Evidence for transverse-momentum- and pseudorapidity-dependent event-plane fluctuations in PbPb and *p*Pb collisions

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A systematic study of the factorization of long-range azimuthal two-particle correlations into a product of single-particle anisotropies is presented as a function of p_T and η of both particles and as a function of the particle multiplicity in PbPb and *p*Pb collisions. The data were taken with the CMS detector for PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV and *p*Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, covering a very wide range of multiplicity. Factorization is observed to be broken as a function of both particle p_T and η. When measured with particles of different p_T, the magnitude of the factorization breakdown for the second Fourier harmonic reaches 20% for very central PbPb collisions but decreases rapidly as the multiplicity decreases. The data are consistent with viscous hydrodynamic predictions, which suggest that the effect of factorization breaking is mainly sensitive to the initial-state conditions rather than to the transport properties (e.g., shear viscosity) of the medium. The factorization breakdown is also computed with particles of different η. The effect is found to be weakest for mid-central PbPb events but becomes larger for more central or peripheral PbPb collisions, and also for very-high-multiplicity *p*Pb collisions. The η-dependent factorization data provide new insights to the longitudinal evolution of the medium formed in heavy ion collisions.

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I. INTRODUCTION

The goal of experiments with heavy ion collisions at ultrarelativistic energies is to study nuclear matter under extreme conditions. By studying the azimuthal anisotropy of particles emitted in such collisions, experiments at the Relativistic Heavy Ion Collider at BNL (RHIC) indicated that a strongly coupled hot and dense medium is created, which exhibits a strong collective-flow behavior [1–4]. At the significantly higher collision energies achieved at the Large Hadron Collider (LHC), the collective phenomena of this quark gluon plasma have also been studied in great detail [5–13].

The collective expansion of the hot medium in heavy ion collisions can be described by hydrodynamic-flow models. Motivated by such models, the azimuthal distribution of emitted particles can be characterized by the Fourier components of the hadron yield distribution in azimuthal angle ϕ [14–16],

$$\frac{dN}{d\phi} \propto 1 + 2\sum_n v_n \cos[n(\phi - \Psi_n)]. \tag{1}$$

Here, the Fourier coefficients v_n characterize the strength of the anisotropic flow, while the azimuthal-flow orientation is represented by the corresponding "event-plane" angle Ψ_n, the direction of maximum final-state particle density. The event-plane angles are related to the event-by-event spatial distribution of the participating nucleons in the initial overlap region. The most widely studied and typically also strongest form of anisotropic flow is the second Fourier component v_2, called "elliptic flow." The elliptic-flow event plane Ψ_2 is correlated with the "participant plane" given by the beam direction and the shorter axis of the approximately elliptical nucleon overlap region. Because of event-by-event fluctuations, higher-order deformations or eccentricities of the initial geometry can also be induced, which lead to higher-order Fourier harmonics (v_n, $n \geqslant 3$) in the final state with respect to their corresponding event-plane angles Ψ_n [17]. Studies of azimuthal anisotropy harmonics provide important information on the fundamental transport properties of the medium, e.g., the ratio of shear viscosity to entropy density, η/s [18–20].

A commonly used experimental method to determine the single-particle azimuthal anisotropy harmonics, v_n, is the measurement of two-particle azimuthal correlations [14–16,21]. The azimuthal distribution of particle pairs as a function of their relative azimuthal angle $\Delta\phi$ can also be characterized by its Fourier components,

$$\frac{dN^{\text{pair}}}{d\Delta\phi} \propto 1 + 2\sum_n V_{n\Delta} \cos(n\Delta\phi). \tag{2}$$

If the dominant source of final-state particle correlations is collective flow, the two-particle Fourier coefficients, $V_{n\Delta}$, are commonly expected to follow the factorization relation:

$$V_{n\Delta} = v_n^a\, v_n^b, \tag{3}$$

where v_n^a and v_n^b represent the single-particle anisotropy harmonics for a pair of particles (a and b) in the event. The particle pairs can be selected from the same or different transverse momentum (p_T) and pseudorapidity (η) ranges. Here, a key assumption is that the event-plane angle Ψ_n in Eq. (1) is a global phase angle for all particles of the entire event, which is canceled when taking the azimuthal angle difference between two particles. As a result, the flow-driven $\Delta\phi$ distribution in Eq. (2) has no dependence on Ψ_n. The

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most common approach to obtain the single-particle v_n in the two-particle method is to fix one particle in a wide p_T (η) region and measure $V_{n\Delta}$ by only varying p_T (η) of the other particle to determine v_n as a function of p_T (η).

However, a significant breakdown of the factorization assumption, up to about 20%, was recently observed for pairs of particles, separated by more than two units in η, from different p_T ranges in ultracentral (0%–0.2% centrality) PbPb collisions [13]. The centrality in heavy ion collisions is defined as a fraction of the total inelastic PbPb cross section, with 0% denoting the most central collisions. While nonflow correlations (such as back-to-back jets) have been speculated to possibly account for this effect, contributions of those short-range correlations to the collective anisotropy are less dominant in high-multiplicity events as the total number of particles increases [22]. It was then realized that, in hydrodynamic models, the assumption of factorization does not hold in general because of fluctuations in the initial overlap region of two nuclei [23,24]. In each event, due to local perturbations in the energy density distribution generating a pressure gradient that drives particles in random directions with differing boosts, the resulting event-plane angles found with final-state particles from different p_T ranges may fluctuate with respect to each other (although still correlated with the initial participant plane). This effect of initial-state fluctuations thus breaks the factorization relation of Eq. (3), which assumes a unique event-plane angle for all particles in an event. As a result, the precise meaning of previous single-particle v_n results should be reinterpreted as being with respect to the event plane determined with particles over a specific, usually wide, p_T range. Quantitative studies of the factorization-breakdown effect as a function of p_T could place stringent constraints on the spatial scale (or granularity) of the fluctuations in the initial state of heavy ion collisions, especially along the radial direction [25–27].

The recent observation of long-range nearside ($\Delta\phi \sim 0$) two-particle correlations in pp [28] and pPb [29–31] collisions raised the question of whether hydrodynamic flow is developed also in these small collision systems. The extracted v_n harmonics in pPb collisions have been studied in detail as a function of p_T and event multiplicity [22,32]. The initial-state geometry of a pPb collision is expected to be entirely driven by fluctuations. If the observed long-range correlations in such collisions indeed originate from hydrodynamic flow, the effect of factorization breakdown should also be observed in the data and described by hydrodynamic models. Since the initial-state geometries of both high-multiplicity pPb and ultracentral PbPb collisions are dominated by fluctuations, it is of great interest to investigate whether the magnitude of factorization breakdown is similar in these two systems.

Furthermore, the factorization breakdown in η is sensitive to event-plane fluctuations at different η [23]. This phenomenon has been investigated in hydrodynamic and parton transport models [33–36]. The observation and study of this effect will provide new insights into the dynamics of longitudinal expansion of the hot quark and gluon medium and serves as an ideal test ground of three-dimensional hydrodynamic models.

This paper presents a comprehensive investigation of the factorization-breakdown effect in two-particle azimuthal Fourier harmonics in PbPb (pPb) collisions at $\sqrt{s_{NN}} = 2.76$ (5.02) TeV to search for evidence of p_T- and η-dependent event-plane fluctuations. The Fourier harmonics of two-particle azimuthal correlations are extracted for pairs with $|\Delta\eta| > 2$ as a function of p_T and η of both particles in a pair. The results are presented over a wide range of centrality or event-multiplicity classes and are compared with hydrodynamic models in PbPb and pPb collisions. As the p_T- and η-dependent aspects of factorization breakdown probe system dynamics in the transverse and longitudinal directions, respectively, an assumption is made that the dependence on each variable can be studied independently by averaging over the other, and two different analysis techniques are applied. These two aspects of the analysis are described in Secs. IV and V separately, including the analysis procedures and results.

II. EXPERIMENTAL SETUP AND DATA SAMPLE

A comprehensive description of the Compact Muon Solenoid (CMS) detector at the CERN LHC together with a definition of the coordinate system used and the relevant kinematic variables can be found in Ref. [37]. The main detector subsystem used in this paper is the tracker, located in a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. The tracker consists of 1440 silicon pixels and 15 148 silicon-strip detector modules, covering the pseudorapidity range $|\eta| < 2.5$. For hadrons with $p_T \approx 1$ GeV/c and $|\eta| \approx 0$, the impact parameter resolution is approximately 100 μm and the p_T resolution is 0.8%.

The electromagnetic calorimeter (ECAL) and the hadron calorimeter (HCAL) are also located inside the solenoid. The ECAL consists of 75 848 lead tungstate crystals arranged in a quasiprojective geometry and distributed in a barrel region ($|\eta| < 1.48$) and two endcaps that extend to $|\eta| = 3.0$. The HCAL barrel and endcaps are sampling calorimeters composed of brass and scintillator plates, covering $|\eta| < 3.0$. In addition, CMS has an extensive forward calorimetry, in particular two steel or quartz-fiber Cherenkov hadronic forward (HF) calorimeters, which cover the pseudorapidity range $2.9 < |\eta| < 5.2$. The HF calorimeters are segmented into towers, each of which is a two-dimensional cell with a granularity of 0.5 in η and 0.349 radians in ϕ. A set of scintillator tiles, the beam scintillator counters (BSC), are mounted on the inner side of the HF calorimeters and are used for triggering and beam-halo rejection. The BSCs cover the range $3.23 < |\eta| < 4.65$. The detailed Monte Carlo (MC) simulation of the CMS detector response is based on GEANT4 [38].

The data sample used in this analysis was collected with the CMS detector during the LHC PbPb run in 2011 and the pPb run in 2013. The total integrated luminosity of the data sets is about 159 μb^{-1} for PbPb, and 35 nb^{-1} for pPb. During the pPb run, the beam energies were 4 TeV for protons and 1.58 TeV per nucleon for lead nuclei, resulting in a center-of-mass energy per nucleon pair of 5.02 TeV. As a result of the energy difference between the colliding beams, the nucleon-nucleon center of mass in the pPb collisions is not at rest in the laboratory frame. Massless particles emitted at $\eta_{\text{c.m.}} = 0$ in the nucleon-nucleon center-of-mass frame will be detected at

$\eta = -0.465$ or 0.465 (clockwise or counterclockwise proton beam) in the laboratory frame.

III. SELECTION OF EVENTS AND TRACKS

Online triggers, offline event selections, and track reconstruction and selections are identical to those used in previous analyses of PbPb and pPb data [13,22] and are briefly outlined in the following sections.

A. PbPb data

Minimum-bias PbPb events were selected by using coincident-trigger signals from both ends of the detector in either BSCs or the HF calorimeters. Events due to detector noise, cosmic rays, out-of-time triggers, and beam background were suppressed by requiring a coincidence of the minimum-bias trigger with bunches colliding in the interaction region. The trigger has an efficiency of $(97 \pm 3)\%$ for hadronic inelastic PbPb collisions. Because of hardware limits on the data-acquisition rate, only a small fraction (2%) of all minimum-bias events were recorded (i.e., the trigger is "prescaled"). To enhance the event sample for very central PbPb collisions, a dedicated online trigger was implemented by simultaneously requiring the HF transverse energy (E_{T}) sum to be greater than 3260 GeV and the pixel cluster multiplicity to be greater than 51 400 (which approximately corresponds to 9500 charged particles over five units of pseudorapidity). The selected events correspond to the 0.2%-most-central PbPb collisions. Other standard PbPb centrality classes presented in this paper are determined based on the total energy deposited in the HF calorimeters [11]. The inefficiencies of the minimum-bias trigger and event selection for very peripheral events are properly taken into account.

To further reduce the background from single-beam interactions (e.g., beam-gas and beam-halo), cosmic muons, and ultraperipheral collisions that lead to the electromagnetic breakup of one or both Pb nuclei [39], offline PbPb event-selection criteria [11] are applied by requiring energy deposits in at least three towers in each of the HF calorimeters, with at least 3 GeV of energy in each tower, and the presence of a reconstructed primary vertex containing at least two tracks. The reconstructed primary vertex is required to be located within ± 15 cm of the average interaction region along the beam axis and within a radius of 0.02 cm in the transverse plane. Following the procedure developed in Ref. [13], events with large signals in both the Zero Degree Calorimeter (ZDC) and HF are identified as having at least one additional interaction, or pileup event, and thus rejected (about 0.1% of all events).

The reconstruction of the primary event vertex and of the trajectories of charged particles in PbPb collisions are based on signals in the silicon pixel and strip detectors and described in detail in Ref. [11]. From studies based on PbPb events simulated using HYDJET v1.8 [40], the combined geometrical acceptance and reconstruction efficiency of the primary tracks is about 70% at $p_{\mathrm{T}} \sim 1$ GeV/c and $|\eta| < 1.0$ for the most central 0%–5% PbPb events, but drops to about 50% for $p_{\mathrm{T}} \sim 0.3$ GeV/c. The fraction of misidentified tracks is kept at the level of <5% over most of the p_{T} (>0.5 GeV/c) and $|\eta|$ (<1.6) ranges. It increases to about 20% for very low p_{T} (<0.5 GeV/c) particles in the forward ($|\eta| \geqslant 2$) region.

B. pPb data

Minimum-bias pPb events were selected by requiring that at least one track with $p_{\mathrm{T}} > 0.4$ GeV/c is found in the pixel tracker in coincidence with a pPb bunch crossing. About 0.1% of all minimum-bias pPb events were recorded. In order to select high-multiplicity pPb collisions, a dedicated high-multiplicity trigger was implemented by using the CMS level-1 (L1) and high-level trigger (HLT) systems. At L1, the total transverse energy measured by using both ECAL and HCAL is required to be greater than a given threshold (20 or 40 GeV). Online track reconstruction for the HLT was based on the three layers of pixel detectors and required a track origin within a cylindrical region, centered at the average interaction point of two beams, of length 30 cm along the beam and radius 0.2 cm perpendicular to the beam. For each event, the vertex reconstructed with the highest number of pixel tracks was selected. The number of pixel tracks ($N_{\mathrm{trk}}^{\mathrm{online}}$) with $|\eta| < 2.4$, $p_{\mathrm{T}} > 0.4$ GeV/c, and a distance of closest approach of 0.4 cm or less to this vertex, was determined for each event.

Offline selections similar to those used for the PbPb data sample are applied to reject nonhadronic pPb interactions. A coincidence of at least one HF calorimeter tower with more than 3 GeV of total energy in each of the HF detectors is required. Events are also required to contain at least one reconstructed primary vertex within 15 cm of the nominal interaction point along the beam axis and within 0.15 cm transverse to the beam trajectory. At least two reconstructed tracks are required to be associated with the primary vertex. Beam-related background is suppressed by rejecting events for which less than 25% of all reconstructed tracks are of sufficiently good quality to be tracks selected for physics analysis, as will be discussed later in this section. Among those pPb interactions simulated with the EPOS [41] and HIJING [42] event generators that have at least one primary particle with total energy $E > 3$ GeV in both η ranges of $-5 < \eta < -3$ and $3 < \eta < 5$, the above criteria are found to select 97%–98% of the events. Pileup events are removed based on the number of tracks associated with each vertex in a bunch crossing and the distance between different vertices [22]. A purity of 99.8% for single pPb collision events is achieved for the highest-multiplicity pPb interactions studied in this paper.

For the pPb analysis, the standard track reconstruction as in pp collisions is applied. The CMS high-purity tracks (as defined in Ref. [43]) are used. Additionally, a reconstructed track is only considered as a primary-track candidate if the significance of the separation along the beam axis (z) between the track and primary vertex, $d_z/\sigma(d_z)$, and the significance of the impact parameter relative to the primary vertex transverse to the beam, $d_{\mathrm{T}}/\sigma(d_{\mathrm{T}})$, are each less than three. The relative uncertainty in the transverse momentum measurement, $\sigma(p_{\mathrm{T}})/p_{\mathrm{T}}$, is required to be less than 10%. To ensure high tracking efficiency and to reduce the rate of misidentified tracks, only tracks within $|\eta| < 2.4$ and with $p_{\mathrm{T}} > 0.3$ GeV/c are used in the analysis.

