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Comparing transverse momentum balance of b jet pairs in pp and PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV

The CMS collaboration

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

Abstract: The transverse momentum balance of pairs of back-to-back b quark jets in PbPb and pp collisions recorded with the CMS detector at the LHC is reported. The center-of-mass energy in both collision systems is 5.02 TeV per nucleon pair. Compared to the pp collision baseline, b quark jets have a larger imbalance in the most central PbPb collisions, as expected from the jet quenching effect. The data are also compared to the corresponding measurement with inclusive dijets. In the most central collisions, the imbalance of b quark dijets is comparable to that of inclusive dijets.

Keywords: Hadron-Hadron scattering (experiments), Heavy-ion collision, Jet physics, Quark Gluon Plasma

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Contents

1 Introduction

Jets are sensitive probes of final-state effects in heavy ion collisions. The jet quenching phenomenon is understood to arise from the interaction of hard-scattered partons with the quark-gluon plasma produced in such collisions [1]. The first observable used to probe this phenomenon at the LHC was the transverse momentum (p_T) balance of back-to-back jets [2–5]. Quenching imparts a net imbalance to dijets that exceeds the imbalance from QCD radiation in vacuum, as measured in pp collisions. This additional imbalance is expected based on the difference of the in-medium path-length traversed by the two jets. However, jet-by-jet fluctuation of the quenching may also play a role, and could even be dominant [6].

The dependence of quenching on the type of parton that initiates the jet may provide insight into the underlying dynamics. Such a dependence could arise directly from the interaction of the initiating parton with the medium. For example, radiative loss via gluon bremsstrahlung is expected to be larger for jets initiated by gluons than for those from quarks. Furthermore, for heavy quarks, radiation is expected to be suppressed in the direction of propagation [7]. A dependence could also arise less directly, via the medium interactions of subleading partons in the shower. For models in which quenching depends on the shower multiplicity, e.g., JEWEL [6, 8], the relatively larger average parton multiplicity of gluon-initiated jets would lead to a larger quenching effect.

In general, the type of parton that initiates the jet is difficult to determine experimentally. A notable exception are jets produced by the fragmentation of bottom quarks. The corresponding b hadron may be identified, for example, by the presence of a soft lepton or a displaced vertex inside the jet. The latter strategy was pursued in the CMS measurement of the b quark jet ("b jet") spectra and the corresponding nuclear modification factor in PbPb collisions at a nucleon-nucleon center of mass energy of $\sqrt{s_{NN}} = 2.76$ TeV [9]. However, there is a potential ambiguity in that measurement. Bottom quarks may be produced not only directly in the hard scattering, but also in the subsequent splitting of gluons into b quark pairs. Jets associated with b hadrons may contain a significant contribution from gluon splitting, both from gluons that participate directly in the hard scattering, as well as those that arise from final-state radiation in the parton shower process.

One way to suppress the contribution of gluon splitting, which tends to produce pairs of b quarks with a relatively small opening angle, is to look at pairs of b jets that are back-to-back in azimuth. As shown in the appendix, this configuration enhances the contribution from primary b quarks, typically produced via the reaction gg $\rightarrow$ b$\bar{\text{b}}$. The p_T balance of such b jets may then be compared with those of inclusive (i.e., nontagged) dijets. This paper presents the first measurement of the p_T balance of b jet pairs ("b dijets") in PbPb, using collisions recorded at $\sqrt{s_{NN}} = 5.02$ TeV. The b dijet data are compared with that of inclusive dijets to search for a possible dependence of the p_T balance on the species of the initiating partons.

2 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity coverage provided by the barrel and endcap detectors over the range of about $3 < \eta < 5$. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid. 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. [10].

Events of interest are selected using a two-tiered trigger system [11]. The first level, composed of custom hardware processors, uses information from the calorimeters and muon detectors. The second level, known as the high-level trigger, consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing.

3 Event and object selection

This analysis is performed using PbPb and pp data recorded in 2015 at a center-of-mass energy per nucleon pair of $\sqrt{s_{NN}} = 5.02$ TeV. The PbPb and pp samples correspond to integrated luminosities of 404 μb^{-1} and 25.8 pb^{-1}, respectively. Events were selected using single-jet triggers in both pp and PbPb collisions. The jet triggers used in this analysis are fully efficient with respect to the offline leading jet selection of $p_T > 100$ GeV. For PbPb collisions, b tagging algorithms are applied at the high-level trigger to reduce the data volume.

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This is achieved by performing a simplified version of the charged-particle tracking and vertex reconstruction in regions of the detector delineated by high-p_T jets. The efficiency of the online b tagging with respect to the corresponding offline algorithm is evaluated using single-jet triggers, and lies in the range of 70–90%, depending on collision centrality.

To reject noncollision processes such as beam-gas interactions, events are required to have at least one reconstructed primary vertex and to deposit an energy of at least 3 GeV in at least 3 towers in each of the two forward calorimeters. The forward calorimeters are also used to estimate the collision centrality, evaluated as a percentile of the total inelastic hadronic cross section, with the most central event corresponding to a centrality of 0%.

The anti-k_T algorithm [12] is used to cluster jets from objects produced by the CMS particle-flow algorithm [13], which combines information from the various subdetector systems. A radius parameter of $R = 0.4$ is used. In PbPb collisions, the heavy ion background is subtracted event-by-event with an algorithm that is a variant of an iterative "noise/pedestal subtraction" technique [14]. The jet energy is calibrated as a function of the η and p_T following the procedure described in ref. [15].

The identification of b jets is achieved using the "combined secondary vertex" (CSV) discriminator. This algorithm takes as input a number of properties of the reconstructed secondary vertex (SV), such as its displacement, the number of associated tracks, and their invariant mass (with the assumption that the tracks are originated by charged pions). For events in which no SV is properly reconstructed, the displacement of selected tracks is used. Details of the b tagging algorithms, and tracking and vertexing in general, can be found in refs. [16] and [17], respectively. Simulated data samples produced with GEANT4 [18] are used to evaluate the b tagging performance and derive various corrections. These samples are generated with PYTHIA version 6.423 [19], tune Z2 [20]. To compare with PbPb data, PYTHIA events are embedded in an underlying event produced with the HYDJET generator, version 1.9 [21].

The performance of the CSV algorithm to identify b jet pairs offline is shown in figure 1. The efficiency and purity are evaluated in simulation as a function of the b-tagging selection variable for pp and PbPb collisions for different centrality intervals. A tight selection on the CSV discriminator is applied in this analysis, as indicated in figure 1, leading to a purity in the range of 85–95% for b dijets, with an efficiency in the range of about 10–35%, depending on collision system and centrality. The degradation of the performance with increasing centrality corresponds to a larger mistagging rate for fixed b tagging efficiency, as also observed in ref. [9]. These jets are mistagged primarily due to vertices from false track combinations.

4 Data analysis

The p_T balance of dijets is measured using the leading and subleading jets. This balance is quantified by the ratio of the subleading to leading jet p_T, denoted x_J. Dijets are selected from the two highest p_T jets within a window of $|\eta| < 1.5$. The p_T of the leading and the subleading jets are required to be above 100 and 40 GeV, respectively. This asymmetric p_T selection is chosen to ensure sensitivity to quenching effects. The subleading jet threshold of 40 GeV is chosen to keep the subleading jet-finding efficiency reasonably high, as will be

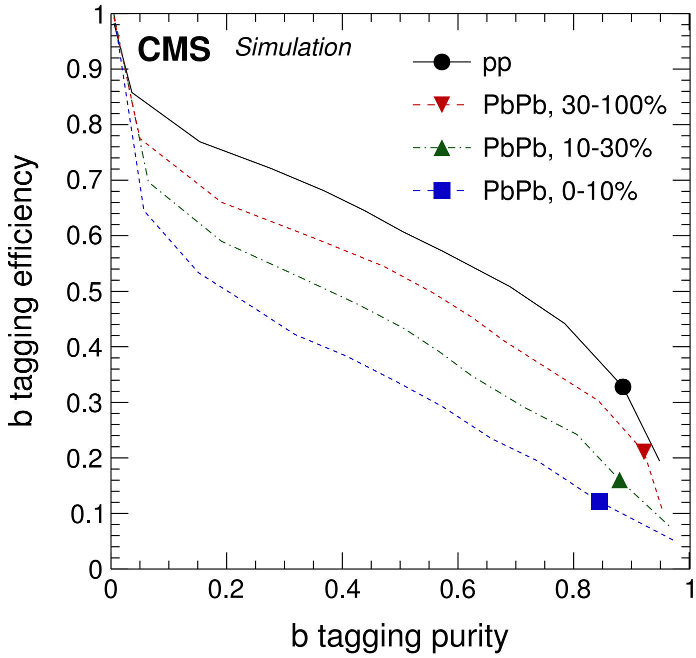

Figure 1. The b dijet purity vs. efficiency as a function of the value of the selection on the CSV discriminator in simulation. The same CSV selection is applied to both jets. Several different centrality intervals of PbPb, as well as pp collisions, are shown, as indicated in the legend. The closed symbols indicate the working point used in this analysis.

described below. The leading jet threshold of 100 GeV is a compromise between statistical precision, on one hand, and maintaining a large lever-arm with the subleading jet, on the other. For the case of b dijets, the leading and subleading jets are chosen prior to b-tagging selection. By restricting the analysis to the two highest p_T jets in the event, the contribution from gluon splitting processes is significantly suppressed.

Pairs of jets from a single hard scattering are referred to as "signal" pairs. To enhance the contribution of such pairs, the jets are required to be back-to-back in azimuthal opening angle with the selection of $|\Delta\phi| > 2\pi/3$. The $\Delta\phi$ distributions in pp collisions for inclusive dijets and dijets for which both the leading and subleading jets are b tagged are shown in the left panel of figure 2. The b-tagged dijets show a more pronounced tail at small $\Delta\phi$, which comes from a larger contribution of 3-jet topologies, as further discussed in the appendix. The $\Delta\phi$ distributions in central (0–10%) PbPb collisions are shown in the right panel of figure 2. For inclusive dijets, an increased contribution (compared to pp collisions) at small $\Delta\phi$ arises from pairs of jets that are not from the same nucleon-nucleon interaction. These combinatorial jet pairs tend to bias the x_J distribution towards low values, i.e., towards large imbalance. To subtract this contribution from the selected dijet pairs, we exploit the fact that such combinatorial pairs are uniform in $\Delta\phi$, and subtract the contribution of pairs from a control region where combinatorial background dominates over the signal pairs. The region is chosen to be $|\Delta\phi| < \pi/3$, which is symmetric to the back-to-back region with respect to the reaction plane, and thus receives the same contribution

