased

- 1: Also at Vienna University of Technology, Vienna, Austria
- 2: Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
- 3: Also at Universidade Federal do ABC, Santo Andre, Brazil
- 4: Also at California Institute of Technology, Pasadena, USA
- 5: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
- 6: Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
- 7: Also at Suez Canal University, Suez, Egypt
- 8: Also at Zewail City of Science and Technology, Zewail, Egypt
- 9: Also at Cairo University, Cairo, Egypt
- 10: Also at Fayoum University, El-Fayoum, Egypt
- 11: Also at British University, Cairo, Egypt
- 12: Now at Ain Shams University, Cairo, Egypt
- 13: Also at Soltan Institute for Nuclear Studies, Warsaw, Poland
- 14: Also at Université de Haute-Alsace, Mulhouse, France
- 15: Now at Joint Institute for Nuclear Research, Dubna, Russia
- 16: Also at Moscow State University, Moscow, Russia
- 17: Also at Brandenburg University of Technology, Cottbus, Germany
- 18: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
- 19: Also at Eötvös Loránd University, Budapest, Hungary
- 20: Also at Tata Institute of Fundamental Research - HECR, Mumbai, India
- 21: Also at University of Visva-Bharati, Santiniketan, India
- 22: Also at Sharif University of Technology, Tehran, Iran
- 23: Also at Isfahan University of Technology, Isfahan, Iran
- 24: Also at Shiraz University, Shiraz, Iran

- 25: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Teheran, Iran
- 26: Also at Facoltà Ingegneria Università di Roma, Roma, Italy
- 27: Also at Università della Basilicata, Potenza, Italy
- 28: Also at Università degli Studi Guglielmo Marconi, Roma, Italy
- 29: Also at Università degli studi di Siena, Siena, Italy
- 30: Also at University of Bucharest, Faculty of Physics, Bucuresti-Magurele, Romania
- 31: Also at Faculty of Physics of University of Belgrade, Belgrade, Serbia
- 32: Also at University of Florida, Gainesville, USA
- 33: Also at University of California, Los Angeles, Los Angeles, USA
- 34: Also at Scuola Normale e Sezione dell' INFN, Pisa, Italy
- 35: Also at INFN Sezione di Roma; Università di Roma "La Sapienza", Roma, Italy
- 36: Also at University of Athens, Athens, Greece
- 37: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
- 38: Also at The University of Kansas, Lawrence, USA
- 39: Also at Paul Scherrer Institut, Villigen, Switzerland
- 40: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
- 41: Also at Gaziosmanpasa University, Tokat, Turkey
- 42: Also at Adiyaman University, Adiyaman, Turkey
- 43: Also at The University of Iowa, Iowa City, USA
- 44: Also at Mersin University, Mersin, Turkey
- 45: Also at Ozyegin University, Istanbul, Turkey
- 46: Also at Kafkas University, Kars, Turkey
- 47: Also at Suleyman Demirel University, Isparta, Turkey
- 48: Also at Ege University, Izmir, Turkey
- 49: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
- 50: Also at INFN Sezione di Perugia; Università di Perugia, Perugia, Italy
- 51: Also at University of Sydney, Sydney, Australia
- 52: Also at Utah Valley University, Orem, USA
- 53: Also at Institute for Nuclear Research, Moscow, Russia
- 54: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
- 55: Also at Argonne National Laboratory, Argonne, USA
- 56: Also at Erzincan University, Erzincan, Turkey
- 57: Also at Kyungpook National University, Daegu, Korea