The entire pPb data set is divided into classes of reconstructed track multiplicity, $N_{\rm trk}^{\rm offline}$, where primary tracks with $|\eta| < 2.4$ and $p_{\rm T} > 0.4$ GeV/c are counted. The multiplicity classification in this analysis is identical to that used in Ref. [22], where more details are provided. The more central (0%–50%) PbPb data, including ultracentral triggered events, are analyzed with a standard reconstruction algorithm used in heavy ion collisions, as described in Sec. III A. In order to compare the pPb and PbPb systems at the same collision multiplicity, peripheral PbPb events for 50%–100% centrality are reprocessed by using the same event selections and track reconstruction as for the pPb analysis.

IV. TRANSVERSE-MOMENTUM DEPENDENCE OF FACTORIZATION BREAKDOWN

A. Analysis technique

The $p_{\rm T}$-dependent factorization breaking effect is investigated by using the same analysis technique of two-particle azimuthal correlations as that applied in Ref. [13]. For simplicity, a pair of two charged tracks are labeled as particle a and b (equivalent to the trigger and associated particles used in previous publications). They are selected from the same or different $p_{\rm T}^a$ and $p_{\rm T}^b$ ranges within $|\eta^{a,b}| < 2.4$. The two-particle Fourier coefficients, $V_{n\Delta}$, are calculated as the average value of $\cos(n\Delta\phi)$ over all particle pairs, which fulfill the requirement of $|\Delta\eta| > 2$ (to avoid the short-range correlations from jets and resonance decays):

$$V_{n\Delta} \equiv \langle\langle\cos(n\Delta\phi)\rangle\rangle_S - \langle\langle\cos(n\Delta\phi)\rangle\rangle_B, \tag{4}$$

in given ranges of $p_{\rm T}^a$ and $p_{\rm T}^b$. Here, $\langle\langle\ \rangle\rangle$ denotes averaging over all particle pairs in each event and over all the events. The subscript S corresponds to the average over pairs taken from the same event, while B represents the mixing of particles from two randomly selected events in the same 2-cm-wide range of the primary vertex position in the z direction and from the same centrality (track multiplicity) class. The $\langle\langle\cos(n\Delta\phi)\rangle\rangle_B$ term, which is typically two orders of magnitude smaller than the corresponding S term, is subtracted to account for the effects of detector nonuniformity. This analysis is equivalent to those in Refs. [10,22,44,45], where the two-particle azimuthal correlation function is first constructed and then fit with a Fourier series. The advantage of the present approach is that the extracted Fourier harmonics will not be affected by the finite bin widths of the histogram in $\Delta\eta$ and $\Delta\phi$ of the two-particle correlation function, which is relevant for higher-order Fourier harmonics.

With the $V_{n\Delta}(p_{\rm T}^a, p_{\rm T}^b)$ values as a function of $p_{\rm T}^a$ and $p_{\rm T}^b$, the factorization ratio,

$$r_n\left(p_{\rm T}^a, p_{\rm T}^b\right) \equiv \frac{V_{n\Delta}\left(p_{\rm T}^a, p_{\rm T}^b\right)}{\sqrt{V_{n\Delta}\left(p_{\rm T}^a, p_{\rm T}^a\right) V_{n\Delta}\left(p_{\rm T}^b, p_{\rm T}^b\right)}}, \tag{5}$$

has been proposed as a direct measurement of the factorization breakdown effect and to explore the $p_{\rm T}$-dependent event-plane-angle fluctuations in the context of hydrodynamics [23]. Here, the $V_{n\Delta}$ coefficients are calculated by pairing particles within the same $p_{\rm T}$ interval (denominator) or from different $p_{\rm T}$ intervals (numerator). If the factorization relation (3) holds, this ratio is expected to be unity. However, with the presence of a $p_{\rm T}$-dependent event-plane angle, it can be shown that the factorization ratio, r_n, is equivalent to

$$r_n\left(p_{\rm T}^a, p_{\rm T}^b\right) = \frac{\left\langle v_n\left(p_{\rm T}^a\right) v_n\left(p_{\rm T}^b\right) \cos\left\{n\left[\Psi_n\left(p_{\rm T}^a\right) - \Psi_n\left(p_{\rm T}^b\right)\right]\right\}\right\rangle}{\sqrt{\left\langle v_n^2\left(p_{\rm T}^a\right)\right\rangle\left\langle v_n^2\left(p_{\rm T}^b\right)\right\rangle}}, \tag{6}$$

where $\Psi_n(p_{\rm T}^a)$ and $\Psi_n(p_{\rm T}^b)$ represent the event-plane angles determined by using particles from $p_{\rm T}^a$ and $p_{\rm T}^b$ intervals, respectively [23,24], and $\langle\rangle$ denotes averaging over all the events. As one can see from Eq. (6), r_n is in general less than unity in the presence of the $p_{\rm T}$-dependent event-plane-angle Ψ_n fluctuations.

B. Results for PbPb data

The first measurement of $p_{\rm T}$-dependent factorization breakdown in PbPb collisions was presented in Ref. [13]. Our analysis is expanded to cover a much wider centrality range from 0% to 50%, and also includes a systematic comparison to hydrodynamic models. The values of $r_2(p_{\rm T}^a, p_{\rm T}^b)$ and $r_3(p_{\rm T}^a, p_{\rm T}^b)$ in PbPb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV are presented as a function of $p_{\rm T}^a - p_{\rm T}^b$ in Figs. 1 and 2 for several $p_{\rm T}^a$ ranges in seven different centrality classes from 0%–0.2% to 40%–50%. The average $p_{\rm T}$ values within each $p_{\rm T}^a$ and $p_{\rm T}^b$ range are used in order to calculate the difference between $p_{\rm T}^a$ and $p_{\rm T}^b$. By construction, the r_n value for the highest analyzed $p_{\rm T}^b$ range, where both particles are selected from the same $p_{\rm T}$ interval, is equal to one. Only results for $p_{\rm T}^a \geqslant p_{\rm T}^b$ are presented, with a maximal $p_{\rm T}^a$ value of 3 GeV/c, a kinematic regime where the hydrodynamic flow effect is believed to be dominant. The error bars correspond to statistical uncertainties, while systematic uncertainties are found to be negligible for the r_n results (mainly because systematic uncertainties of $V_{n\Delta}$ are typically on the order of a few percent, and ratios of $V_{n\Delta}$ are taken to form r_n in this paper, where systematic uncertainties mostly cancel), and thus are not shown in any of the figures.

A clear deviation from unity of the r_2 value (Fig. 1) is observed for the highest $p_{\rm T}$ ranges in very central PbPb collisions. For each centrality class, the effect becomes more pronounced with an increase of $p_{\rm T}^a$ and also the difference between $p_{\rm T}^a$ and $p_{\rm T}^b$ values. This trend is expected as event-by-event initial-state-geometry fluctuations play a more dominant role as the collisions become more central. The factorization-breakdown effect reaches 20% in the ultracentral 0%–0.2% events for the greatest difference between $p_{\rm T}^a$ and $p_{\rm T}^b$. For more peripheral centrality classes, the maximum effect is a few percent. Calculations using viscous hydrodynamics [24] are performed in all centrality classes and are shown as the curves in Fig. 1. To focus on the effect of initial-state fluctuations, the η/s value is fixed at 0.12. Two different models of initial conditions, MC-Glauber [46,47] and MC Kharzeev–Levin–Nardi (MC-KLN; motivated by the concept of gluon saturation) [48], are compared to data. The qualitative trend of the data is consistent with hydrodynamic calculations. However, quantitatively, neither of the two models can describe all the data. The MC-Glauber model matches better the data for

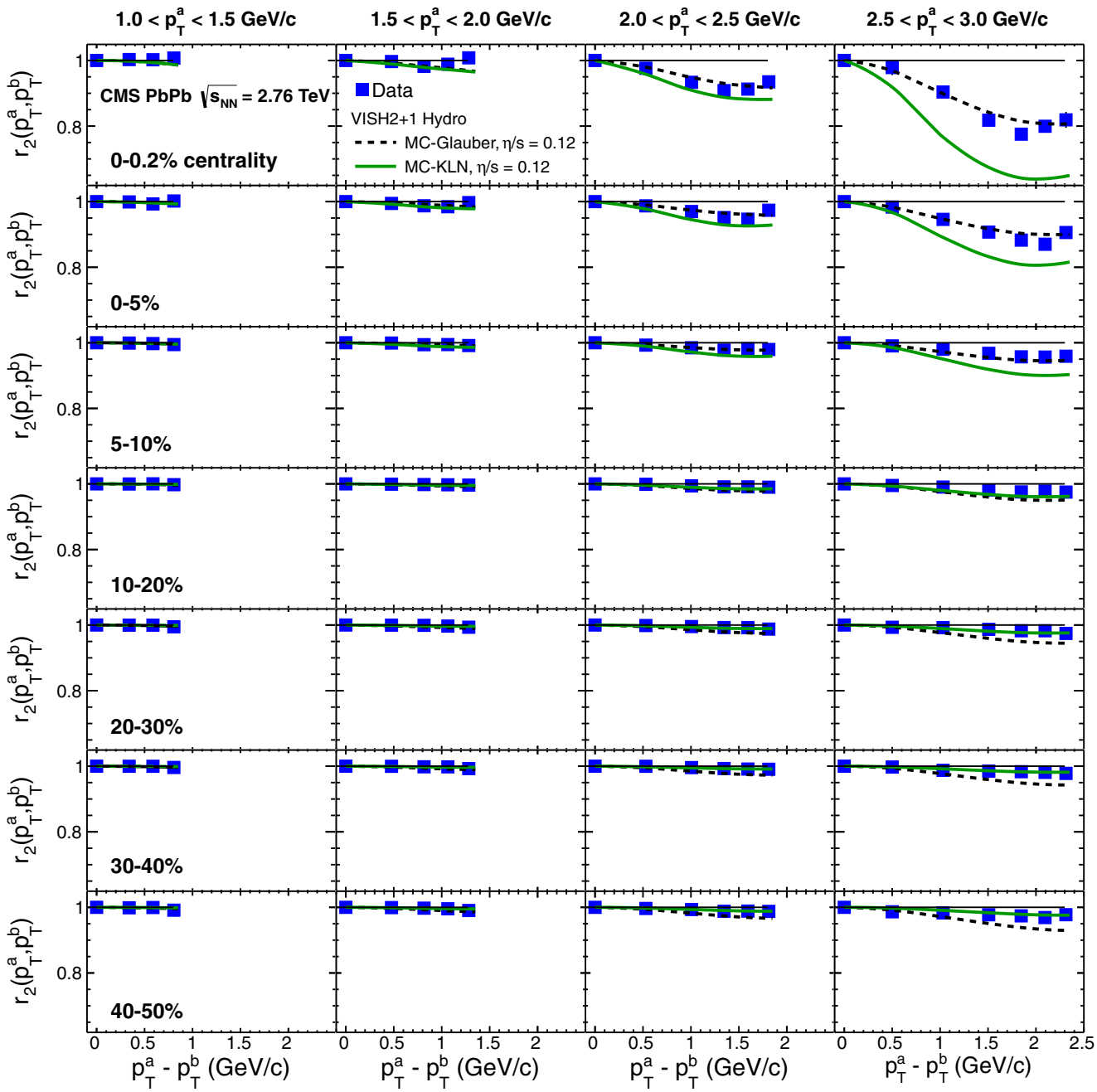

FIG. 1. (Color online) The p_{T}-dependent factorization ratio, r_2, as a function of $p_{\mathrm{T}}^a - p_{\mathrm{T}}^b$ in bins of p_{T}^a for different centrality ranges of PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV. The curves show the calculations from a viscous hydrodynamic model [24] using MC-Glauber and MC-KLN initial-condition models, and an η/s value of 0.12. Each row represents a different centrality range, while each column corresponds to a different p_{T}^a range. The horizontal solid lines denote the r_2 value of unity. The error bars correspond to statistical uncertainties, while systematic uncertainties are negligible for the r_n results and thus are not shown.

central collisions, while MC-KLN model appears to describe the data in the peripheral centrality range.

For the third-order harmonics ($n = 3$), the effect of factorization breakdown is significantly smaller than for the second-order harmonics. Only a weak centrality dependence of r_3 is seen in Fig. 2. The biggest deviation of r_3 from unity is about 5% at large values of $p_{\mathrm{T}}^a - p_{\mathrm{T}}^b$ (i.e., >1 GeV/c). Again, the qualitative features of the data are described by the hydrodynamic model, although the effects are overestimated for peripheral collisions by the model. Calculations of r_3 using two different initial-state models yield similar results, with the MC-KLN model showing a slightly stronger centrality dependence.

To understand better how the effects of factorization breakdown and p_{T}-dependent event-plane fluctuations are influenced by the initial-state conditions and the value of η/s

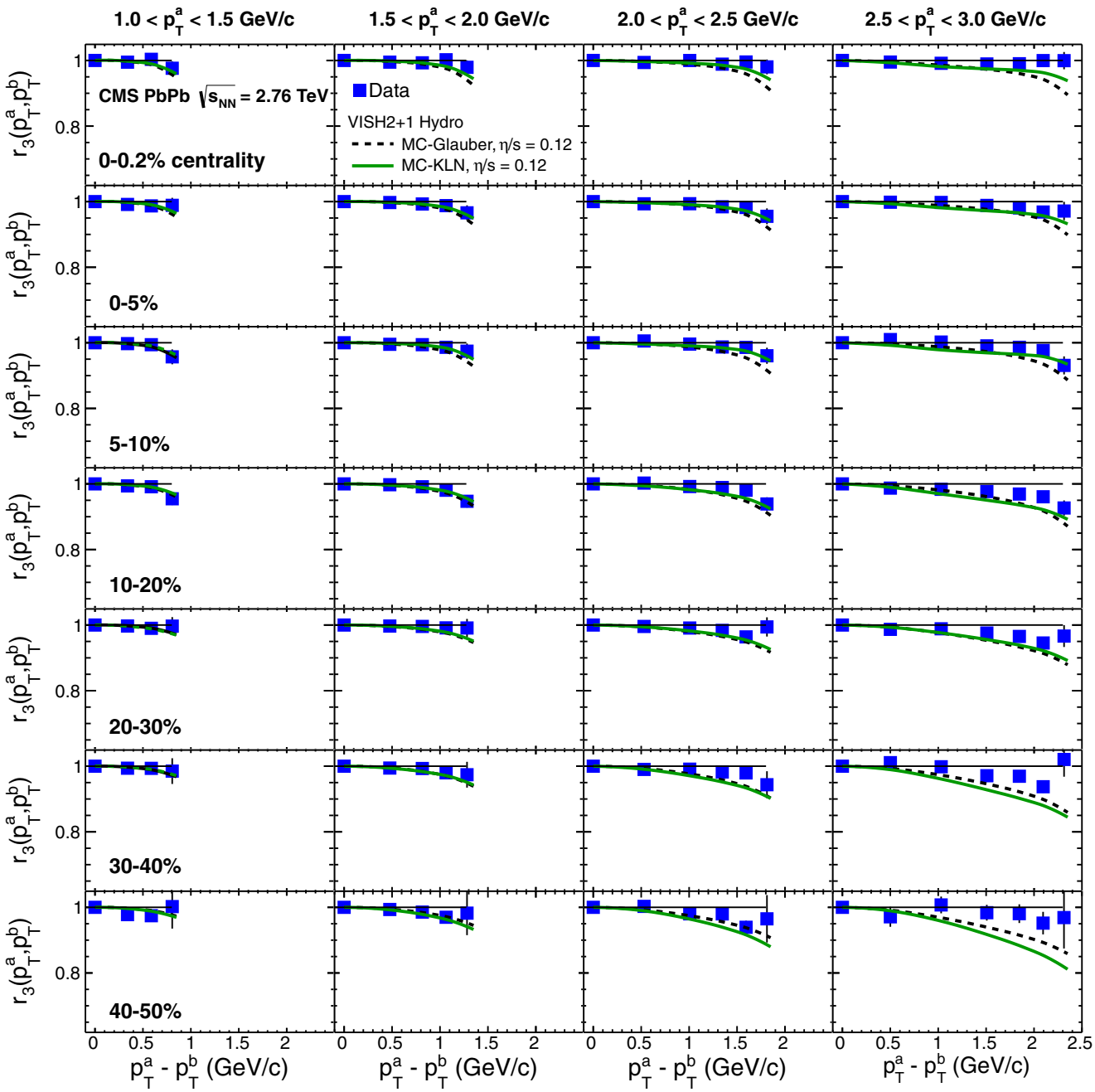

FIG. 2. (Color online) Similar distributions as shown in Fig. 1, but for the factorization ratio r_3.

in hydrodynamic models, a detailed comparison of measured r_2 values in 0%–0.2% centrality PbPb collisions (where the effect is most evident) to hydrodynamic calculations is shown in Fig. 3. For this comparison, calculations with MC-Glauber and MC-KLN initial conditions are each performed for three different η/s values and compared to data. For each initial-state model, the r_2 values are found to be largely insensitive to different values of η/s. This is because, in defining $r_n(p_{\mathrm{T}}^a, p_{\mathrm{T}}^b)$, the magnitudes of anisotropy harmonics, which have a much greater sensitivity to η/s, are mostly canceled. Fluctuations of the event-plane angle in p_{T} are mainly driven by the nonsmooth local fluctuations in the initial energy density distribution. This comparison shows that the use of r_n data can provide new constraints on the detailed modeling of the initial-state condition and the fluctuations of the medium created in heavy ion collisions, which is independent of the η/s value. The better constraints on the initial-state conditions found using the r_n data will, in turn, improve the uncertainties of determining the medium's transport properties (e.g., η/s) using other experimental observables (e.g., the v_n magnitude, which is sensitive to both the initial state and η/s).