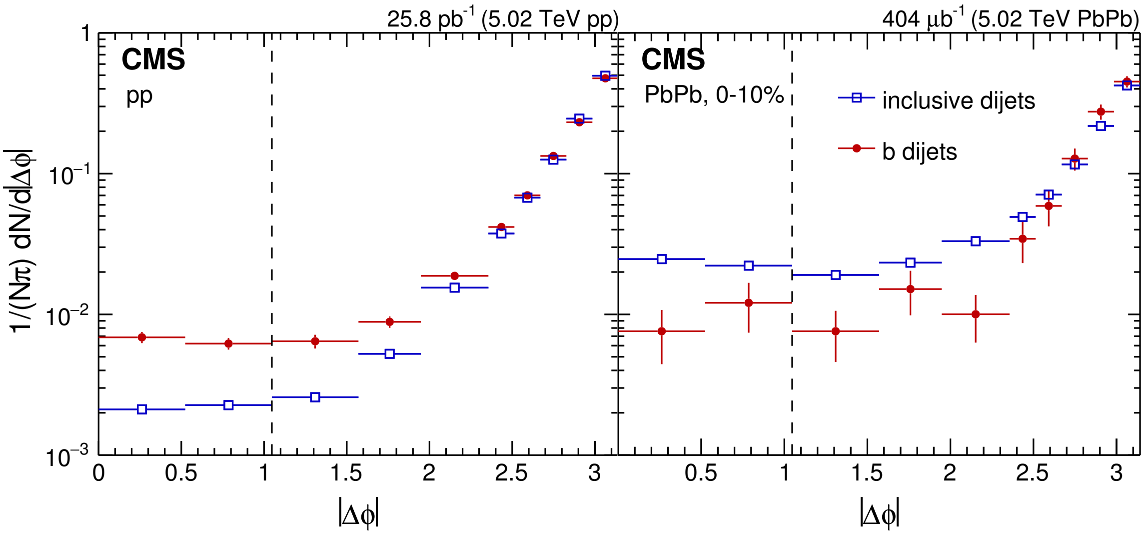

Figure 2. Distributions of the azimuthal opening angle ($\Delta\phi$) between the leading and subleading jets for pp (left) and central (0–10%) PbPb collisions (right) for inclusive dijets and b dijets. The small-angle region ($|\Delta\phi| < \pi/3$), the boundary of which is indicated by a dashed line, is used to evaluate the combinatorial contribution in PbPb collisions. The vertical bars represent statistical uncertainties, while the horizontal bars represent the bin widths.

from elliptic flow. Higher order anisotropies are assumed to be negligible for this range in p_{T}. Since combinatorial jets are unlikely to pass the b tagging selection, the near-angle contribution is smaller for b dijets than inclusive dijets.

In addition to subtracting the combinatorial component, one also needs to correct for the contribution of signal pairs that are lost when there is a combinatorial jet of higher p_{T} than the signal partner jet. To achieve this, an efficiency correction is derived, which is the inverse of the probability that a partner jet of a given p_{T} was found, i.e., not obscured by a combinatorial jet of larger p_{T}. This efficiency is again estimated from data using the small-angle control region, $|\Delta\phi| < \pi/3$. For a given centrality class, we obtain the spectrum of the highest transverse momentum ($p_{\mathrm{T}}^{\mathrm{max}}$) partner jet in this region in each event. Assuming that all partner jets in this region are combinatorial, one can derive the probability that a signal partner jet is obscured, as a function of p_{T}. This efficiency for detecting the signal partner jet is the cumulative distribution function of this $p_{\mathrm{T}}^{\mathrm{max}}$ spectrum:

$$\epsilon(p_{\mathrm{T}}) \equiv 1 - \frac{1}{N}\int_{p_{\mathrm{T}}}^{\infty} \frac{\mathrm{d}N}{\mathrm{d}p_{\mathrm{T}}^{\mathrm{max}}}\mathrm{d}p_{\mathrm{T}}^{\mathrm{max}}. \tag{4.1}$$

The efficiency is obtained from a fit to the data in fine bins of centrality, using the Gompertz function, $f(p_{\mathrm{T}}) = \exp[b\exp(cp_{\mathrm{T}})]$, where b and c are free parameters. The fits obtained are shown in figure 3. For each event, the values of b and c for the given centrality are obtained by linear interpolation. The function with these interpolated parameters is then evaluated at the p_{T} of the subleading jet.

Although the self-normalized quantities presented in this analysis do not depend on the absolute b tagging efficiency, the relative efficiency as a function of the p_{T} and η must

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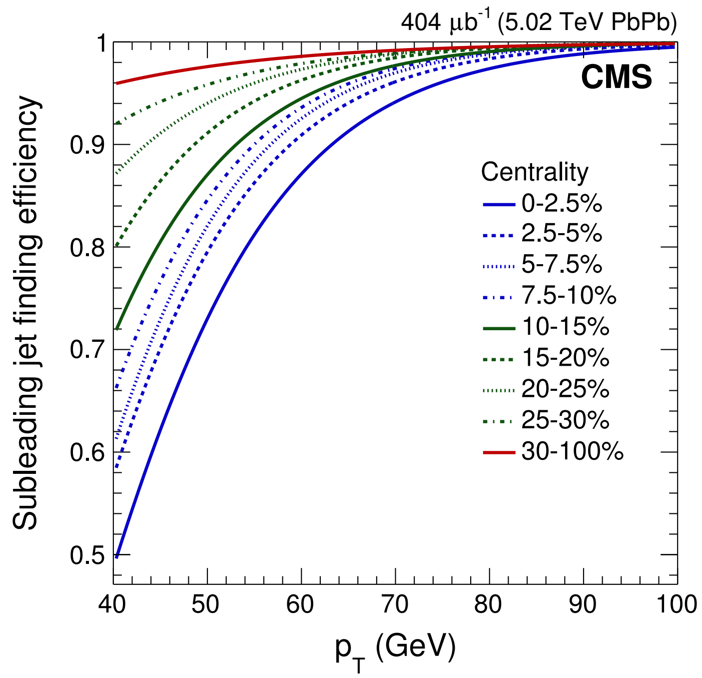

Figure 3. The efficiency of finding a signal partner jet as function of its p_T in PbPb collisions, as evaluated from the small-angle jet pair control region. The corrections are shown in the fine centrality bins used in the analysis.

be taken into account. Corrections are derived from simulation for both the leading and subleading jet. We also correct for the variation of the b tagging efficiency within the centrality selections presented in this analysis.

In order to probe for quenching or other nuclear effects on the balance distributions, a baseline is constructed using pp data as a reference. Since the deterioration of the jet p_T resolution with increasing collision centrality introduces an additional imbalance in the x_J distributions, a direct comparison of PbPb and pp measurements does not solely reflect the nuclear modifications. This issue is addressed by smearing the transverse momentum of the jets in pp data by the amount that corresponds to the additional underlying event fluctuations estimated from HYDJET simulations that have been tuned to match the underlying event density in PbPb data.

As in ref. [22], the jet p_T resolution is parametrized according the following form, typical for calorimeter energy resolutions.

$$\sigma(p_T)/p_T = \sqrt{C^2 + S^2/p_T + N^2/p_T^2} \tag{4.2}$$

In pp collisions, the constant (C) and stochastic (S) terms are 0.06 and $0.8\sqrt{\text{GeV}}$, respectively. In PbPb collisions the S term has a slightly larger value of $1.0\sqrt{\text{GeV}}$, due to the underlying event subtraction. The noise parameter (N) depends on collision centrality, according to $N = 14.82 - \text{centrality}\ (\%)/5.40(\text{GeV})$. This term is neglected in pp collisions.

Source	pp	30–100%	10–30%	0–10%
Combinatorial subtraction	—	0.001	0.006	0.014
Subleading jet finding	—	0.002	0.004	0.004
Energy scale	0.001	0.006	0.010	0.013
Jet resolution	0.007	0.008	0.010	0.012
Total	0.007	0.010	0.016	0.023
Combinatorial subtraction	—	0.008	0.008	0.008
Subleading jet finding	—	0.002	0.004	0.004
Tagging efficiency	0.002	0.003	0.003	0.009
Signal mistagging	0.002	0.004	0.006	0.006
Jet energy scale	0.001	0.006	0.010	0.013
Jet resolution	0.007	0.008	0.010	0.012
Total	0.008	0.014	0.018	0.023

Table 1. Absolute systematic uncertainties on $\langle x_J \rangle$ for inclusive (upper sub-table) and b (lower sub-table) dijets.

5 Systematic uncertainties

The sources of systematic uncertainties in $\langle x_J \rangle$ for the inclusive dijet and b dijet measurements are summarized in table 1 and discussed directly below.

Combinatorial jet pair subtraction. The systematic uncertainty in the combinatorial background subtraction in PbPb collisions is evaluated by varying the contribution of the near-angle control region. For inclusive dijets, where the near-angle region is dominated by combinatorial jets, the size of the contribution is varied by 30%, which is sufficient to cover the nonclosure of the subtraction procedure in simulation (the difference between the output of the analysis procedure and the generated input for the simulation). For b dijets, the number of jet pairs in the near-angle control region is reduced by the b tagging requirement, and is much less centrality-dependent than for inclusive dijets. Simulations based on HYDJET embedding show that the dominant contribution in this region corresponds to signal jets from gluon splitting. We therefore use the entire yield in the near-angle region in pp data to estimate the systematic uncertainty in the subtraction procedure in PbPb data.

Subleading jet finding efficiency. The uncertainty on the efficiency correction for finding the subleading jet is attributed to several effects: a contribution of signal jets in the near-angle control region ($|\Delta\phi| < \pi/3$), the finite centrality binning used and the imperfect description of the Gompertz fit function employed. The systematic uncertainty associated with these corrections is evaluated from the nonclosure in HYDJET-embedded simulated samples.

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Jet energy scale. The uncertainty on the (inclusive) jet energy scale in pp collisions is evaluated from in-situ studies to be 1% for the η range used in this analysis [15, 22]. The same jet energy scale and uncertainty are found to apply to b jets, based on studies of $Z \to b\bar{b}$. In-situ studies were also carried out in peripheral PbPb collisions in ref. [4], albeit with limited statistics. A 4% uncertainty is assigned to cover the observed difference between data and simulation. The modification of jet fragmentation pattern due to quenching is also a source of systematic uncertainty on the jet energy scale that can be as large as 5% for the most central collisions [23, 24]. Finally, underlying event subtraction leads to an uncertainty in the jet energy scale of up to 2% for central collisions [4, 25].

To propagate the uncertainties to the x_J distributions, the correlation between the leading and subleading jet energy scales must be taken into account. For a given jet pair, the ratio x_J is insensitive to an overall shift of the jet energy scale by a multiplicative factor. Such a shift does, however, effectively change the leading and subleading jet thresholds. The total correlated shift from the above mentioned sources was estimated to be as large as 6.5% in central events. For b dijets, there is an additional systematic uncertainty due to the bias of the b tagging on the jet energy scale, which was evaluated in simulation and found to be 1% in pp collisions and 2% in PbPb collisions.

There is also a component of the systematic uncertainty that is uncorrelated between the leading and subleading jet. The subleading jet is also more sensitive to the underlying event subtraction systematics than the leading jet is. To be conservative, we applied the entire uncertainty of 2% to the subleading jet, independently of the leading jet. In addition, to cover the p_T dependence of the modification of the fragmentation pattern due to quenching, the jet energy scale is shifted by a fixed amount, up to 2 GeV in central events.

Jet energy resolution. The uncertainly from the jet resolution is propagated by varying the resolution parametrization in eq. (4.2). The effect on the x_J distribution is evaluated by applying these alternate smearing parametrizations to particle-level jets. In pp collisions, the C and S parameters are varied by 0.02 and $0.2\sqrt{\text{GeV}}$, respectively. For PbPb collisions, in addition, the N term is varied by 2 GeV, which covers the difference in underlying event between data and simulation, and the variation of the resolution within the wide centrality bins. Although the results are not unfolded for the resolution effects, the uncertainty is fully included in the data points in order to correctly evaluate any theoretical models that fold in the resolution effects for comparison.