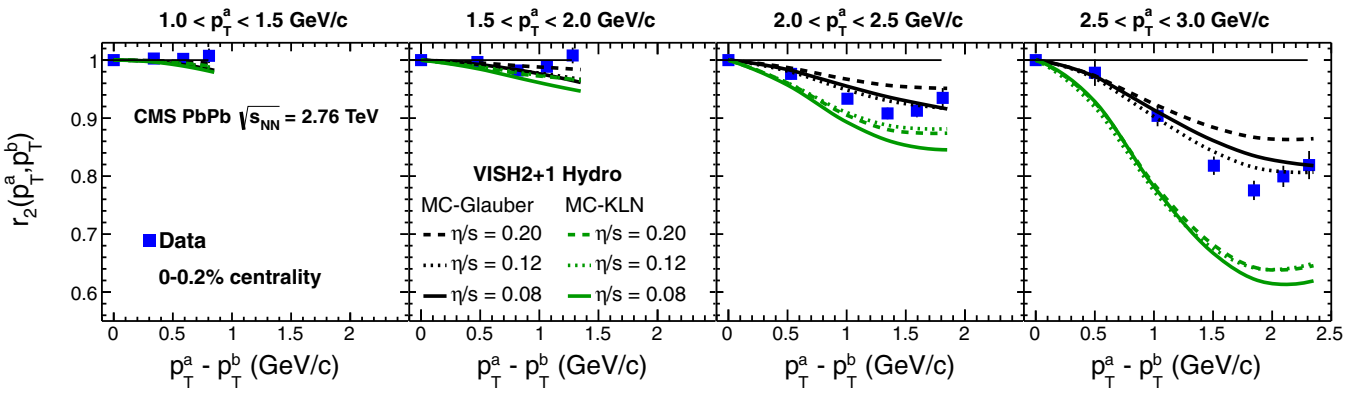

FIG. 3. (Color online) Factorization ratio, r_2, as a function of $p_T^a - p_T^b$ in bins of p_T^a for 0%–0.2% centrality PbPb data at $\sqrt{s_{NN}} = 2.76$ TeV compared to viscous hydrodynamic calculations [24] using MC-Glauber and MC-KLN initial-condition models, and three different values of η/s. The horizontal solid lines denote the r_2 value of unity. The error bars correspond to statistical uncertainties, while systematic uncertainties are negligible for the r_n results and thus are not shown.

C. Results for *p*Pb data

To gain insights into the origin of long-range correlations observed in high-multiplicity *p*Pb collisions, the measurement of r_2 and r_3 is also performed for *p*Pb data at $\sqrt{s_{NN}} = 5.02$ TeV for four different high-multiplicity ranges. The results are shown in Figs. 4 and 5, in the same format as those for PbPb collisions, for four p_T^a ranges (of increasing p_T from left to right panels) as a function of $p_T^a - p_T^b$.

Breakdown of factorization is observed in the r_2 results of *p*Pb collisions for all multiplicity ranges investigated in this paper. Similar to PbPb collisions, for any multiplicity range, the effect gets larger with an increase in the difference between p_T^a and p_T^b. However, the observed factorization breakdown reaches only up to 2%–3% for the largest value of $p_T^a - p_T^b$ at $2.5 < p_T^a < 3.0$ GeV/c. This is significantly smaller than that seen in central PbPb collisions. Little multiplicity dependence of r_2 is observed in *p*Pb collisions. Comparison of the CMS data to hydrodynamic predictions for *p*Pb collisions in Ref. [25] is also shown. In this hydrodynamic calculation, a modified MC-Glauber initial-state model is employed for *p*Pb collisions where the contributing entropy density of each participating nucleon in the transverse plane is distributed according to a two-dimensional (2D) Gaussian distribution. The width of the transverse Gaussian function can be chosen to vary the transverse granularity of fluctuations, to which the r_n values are found to be most sensitive. The r_2 data are better described by calculations with a width parameter of 0.4 fm (curves in Fig. 4), while a width of 0.8 fm gives an r_n value of nearly unity (not shown) and thus underestimates the effect observed in the data. For both cases, the calculations are found to be insensitive to different η/s values, consistent with the hydrodynamic calculations used for more central PbPb collisions presented earlier.

Results of r_3 are shown in Fig. 5, presented in the same format as for r_2. Within current statistical precision, no evident breakdown of factorization is found in very-high-multiplicity *p*Pb events ($185 < N_{trk}^{offline} < 260$), while the r_3 value exceeds unity for much-lower-multiplicity *p*Pb events at high p_T, particularly for $120 < N_{trk}^{offline} < 150$. This is a clear indication of significant nonflow effects as the event multiplicity decreases, because the r_n values predicted by hydrodynamic models with p_T-dependent event-plane-angle fluctuations would always be equal to or less than one, according to Eq. (6). One obvious possibility is back-to-back jet correlations, which would give a large negative contribution to $V_{3\Delta}$ at high p_T^a and p_T^b values in low-multiplicity events [10]. This would lead to a significant reduction of the denominator of Eq. (6) and drives the r_3 value up above unity. Very little effect of factorization breakdown for $n = 3$ is predicted in Ref. [25], which is consistent with the data except for the low-multiplicity ranges.

D. Comparison of *p*Pb and PbPb data

Figure 6 compares 5.02 TeV *p*Pb and 2.76 TeV peripheral PbPb collisions over the same multiplicity ranges. Because of the statistical limitation of the PbPb data, the multiplicity ranges used in Figs. 4 and 5 for *p*Pb data are combined into two $N_{trk}^{offline}$ classes, $100 \leqslant N_{trk}^{offline} < 185$ (top) and $185 \leqslant N_{trk}^{offline} < 260$ (bottom). At a similar $N_{trk}^{offline}$ range, the magnitudes of factorization breakdown in *p*Pb and PbPb collisions depart from unity by less than 8%, with slightly smaller deviations for *p*Pb data, although the statistical precision is limited. For both high-multiplicity *p*Pb and peripheral PbPb collisions, the observed effect is significantly smaller than that for 0%–0.2% centrality ultracentral PbPb collisions (up to 20% away from unity). The similar behavior (e.g., p_T dependence) of factorization data in *p*Pb as in PbPb collisions may provide new insight into the possible hydrodynamic-flow origin of long-range two-particle correlations in the *p*Pb system, particularly in providing new information on the nature of initial-state fluctuations in a much smaller volume.

To study directly the multiplicity dependence of the effect in PbPb and *p*Pb collisions, the r_2 and r_3 results for $2.5 < p_T^a < 3.0$ GeV/c and $0.3 < p_T^b < 0.5$ GeV/c (where the difference between p_T^a and p_T^b is the greatest, $p_T^a - p_T^b \approx 2$ GeV/c) are shown in Fig. 7 as a function of event multiplicity in *p*Pb and PbPb collisions. Here, the number of tracks is still counted with $|\eta| < 2.4$ and $p_T > 0.4$ GeV/c but corrected for the detector inefficiency, since a different track reconstruction algorithm

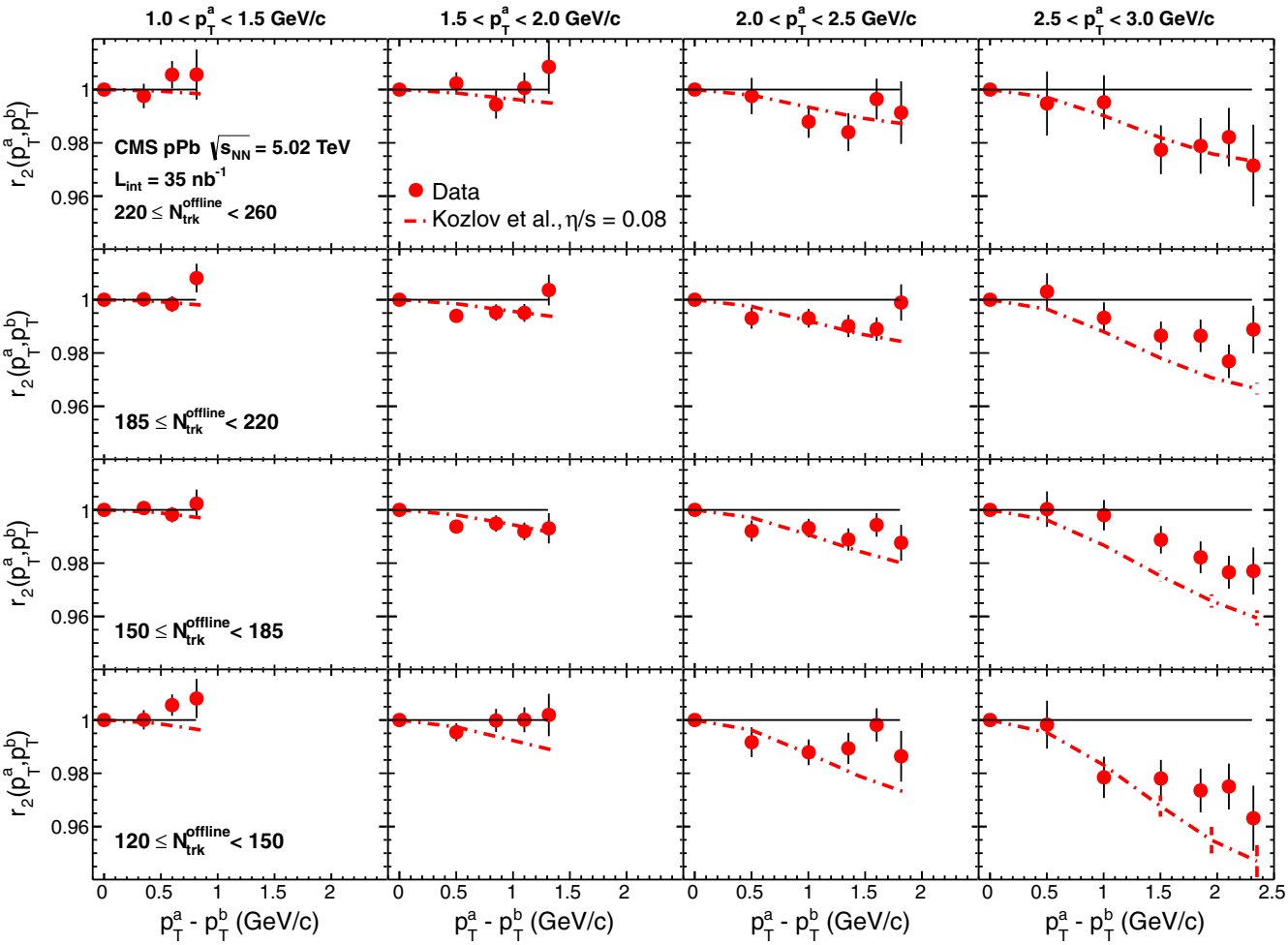

FIG. 4. (Color online) The p_T-dependent factorization ratio r_2 as a function of $p_T^a - p_T^b$ in bins of p_T^a for four $N_{trk}^{offline}$ ranges in 5.02 TeV pPb collisions. The curves show the predictions from hydrodynamic calculations for pPb collisions of Ref. [25]. The horizontal solid lines denote the r_2 value of unity. The error bars correspond to statistical uncertainties, while systematic uncertainties are negligible for the r_n results and thus are not shown.

is used for the pPb and central PbPb data. Additionally, at the top of the figure, a centrality axis is shown which is applicable only to PbPb collisions. The breakdown of factorization for r_2 in PbPb events increases dramatically as the collisions become more central than 0%–5%, while the effect in r_3 remains at the 2%–3% level, largely independent of centrality. For more peripheral PbPb events from 20% to 80% centrality, the deviation of r_2 from unity increases slightly from about 2% to 5%. Calculations using a hydrodynamic model in PbPb collisions [24] with MC-Glauber and MC-KLN initial conditions and $\eta/s = 0.12$ are also shown as dotted and dash-dotted curves, respectively, as a function of centrality. As pointed out earlier, neither of the two calculations can describe the data quantitatively over the entire centrality range, although the qualitative trend is reproduced. The r_2 values for pPb show little multiplicity dependence, consistent with hydrodynamic predictions in Ref. [25]. The r_3 values for pPb go significantly above unity at lower multiplicities, because of the onset of nonflow correlations. The discrepancy in the hydrodynamic calculations of r_2 for peripheral PbPb collisions between Refs. [24,25] may be related to differences in some model parameters (e.g., transverse size of the nucleon). This should be investigated in the future.

Although the factorization results presented in this paper suggest a breakdown of the assumption commonly applied in studying collective flow using two-particle correlations [Eq. (3)], previous v_n measurements from the two-particle method still remain valid. However, they should be more precisely interpreted as the v_n values obtained with respect to an averaged event plane by using particles from a given kinematic regime (usually over a wide p_T range). The studies in this paper also point out the importance of applying the same conditions for theoretical calculations when comparing with the experimental data.

V. PSEUDORAPIDITY DEPENDENCE OF FACTORIZATION BREAKDOWN

A. Analysis technique

In principle, the η-dependent factorization breakdown and event-plane-angle fluctuations can be examined by using a formalism similar to Eq. (5) by replacing p_T^a and p_T^b by

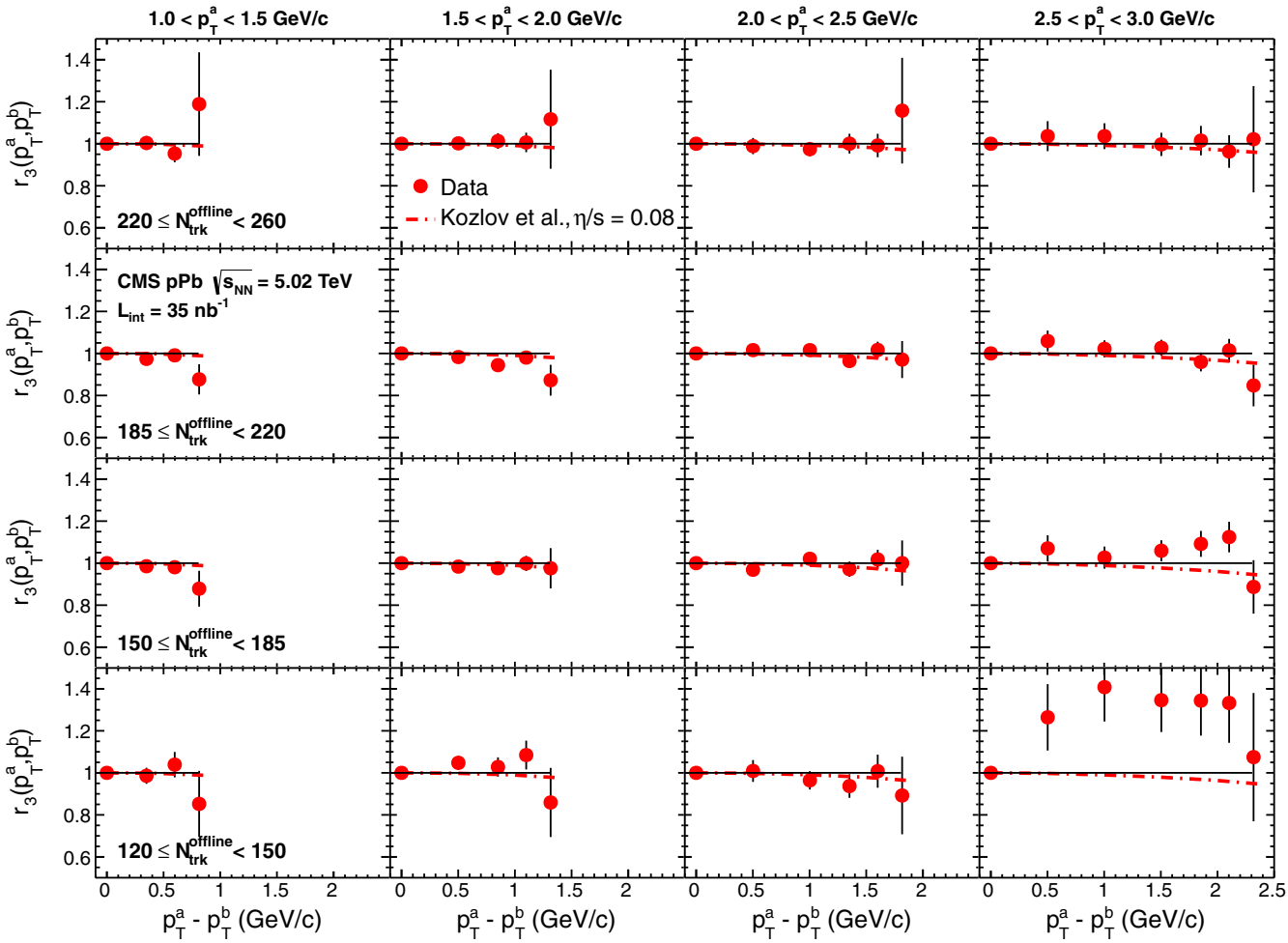

FIG. 5. (Color online) Similar distributions as shown in Fig. 4, but for the factorization ratio r_3.

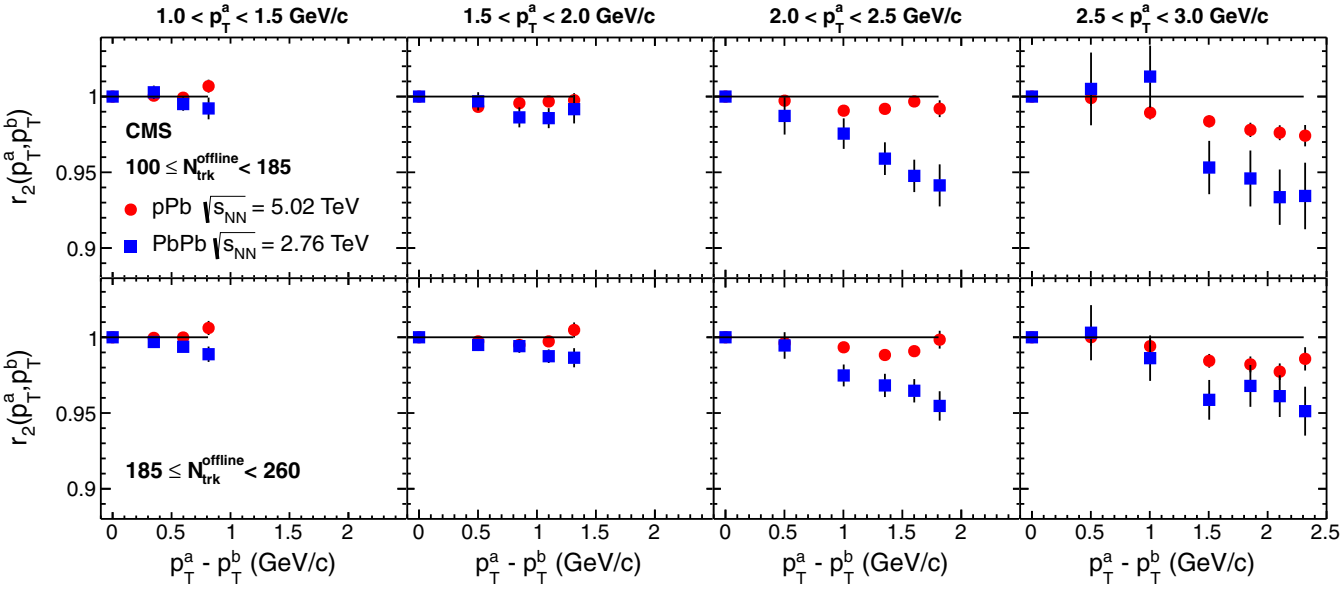

FIG. 6. (Color online) The p_T-dependent factorization ratio r_2 as a function of $p_T^a - p_T^b$ in bins of p_T^a for two $N_{trk}^{offline}$ ranges of 5.02 TeV pPb and 2.76 TeV PbPb collisions. The horizontal solid lines denote the r_2 value of unity. The error bars correspond to statistical uncertainties, while systematic uncertainties are negligible for the r_n results and thus are not shown.

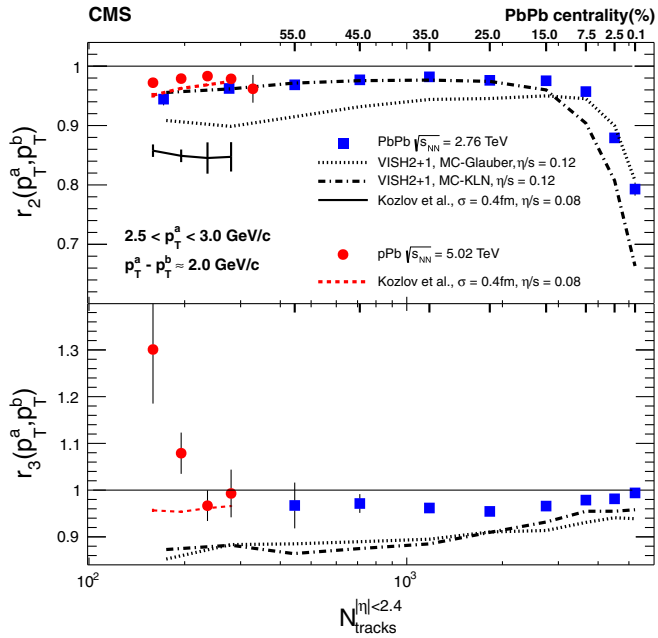

FIG. 7. (Color online) The p_{T}-dependent factorization ratios r_2 and r_3 as a function of event multiplicity in pPb and PbPb collisions. The curves show the calculations for PbPb collisions from viscous hydrodynamics in Ref. [24] with MC-Glauber and MC-KLN initial-condition models and $\eta/s = 0.12$, and also from hydrodynamic predictions for PbPb and pPb data in Ref. [25]. The horizontal solid lines denote the r_2 (top) and r_3 (bottom) value of unity. The error bars correspond to statistical uncertainties, while systematic uncertainties are negligible for the r_n results and thus are not shown.

η^a and η^b. However, the main issue with this approach is that the requirement of $|\Delta\eta| > 2$ for removing short-range two-particle correlations cannot be fulfilled anymore because the denominator of the factorization ratio takes the $V_{n\Delta}(\eta^a,\eta^b)$ components, where $\eta^a \approx \eta^b$. The correlation signal from collective flow is strongly contaminated by short-range jet-like correlations. To avoid this problem, an alternative observable is developed for the study of η-dependent factorization by taking advantage of the wide η coverage of the CMS tracker and HF calorimeters.

The η-dependent factorization ratio $r_n(\eta^a,\eta^b)$ is defined as

$$r_n(\eta^a,\eta^b) \equiv \frac{V_{n\Delta}(-\eta^a,\eta^b)}{V_{n\Delta}(\eta^a,\eta^b)}, \tag{7}$$

where $V_{n\Delta}(\eta^a,\eta^b)$ is calculated in the same way as Eq. (4) but for pairs of particles taken from varied η^a and η^b regions in fixed p_{T}^a and p_{T}^b ranges. Here, particle a is chosen from charged tracks with $0.3 < p_{\mathrm{T}}^a < 3.0$ GeV/c and $|\eta^a| < 2.4$, while particle b is selected from the HF calorimeter towers with the energy exceeding 1 GeV (with a total coverage of $2.9 < |\eta| < 5.2$) without any explicit transverse energy (E_{T}) threshold for each tower. With this approach, the η values of both particles from a pair can be varied over a wide range, while it is possible to ensure a large η gap by combining detector components covering central and forward η regions. As illustrated by the schematic in Fig. 8, for $4.4 < \eta^b < 5.0$ from the HF calorimeters, a minimum η gap of two units between a calorimeter tower and any charged particle from the silicon tracker is guaranteed. Away-side back-to-back jet correlations could still be present but they are shown to have a negligible contribution at low p_{T} because of very high multiplicities [22], especially in central PbPb collisions. To account for any occupancy effect of the HF detectors due to large granularities in η and ϕ, each tower is weighted by its E_{T} value when calculating the average in Eq. (4). For consistency, each track is also weighted by its p_{T} value. The finite azimuthal resolution of the HF towers (0.349 radians) has negligible effects on the $V_{n\Delta}$ calculation, which takes an E_{T}-weighted average of 36 tower segments over a 2π coverage.

If, for each event, the event-plane angle Ψ_n does vary for particles produced at different η regions, the following relation for $r_n(\eta^a,\eta^b)$ can be derived:

$$r_n(\eta^a,\eta^b) = \frac{\langle v_n(-\eta^a)v_n(\eta^b)\cos\{n[\Psi_n(-\eta^a) - \Psi_n(\eta^b)]\}\rangle}{\langle v_n(\eta^a)v_n(\eta^b)\cos\{n[\Psi_n(\eta^a) - \Psi_n(\eta^b)]\}\rangle}. \tag{8}$$

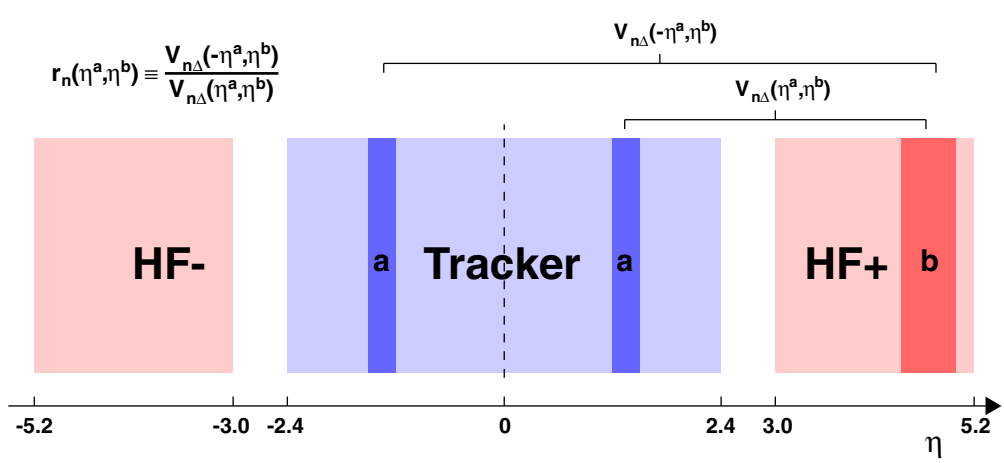

FIG. 8. (Color online) A schematic illustration of the acceptance coverage of the CMS tracker and HF calorimeters, and the procedure for deriving the η-dependent factorization ratio $r_n(\eta^a,\eta^b)$.

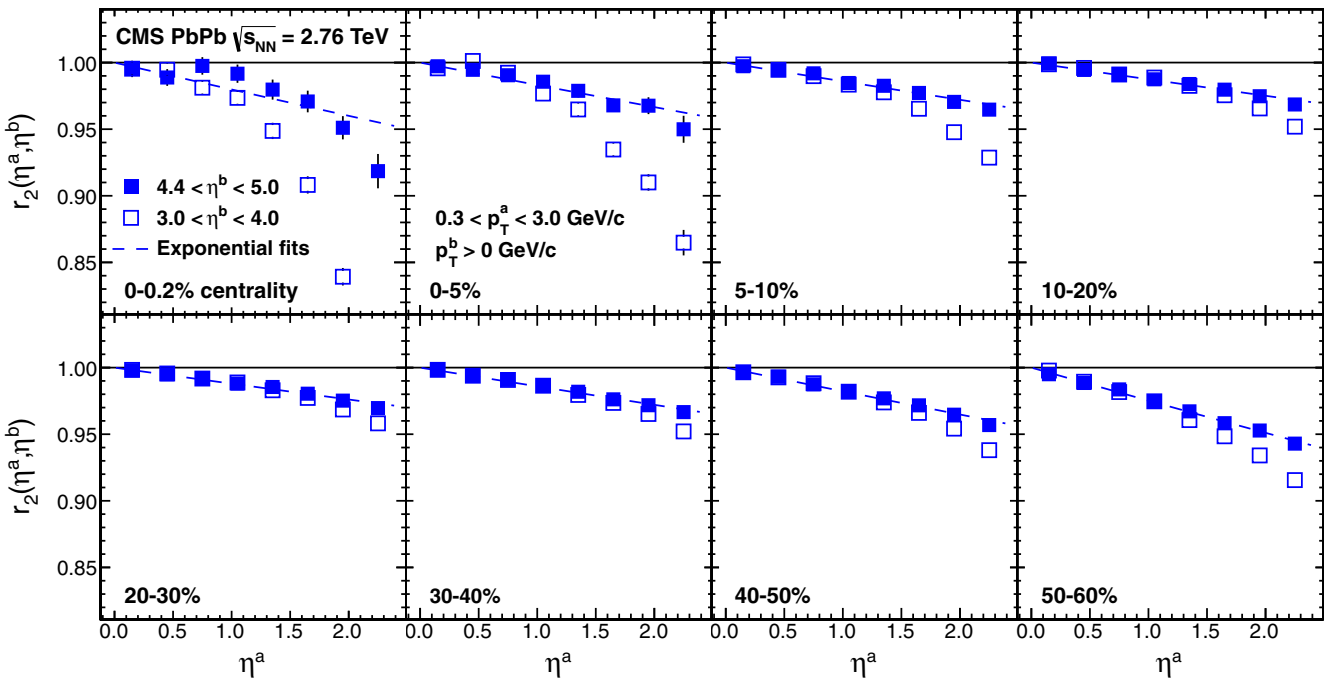

FIG. 9. (Color online) The η-dependent factorization ratio r_2 as a function of η^a for $3.0 < \eta^b < 4.0$ and $4.4 < \eta^b < 5.0$, averaged over $0.3 < p_T^a < 3.0$ GeV/c, in eight centrality classes of PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The curves correspond to fits to the data for $4.4 < \eta^b < 5.0$ given by Eq. (12). The horizontal solid lines denote the r_2 value of unity. The error bars correspond to statistical uncertainties, while systematic uncertainties are negligible for the r_n results and thus are not shown.