Tagging efficiency (b jets only). The tagging efficiency has a fairly flat p_T dependence, such that it has only a mild effect on the observed mean x_J values ($\langle x_J \rangle$). The values of the corrections are varied by 50% as a conservative estimate of the systematic uncertainty in these corrections. This is sufficient to cover possible differences in data and simulation observed with studies of the b jet tagging efficiency in control samples in data [9, 16].

Mistagging (b jets only). The effect of mistagging signal (i.e., not combinatorial) dijets where one or both jets is not associated with a b quark is evaluated by inverting the b tagging selection for both the leading and subleading jets, both independently and

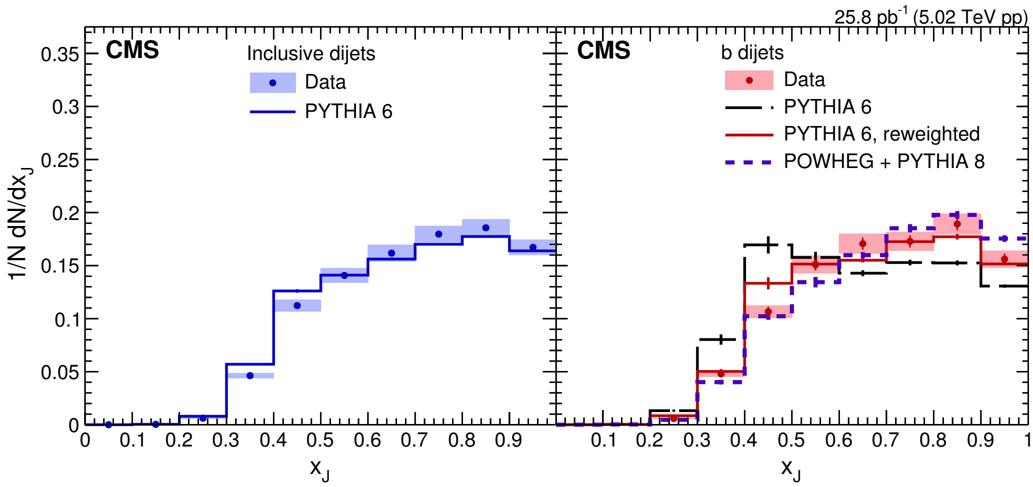

Figure 4. Distributions of x_J in pp collisions for inclusive dijets (left) and b dijets (right). Systematic uncertainties are shown as shaded boxes, while statistical uncertainties are shown as vertical lines. The data are compared to simulations performed using POWHEG and PYTHIA, as described in the text.

simultaneously. The systematic uncertainty associated with mistagging is based on the imbalance of the inverted selections, taking into account the purity of the b dijet selection in simulation, which is around 85–90%, depending slightly on centrality.

6 Results

The p_T balance, as quantified by the distribution of x_J, is presented for both inclusive and b dijets. Both sets of dijets use leading and subleading jet p_T thresholds of 100 and 40 GeV, respectively, selected from jets in $|\eta| < 1.5$. Figure 4 shows the distribution in pp collisions. The data are compared with simulations performed with PYTHIA 6, which was found to give an adequate description of the dijet balance for inclusive jets. The agreement of PYTHIA 6 with data is notably worse for b dijets, where the simulated distribution is broadened towards imbalanced jet pairs. This broad feature is not observed in the b dijet data, which instead shows an x_J distribution that resembles that of inclusive dijets. It was found that improved agreement could be obtained by reweighting the contributions of heavy-flavor production processes in PYTHIA 6, a procedure which is discussed in the appendix. The reweighted distribution is also shown in figure 4. Finally, the data are also compared to simulations based on next-to-leading order matrix elements, as encoded in the hvq package [26] of the POWHEG BOX [27] (v2) generator. Hadronization in the POWHEG method [28, 29] is performed by matching the matrix elements to parton showers, which in this case are generated with PYTHIA 8.212 [30], tune CUETP8M1 [31]. The POWHEG + PYTHIA 8 simulations are found to give a good description of the b dijet data.

Figure 5 shows the x_J distributions for inclusive dijets and b dijets for three different centrality selections of PbPb collisions. Here the data are compared to the reference obtained from pp data by smearing the p_T of each jet according to a parametrization of the resolution for the given centrality class. Figure 6 shows the $\langle x_J \rangle$ values from these distributions, as well as the difference between the $\langle x_J \rangle$ in PbPb and the smeared pp reference. The data are plotted as a function of the number of participants estimated from a Monte Carlo Glauber model [32, 33]. The number of participants is weighted by the number of collisions to account for the hard scattering bias within each bin. Both the inclusive dijet and b dijet data show a tendency towards increasing imbalance with increasing centrality. While the reference data also become more imbalanced because of resolution effects, the magnitude of the effect is clearly smaller. The effect is understood to result from jet quenching, as observed in previous inclusive dijet results [3, 34]. For inclusive dijets, a clear quenching signal is observed already for the 30–100% centrality bin. For b dijets, on the other hand, the imbalance is compatible with the pp reference in the 30–100% bin. In the 10–30% bin, the b dijet data point lies between the inclusive dijet one and the pp reference, within two standard deviations of both. Only in the most central bin (0–10%) is the b dijet quenching significant at the level of about three standard deviations, with a value close to that observed for inclusive dijets.

7 Conclusions

In this paper, transverse momentum (p_T) correlations of b quark jet pairs (b dijets) have been measured in PbPb collisions for the first time, and compared to results from pp collisions. In pp collisions, a similar p_T balance distribution was observed for inclusive dijets and b dijets. For the latter case, POWHEG was found to give a better description than PYTHIA 6 alone (without reweighting), suggesting that next-to-leading order effects are important for the modeling of this observable. This should be taken into consideration for models of parton energy loss in nucleus-nucleus collisions, which often use leading order calculations or generators as input. In PbPb collisions the net p_T imbalance was observed to be larger in the most central collisions for b dijets, as had already been observed for inclusive dijets. This effect can be understood to originate from the energy loss of partons in the quark-gluon plasma. In the most central bin, the observed quenching effect is of comparable magnitude for b dijets and for inclusive dijets, the latter of which contains a mixture of quark and gluon jets. Insofar as parton energy loss is thought to depend on the type of parton that initiates the parton shower, this measurement can place constraints on the underlying dynamics of the interaction of the parton with the quark-gluon plasma.

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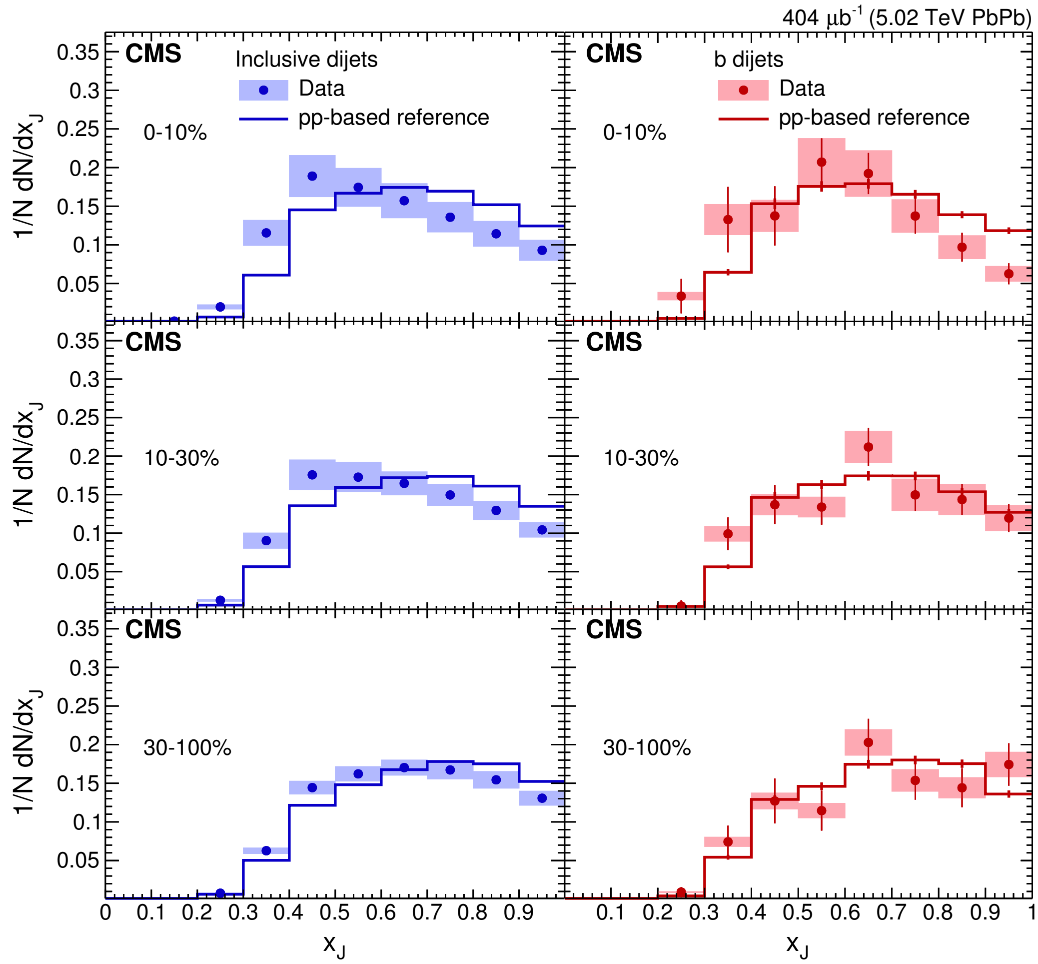

Figure 5. Distributions of x_J in PbPb collisions for inclusive dijets (left) and b dijets (right). Systematic uncertainties are shown as shaded boxes, while statistical uncertainties are shown as vertical lines. The top, middle and bottom rows show the 0–10, 10–30 and 30–100% centrality selections, respectively. The data are compared to a reference obtained by smearing pp according to the jet resolution for the given centrality class, as described in the text.

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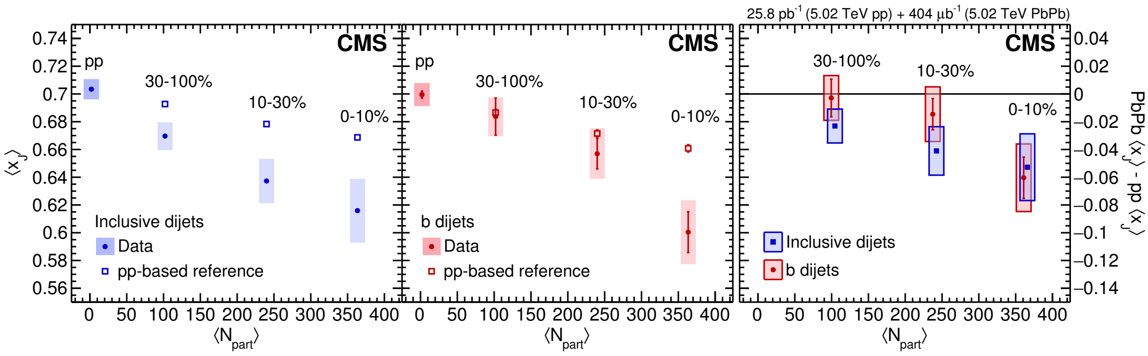

Figure 6. $\langle x_\mathrm{J} \rangle$ for inclusive (left) dijets and b dijets (center) in pp collisions and for different centrality selections of PbPb collisions. The right panel shows the difference in the $\langle x_\mathrm{J} \rangle$ values between PbPb and the smeared pp reference. Systematic uncertainties are shown as shaded boxes, while statistical uncertainties are shown as vertical lines.