In symmetric collision systems like PbPb, v_n harmonics from symmetric positive $[v_n(\eta^a)]$ and negative $[v_n(-\eta^a)]$ η regions are identical after averaging over all events. Therefore, Eq. (8) can be approximated by

$$r_n(\eta^a,\eta^b) \approx \frac{\langle\cos\{n[\Psi_n(-\eta^a) - \Psi_n(\eta^b)]\}\rangle}{\langle\cos\{n[\Psi_n(\eta^a) - \Psi_n(\eta^b)]\}\rangle}. \tag{9}$$

Here, the approximation is due to the fact that the flow magnitude v_n and the orientation angle Ψ_n are inside the same averaging over all the events in the numerator of Eq. (8). As a result, $r_n(\eta^a,\eta^b)$ represents a measurement of relative event-plane-angle fluctuations in η for planes separated by $|\eta^a + \eta^b|$ and $|\eta^a - \eta^b|$. Similar to $r_n(p_T^a, p_T^b)$, $r_n(\eta^a,\eta^b)$ is equal to unity if the factorization holds but factorization breaks down in general in the presence of event-plane fluctuations in η.

For an asymmetric collision system like pPb, $v_n(\eta^a)$ and $v_n(-\eta^a)$ are not identical in general, and thus η-dependent event-plane-fluctuation effects cannot be isolated in Eq. (8). However, by taking a product of $r_n(\eta^a,\eta^b)$ and $r_n(-\eta^a,-\eta^b)$, the v_n terms can be removed:

$$\sqrt{r_n(\eta^a,\eta^b)r_n(-\eta^a,-\eta^b)} \approx \sqrt{\frac{\langle\cos\{n[\Psi_n(-\eta^a) - \Psi_n(\eta^b)]\}\rangle}{\langle\cos\{n[\Psi_n(\eta^a) - \Psi_n(\eta^b)]\}\rangle}\,\frac{\langle\cos\{n[\Psi_n(\eta^a) - \Psi_n(-\eta^b)]\}\rangle}{\langle\cos\{n[\Psi_n(-\eta^a) - \Psi_n(-\eta^b)]\}\rangle}}. \tag{10}$$

In this way, the η-dependent event-plane-angle fluctuations in pPb collisions can also be studied.

B. Results for PbPb data

The results of η-dependent factorization ratios r_2, r_3, and r_4 in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV are shown in Figs. 9–11, as a function of η^a for eight different centrality classes from 0%–0.2% to 50%–60% (except for r_4, for which only three centrality classes are shown because of statistical limitations). The $r_2(\eta^a,\eta^b)$ values are calculated in η^a bins of 0.3 units, and the η^a value at the center of each bin is used in the plots. Data obtained with calorimeter tower η ranges $3.0 < \eta^b < 4.0$ and $4.4 < \eta^b < 5.0$ are both presented. Since PbPb is a symmetric system, the $V_n(\eta^a,\eta^b)$ and $V_n(-\eta^a,-\eta^b)$ coefficients are combined before calculating the r_n ratios in order to achieve the optimal statistical precision. Charged tracks within $0.3 < p_T < 3.0$ GeV/c and all calorimeter towers ($E > 1$ GeV) are used. When $\eta^a = 0$, the r_n value is equal to unity by construction since both the numerator and denominator of r_n have the same η gap between particles a and b, as indicated in Eq. (9). As η^a increases, a significant decrease of r_n below unity is observed, which may suggest the presence of η-dependent event-plane-angle fluctuations.

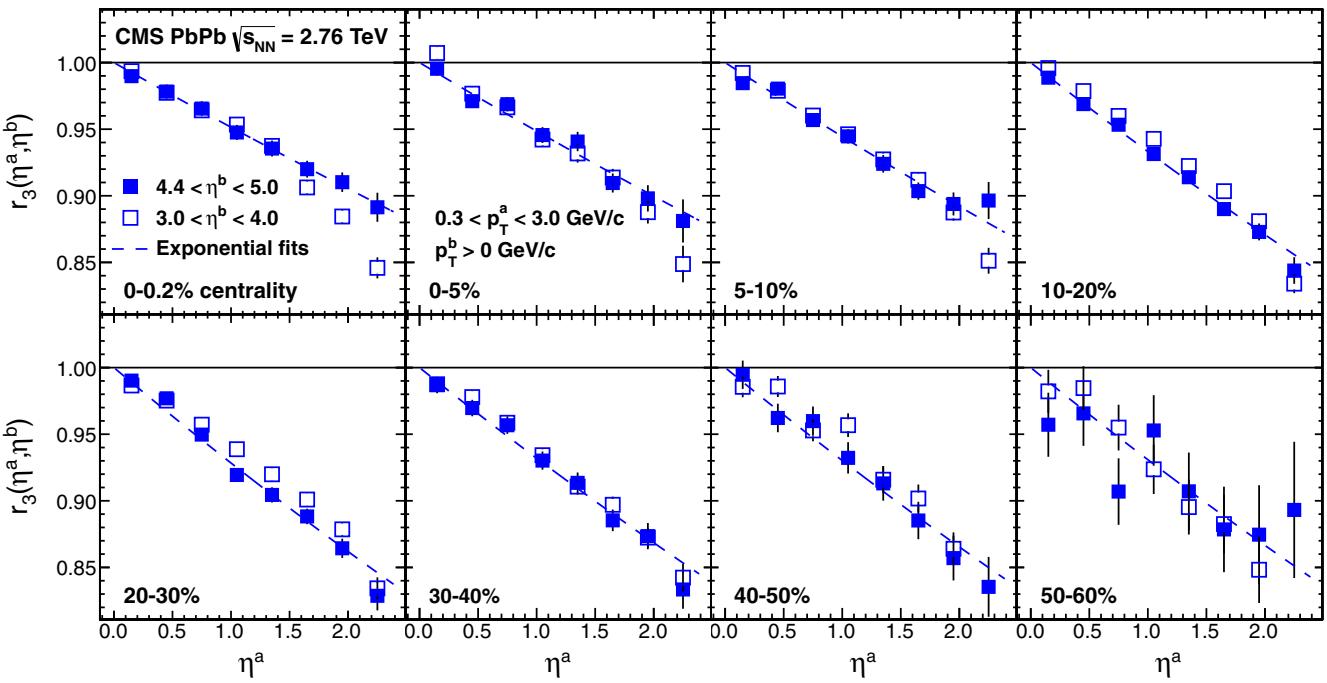

FIG. 10. (Color online) Similar distributions as shown in Fig. 9, but for the factorization ratio r_3.

The r_2 values for $4.4 < \eta^b < 5.0$ are found to decrease with η^a approximately linearly for most of the centrality classes up to a few percent deviation below unity at $\eta^a \sim 2.4$. This behavior is slightly different for the most-central 0%–0.2% events, where the decrease of r_2 becomes more significant at $\eta^a \sim 1$. For $3.0 < \eta^b < 4.0$, the r_2 value exhibits a much stronger factorization-breakdown effect for an $\eta^a > 1$. This can be understood as the effect of short-range jet-like correlations when the η gap between two particles is less than two, which increases the denominator of Eq. (7). However, for $\eta^a < 1$, the r_2 results are found to be consistent with each other, independent of η^b (except for 0%–0.2% centrality). This demonstrates that contributions of short-range jet-like correlations are almost completely suppressed if the requirement of $|\Delta\eta| > 2$ to both numerator and denominator of $r_n(\eta^a,\eta^b)$ is imposed.

The effect of η-dependent factorization breakdown is much stronger for higher-order harmonics r_3 and r_4, shown in Figs. 10 and 11. For r_3, this trend is opposite to what is observed for the p_T-dependent factorization ratio. For all centrality ranges (including 0%–0.2%), an approximate linear dependence of r_3 and r_4 is seen. Results from the two different η^b ranges agree over most of the η^a range within statistical uncertainties. This might suggest that short-range jet-like correlations have much smaller effects on higher-order harmonics.

As observed in Figs. 9–11, the $r_n(\eta^a,\eta^b)$ values are independent of η^b, for η^a ranges where contributions of

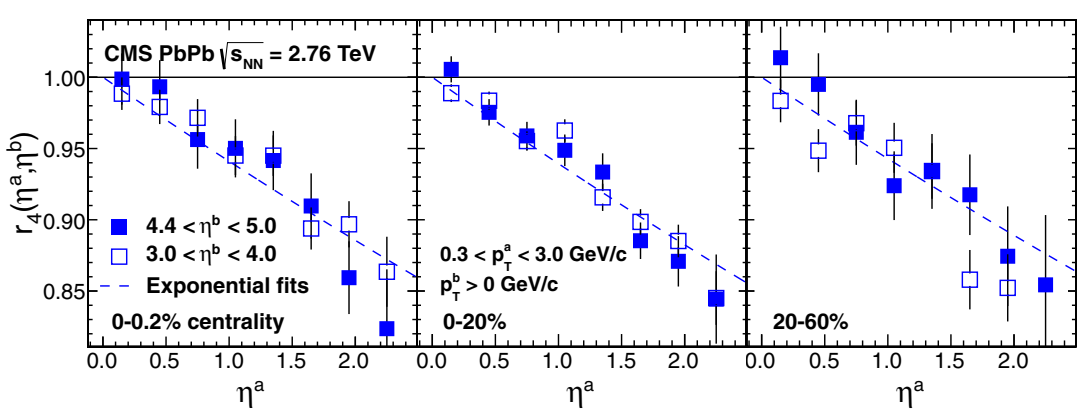

FIG. 11. (Color online) Similar distributions as shown in Fig. 9, but for the factorization ratio r_4 in fewer centrality ranges.

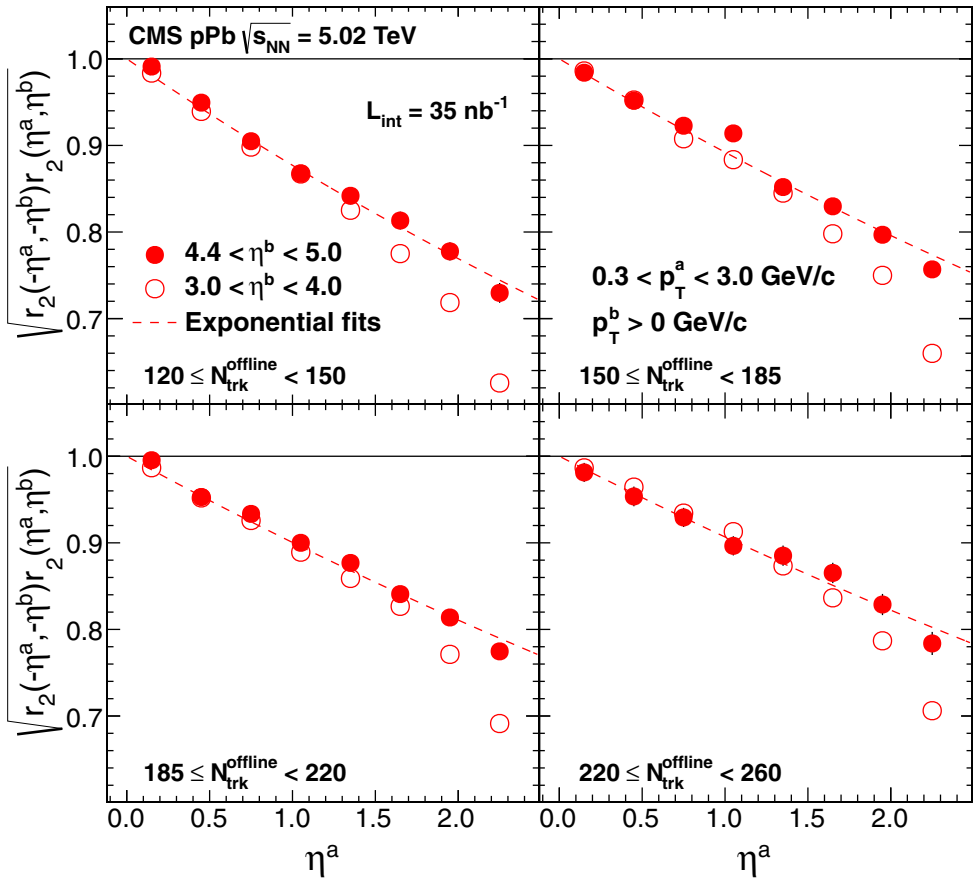

FIG. 12. (Color online) The square root of the product of factorization ratios, $\sqrt{r_2(\eta^a,\eta^b)r_2(-\eta^a,-\eta^b)}$, as a function of η^a for $3.0 < \eta^b < 4.0$ and $4.4 < \eta^b < 5.0$, averaged over $0.3 < p_T^a < 3.0$ GeV/c, in four multiplicity classes of pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The curves correspond to fits to the data for $4.4 < \eta^b < 5.0$ using Eq. (12). The horizontal solid lines denote the r_2 value of unity. The error bars correspond to statistical uncertainties, while systematic uncertainties are negligible for the r_2 results and thus are not shown.

only long-range ($|\Delta\eta| > 2$) correlations are included. To quantify the dependence of r_n values on η^a, a simple empirical parametrization is introduced:

$$\cos\{n[\Psi_n(\eta^a) - \Psi_n(\eta^b)]\} = e^{-F_n^\eta|\eta^a-\eta^b|}, \tag{11}$$

which is based on the assumption that relative fluctuations between two event-plane angles depend only on their pseudorapidity difference. At small $\Delta\eta$ values, the exponential function form can be approximated by a linear function of $\Delta\eta$, consistent with the observation in the data. By plugging Eq. (11) into Eq. (9), r_n can be expressed as

$$r_n(\eta^a,\eta^b) \approx e^{-2F_n^\eta\eta^a}, \tag{12}$$

which is independent of η^b, consistent with the results in Figs. 9–11. According to Eqs. (11) and (12), $r_n(\eta^a,\eta^b)$ also corresponds to a measurement of event-plane fluctuations between $\Psi_n(\eta^a)$ and $\Psi_n(-\eta^a)$,

$$r_n(\eta^a,\eta^b) \approx \langle\cos\{n[\Psi_n(-\eta^a) - \Psi_n(\eta^a)]\}\rangle. \tag{13}$$

The r_2 data for $4.4 < \eta^b < 5.0$ are well fit with a functional form given by Eq. (12) for most centrality classes [χ^2/(degree of freedom) ~ 1], except for 0%–0.2% centrality, where the r_2 value deviates from unity much faster as η^a increases. Note that the parameter F_n^η is purely empirical, without any clear physical meaning at present. It is introduced mainly for quantitatively evaluating the centrality evolution of the factorization-breakdown effect, as will be discussed later in Sec. V D.

C. Results for pPb data

Studies of η-dependent factorization breakdown of two-particle correlations are also performed in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV for four high-multiplicity ranges, shown in Fig. 12 for the second-order harmonics. Results for higher-order harmonics in pPb cannot be obtained due to statistical limitation. As pointed out in Sec. V A, because of asymmetry of pPb collisions in η, the factorization ratio $r_n(\eta^a,\eta^b)$ is sensitive to asymmetry in the magnitude of v_n and thus does not reflect only the effect of event-plane-angle fluctuations. Therefore, the results are presented as the square root of the product of $r_n(\eta^a,\eta^b)$ and $r_n(-\eta^a,-\eta^b)$, which is designed to remove the sensitivity to the magnitude of v_n [see Eq. (10) for details]. Similar to those in PbPb collisions, two different η ranges of HF towers, $3.0 < \eta^b < 4.0$ and $4.4 < \eta^b < 5.0$, are compared.

A significant breakdown of factorization in η is also observed in pPb collisions as η^a increases. Similar to the PbPb results, the factorization breakdown is approximately independent of η^b for $\eta^a < 1$ for all multiplicity ranges but shows a much larger deviation from unity for $3.0 < \eta^b < 4.0$ as η^a increases beyond one unit because of short-range correlations. The fits to the data for $4.4 < \eta^b < 5.0$ using Eq. (12) are also shown; the data are well described over the accessible η^a range. It should be noted that the assumption made in Eq. (11) is purely an empirical parametrization for quantifying the behavior of the data. Since pPb collisions are asymmetric, this assumption could be invalid. More detailed investigations on how r_n depends on η^a and η^b in the proton- and lead-going directions, respectively, are needed in future work.

D. Comparison of *p*Pb and PbPb data

The extracted F_n^η parameters are plotted as a function of event multiplicity in Fig. 13, in pPb collisions for $n = 2$ and PbPb collisions for $n = 2$ to 4. The F_2^η value reaches its minimum around midcentral (~20%) PbPb events and increases significantly for more peripheral PbPb events and also for pPb events, where the relative fluctuations of v_2 are larger [12]. Toward the most central PbPb events, the F_2^η value also shows a tendency to increase slightly, although the r_n data for 0%–0.2% centrality are not well described by Eq. (12). At a similar multiplicity, magnitudes of the F_2^η parameter in pPb are significantly larger than those in PbPb and decrease with increasing event multiplicity. In PbPb collisions, a much stronger η-dependent factorization breakdown is seen for higher-order harmonics than for the second order, as shown by the F_3^η and F_4^η parameters. There is little centrality dependence for $n = 3$, except for the most central 0%–20% PbPb collisions. Within current statistical uncertainties, no centrality dependence is observed for $n = 4$.

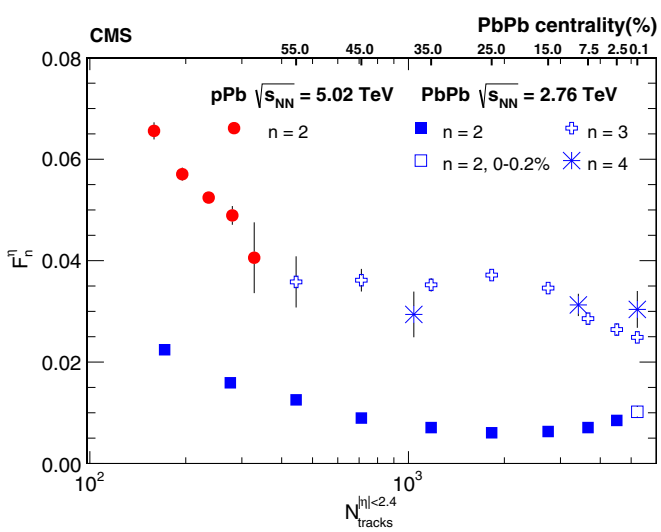

FIG. 13. (Color online) The F_n^η parameter as defined in Eq. (12) as a function of event multiplicity in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV for $n = 2$ to 4 and pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV for $n = 2$. The error bars correspond to statistical uncertainties, while systematic uncertainties are negligible for the r_n results and thus are not shown.

VI. SUMMARY

Factorization of azimuthal two-particle correlations into single-particle anisotropies has been studied as a function of transverse momentum and pseudorapidity of each particle from a pair, in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV and pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, and over a wide multiplicity range. The factorization assumption is found to be broken as a function of both p_T and η. The effect of p_T-dependent factorization breakdown for the second-order Fourier harmonic is found to increase with the difference in p_T between the two particles. The factorization breakdown reaches 20% for the most central PbPb collisions, while it decreases rapidly for more peripheral collisions. The effect is significantly smaller (2%–3%) in high-multiplicity pPb collisions. In both PbPb and pPb samples over the full centrality or multiplicity range, little effect is observed for the third-order harmonic. For the η dependence, the observed factorization breakdown shows an approximately linear increase with the η gap between two particles for all centrality and multiplicity classes in PbPb and pPb collisions. The effect is weakest for mid-central PbPb events but becomes larger for more central or peripheral PbPb collisions, and also for very high-multiplicity pPb collisions. Moreover, a much stronger η-dependent effect is seen for the third- and fourth-order harmonics than the second-order harmonics in PbPb collisions. This relation between the second and third order is opposite to that seen in the p_T-dependent factorization studies. The observed factorization breakdown presented here does not invalidate previous v_n measurements. Instead, the previous values should be reinterpreted as measuring anisotropies with respect to the event plane averaged over a given kinematic region. Furthermore, it is important to compare data and theoretical calculations following exactly the same procedure.

The factorization data have been compared to hydrodynamic calculations with fluctuating initial-state conditions. The p_T-dependent factorization data are qualitatively described by viscous hydrodynamic models, which are shown to be largely insensitive to the value of shear viscosity to entropy density ratio of the medium. This observation offers great promise for using the factorization data to disentangle contributions of the initial-state conditions and the medium's transport properties to the observed collective-flow phenomena in the final state. The new studies of η-dependent factorization breakdown give an indication of initial-state fluctuations along the longitudinal direction. This will provide new insights into the longitudinal dynamics of relativistic heavy ion collisions and help improve the three-dimensional modeling of the evolution of the strongly coupled quark gluon medium.

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Kleinwort,[37] I. Korol,[37] W. Lange,[37] J. Leonard,[37] K. Lipka,[37] A. Lobanov,[37] R. Mankel,[37] I. Marfin,[37,q] I.-A. Melzer-Pellmann,[37] A. B. Meyer,[37] G. Mittag,[37] J. Mnich,[37] A. Mussgiller,[37] S. Naumann-Emme,[37] A. Nayak,[37] E. Ntomari,[37] H. Perrey,[37] D. Pitzl,[37] R. Placakyte,[37] A. Raspereza,[37] P. M. Ribeiro Cipriano,[37] B. Roland,[37] E. Ron,[37] M.Ö. Sahin,[37] J. Salfeld-Nebgen,[37] P. Saxena,[37] T. Schoerner-Sadenius,[37] M. Schröder,[37] C. Seitz,[37] S. Spannagel,[37] C. Wissing,[37] V. Blobel,[38] M. Centis Vignali,[38] A. R. Draeger,[38] J. Erfle,[38] E. Garutti,[38] K. Goebel,[38] D. Gonzalez,[38] M. Görner,[38] J. Haller,[38] M. Hoffmann,[38] R. S. Höing,[38] A. Junkes,[38] H. Kirschenmann,[38] R. Klanner,[38] R. Kogler,[38] T. Lapsien,[38] T. Lenz,[38] I. Marchesini,[38] D. Marconi,[38] D. Nowatschin,[38] J. Ott,[38] T. Peiffer,[38] A. Perieanu,[38] N. Pietsch,[38] J. Poehlsen,[38] D. Rathjens,[38] C. Sander,[38] H. Schettler,[38] P. Schleper,[38] E. Schlieckau,[38] A. Schmidt,[38] M. Seidel,[38] V. Sola,[38] H. Stadie,[38] G. Steinbrück,[38] H. Tholen,[38] D. Troendle,[38] E. Usai,[38] L. Vanelderen,[38] A. Vanhoefer,[38] M. Akbiyik,[39] C. Barth,[39] C. Baus,[39] J. Berger,[39] C. Böser,[39] E. Butz,[39] T. Chwalek,[39] F. Colombo,[39] W. De Boer,[39] A. Descroix,[39] A. Dierlamm,[39] M. Feindt,[39] F. Frensch,[39] M. Giffels,[39] A. Gilbert,[39] F. Hartmann,[39,b] U. Husemann,[39] I. Katkov,[39,e] A. Kornmayer,[39,b] P. Lobelle Pardo,[39] M. U. Mozer,[39] T. Müller,[39] Th. Müller,[39] M. Plagge,[39] G. Quast,[39] K. Rabbertz,[39] S. Röcker,[39] F. Roscher,[39] H. J. Simonis,[39] F. M. Stober,[39] R. Ulrich,[39] J. Wagner-Kuhr,[39] S. Wayand,[39] T. Weiler,[39] C. Wöhrmann,[39] R. Wolf,[39] G. Anagnostou,[40] G. Daskalakis,[40] T. Geralis,[40] V. A. Giakoumopoulou,[40] A. Kyriakis,[40] D. Loukas,[40] A. Markou,[40] A. Psallidas,[40] I. Topsis-Giotis,[40] A. Agapitos,[41]

S. Kesisoglou,[41] A. Panagiotou,[41] N. Saoulidou,[41] E. Tziaferi,[41] I. Evangelou,[42] G. Flouris,[42] C. Foudas,[42] P. Kokkas,[42] N. Loukas,[42] N. Manthos,[42] I. Papadopoulos,[42] E. Paradas,[42] J. Strologas,[42] G. Bencze,[43] C. Hajdu,[43] P. Hidas,[43] D. Horvath,[43,r] F. Sikler,[43] V. Veszpremi,[43] G. Vesztergombi,[43,s] A. J. Zsigmond,[43] N. Beni,[44] S. Czellar,[44] J. Karancsi,[44,t] J. Molnar,[44] J. Palinkas,[44] Z. Szillasi,[44] M. Bartók,[45,u] A. Makovec,[45] P. Raics,[45] Z. L. Trocsanyi,[45] P. Mal,[46] K. Mandal,[46] N. Sahoo,[46] S. K. Swain,[46] S. B. Beri,[47] V. Bhatnagar,[47] R. Chawla,[47] R. Gupta,[47] U. Bhawandeep,[47] A. K. Kalsi,[47] A. Kaur,[47] M. Kaur,[47] R. Kumar,[47] A. Mehta,[47] M. Mittal,[47] N. Nishu,[47] J. B. Singh,[47] Ashok Kumar,[48] Arun Kumar,[48] A. Bhardwaj,[48] B. C. Choudhary,[48] A. Kumar,[48] S. Malhotra,[48] M. Naimuddin,[48] K. Ranjan,[48] R. Sharma,[48] V. Sharma,[48] S. Banerjee,[49] S. Bhattacharya,[49] K. Chatterjee,[49] S. Dutta,[49] B. Gomber,[49] Sa. Jain,[49] Sh. Jain,[49] R. Khurana,[49] N. Majumdar,[49] A. Modak,[49] K. Mondal,[49] S. Mukherjee,[49] S. Mukhopadhyay,[49] A. Roy,[49] D. Roy,[49] S. Roy Chowdhury,[49] S. Sarkar,[49] M. Sharan,[49] A. Abdulsalam,[50] D. Dutta,[50] V. Jha,[50] V. Kumar,[50] A. K. Mohanty,[50,b] L. M. Pant,[50] P. Shukla,[50] A. Topkar,[50] T. Aziz,[51] S. Banerjee,[51] S. Bhowmik,[51,v] R. M. Chatterjee,[51] R. K. Dewanjee,[51] S. Dugad,[51] S. Ganguly,[51] S. Ghosh,[51] M. Guchait,[51] A. Gurtu,[51,w] G. Kole,[51] S. Kumar,[51] M. Maity,[51,v] G. Majumder,[51] K. Mazumdar,[51] G. B. Mohanty,[51] B. Parida,[51] K. Sudhakar,[51] N. Sur,[51] B. Sutar,[51] N. Wickramage,[51,x] S. Sharma,[52] H. Bakhshiansohi,[53] H. Behnamian,[53] S. M. Etesami,[53,y] A. Fahim,[53,z] R. Goldouzian,[53] M. Khakzad,[53] M. Mohammadi Najafabadi,[53] M. Naseri,[53] S. Paktinat Mehdiabadi,[53] F. Rezaei Hosseinabadi,[53] B. Safarzadeh,[53,aa] M. Zeinali,[53] M. Felcini,[54] M. Grunewald,[54] M. Abbrescia,[55a,55b] C. Calabria,[55a 55b] C. Caputo,[55a,55b] S. S. Chhibra,[55a,55b] A. Colaleo,[55a] D. Creanza,[55a 55c] L. Cristella,[55a,55b] N. De Filippis,[55a 55c] M. De Palma,[55a,55b] L. Fiore,[55a] G. Iaselli,[55a a55c] G. Maggi,[55a,55c] M. Maggi,[55a] G. Miniello,[55a,55b] S. My,[55a,55c] S. Nuzzo,[55a,55b] A. Pompili,[55a,55b] G. Pugliese,[55a,55c] R. Radogna,[55a,55b,b] A. Ranieri,[55a] G. Selvaggi,[55a,55b] A. Sharma,[55a] L. Silvestris,[55a,b] R. Venditti,[55a,55b] P. Verwilligen,[55a] G. Abbiendi,[56a] C. Battilana,[56a] A. C. Benvenuti,[56a] D. Bonacorsi,[56a,56b] S. Braibant-Giacomelli,[56a,56b] L. Brigliadori,[56a,56b] R. Campanini,[56a,56b] P. Capiluppi,[56a,56b] A. Castro,[56a,56b] F. R. Cavallo,[56a] G. Codispoti,[56a,56b] M. Cuffiani,[56a,56b] G. M. Dallavalle,[56a] F. Fabbri,[56a] A. Fanfani,[56a,56b] D. Fasanella,[56a,56b] P. Giacomelli,[56a] C. Grandi,[56a] L. Guiducci,[56a,56b] S. Marcellini,[56a] G. Masetti,[56a] A. Montanari,[56a] F. L. Navarria,[56a,56b] A. Perrotta,[56a] A. M. Rossi,[56a,56b] T. Rovelli,[56a,56b] G. P. Siroli,[56a,56b] N. Tosi,[56a,56b] R. Travaglini,[56a,56b] G. Cappello,[57a] M. Chiorboli,[57a,57b] S. Costa,[57a,57b] F. Giordano,[57a,b] R. Potenza,[57a,57b] A. Tricomi,[57a,57b] C. Tuve,[57a,57b] G. Barbagli,[58a] V. Ciulli,[58a,58b] C. Civinini,[58a] R. D'Alessandro,[58a,58b] E. Focardi,[58a,58b] E. Gallo,[58a] S. Gonzi,[58a,58b] V. Gori,[58a,58b] P. Lenzi,[58a,58b] M. Meschini,[58a] S. Paoletti,[58a] G. Sguazzoni,[58a] A. Tropiano,[58a,58b] L. Benussi,[59] S. Bianco,[59] F. Fabbri,[59] D. Piccolo,[59] V. Calvelli,[60a,60b] F. Ferro,[60a] M. Lo Vetere,[60a,60b] E. Robutti,[60a] S. Tosi,[60a,60b] M. E. Dinardo,[61a,61b] S. Fiorendi,[61a,61b] S. Gennai,[61a,b] R. Gerosa,[61a,61b] A. Ghezzi,[61a,61b] P. Govoni,[61a,61b] M. T. Lucchini,[61a,61b,b] S. Malvezzi,[61a] R. A. Manzoni,[61a,61b] B. Marzocchi,[61a,61b,b] D. Menasce,[61a] L. Moroni,[61a] M. Paganoni,[61a,61b] D. Pedrini,[61a] S. Ragazzi,[61a,61b] N. Redaelli,[61a] T. Tabarelli de Fatis,[61a,61b] S. Buontempo,[62a] N. Cavallo,[62a,62c] S. Di Guida,[62a 62d,b] M. Esposito,[62a,62b] F. Fabozzi,[62a,62c] A. O. M. Iorio,[62a,62b] G. Lanza,[62a] L. Lista,[62a] S. Meola,[62a 62d,b] M. Merola,[62a] P. Paolucci,[62a,b] C. Sciacca,[62a,62b] P. Azzi,[63a,b] N. Bacchetta,[63a] D. Bisello,[63a,63b] A. Branca,[63a,63b] R. Carlin,[63a,63b] A. Carvalho Antunes De Oliveira,[63a,63b] P. Checchia,[63a] M. Dall'Osso,[63a,63b] T. Dorigo,[63a] U. Gasparini,[63a,63b] A. Gozzelino,[63a] K. Kanishchev,[63a,63c] S. Lacaprara,[63a] M. Margoni,[63a,63b] A. T. Meneguzzo,[63a,63b] J. Pazzini,[63a,63b] M. Pegoraro,[63a] N. Pozzobon,[63a,63b] P. Ronchese,[63a,63b] F. Simonetto,[63a,63b] E. Torassa,[63a] M. Tosi,[63a,63b] S. Vanini,[63a,63b] S. Ventura,[63a] M. Zanetti,[63a] P. Zotto,[63a,63b] A. Zucchetta,[63a,63b] M. Gabusi,[64a,64b] A. Magnani,[64a] S. P. Ratti,[64a,64b] V. Re,[64a] C. Riccardi,[64a,64b] P. Salvini,[64a] I. Vai,[64a] P. Vitulo,[64a,64b] L. Alunni Solestizi,[65a,65b] M. Biasini,[65a,65b] G. M. Bilei,[65a] D. Ciangottini,[65a,65b,b] L. Fanò,[65a,65b] P. Lariccia,[65a,65b] G. Mantovani,[65a,65b] M. Menichelli,[65a] A. Saha,[65a] A. Santocchia,[65a,65b] A. Spiezia,[65a,65b,b] K. Androsov,[66a,ab] P. Azzurri,[66a] G. Bagliesi,[66a] J. Bernardini,[66a] T. Boccali,[66a] G. Broccolo,[66a,66c] R. Castaldi,[66a] M. A. Ciocci,[66a,ab] R. Dell'Orso,[66a] S. Donato,[66a,66c,b] G. Fedi,[66a] F. Fiori,[66a,66c] L. Foà,[66a 66c,*] A. Giassi,[66a] M. T. Grippo,[66a,ab] F. Ligabue,[66a,66c] T. Lomtadze,[66a] L. Martini,[66a,66b] A. Messineo,[66a,66b] C. S. Moon,[66a,ac] F. Palla,[66a] A. Rizzi,[66a,66b] A. Savoy-Navarro,[66a,ad] A. T. Serban,[66a] P. Spagnolo,[66a] P. Squillacioti,[66a,ab] R. Tenchini,[66a] G. Tonelli,[66a,66b] A. Venturi,[66a] P. G. Verdini,[66a] L. Barone,[67a,67b] F. Cavallari,[67a] G. D'imperio,[67a,67b] D. Del Re,[67a,67b] M. Diemoz,[67a] S. Gelli,[67a,67b] C. Jorda,[67a] E. Longo,[67a,67b] F. Margaroli,[67a,67b] P. Meridiani,[67a] F. Micheli,[67a,67b] G. Organtini,[67a,67b] R. Paramatti,[67a] F. Preiato,[67a,67b] S. Rahatlou,[67a,67b] C. Rovelli,[67a] F. Santanastasio,[67a,67b] L. Soffi,[67a,67b] P. Traczyk,[67a,67b,b] N. Amapane,[68a,68b] R. Arcidiacono,[68a,68c] S. Argiro,[68a,68b] M. Arneodo,[68a,68c] R. Bellan,[68a,68b] C. Biino,[68a] N. Cartiglia,[68a] S. Casasso,[68a,68b] M. Costa,[68a,68b] R. Covarelli,[68a] A. Degano,[68a,68b] N. Demaria,[68a] L. Finco,[68a,68b,b] B. Kiani,[68a,68b] C. Mariotti,[68a] S. Maselli,[68a] E. Migliore,[68a,68b] V. Monaco,[68a,68b] M. Musich,[68a] M. M. Obertino,[68a,68c] L. Pacher,[68a,68b] N. Pastrone,[68a] M. Pelliccioni,[68a] G. L. Pinna Angioni,[68a,68b] A. Romero,[68a,68b] M. Ruspa,[68a,68c] R. Sacchi,[68a,68b] A. Solano,[68a,68b] A. Staiano,[68a] U. Tamponi,[68a] S. Belforte,[69a] V. Candelise,[69a,69b,b] M. Casarsa,[69a] F. Cossutti,[69a] G. Della Ricca,[69a,69b] B. Gobbo,[69a] C. La Licata,[69a,69b] M. Marone,[69a,69b] A. Schizzi,[69a,69b] T. Umer,[69a,69b] A. Zanetti,[69a] S. Chang,[70] A. Kropivnitskaya,[70] S. K. Nam,[70] D. H. Kim,[71] G. N. Kim,[71] M. S. Kim,[71] D. J. Kong,[71] S. Lee,[71] Y. D. Oh,[71] H. Park,[71] A. Sakharov,[71] D. C. Son,[71] H. Kim,[72] T. J. Kim,[72] M. S. Ryu,[72] S. Song,[73] S. Choi,[74] Y. Go,[74] D. Gyun,[74] B. Hong,[74] M. Jo,[74] H. Kim,[74] Y. Kim,[74] B. Lee,[74] K. Lee,[74] K. S. Lee,[74] S. Lee,[74] S. K. Park,[74] Y. Roh,[74] H. D. Yoo,[75] M. Choi,[76] J. H. Kim,[76] J. S. H. Lee,[76] I. C. Park,[76] G. Ryu,[76] Y. Choi,[77] Y. K. Choi,[77] J. Goh,[77] D. Kim,[77] E. Kwon,[77] J. Lee,[77] I. Yu,[77] A. Juodagalvis,[78] J. Vaitkus,[78] Z. A. Ibrahim,[79] J. R. Komaragiri,[79] M. A. B. Md Ali,[79,ae] F. Mohamad Idris,[79] W. A. T. Wan Abdullah,[79] E. Casimiro Linares,[80] H. Castilla-Valdez,[80] E. De La Cruz-Burelo,[80] I. Heredia-de La Cruz,[80] A. Hernandez-Almada,[80] R. Lopez-Fernandez,[80] G. Ramirez Sanchez,[80] A. Sanchez-Hernandez,[80] S. Carrillo Moreno,[81] F. Vazquez Valencia,[81] S. Carpinteyro,[82] I. Pedraza,[82] H. A. Salazar Ibarguen,[82] A. Morelos Pineda,[83]