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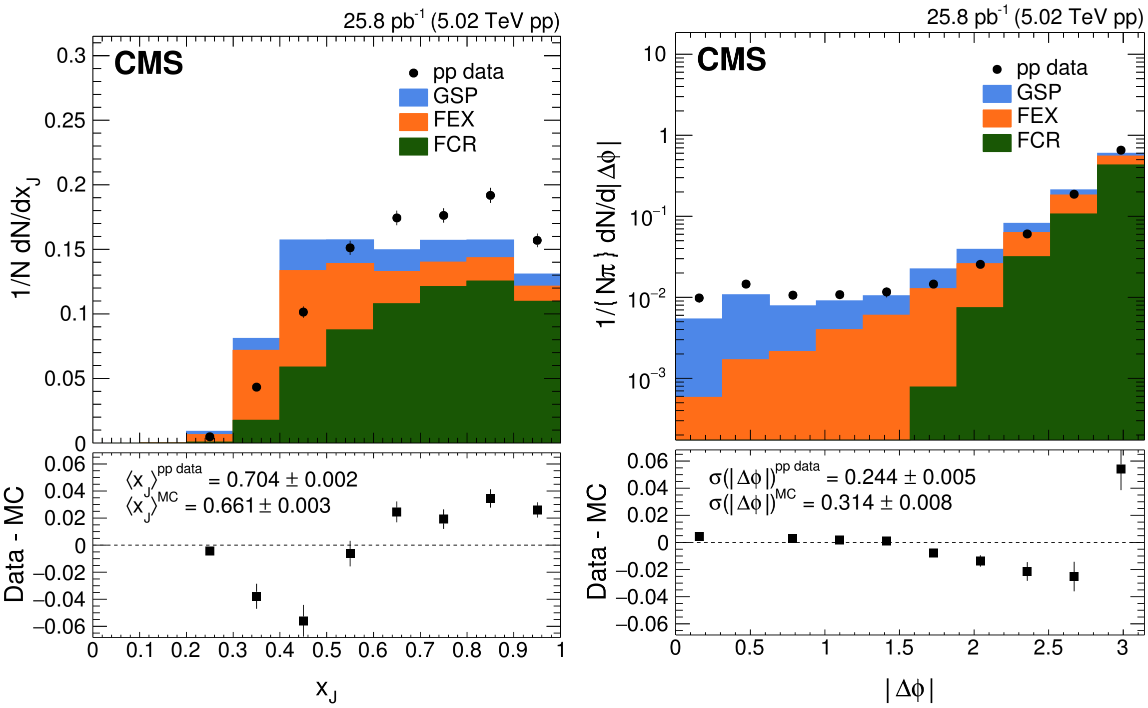

Figure 7. The distributions of x_J (left) and $\Delta\phi$ (right) in pp collisions before flavor process reweighting. Data are shown in solid points, while the stacked histograms show the contributions of different processes in PYTHIA 6 (see text for details). The bottom set of panels show the difference between data and simulation (MC).

A Heavy flavor subprocess reweighting

Whereas tunes of PYTHIA 6 used to compare to LHC data give a reasonable description of the dijet balance for inclusive jets (e.g., in ref. [34]), they fail to adequately describe the angular and p_T correlations between b jet pairs for the kinematic range probed by this measurement, as shown in the x_J and $\Delta\phi$ distributions in figure 7. To understand the nature of this discrepancy simulated $b\overline{b}$ events are separated into three categories, depending on the number of outgoing b (or $\overline{b}$) quarks in the $2 \to 2$ hard scattering. In the flavor creation process (denoted FCR), both of the outgoing particles are b quarks. The gluon fusion reaction ($gg \to b\overline{b}$) dominates, with a small contribution from quark-antiquark annihilation ($q\overline{q} \to b\overline{b}$). In the flavor excitation process (FEX) only one of the outgoing particles is b quark. In this case, a virtual gluon in one of the protons has split into a $b\overline{b}$ pair and one of the b quarks enters the hard scattering. In the process referred to here as gluon splitting (GSP), neither of the outgoing particles is a b quark. The parent may be a gluon that participates in the hard scattering or a gluon that appears elsewhere in the event, for example in a parton shower.

The discrepancy of PYTHIA 6 with the data is driven by the poor modeling of the FEX contribution, which tends to give b dijet pairs that are too asymmetric in p_T. This discrepancy was already noted by the CDF Collaboration [35], and may be understood as follows.

Category	FCR	GSP	FEX	Data	Simulation
$\|\Delta\phi_{1,2}\| > 2\pi/3$	57%	17%	26%	56%	46%
$\|\Delta\phi_{1,3}\| > 2\pi/3$	11%	27%	62%	37%	49%
$\|\Delta\phi_{1,3}\| < \pi/3$	0%	83%	17%	7%	5%

Table 2. Relative contributions of the three heavy-flavor production sub-processes in PYTHIA 6 to the jet pair categories, as well as the relative abundance of the three categories in data and simulation.

Process	Default	Reweighted
FCR	53%	70%
FEX	33%	9%
GSP	14%	21%

Table 3. Contributions of the three production processes to selected dijets in PYTHIA 6 before and after reweighting.

The partner b quark in the FEX process is treated as initial-state radiation. The PYTHIA 6 tunes require large initial-state radiation to describe TeV scale collider data. However, such tunes over-predict the probability that the partner b quark at mid-rapidity and enters the kinematic selections used in this analysis. While an improved modeling of this process can be achieved by softening the initial-state radiation, this would have an impact on other observables, in particular the overall dijet p_T balance. Instead, the contribution of the three heavy-flavor production modes are reweighted according to the following procedure. Three exclusive categories of events are defined, using jets within $|\eta| < 1.5$:

- The two highest p_T jets are b-tagged and back-to-back ($|\Delta\phi_{1,2}| > 2\pi/3$);
- The first and third highest p_T jet are b-tagged and back-to-back ($|\Delta\phi_{1,3}| > 2\pi/3$);
- The first and third highest p_T jet are b-tagged and nearby ($|\Delta\phi_{1,3}| < \pi/3$).

In simulation, these categories are found to be dominated by FCR, FEX, and GSP events, respectively. The contribution of each process in simulation is reweighted such that the relative abundance of these three categories of events are the same as in data. The relative contributions of the three heavy-flavor production sub-processes to these categories are shown in table 2. Also shown in table 2 are the relative occurrences of the three categories in data and simulation. Finally, table 3 shows the relative contribution of the three production processes to selected b dijets before and after the reweighting. The contribution of the FCR process to the selected b dijet events is found to be at the level of 70% in PYTHIA 6 after the reweighting procedure is applied. Figure 8 shows the improved agreement of the x_J and $\Delta\phi$ distributions between data and simulation after reweighting.

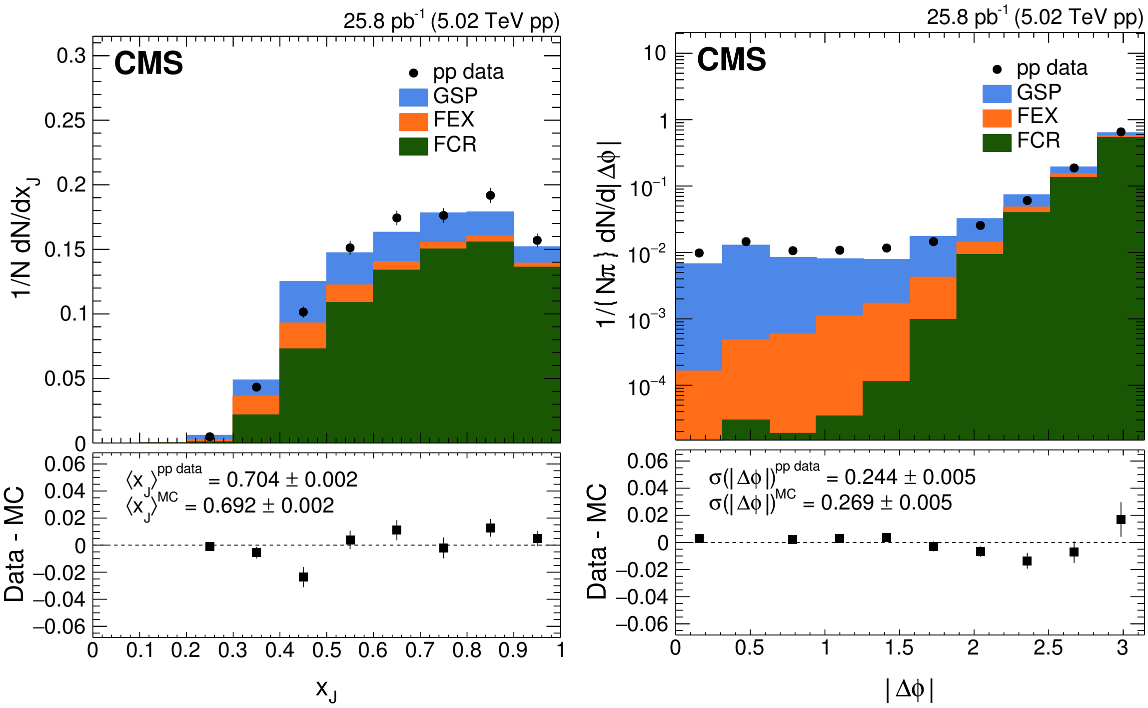

Figure 8. The distributions of x_J (left) and $\Delta\phi$ (right) in pp collisions after flavor process reweighting. Data are shown in solid points, while the stacked histograms show the contributions of different processes in PYTHIA 6 (see text for details). The bottom set of panels show the difference between data and simulation (MC).

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The CMS collaboration

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

Institut für Hochenergiephysik, Wien, Austria
W. Adam, F. Ambrogi, E. Asilar, T. Bergauer, J. Brandstetter, E. Brondolin, M. Dragicevic, J. Erö, A. Escalante Del Valle, M. Flechl, M. Friedl, R. Frühwirth[1], V.M. Ghete, J. Grossmann, J. Hrubec, M. Jeitler[1], A. König, N. Krammer, I. Krätschmer, D. Liko, T. Madlener, I. Mikulec, E. Pree, N. Rad, H. Rohringer, J. Schieck[1], R. Schöfbeck, M. Spanring, D. Spitzbart, A. Taurok, W. Waltenberger, J. Wittmann, C.-E. Wulz[1], M. Zarucki

Institute for Nuclear Problems, Minsk, Belarus
V. Chekhovsky, V. Mossolov, J. Suarez Gonzalez

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

Vrije Universiteit Brussel, Brussel, Belgium
S. Abu Zeid, F. Blekman, J. D'Hondt, I. De Bruyn, J. De Clercq, K. Deroover, G. Flouris, D. Lontkovskyi, S. Lowette, I. Marchesini, S. Moortgat, L. Moreels, Q. Python, K. Skovpen, S. Tavernier, W. Van Doninck, P. Van Mulders, I. Van Parijs

Université Libre de Bruxelles, Bruxelles, Belgium
D. Beghin, B. Bilin, H. Brun, B. Clerbaux, G. De Lentdecker, H. Delannoy, B. Dorney, G. Fasanella, L. Favart, R. Goldouzian, A. Grebenyuk, A.K. Kalsi, T. Lenzi, J. Luetic, T. Seva, E. Starling, C. Vander Velde, P. Vanlaer, D. Vannerom, R. Yonamine

Ghent University, Ghent, Belgium
T. Cornelis, D. Dobur, A. Fagot, M. Gul, I. Khvastunov[2], D. Poyraz, C. Roskas, D. Trocino, M. Tytgat, W. Verbeke, B. Vermassen, M. Vit, N. Zaganidis

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
H. Bakhshiansohi, O. Bondu, S. Brochet, G. Bruno, C. Caputo, A. Caudron, P. David, S. De Visscher, C. Delaere, M. Delcourt, B. Francois, A. Giammanco, G. Krintiras, V. Lemaitre, A. Magitteri, A. Mertens, M. Musich, K. Piotrzkowski, L. Quertenmont, A. Saggio, M. Vidal Marono, S. Wertz, J. Zobec

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

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato[3], E. Coelho, E.M. Da Costa, G.G. Da Silveira[4], D. De Jesus Damiao, S. Fonseca De Souza, H. Malbouisson, M. Medina Jaime[5], M. Melo De Almeida, C. Mora Herrera, L. Mundim, H. Nogima, L.J. Sanchez

Rosas, A. Santoro, A. Sznajder, M. Thiel, E.J. Tonelli Manganote[3], F. Torres Da Silva De Araujo, A. Vilela Pereira

Universidade Estadual Paulista [a], Universidade Federal do ABC [b], São Paulo, Brazil

S. Ahuja[a], C.A. Bernardes[a], L. Calligaris[a], T.R. Fernandez Perez Tomei[a], E.M. Gregores[b], P.G. Mercadante[b], S.F. Novaes[a], Sandra S. Padula[a], D. Romero Abad[b], J.C. Ruiz Vargas[a]

Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria

A. Aleksandrov, R. Hadjiiska, P. Iaydjiev, A. Marinov, M. Misheva, M. Rodozov, M. Shopova, G. Sultanov

University of Sofia, Sofia, Bulgaria

A. Dimitrov, L. Litov, B. Pavlov, P. Petkov

Beihang University, Beijing, China

W. Fang[6], X. Gao[6], L. Yuan

Institute of High Energy Physics, Beijing, China

M. Ahmad, J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, Y. Chen, C.H. Jiang, D. Leggat, H. Liao, Z. Liu, F. Romeo, S.M. Shaheen, A. Spiezia, J. Tao, C. Wang, Z. Wang, E. Yazgan, H. Zhang, J. Zhao

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China

Y. Ban, G. Chen, J. Li, Q. Li, S. Liu, Y. Mao, S.J. Qian, D. Wang, Z. Xu

Tsinghua University, Beijing, China

Y. Wang

Universidad de Los Andes, Bogota, Colombia

C. Avila, A. Cabrera, C.A. Carrillo Montoya, L.F. Chaparro Sierra, C. Florez, C.F. González Hernández, M.A. Segura Delgado

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia

B. Courbon, N. Godinovic, D. Lelas, I. Puljak, 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, B. Mesic, A. Starodumov[7], T. Susa

University of Cyprus, Nicosia, Cyprus

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

Charles University, Prague, Czech Republic

M. Finger[8], M. Finger Jr.[8]

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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
H. Abdalla[9], M.A. Mahmoud[10,11], Y. Mohammed[10]

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
S. Bhowmik, R.K. Dewanjee, M. Kadastik, L. Perrini, M. Raidal, C. Veelken

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

Helsinki Institute of Physics, Helsinki, Finland
J. Havukainen, J.K. Heikkilä, T. Järvinen, V. Karimäki, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Laurila, S. Lehti, T. Lindén, P. Luukka, T. Mäenpää, H. Siikonen, E. Tuominen, J. Tuominiemi

Lappeenranta University of Technology, Lappeenranta, Finland
T. Tuuva

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
M. Besancon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, S. Ghosh, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, C. Leloup, E. Locci, M. Machet, J. Malcles, G. Negro, J. Rander, A. Rosowsky, M.Ö. Sahin, M. Titov

Laboratoire Leprince-Ringuet, Ecole polytechnique, CNRS/IN2P3, Université Paris-Saclay, Palaiseau, France
A. Abdulsalam[12], C. Amendola, I. Antropov, S. Baffioni, F. Beaudette, P. Busson, L. Cadamuro, C. Charlot, R. Granier de Cassagnac, M. Jo, I. Kucher, S. Lisniak, A. Lobanov, J. Martin Blanco, M. Nguyen, C. Ochando, G. Ortona, P. Paganini, P. Pigard, R. Salerno, J.B. Sauvan, Y. Sirois, A.G. Stahl Leiton, Y. Yilmaz, A. Zabi, A. Zghiche

Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France
J.-L. Agram[13], J. Andrea, D. Bloch, J.-M. Brom, E.C. Chabert, C. Collard, E. Conte[13], X. Coubez, F. Drouhin[13], J.-C. Fontaine[13], D. Gelé, U. Goerlach, M. Jansová, P. Juillot, A.-C. Le Bihan, N. Tonon, P. Van Hove

Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France
S. Gadrat

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France
S. Beauceron, C. Bernet, G. Boudoul, N. Chanon, R. Chierici, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, L. Finco, S. Gascon, M. Gouzevitch, G. Grenier, B. Ille, F. Lagarde, I.B. Laktineh, H. Lattaud, M. Lethuillier, L. Mirabito, A.L. Pequegnot, S. Perries, A. Popov[14], V. Sordini, M. Vander Donckt, S. Viret, S. Zhang

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Georgian Technical University, Tbilisi, Georgia
T. Toriashvili[15]

Tbilisi State University, Tbilisi, Georgia
Z. Tsamalaidze[8]

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
C. Autermann, L. Feld, M.K. Kiesel, K. Klein, M. Lipinski, M. Preuten, M.P. Rauch, C. Schomakers, J. Schulz, M. Teroerde, B. Wittmer, V. Zhukov[14]

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
A. Albert, D. Duchardt, M. Endres, M. Erdmann, S. Erdweg, T. Esch, R. Fischer, A. Güth, T. Hebbeker, C. Heidemann, K. Hoepfner, S. Knutzen, M. Merschmeyer, A. Meyer, P. Millet, S. Mukherjee, T. Pook, M. Radziej, H. Reithler, M. Rieger, F. Scheuch, D. Teyssier, S. Thüer

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
G. Flügge, B. Kargoll, T. Kress, A. Künsken, T. Müller, A. Nehrkorn, A. Nowack, C. Pistone, O. Pooth, A. Stahl[16]

Deutsches Elektronen-Synchrotron, Hamburg, Germany
M. Aldaya Martin, T. Arndt, C. Asawatangtrakuldee, K. Beernaert, O. Behnke, U. Behrens, A. Bermúdez Martínez, A.A. Bin Anuar, K. Borras[17], V. Botta, A. Campbell, P. Connor, C. Contreras-Campana, F. Costanza, V. Danilov, A. De Wit, C. Diez Pardos, D. Domínguez Damiani, G. Eckerlin, D. Eckstein, T. Eichhorn, E. Eren, E. Gallo[18], J. Garay Garcia, A. Geiser, J.M. Grados Luyando, A. Grohsjean, P. Gunnellini, M. Guthoff, A. Harb, J. Hauk, M. Hempel[19], H. Jung, M. Kasemann, J. Keaveney, C. Kleinwort, J. Knolle, I. Korol, D. Krücker, W. Lange, A. Lelek, T. Lenz, K. Lipka, W. Lohmann[19], R. Mankel, I.-A. Melzer-Pellmann, A.B. Meyer, M. Meyer, M. Missiroli, G. Mittag, J. Mnich, A. Mussgiller, D. Pitzl, A. Raspereza, M. Savitskyi, P. Saxena, R. Shevchenko, N. Stefaniuk, H. Tholen, G.P. Van Onsem, R. Walsh, Y. Wen, K. Wichmann, C. Wissing, O. Zenaiev

University of Hamburg, Hamburg, Germany
R. Aggleton, S. Bein, V. Blobel, M. Centis Vignali, T. Dreyer, E. Garutti, D. Gonzalez, J. Haller, A. Hinzmann, M. Hoffmann, A. Karavdina, G. Kasieczka, R. Klanner, R. Kogler, N. Kovalchuk, S. Kurz, D. Marconi, J. Multhaup, M. Niedziela, D. Nowatschin, T. Peiffer, A. Perieanu, A. Reimers, C. Scharf, P. Schleper, A. Schmidt, S. Schumann, J. Schwandt, J. Sonneveld, H. Stadie, G. Steinbrück, F.M. Stober, M. Stöver, D. Troendle, E. Usai, A. Vanhoefer, B. Vormwald

Institut für Experimentelle Teilchenphysik, Karlsruhe, Germany
M. Akbiyik, C. Barth, M. Baselga, S. Baur, E. Butz, R. Caspart, T. Chwalek, F. Colombo, W. De Boer, A. Dierlamm, N. Faltermann, B. Freund, R. Friese, M. Giffels, M.A. Harrendorf, F. Hartmann[16], S.M. Heindl, U. Husemann, F. Kassel[16], S. Kudella, H. Mildner, M.U. Mozer, Th. Müller, M. Plagge, G. Quast, K. Rabbertz, M. Schröder, I. Shvetsov,

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G. Sieber, H.J. Simonis, R. Ulrich, S. Wayand, M. Weber, T. Weiler, S. Williamson, C. Wöhrmann, R. Wolf

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

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

National and Kapodistrian University of Athens, Athens, Greece

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

National Technical University of Athens, Athens, Greece

K. Kousouris, I. Papakrivopoulos

University of Ioánnina, Ioánnina, Greece

I. Evangelou, C. Foudas, P. Gianneios, P. Katsoulis, P. Kokkas, S. Mallios, N. Manthos, I. Papadopoulos, E. Paradas, J. Strologas, F.A. Triantis, D. Tsitsonis

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

M. Csanad, N. Filipovic, G. Pasztor, O. Surányi, G.I. Veres[20]

Wigner Research Centre for Physics, Budapest, Hungary

G. Bencze, C. Hajdu, D. Horvath[21], Á. Hunyadi, F. Sikler, V. Veszpremi, G. Vesztergombi[20], T.Á. Vámi

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

N. Beni, S. Czellar, J. Karancsi[22], A. Makovec, J. Molnar, Z. Szillasi

Institute of Physics, University of Debrecen, Debrecen, Hungary

M. Bartók[20], P. Raics, Z.L. Trocsanyi, B. Ujvari

Indian Institute of Science (IISc), Bangalore, India

S. Choudhury, J.R. Komaragiri

National Institute of Science Education and Research, Bhubaneswar, India

S. Bahinipati[23], P. Mal, K. Mandal, A. Nayak[24], D.K. Sahoo[23], S.K. Swain

Panjab University, Chandigarh, India

S. Bansal, S.B. Beri, V. Bhatnagar, S. Chauhan, R. Chawla, N. Dhingra, R. Gupta, A. Kaur, M. Kaur, S. Kaur, R. Kumar, P. Kumari, M. Lohan, A. Mehta, S. Sharma, J.B. Singh, G. Walia