D. Krofcheck,[84] P. H. Butler,[85] S. Reucroft,[85] A. Ahmad,[86] M. Ahmad,[86] Q. Hassan,[86] H. R. Hoorani,[86] W. A. Khan,[86] T. Khurshid,[86] M. Shoaib,[86] H. Bialkowska,[87] M. Bluj,[87] B. Boimska,[87] T. Frueboes,[87] M. Górski,[87] M. Kazana,[87] K. Nawrocki,[87] K. Romanowska-Rybinska,[87] M. Szleper,[87] P. Zalewski,[87] G. Brona,[88] K. Bunkowski,[88] K. Doroba,[88] A. Kalinowski,[88] M. Konecki,[88] J. Krolikowski,[88] M. Misiura,[88] M. Olszewski,[88] M. Walczak,[88] P. Bargassa,[89] C. Beirão Da Cruz E Silva,[89] A. Di Francesco,[89] P. Faccioli,[89] P. G. Ferreira Parracho,[89] M. Gallinaro,[89] L. Lloret Iglesias,[89] F. Nguyen,[89] J. Rodrigues Antunes,[89] J. Seixas,[89] O. Toldaiev,[89] D. Vadruccio,[89] J. Varela,[89] P. Vischia,[89] S. Afanasiev,[90] P. Bunin,[90] M. Gavrilenko,[90] I. Golutvin,[90] I. Gorbunov,[90] A. Kamenev,[90] V. Karjavin,[90] V. Konoplyanikov,[90] A. Lanev,[90] A. Malakhov,[90] V. Matveev,[90,af] P. Moisenz,[90] V. Palichik,[90] V. Perelygin,[90] S. Shmatov,[90] S. Shulha,[90] N. Skatchkov,[90] V. Smirnov,[90] T. Toriashvili,[90,ag] A. Zarubin,[90] V. Golovtsov,[91] Y. Ivanov,[91] V. Kim,[91,ah] E. Kuznetsova,[91] P. Levchenko,[91] V. Murzin,[91] V. Oreshkin,[91] I. Smirnov,[91] V. Sulimov,[91] L. Uvarov,[91] S. Vavilov,[91] A. Vorobyev,[91] Yu. Andreev,[92] A. Dermenev,[92] S. Gninenko,[92] N. Golubev,[92] A. Karneyeu,[92] M. Kirsanov,[92] N. Krasnikov,[92] A. Pashenkov,[92] D. Tlisov,[92] A. Toropin,[92] V. Epshteyn,[93] V. Gavrilov,[93] N. Lychkovskaya,[93] V. Popov,[93] I. Pozdnyakov,[93] G. Safronov,[93] A. Spiridonov,[93] E. Vlasov,[93] A. Zhokin,[93] V. Andreev,[94] M. Azarkin,[94,ai] I. Dremin,[94,ai] M. Kirakosyan,[94] A. Leonidov,[94,ai] G. Mesyats,[94] S. V. Rusakov,[94] A. Vinogradov,[94] A. Baskakov,[95] A. Belyaev,[95] E. Boos,[95] A. Demiyanov,[95] A. Ershov,[95] A. Gribushin,[95] O. Kodolova,[95] V. Korotkikh,[95] I. Lokhtin,[95] I. Myagkov,[95] S. Obraztsov,[95] S. Petrushanko,[95] V. Savrin,[95] A. Snigirev,[95] I. Vardanyan,[95] I. Azhgirey,[96] I. Bayshev,[96] S. Bitioukov,[96] V. Kachanov,[96] A. Kalinin,[96] D. Konstantinov,[96] V. Krychkine,[96] V. Petrov,[96] R. Ryutin,[96] A. Sobol,[96] L. Tourtchanovitch,[96] S. Troshin,[96] N. Tyurin,[96] A. Uzunian,[96] A. Volkov,[96] P. Adzic,[97,aj] D. Devetak,[97] M. Ekmedzic,[97] J. Milosevic,[97] V. Rekovic,[97] J. Alcaraz Maestre,[98] E. Calvo,[98] M. Cerrada,[98] M. Chamizo Llatas,[98] N. Colino,[98] B. De La Cruz,[98] A. Delgado Peris,[98] D. Domínguez Vázquez,[98] A. Escalante Del Valle,[98] C. Fernandez Bedoya,[98] J. P. Fernández Ramos,[98] J. Flix,[98] M. C. Fouz,[98] P. Garcia-Abia,[98] O. Gonzalez Lopez,[98] S. Goy Lopez,[98] J. M. Hernandez,[98] M. I. Josa,[98] E. Navarro De Martino,[98] A. Pérez-Calero Yzquierdo,[98] J. Puerta Pelayo,[98] A. Quintario Olmeda,[98] I. Redondo,[98] L. Romero,[98] M. S. Soares,[98] C. Albajar,[99] J. F. de Trocóniz,[99] M. Missiroli,[99] D. Moran,[99] H. Brun,[100] J. Cuevas,[100] J. Fernandez Menendez,[100] S. Folgueras,[100] I. Gonzalez Caballero,[100] E. Palencia Cortezon,[100] J. M. Vizan Garcia,[100] J. A. Brochero Cifuentes,[101] I. J. Cabrillo,[101] A. Calderon,[101] J. R. Castiñeiras De Saa,[101] J. Duarte Campderros,[101] M. Fernandez,[101] G. Gomez,[101] A. Graziano,[101] A. Lopez Virto,[101] J. Marco,[101] R. Marco,[101] C. Martinez Rivero,[101] F. Matorras,[101] F. J. Munoz Sanchez,[101] J. Piedra Gomez,[101] T. Rodrigo,[101] A. Y. Rodríguez-Marrero,[101] A. Ruiz-Jimeno,[101] L. Scodellaro,[101] I. Vila,[101] R. Vilar Cortabitarte,[101] D. Abbaneo,[102] E. Auffray,[102] G. Auzinger,[102] M. Bachtis,[102] P. Baillon,[102] A. H. Ball,[102] D. Barney,[102] A. Benaglia,[102] J. Bendavid,[102] L. Benhabib,[102] J. F. Benitez,[102] G. M. Berruti,[102] P. Bloch,[102] A. Bocci,[102] A. Bonato,[102] C. Botta,[102] H. Breuker,[102] T. Camporesi,[102] G. Cerminara,[102] S. Colafranceschi,[102,ak] M. D'Alfonso,[102] D. d'Enterria,[102] A. Dabrowski,[102] V. Daponte,[102] A. David,[102] M. De Gruttola,[102] F. De Guio,[102] A. De Roeck,[102] S. De Visscher,[102] E. Di Marco,[102] M. Dobson,[102] M. Dordevic,[102] N. Dupont-Sagorin,[102] A. Elliott-Peisert,[102] G. Franzoni,[102] W. Funk,[102] D. Gigi,[102] K. Gill,[102] D. Giordano,[102] M. Girone,[102] F. Glege,[102] R. Guida,[102] S. Gundacker,[102] M. Guthoff,[102] J. Hammer,[102] M. Hansen,[102] P. Harris,[102] J. Hegeman,[102] V. Innocente,[102] P. Janot,[102] M. J. Kortelainen,[102] K. Kousouris,[102] K. Krajczar,[102] P. Lecoq,[102] C. Lourenço,[102] N. Magini,[102] L. Malgeri,[102] M. Mannelli,[102] J. Marrouche,[102] A. Martelli,[102] L. Masetti,[102] F. Meijers,[102] S. Mersi,[102] E. Meschi,[102] F. Moortgat,[102] S. Morovic,[102] M. Mulders,[102] M. V. Nemallapudi,[102] H. Neugebauer,[102] S. Orfanelli,[102] L. Orsini,[102] L. Pape,[102] E. Perez,[102] A. Petrilli,[102] G. Petrucciani,[102] A. Pfeiffer,[102] D. Piparo,[102] A. Racz,[102] G. Rolandi,[102,al] M. Rovere,[102] M. Ruan,[102] H. Sakulin,[102] C. Schäfer,[102] C. Schwick,[102] A. Sharma,[102] P. Silva,[102] M. Simon,[102] P. Sphicas,[102,am] D. Spiga,[102] J. Steggemann,[102] B. Stieger,[102] M. Stoye,[102] Y. Takahashi,[102] D. Treille,[102] A. Tsirou,[102] G. I. Veres,[102,s] N. Wardle,[102] H. K. Wöhri,[102] A. Zagozdzinska,[102,an] W. D. Zeuner,[102] W. Bertl,[103] K. Deiters,[103] W. Erdmann,[103] R. Horisberger,[103] Q. Ingram,[103] H. C. Kaestli,[103] D. Kotlinski,[103] U. Langenegger,[103] T. Rohe,[103] F. Bachmair,[104] L. Bäni,[104] L. Bianchini,[104] M. A. Buchmann,[104] B. Casal,[104] G. Dissertori,[104] M. Dittmar,[104] M. Donegà,[104] M. Dünser,[104] P. Eller,[104] C. Grab,[104] C. Heidegger,[104] D. Hits,[104] J. Hoss,[104] G. Kasieczka,[104] W. Lustermann,[104] B. Mangano,[104] A. C. Marini,[104] M. Marionneau,[104] P. Martinez Ruiz del Arbol,[104] M. Masciovecchio,[104] D. Meister,[104] N. Mohr,[104] P. Musella,[104] F. Nessi-Tedaldi,[104] F. Pandolfi,[104] J. Pata,[104] F. Pauss,[104] L. Perrozzi,[104] M. Peruzzi,[104] M. Quittnat,[104] M. Rossini,[104] A. Starodumov,[104,ao] M. Takahashi,[104] V. R. Tavolaro,[104] K. Theofilatos,[104] R. Wallny,[104] H. A. Weber,[104] T. K. Aarrestad,[105] C. Amsler,[105,ap] M. F. Canelli,[105] V. Chiochia,[105] A. De Cosa,[105] C. Galloni,[105] A. Hinzmann,[105] T. Hreus,[105] B. Kilminster,[105] C. Lange,[105] J. Ngadiuba,[105] D. Pinna,[105] P. Robmann,[105] F. J. Ronga,[105] D. Salerno,[105] S. Taroni,[105] Y. Yang,[105] M. Cardaci,[106] K. H. Chen,[106] T. H. Doan,[106] C. Ferro,[106] M. Konyushikhin,[106] C. M. Kuo,[106] W. Lin,[106] Y. J. Lu,[106] R. Volpe,[106] S. S. Yu,[106] P. Chang,[107] Y. H. Chang,[107] Y. Chao,[107] K. F. Chen,[107] P. H. Chen,[107] C. Dietz,[107] U. Grundler,[107] W.-S. Hou,[107] Y. Hsiung,[107] Y. F. Liu,[107] R.-S. Lu,[107] M. Miñano Moya,[107] E. Petrakou,[107] J. f. Tsai,[107] Y. M. Tzeng,[107] R. Wilken,[107] B. Asavapibhop,[108] G. Singh,[108] N. Srimanobhas,[108] N. Suwonjandee,[108] A. Adiguzel,[109] S. Cerci,[109,aq] C. Dozen,[109] S. Girgis,[109] G. Gokbulut,[109] Y. Guler,[109] E. Gurpinar,[109] I. Hos,[109] E. E. Kangal,[109,ar] A. Kayis Topaksu,[109] G. Onengut,[109,as] K. Ozdemir,[109,at] S. Ozturk,[109,au] B. Tali,[109,aq] H. Topakli,[109,au] M. Vergili,[109] C. Zorbilmez,[109] I. V. Akin,[110] B. Bilin,[110] S. Bilmis,[110] B. Isildak,[110,av] G. Karapinar,[110,aw] U. E. Surat,[110] M. Yalvac,[110] M. Zeyrek,[110] E. A. Albayrak,[111,ax] E. Gülmez,[111] M. Kaya,[111,ay] O. Kaya,[111,az] T. Yetkin,[111,ba] K. Cankocak,[112] Y. O. Günaydin,[112,bb] F. I. Vardarlı,[112] B. Grynyov,[113] L. Levchuk,[114] P. Sorokin,[114] R. Aggleton,[115] F. Ball,[115] L. Beck,[115] J. J. Brooke,[115] E. Clement,[115] D. Cussans,[115] H. Flacher,[115] J. Goldstein,[115] M. Grimes,[115] G. P. Heath,[115] H. F. Heath,[115] J. Jacob,[115] L. Kreczko,[115] C. Lucas,[115] Z. Meng,[115]