University of Delhi, Delhi, India

Ashok Kumar, Aashaq Shah, A. Bhardwaj, B.C. Choudhary, R.B. Garg, S. Keshri, A. Kumar, S. Malhotra, M. Naimuddin, K. Ranjan, R. Sharma

Saha Institute of Nuclear Physics, HBNI, Kolkata, India

R. Bhardwaj[25], R. Bhattacharya, S. Bhattacharya, U. Bhawandeep[25], D. Bhowmik, S. Dey, S. Dutt[25], S. Dutta, S. Ghosh, N. Majumdar, K. Mondal, S. Mukhopadhyay, S. Nandan, A. Purohit, P.K. Rout, A. Roy, S. Roy Chowdhury, S. Sarkar, M. Sharan, B. Singh, S. Thakur[25]

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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[16], P.K. Netrakanti, L.M. Pant, P. Shukla, A. Topkar

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

Tata Institute of Fundamental Research-B, Mumbai, India
S. Banerjee, S. Bhattacharya, S. Chatterjee, P. Das, M. Guchait, Sa. Jain, S. Kumar, M. Maity[26], G. Majumder, K. Mazumdar, N. Sahoo, T. Sarkar[26], N. Wickramage[27]

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

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
S. Chenarani[28], E. Eskandari Tadavani, S.M. Etesami[28], M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi[29], F. Rezaei Hosseinabadi, B. Safarzadeh[30], M. Zeinali

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

INFN Sezione di Bari [a], Università di Bari [b], Politecnico di Bari [c], Bari, Italy
M. Abbrescia[a,b], C. Calabria[a,b], A. Colaleo[a], D. Creanza[a,c], L. Cristella[a,b], N. De Filippis[a,c], M. De Palma[a,b], A. Di Florio[a,b], F. Errico[a,b], L. Fiore[a], A. Gelmi[a,b], G. Iaselli[a,c], S. Lezki[a,b], G. Maggi[a,c], M. Maggi[a], B. Marangelli[a,b], G. Miniello[a,b], S. My[a,b], S. Nuzzo[a,b], A. Pompili[a,b], G. Pugliese[a,c], R. Radogna[a], A. Ranieri[a], G. Selvaggi[a,b], A. Sharma[a], L. Silvestris[a,16], R. Venditti[a], P. Verwilligen[a], G. Zito[a]

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

INFN Sezione di Catania [a], Università di Catania [b], Catania, Italy
S. Albergo[a,b], S. Costa[a,b], A. Di Mattia[a], F. Giordano[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], K. Chatterjee[a,b], V. Ciulli[a,b], C. Civinini[a], R. D'Alessandro[a,b], E. Focardi[a,b], G. Latino, P. Lenzi[a,b], M. Meschini[a], S. Paoletti[a], L. Russo[a,31], G. Sguazzoni[a], D. Strom[a], L. Viliani[a]

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INFN Laboratori Nazionali di Frascati, Frascati, Italy

L. Benussi, S. Bianco, F. Fabbri, D. Piccolo, F. Primavera[16]

INFN Sezione di Genova [a], Università di Genova [b], Genova, Italy

V. Calvelli[a,b], F. Ferro[a], F. Ravera[a,b], E. Robutti[a], S. Tosi[a,b]

INFN Sezione di Milano-Bicocca [a], Università di Milano-Bicocca [b], Milano, Italy

A. Benaglia[a], A. Beschi[b], L. Brianza[a,b], F. Brivio[a,b], V. Ciriolo[a,b,16], M.E. Dinardo[a,b], S. Fiorendi[a,b], S. Gennai[a], A. Ghezzi[a,b], P. Govoni[a,b], M. Malberti[a,b], S. Malvezzi[a], R.A. Manzoni[a,b], D. Menasce[a], L. Moroni[a], M. Paganoni[a,b], K. Pauwels[a,b], D. Pedrini[a], S. Pigazzini[a,b,32], S. Ragazzi[a,b], T. Tabarelli de Fatis[a,b]

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

S. Buontempo[a], N. Cavallo[a,c], S. Di Guida[a,d,16], F. Fabozzi[a,c], F. Fienga[a,b], G. Galati[a,b], A.O.M. Iorio[a,b], W.A. Khan[a], L. Lista[a], S. Meola[a,d,16], P. Paolucci[a,16], C. Sciacca[a,b], F. Thyssen[a], E. Voevodina[a,b]

INFN Sezione di Padova [a], Università di Padova [b], Padova, Italy, Università di Trento [c], Trento, Italy

P. Azzi[a], N. Bacchetta[a], L. Benato[a,b], D. Bisello[a,b], A. Boletti[a,b], R. Carlin[a,b], A. Carvalho Antunes De Oliveira[a,b], P. Checchia[a], M. Dall'Osso[a,b], P. De Castro Manzano[a], T. Dorigo[a], U. Dosselli[a], F. Gasparini[a,b], U. Gasparini[a,b], A. Gozzelino[a], S. Lacaprara[a], P. Lujan, M. Margoni[a,b], N. Pozzobon[a,b], P. Ronchese[a,b], R. Rossin[a,b], F. Simonetto[a,b], A. Tiko, E. Torassa[a], M. Zanetti[a,b], P. Zotto[a,b], G. Zumerle[a,b]

INFN Sezione di Pavia [a], Università di Pavia [b], Pavia, Italy

A. Braghieri[a], A. Magnani[a], P. Montagna[a,b], S.P. Ratti[a,b], V. Re[a], M. Ressegotti[a,b], C. Riccardi[a,b], P. Salvini[a], I. Vai[a,b], P. Vitulo[a,b]

INFN Sezione di Perugia [a], Università di Perugia [b], Perugia, Italy

L. Alunni Solestizi[a,b], M. Biasini[a,b], G.M. Bilei[a], C. Cecchi[a,b], D. Ciangottini[a,b], L. Fanò[a,b], P. Lariccia[a,b], R. Leonardi[a,b], E. Manoni[a], G. Mantovani[a,b], V. Mariani[a,b], M. Menichelli[a], A. Rossi[a,b], A. Santocchia[a,b], D. Spiga[a]

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

K. Androsov[a], P. Azzurri[a,16], G. Bagliesi[a], L. Bianchini[a], T. Boccali[a], L. Borrello, R. Castaldi[a], M.A. Ciocci[a,b], R. Dell'Orso[a], G. Fedi[a], L. Giannini[a,c], A. Giassi[a], M.T. Grippo[a,31], F. Ligabue[a,c], T. Lomtadze[a], E. Manca[a,c], G. Mandorli[a,c], A. Messineo[a,b], F. Palla[a], A. Rizzi[a,b], P. Spagnolo[a], R. Tenchini[a], G. Tonelli[a,b], A. Venturi[a], P.G. Verdini[a]

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INFN Sezione di Roma [a], Sapienza Università di Roma [b], Rome, Italy
L. Barone[a,b], F. Cavallari[a], M. Cipriani[a,b], N. Daci[a], D. Del Re[a,b], E. Di Marco[a,b], M. Diemoz[a], S. Gelli[a,b], E. Longo[a,b], B. Marzocchi[a,b], P. Meridiani[a], G. Organtini[a,b], F. Pandolfi[a], R. Paramatti[a,b], F. Preiato[a,b], S. Rahatlou[a,b], C. Rovelli[a], F. Santanastasio[a,b]

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

INFN Sezione di Trieste [a], Università di Trieste [b], Trieste, Italy
S. Belforte[a], M. Casarsa[a], F. Cossutti[a], G. Della Ricca[a,b], A. Zanetti[a]

Kyungpook National University
D.H. Kim, G.N. Kim, M.S. Kim, J. Lee, S. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, S. Sekmen, D.C. Son, Y.C. Yang

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
H. Kim, D.H. Moon, G. Oh

Hanyang University, Seoul, Korea
J.A. Brochero Cifuentes, J. Goh, T.J. Kim

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

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

University of Seoul, Seoul, Korea
H. Kim, J.H. Kim, J.S.H. Lee, I.C. Park

Sungkyunkwan University, Suwon, Korea
Y. Choi, C. Hwang, J. Lee, I. Yu

Vilnius University, Vilnius, Lithuania
V. Dudenas, A. Juodagalvis, J. Vaitkus

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
I. Ahmed, Z.A. Ibrahim, M.A.B. Md Ali[33], F. Mohamad Idris[34], W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

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Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
Reyes-Almanza, R, Ramirez-Sanchez, G., Duran-Osuna, M. C., H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz[35], Rabadan-Trejo, R. I., R. Lopez-Fernandez, J. Mejia Guisao, A. Sanchez-Hernandez

Universidad Iberoamericana, Mexico City, Mexico
S. Carrillo Moreno, C. Oropeza Barrera, F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
J. Eysermans, I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico
A. Morelos Pineda

University of Auckland, Auckland, New Zealand
D. Krofcheck

University of Canterbury, Christchurch, New Zealand
P.H. Butler

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

National Centre for Nuclear Research, Swierk, Poland
H. Bialkowska, M. Bluj, B. Boimska, T. Frueboes, M. Górski, M. Kazana, K. Nawrocki, M. Szleper, P. Traczyk, P. Zalewski

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
K. Bunkowski, A. Byszuk[36], K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, A. Pyskir, M. Walczak

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

Joint Institute for Nuclear Research, Dubna, Russia
S. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavin, A. Lanev, A. Malakhov, V. Matveev[37,38], P. Moisenz, V. Palichik, V. Perelygin, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, N. Voytishin, A. Zarubin

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia
Y. Ivanov, V. Kim[39], E. Kuznetsova[40], P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev

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Institute for Nuclear Research, Moscow, Russia

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

Institute for Theoretical and Experimental Physics, Moscow, Russia

V. Epshteyn, V. Gavrilov, N. Lychkovskaya, V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, A. Stepennov, V. Stolin, M. Toms, E. Vlasov, A. Zhokin

Moscow Institute of Physics and Technology, Moscow, Russia

T. Aushev, A. Bylinkin[38]

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

R. Chistov[41], M. Danilov[41], P. Parygin, D. Philippov, S. Polikarpov, E. Tarkovskii

P.N. Lebedev Physical Institute, Moscow, Russia

V. Andreev, M. Azarkin[38], I. Dremin[38], M. Kirakosyan[38], S.V. Rusakov, A. Terkulov

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

A. Baskakov, A. Belyaev, E. Boos, A. Demiyanov, A. Ershov, A. Gribushin, O. Kodolova, V. Korotkikh, I. Lokhtin, I. Miagkov, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev, I. Vardanyan

Novosibirsk State University (NSU), Novosibirsk, Russia

V. Blinov[42], D. Shtol[42], Y. Skovpen[42]

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

I. Azhgirey, I. Bayshev, S. Bitioukov, D. Elumakhov, A. Godizov, V. Kachanov, A. Kalinin, D. Konstantinov, P. Mandrik, V. Petrov, R. Ryutin, A. Sobol, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

National Research Tomsk Polytechnic University, Tomsk, Russia

A. Babaev

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

P. Adzic[43], P. Cirkovic, D. Devetak, M. Dordevic, J. Milosevic

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

J. Alcaraz Maestre, I. Bachiller, M. Barrio Luna, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, C. Fernandez Bedoya, J.P. Fernández Ramos, J. Flix, M.C. Fouz, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, D. Moran, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, L. Romero, M.S. Soares, A. Triossi, A. Álvarez Fernández

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Universidad Autónoma de Madrid, Madrid, Spain

C. Albajar, J.F. de Trocóniz

Universidad de Oviedo, Oviedo, Spain

J. Cuevas, C. Erice, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, J.R. González Fernández, E. Palencia Cortezon, S. Sanchez Cruz, P. Vischia, J.M. Vizan Garcia

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

I.J. Cabrillo, A. Calderon, B. Chazin Quero, J. Duarte Campderros, M. Fernandez, P.J. Fernández Manteca, J. Garcia-Ferrero, A. García Alonso, G. Gomez, A. Lopez Virto, J. Marco, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, J. Piedra Gomez, C. Prieels, T. Rodrigo, A. Ruiz-Jimeno, L. Scodellaro, N. Trevisani, I. Vila, R. Vilar Cortabitarte

CERN, European Organization for Nuclear Research, Geneva, Switzerland

D. Abbaneo, B. Akgun, E. Auffray, P. Baillon, A.H. Ball, D. Barney, J. Bendavid, M. Bianco, A. Bocci, C. Botta, T. Camporesi, M. Cepeda, G. Cerminara, E. Chapon, Y. Chen, D. d'Enterria, A. Dabrowski, V. Daponte, A. David, M. De Gruttola, A. De Roeck, N. Deelen, M. Dobson, T. du Pree, M. Dünser, N. Dupont, A. Elliott-Peisert, P. Everaerts, F. Fallavollita[44], G. Franzoni, J. Fulcher, W. Funk, D. Gigi, A. Gilbert, K. Gill, F. Glege, D. Gulhan, J. Hegeman, V. Innocente, A. Jafari, P. Janot, O. Karacheban[19], J. Kieseler, V. Knünz, A. Kornmayer, M. Krammer[1], C. Lange, P. Lecoq, C. Lourenço, M.T. Lucchini, L. Malgeri, M. Mannelli, A. Martelli, F. Meijers, J.A. Merlin, S. Mersi, E. Meschi, P. Milenovic[45], F. Moortgat, M. Mulders, H. Neugebauer, J. Ngadiuba, S. Orfanelli, L. Orsini, F. Pantaleo[16], L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, F.M. Pitters, D. Rabady, A. Racz, T. Reis, G. Rolandi[46], M. Rovere, H. Sakulin, C. Schäfer, C. Schwick, M. Seidel, M. Selvaggi, A. Sharma, P. Silva, P. Sphicas[47], A. Stakia, J. Steggemann, M. Stoye, M. Tosi, D. Treille, A. Tsirou, V. Veckalns[48], M. Verweij, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland

W. Bertl[†], L. Caminada[49], K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe, S.A. Wiederkehr

ETH Zurich - Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland

M. Backhaus, L. Bäni, P. Berger, B. Casal, N. Chernyavskaya, G. Dissertori, M. Dittmar, M. Donegà, C. Dorfer, C. Grab, C. Heidegger, D. Hits, J. Hoss, T. Klijnsma, W. Lustermann, M. Marionneau, M.T. Meinhard, D. Meister, F. Micheli, P. Musella, F. Nessi-Tedaldi, J. Pata, F. Pauss, G. Perrin, L. Perrozzi, M. Quittnat, M. Reichmann, D. Ruini, D.A. Sanz Becerra, M. Schönenberger, L. Shchutska, V.R. Tavolaro, K. Theofilatos, M.L. Vesterbacka Olsson, R. Wallny, D.H. Zhu

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Universität Zürich, Zurich, Switzerland

T.K. Aarrestad, C. Amsler[50], D. Brzhechko, M.F. Canelli, A. De Cosa, R. Del Burgo, S. Donato, C. Galloni, T. Hreus, B. Kilminster, I. Neutelings, D. Pinna, G. Rauco, P. Robmann, D. Salerno, K. Schweiger, C. Seitz, Y. Takahashi, A. Zucchetta

National Central University, Chung-Li, Taiwan

V. Candelise, Y.H. Chang, K.y. Cheng, T.H. Doan, Sh. Jain, R. Khurana, C.M. Kuo, W. Lin, A. Pozdnyakov, S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan

Arun Kumar, P. Chang, Y. Chao, K.F. Chen, P.H. Chen, F. Fiori, W.-S. Hou, Y. Hsiung, Y.F. Liu, R.-S. Lu, E. Paganis, A. Psallidas, A. Steen, J.f. Tsai

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

B. Asavapibhop, K. Kovitanggoon, G. Singh, N. Srimanobhas

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

A. Bat, F. Boran, S. Cerci[51], S. Damarseckin, Z.S. Demiroglu, C. Dozen, I. Dumanoglu, S. Girgis, G. Gokbulut, Y. Guler, I. Hos[52], E.E. Kangal[53], O. Kara, A. Kayis Topaksu, U. Kiminsu, M. Oglakci, G. Onengut, K. Ozdemir[54], D. Sunar Cerci[51], U.G. Tok, H. Topakli[55], S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

Middle East Technical University, Physics Department, Ankara, Turkey

G. Karapinar[56], K. Ocalan[57], M. Yalvac, M. Zeyrek

Bogazici University, Istanbul, Turkey

E. Gülmez, M. Kaya[58], O. Kaya[59], S. Tekten, E.A. Yetkin[60]

Istanbul Technical University, Istanbul, Turkey

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

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

B. Grynyov

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

L. Levchuk

University of Bristol, Bristol, United Kingdom

F. Ball, L. Beck, J.J. Brooke, D. Burns, E. Clement, D. Cussans, O. Davignon, H. Flacher, J. Goldstein, G.P. Heath, H.F. Heath, L. Kreczko, D.M. Newbold[61], S. Paramesvaran, T. Sakuma, S. Seif El Nasr-storey, D. Smith, V.J. Smith

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Rutherford Appleton Laboratory, Didcot, United Kingdom
A. Belyaev[62], C. Brew, R.M. Brown, D. Cieri, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, J. Linacre, E. Olaiya, D. Petyt, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams, W.J. Womersley

Imperial College, London, United Kingdom
G. Auzinger, R. Bainbridge, P. Bloch, J. Borg, S. Breeze, O. Buchmuller, A. Bundock, S. Casasso, D. Colling, L. Corpe, P. Dauncey, G. Davies, M. Della Negra, R. Di Maria, A. Elwood, Y. Haddad, G. Hall, G. Iles, T. James, M. Komm, R. Lane, C. Laner, L. Lyons, A.-M. Magnan, S. Malik, L. Mastrolorenzo, T. Matsushita, J. Nash[63], A. Nikitenko[7], V. Palladino, M. Pesaresi, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, T. Strebler, S. Summers, A. Tapper, K. Uchida, M. Vazquez Acosta[64], T. Virdee[16], N. Wardle, D. Winterbottom, J. Wright, S.C. Zenz

Brunel University, Uxbridge, United Kingdom
J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, A. Morton, I.D. Reid, L. Teodorescu, S. Zahid

Baylor University, Waco, U.S.A.
A. Borzou, K. Call, J. Dittmann, K. Hatakeyama, H. Liu, N. Pastika, C. Smith

Catholic University of America, Washington DC, U.S.A.
R. Bartek, A. Dominguez

The University of Alabama, Tuscaloosa, U.S.A.
A. Buccilli, S.I. Cooper, C. Henderson, P. Rumerio, C. West

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

Brown University, Providence, U.S.A.
G. Benelli, D. Cutts, M. Hadley, J. Hakala, U. Heintz, J.M. Hogan[65], K.H.M. Kwok, E. Laird, G. Landsberg, J. Lee, Z. Mao, M. Narain, J. Pazzini, S. Piperov, S. Sagir, R. Syarif, D. Yu

University of California, Davis, Davis, U.S.A.
R. Band, C. Brainerd, R. Breedon, D. Burns, M. Calderon De La Barca Sanchez, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, C. Flores, G. Funk, W. Ko, R. Lander, C. Mclean, M. Mulhearn, D. Pellett, J. Pilot, S. Shalhout, M. Shi, J. Smith, D. Stolp, D. Taylor, K. Tos, M. Tripathi, Z. Wang, F. Zhang

University of California, Los Angeles, U.S.A.
M. Bachtis, C. Bravo, R. Cousins, A. Dasgupta, A. Florent, J. Hauser, M. Ignatenko, N. Mccoll, S. Regnard, D. Saltzberg, C. Schnaible, V. Valuev

University of California, Riverside, Riverside, U.S.A.
E. Bouvier, K. Burt, R. Clare, J. Ellison, J.W. Gary, S.M.A. Ghiasi Shirazi, G. Hanson, G. Karapostoli, E. Kennedy, F. Lacroix, O.R. Long, M. Olmedo Negrete, M.I. Paneva, W. Si, L. Wang, H. Wei, S. Wimpenny, B. R. Yates

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University of California, San Diego, La Jolla, U.S.A.

J.G. Branson, S. Cittolin, M. Derdzinski, R. Gerosa, D. Gilbert, B. Hashemi, A. Holzner, D. Klein, G. Kole, V. Krutelyov, J. Letts, M. Masciovecchio, D. Olivito, S. Padhi, M. Pieri, M. Sani, V. Sharma, S. Simon, M. Tadel, A. Vartak, S. Wasserbaech[66], J. Wood, F. Würthwein, A. Yagil, G. Zevi Della Porta

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

N. Amin, R. Bhandari, J. Bradmiller-Feld, C. Campagnari, M. Citron, A. Dishaw, V. Dutta, M. Franco Sevilla, L. Gouskos, R. Heller, J. Incandela, A. Ovcharova, H. Qu, J. Richman, D. Stuart, I. Suarez, J. Yoo

California Institute of Technology, Pasadena, U.S.A.

D. Anderson, A. Bornheim, J. Bunn, J.M. Lawhorn, H.B. Newman, T. Q. Nguyen, C. Pena, M. Spiropulu, J.R. Vlimant, R. Wilkinson, S. Xie, Z. Zhang, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, U.S.A.

M.B. Andrews, T. Ferguson, T. Mudholkar, M. Paulini, J. Russ, M. Sun, H. Vogel, I. Vorobiev, M. Weinberg

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

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

Cornell University, Ithaca, U.S.A.

J. Alexander, J. Chaves, Y. Cheng, J. Chu, A. Datta, K. Mcdermott, N. Mirman, J.R. Patterson, D. Quach, A. Rinkevicius, A. Ryd, L. Skinnari, L. Soffi, S.M. Tan, Z. Tao, J. Thom, J. Tucker, P. Wittich, M. Zientek

Fermi National Accelerator Laboratory, Batavia, U.S.A.

S. Abdullin, M. Albrow, M. Alyari, G. Apollinari, A. Apresyan, A. Apyan, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, G. Bolla[†], K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, M. Cremonesi, J. Duarte, V.D. Elvira, J. Freeman, Z. Gecse, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, J. Hanlon, R.M. Harris, S. Hasegawa, J. Hirschauer, Z. Hu, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, B. Klima, M.J. Kortelainen, B. Kreis, S. Lammel, D. Lincoln, R. Lipton, M. Liu, T. Liu, R. Lopes De Sá, J. Lykken, K. Maeshima, N. Magini, J.M. Marraffino, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, V. O'Dell, K. Pedro, O. Prokofyev, G. Rakness, L. Ristori, A. Savoy-Navarro[67], B. Schneider, E. Sexton-Kennedy, A. Soha, W.J. Spalding, L. Spiegel, S. Stoynev, J. Strait, N. Strobbe, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, C. Vernieri, M. Verzocchi, R. Vidal, M. Wang, H.A. Weber, A. Whitbeck, W. Wu

University of Florida, Gainesville, U.S.A.

D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, A. Brinkerhoff, A. Carnes, M. Carver, D. Curry, R.D. Field, I.K. Furic, S.V. Gleyzer, B.M. Joshi, J. Konigsberg, A. Korytov,

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K. Kotov, P. Ma, K. Matchev, H. Mei, G. Mitselmakher, K. Shi, D. Sperka, N. Terentyev, L. Thomas, J. Wang, S. Wang, J. Yelton

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

Y.R. Joshi, S. Linn, P. Markowitz, J.L. Rodriguez

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

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

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

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

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

M.R. Adams, L. Apanasevich, D. Berry, R.R. Betts, R. Cavanaugh, X. Chen, S. Dittmer, O. Evdokimov, C.E. Gerber, D.A. Hangal, D.J. Hofman, K. Jung, J. Kamin, I.D. Sandoval Gonzalez, M.B. Tonjes, N. Varelas, H. Wang, Z. Wu, J. Zhang

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

B. Bilki[68], W. Clarida, K. Dilsiz[69], S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, H. Mermerkaya[70], A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul[71], Y. Onel, F. Ozok[72], A. Penzo, C. Snyder, E. Tiras, J. Wetzel, K. Yi

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

B. Blumenfeld, A. Cocoros, N. Eminizer, D. Fehling, L. Feng, A.V. Gritsan, P. Maksimovic, J. Roskes, U. Sarica, M. Swartz, M. Xiao, C. You

The University of Kansas, Lawrence, U.S.A.

A. Al-bataineh, P. Baringer, A. Bean, S. Boren, J. Bowen, J. Castle, S. Khalil, A. Kropivnitskaya, D. Majumder, W. Mcbrayer, M. Murray, C. Rogan, C. Royon, S. Sanders, E. Schmitz, J.D. Tapia Takaki, Q. Wang

Kansas State University, Manhattan, U.S.A.

A. Ivanov, K. Kaadze, Y. Maravin, A. Modak, A. Mohammadi, L.K. Saini, N. Skhirtladze

Lawrence Livermore National Laboratory, Livermore, U.S.A.

F. Rebassoo, D. Wright

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

A. Baden, O. Baron, A. Belloni, S.C. Eno, Y. Feng, C. Ferraioli, N.J. Hadley, S. Jabeen, G.Y. Jeng, R.G. Kellogg, J. Kunkle, A.C. Mignerey, F. Ricci-Tam, Y.H. Shin, A. Skuja, S.C. Tonwar

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

D. Abercrombie, B. Allen, V. Azzolini, R. Barbieri, A. Baty, G. Bauer, R. Bi, S. Brandt, W. Busza, I.A. Cali, M. D'Alfonso, Z. Demiragli, G. Gomez Ceballos, M. Goncharov, P. Harris, D. Hsu, M. Hu, Y. Iiyama, G.M. Innocenti, M. Klute, D. Kovalskyi, Y.-J. Lee, A. Levin, P.D. Luckey, B. Maier, A.C. Marini, C. Mcginn, C. Mironov, S. Narayanan,

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X. Niu, C. Paus, C. Roland, G. Roland, G.S.F. Stephans, K. Sumorok, K. Tatar, D. Velicanu, J. Wang, T.W. Wang, B. Wyslouch, S. Zhaozhong

University of Minnesota, Minneapolis, U.S.A.

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

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

J.G. Acosta, S. Oliveros

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

E. Avdeeva, K. Bloom, D.R. Claes, C. Fangmeier, F. Golf, R. Gonzalez Suarez, R. Kamalieddin, I. Kravchenko, J. Monroy, J.E. Siado, G.R. Snow, B. Stieger

State University of New York at Buffalo, Buffalo, U.S.A.

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

Northeastern University, Boston, U.S.A.

G. Alverson, E. Barberis, C. Freer, A. Hortiangtham, A. Massironi, D.M. Morse, T. Orimoto, R. Teixeira De Lima, T. Wamorkar, B. Wang, A. Wisecarver, D. Wood

Northwestern University, Evanston, U.S.A.

S. Bhattacharya, O. Charaf, K.A. Hahn, N. Mucia, N. Odell, M.H. Schmitt, K. Sung, M. Trovato, M. Velasco

University of Notre Dame, Notre Dame, U.S.A.

R. Bucci, N. Dev, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon, W. Li, N. Loukas, N. Marinelli, F. Meng, C. Mueller, Y. Musienko[37], M. Planer, A. Reinsvold, R. Ruchti, P. Siddireddy, G. Smith, S. Taroni, M. Wayne, A. Wightman, M. Wolf, A. Woodard

The Ohio State University, Columbus, U.S.A.

J. Alimena, L. Antonelli, B. Bylsma, L.S. Durkin, S. Flowers, B. Francis, A. Hart, C. Hill, W. Ji, T.Y. Ling, W. Luo, B.L. Winer, H.W. Wulsin

Princeton University, Princeton, U.S.A.

S. Cooperstein, O. Driga, P. Elmer, J. Hardenbrook, P. Hebda, S. Higginbotham, A. Kalogeropoulos, D. Lange, J. Luo, D. Marlow, K. Mei, I. Ojalvo, J. Olsen, C. Palmer, P. Piroué, J. Salfeld-Nebgen, D. Stickland, C. Tully

University of Puerto Rico, Mayaguez, U.S.A.

S. Malik, S. Norberg

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

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

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

T. Cheng, J. Dolen, N. Parashar

Rice University, Houston, U.S.A.
Z. Chen, K.M. Ecklund, S. Freed, F.J.M. Geurts, M. Guilbaud, M. Kilpatrick, W. Li, B. Michlin, B.P. Padley, J. Roberts, J. Rorie, W. Shi, Z. Tu, J. Zabel, A. Zhang

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

The Rockefeller University, New York, U.S.A.
R. Ciesielski, K. Goulianos, C. Mesropian

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

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

Texas A&M University, College Station, U.S.A.
O. Bouhali[73], A. Castaneda Hernandez[73], A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, T. Kamon[74], R. Mueller, Y. Pakhotin, R. Patel, A. Perloff, L. Perniè, D. Rathjens, A. Safonov, A. Tatarinov

Texas Tech University, Lubbock, U.S.A.
N. Akchurin, J. Damgov, F. De Guio, P.R. Dudero, J. Faulkner, E. Gurpinar, S. Kunori, K. Lamichhane, S.W. Lee, T. Mengke, S. Muthumuni, T. Peltola, S. Undleeb, I. Volobouev, Z. Wang

Vanderbilt University, Nashville, U.S.A.
S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, A. Melo, H. Ni, K. Padeken, J.D. Ruiz Alvarez, P. Sheldon, S. Tuo, J. Velkovska, Q. Xu

University of Virginia, Charlottesville, U.S.A.
M.W. Arenton, P. Barria, B. Cox, R. Hirosky, M. Joyce, A. Ledovskoy, H. Li, C. Neu, T. Sinthuprasith, Y. Wang, E. Wolfe, F. Xia

Wayne State University, Detroit, U.S.A.
R. Harr, P.E. Karchin, N. Poudyal, J. Sturdy, P. Thapa, S. Zaleski

University of Wisconsin - Madison, Madison, WI, U.S.A.
M. Brodski, J. Buchanan, C. Caillol, D. Carlsmith, S. Dasu, L. Dodd, S. Duric, B. Gomber, M. Grothe, M. Herndon, A. Hervé, U. Hussain, P. Klabbers, A. Lanaro, A. Levine, K. Long, R. Loveless, V. Rekovic, T. Ruggles, A. Savin, N. Smith, W.H. Smith, N. Woods

†: Deceased
1: Also at Vienna University of Technology, Vienna, Austria

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2: Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
3: Also at Universidade Estadual de Campinas, Campinas, Brazil
4: Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil
5: Also at Universidade Federal de Pelotas, Pelotas, Brazil
6: Also at Université Libre de Bruxelles, Bruxelles, Belgium
7: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
8: Also at Joint Institute for Nuclear Research, Dubna, Russia
9: Also at Cairo University, Cairo, Egypt
10: Also at Fayoum University, El-Fayoum, Egypt
11: Now at British University in Egypt, Cairo, Egypt
12: Also at Department of Physics, King Abdulaziz University, Jeddah, Saudi Arabia
13: Also at Université de Haute Alsace, Mulhouse, France
14: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
15: Also at Tbilisi State University, Tbilisi, Georgia
16: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
17: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
18: Also at University of Hamburg, Hamburg, Germany
19: Also at Brandenburg University of Technology, Cottbus, Germany
20: Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
21: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
22: Also at Institute of Physics, University of Debrecen, Debrecen, Hungary
23: Also at Indian Institute of Technology Bhubaneswar, Bhubaneswar, India
24: Also at Institute of Physics, Bhubaneswar, India
25: Also at Shoolini University, Solan, India
26: Also at University of Visva-Bharati, Santiniketan, India
27: Also at University of Ruhuna, Matara, Sri Lanka
28: Also at Isfahan University of Technology, Isfahan, Iran
29: Also at Yazd University, Yazd, Iran
30: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
31: Also at Università degli Studi di Siena, Siena, Italy
32: Also at INFN Sezione di Milano-Bicocca; Università di Milano-Bicocca, Milano, Italy
33: Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia
34: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia
35: Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico
36: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
37: Also at Institute for Nuclear Research, Moscow, Russia
38: Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
39: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
40: Also at University of Florida, Gainesville, U.S.A.
41: Also at P.N. Lebedev Physical Institute, Moscow, Russia
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 Pavia; Università di Pavia, Pavia, Italy
45: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences,

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Belgrade, Serbia
46: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy
47: Also at National and Kapodistrian University of Athens, Athens, Greece
48: Also at Riga Technical University, Riga, Latvia
49: Also at Universität Zürich, Zurich, Switzerland
50: Also at Stefan Meyer Institute for Subatomic Physics (SMI), Vienna, Austria
51: Also at Adiyaman University, Adiyaman, Turkey
52: Also at Istanbul Aydin University, Istanbul, Turkey
53: Also at Mersin University, Mersin, Turkey
54: Also at Piri Reis University, Istanbul, Turkey
55: Also at Gaziosmanpasa University, Tokat, Turkey
56: Also at Izmir Institute of Technology, Izmir, Turkey
57: Also at Necmettin Erbakan University, Konya, Turkey
58: Also at Marmara University, Istanbul, Turkey
59: Also at Kafkas University, Kars, Turkey
60: Also at Istanbul Bilgi University, Istanbul, Turkey
61: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
62: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
63: Also at Monash University, Faculty of Science, Clayton, Australia
64: Also at Instituto de Astrofísica de Canarias, La Laguna, Spain
65: Also at Bethel University, ST. PAUL, U.S.A.
66: Also at Utah Valley University, Orem, U.S.A.
67: Also at Purdue University, West Lafayette, U.S.A.
68: Also at Beykent University, Istanbul, Turkey
69: Also at Bingol University, Bingol, Turkey
70: Also at Erzincan University, Erzincan, Turkey
71: Also at Sinop University, Sinop, Turkey
72: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
73: Also at Texas A&M University at Qatar, Doha, Qatar
74: Also at Kyungpook National University, Daegu, Korea

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