D. M. Newbold,[115,bc] S. Paramesvaran,[115] A. Poll,[115] T. Sakuma,[115] S. Seif El Nasr-storey,[115] S. Senkin,[115] D. Smith,[115] V. J. Smith,[115] A. Belyaev,[116,bd] C. Brew,[116] R. M. Brown,[116] D. J. A. Cockerill,[116] J. A. Coughlan,[116] K. Harder,[116] S. Harper,[116] E. Olaiya,[116] D. Petyt,[116] C. H. Shepherd-Themistocleous,[116] A. Thea,[116] I. R. Tomalin,[116] T. Williams,[116] W. J. Womersley,[116] S. D. Worm,[116] M. Baber,[117] R. Bainbridge,[117] O. Buchmuller,[117] A. Bundock,[117] D. Burton,[117] M. Citron,[117] D. Colling,[117] L. Corpe,[117] N. Cripps,[117] P. Dauncey,[117] G. Davies,[117] A. De Wit,[117] M. Della Negra,[117] P. Dunne,[117] A. Elwood,[117] W. Ferguson,[117] J. Fulcher,[117] D. Futyan,[117] G. Hall,[117] G. Iles,[117] M. Jarvis,[117] G. Karapostoli,[117] M. Kenzie,[117] R. Lane,[117] R. Lucas,[117,bc] L. Lyons,[117] A.-M. Magnan,[117] S. Malik,[117] B. Mathias,[117] J. Nash,[117] A. Nikitenko,[117,ao] J. Pela,[117] M. Pesaresi,[117] K. Petridis,[117] D. M. Raymond,[117] A. Richards,[117] S. Rogerson,[117] A. Rose,[117] C. Seez,[117] P. Sharp,[117,*] A. Tapper,[117] K. Uchida,[117] M. Vazquez Acosta,[117] T. Virdee,[117] S. C. Zenz,[117] J. E. Cole,[118] P. R. Hobson,[118] A. Khan,[118] P. Kyberd,[118] D. Leggat,[118] D. Leslie,[118] I. D. Reid,[118] P. Symonds,[118] L. Teodorescu,[118] M. Turner,[118] J. Dittmann,[119] K. Hatakeyama,[119] A. Kasmi,[119] H. Liu,[119] N. Pastika,[119] T. Scarborough,[119] Z. Wu,[119] O. Charaf,[120] S. I. Cooper,[120] C. Henderson,[120] P. Rumerio,[120] A. Avetisyan,[121] T. Bose,[121] C. Fantasia,[121] D. Gastler,[121] P. Lawson,[121] D. Rankin,[121] C. Richardson,[121] J. Rohlf,[121] J. St. John,[121] L. Sulak,[121] D. Zou,[121] J. Alimena,[122] E. Berry,[122] S. Bhattacharya,[122] D. Cutts,[122] Z. Demiragli,[122] N. Dhingra,[122] A. Ferapontov,[122] A. Garabedian,[122] U. Heintz,[122] E. Laird,[122] G. Landsberg,[122] Z. Mao,[122] M. Narain,[122] S. Sagir,[122] T. Sinthuprasith,[122] R. Breedon,[123] G. Breto,[123] M. Calderon De La Barca Sanchez,[123] S. Chauhan,[123] M. Chertok,[123] J. Conway,[123] R. Conway,[123] P. T. Cox,[123] R. Erbacher,[123] M. Gardner,[123] W. Ko,[123] R. Lander,[123] M. Mulhearn,[123] D. Pellett,[123] J. Pilot,[123] F. Ricci-Tam,[123] S. Shalhout,[123] J. Smith,[123] M. Squires,[123] D. Stolp,[123] M. Tripathi,[123] S. Wilbur,[123] R. Yohay,[123] R. Cousins,[124] P. Everaerts,[124] C. Farrell,[124] J. Hauser,[124] M. Ignatenko,[124] G. Rakness,[124] D. Saltzberg,[124] E. Takasugi,[124] V. Valuev,[124] M. Weber,[124] K. Burt,[125] R. Clare,[125] J. Ellison,[125] J. W. Gary,[125] G. Hanson,[125] J. Heilman,[125] M. Ivova Rikova,[125] P. Jandir,[125] E. Kennedy,[125] F. Lacroix,[125] O. R. Long,[125] A. Luthra,[125] M. Malberti,[125] M. Olmedo Negrete,[125] A. Shrinivas,[125] S. Sumowidagdo,[125] H. Wei,[125] S. Wimpenny,[125] J. G. Branson,[126] G. B. Cerati,[126] S. Cittolin,[126] R. T. D'Agnolo,[126] A. Holzner,[126] R. Kelley,[126] D. Klein,[126] D. Kovalskyi,[126] J. Letts,[126] I. Macneill,[126] D. Olivito,[126] S. Padhi,[126] C. Palmer,[126] M. Pieri,[126] M. Sani,[126] V. Sharma,[126] S. Simon,[126] M. Tadel,[126] Y. Tu,[126] A. Vartak,[126] S. Wasserbaech,[126,be] C. Welke,[126] F. Würthwein,[126] A. Yagil,[126] G. Zevi Della Porta,[126] D. Barge,[127] J. Bradmiller-Feld,[127] C. Campagnari,[127] A. Dishaw,[127] V. Dutta,[127] K. Flowers,[127] M. Franco Sevilla,[127] P. Geffert,[127] C. George,[127] F. Golf,[127] L. Gouskos,[127] J. Gran,[127] J. Incandela,[127] C. Justus,[127] N. Mccoll,[127] S. D. Mullin,[127] J. Richman,[127] D. Stuart,[127] W. To,[127] C. West,[127] J. Yoo,[127] D. Anderson,[128] A. Apresyan,[128] A. Bornheim,[128] J. Bunn,[128] Y. Chen,[128] J. Duarte,[128] A. Mott,[128] H. B. Newman,[128] C. Pena,[128] M. Pierini,[128] M. Spiropulu,[128] J. R. Vlimant,[128] S. Xie,[128] R. Y. Zhu,[128] V. Azzolini,[129] A. Calamba,[129] B. Carlson,[129] T. Ferguson,[129] Y. Iiyama,[129] M. Paulini,[129] J. Russ,[129] M. Sun,[129] H. Vogel,[129] I. Vorobiev,[129] J. P. Cumalat,[130] W. T. Ford,[130] A. Gaz,[130] F. Jensen,[130] A. Johnson,[130] M. Krohn,[130] T. Mulholland,[130] U. Nauenberg,[130] J. G. Smith,[130] K. Stenson,[130] S. R. Wagner,[130] J. Alexander,[131] A. Chatterjee,[131] J. Chaves,[131] J. Chu,[131] S. Dittmer,[131] N. Eggert,[131] N. Mirman,[131] G. Nicolas Kaufman,[131] J. R. Patterson,[131] A. Ryd,[131] L. Skinnari,[131] W. Sun,[131] S. M. Tan,[131] W. D. Teo,[131] J. Thom,[131] J. Thompson,[131] J. Tucker,[131] Y. Weng,[131] P. Wittich,[131] S. Abdullin,[132] M. Albrow,[132] J. Anderson,[132] G. Apollinari,[132] L. A. T. Bauerdick,[132] A. Beretvas,[132] J. Berryhill,[132] P. C. Bhat,[132] G. Bolla,[132] K. Burkett,[132] J. N. Butler,[132] H. W. K. Cheung,[132] F. Chlebana,[132] S. Cihangir,[132] V. D. Elvira,[132] I. Fisk,[132] J. Freeman,[132] E. Gottschalk,[132] L. Gray,[132] D. Green,[132] S. Grünendahl,[132] O. Gutsche,[132] J. Hanlon,[132] D. Hare,[132] R. M. Harris,[132] J. Hirschauer,[132] B. Hooberman,[132] Z. Hu,[132] S. Jindariani,[132] M. Johnson,[132] U. Joshi,[132] A. W. Jung,[132] B. Klima,[132] B. Kreis,[132] S. Kwan,[132,*] S. Lammel,[132] J. Linacre,[132] D. Lincoln,[132] R. Lipton,[132] T. Liu,[132] R. Lopes De Sá,[132] J. Lykken,[132] K. Maeshima,[132] J. M. Marraffino,[132] V. I. Martinez Outschoorn,[132] S. Maruyama,[132] D. Mason,[132] P. McBride,[132] P. Merkel,[132] K. Mishra,[132] S. Mrenna,[132] S. Nahn,[132] C. Newman-Holmes,[132] V. O'Dell,[132] O. Prokofyev,[132] E. Sexton-Kennedy,[132] A. Soha,[132] W. J. Spalding,[132] L. Spiegel,[132] L. Taylor,[132] S. Tkaczyk,[132] N. V. Tran,[132] L. Uplegger,[132] E. W. Vaandering,[132] C. Vernieri,[132] M. Verzocchi,[132] R. Vidal,[132] A. Whitbeck,[132] F. Yang,[132] H. Yin,[132] D. Acosta,[133] P. Avery,[133] P. Bortignon,[133] D. Bourilkov,[133] A. Carnes,[133] M. Carver,[133] D. Curry,[133] S. Das,[133] G. P. Di Giovanni,[133] R. D. Field,[133] M. Fisher,[133] I. K. Furic,[133] J. Hugon,[133] J. Konigsberg,[133] A. Korytov,[133] T. Kypreos,[133] J. F. Low,[133] P. Ma,[133] K. Matchev,[133] H. Mei,[133] P. Milenovic,[133,bf] G. Mitselmakher,[133] L. Muniz,[133] D. Rank,[133] A. Rinkevicius,[133] L. Shchutska,[133] M. Snowball,[133] D. Sperka,[133] S. J. Wang,[133] J. Yelton,[133] S. Hewamanage,[134] S. Linn,[134] P. Markowitz,[134] G. Martinez,[134] J. L. Rodriguez,[134] A. Ackert,[135] J. R. Adams,[135] T. Adams,[135] A. Askew,[135] J. Bochenek,[135] B. Diamond,[135] J. Haas,[135] S. Hagopian,[135] V. Hagopian,[135] K. F. Johnson,[135] A. Khatiwada,[135] H. Prosper,[135] V. Veeraraghavan,[135] M. Weinberg,[135] V. Bhopatkar,[136] M. Hohlmann,[136] H. Kalakhety,[136] D. Mareskas-palcek,[136] T. Roy,[136] F. Yumiceva,[136] M. R. Adams,[137] L. Apanasevich,[137] D. Berry,[137] R. R. Betts,[137] I. Bucinskaite,[137] R. Cavanaugh,[137] O. Evdokimov,[137] L. Gauthier,[137] C. E. Gerber,[137] D. J. Hofman,[137] P. Kurt,[137] C. O'Brien,[137] I. D. Sandoval Gonzalez,[137] C. Silkworth,[137] P. Turner,[137] N. Varelas,[137] M. Zakaria,[137] B. Bilki,[138,bg] W. Clarida,[138] K. Dilsiz,[138] R. P. Gandrajula,[138] M. Haytmyradov,[138] V. Khristenko,[138] J.-P. Merlo,[138] H. Mermerkaya,[138,bh] A. Mestvirishvili,[138] A. Moeller,[138] J. Nachtman,[138] H. Ogul,[138] Y. Onel,[138] F. Ozok,[138,ax] A. Penzo,[138] S. Sen,[138] C. Snyder,[138] P. Tan,[138] E. Tiras,[138] J. Wetzel,[138] K. Yi,[138] I. Anderson,[139] B. A. Barnett,[139] B. Blumenfeld,[139] D. Fehling,[139] L. Feng,[139] A. V. Gritsan,[139] P. Maksimovic,[139] C. Martin,[139] K. Nash,[139] M. Osherson,[139] M. Swartz,[139] M. Xiao,[139] Y. Xin,[139] P. Baringer,[140] A. Bean,[140] G. Benelli,[140] C. Bruner,[140] J. Gray,[140] R. P. Kenny III,[140] D. Majumder,[140] M. Malek,[140] M. Murray,[140] D. Noonan,[140] S. Sanders,[140] R. Stringer,[140] Q. Wang,[140] J. S. Wood,[140] I. Chakaberia,[141] A. Ivanov,[141] K. Kaadze,[141] S. Khalil,[141] M. Makouski,[141] Y. Maravin,[141]

L. K. Saini,[141] N. Skhirtladze,[141] I. Svintradze,[141] D. Lange,[142] F. Rebassoo,[142] D. Wright,[142] C. Anelli,[143] A. Baden,[143] O. Baron,[143] A. Belloni,[143] B. Calvert,[143] S. C. Eno,[143] J. A. Gomez,[143] N. J. Hadley,[143] S. Jabeen,[143] R. G. Kellogg,[143] T. Kolberg,[143] Y. Lu,[143] A. C. Mignerey,[143] K. Pedro,[143] Y. H. Shin,[143] A. Skuja,[143] M. B. Tonjes,[143] S. C. Tonwar,[143] A. Apyan,[144] R. Barbieri,[144] A. Baty,[144] K. Bierwagen,[144] S. Brandt,[144] W. Busza,[144] I. A. Cali,[144] L. Di Matteo,[144] G. Gomez Ceballos,[144] M. Goncharov,[144] D. Gulhan,[144] M. Klute,[144] Y. S. Lai,[144] Y.-J. Lee,[144] A. Levin,[144] P. D. Luckey,[144] C. Mcginn,[144] X. Niu,[144] C. Paus,[144] D. Ralph,[144] C. Roland,[144] G. Roland,[144] G. S. F. Stephans,[144] K. Sumorok,[144] M. Varma,[144] D. Velicanu,[144] J. Veverka,[144] J. Wang,[144] T. W. Wang,[144] B. Wyslouch,[144] M. Yang,[144] V. Zhukova,[144] B. Dahmes,[145] A. Finkel,[145] A. Gude,[145] S. C. Kao,[145] K. Klapoetke,[145] Y. Kubota,[145] J. Mans,[145] S. Nourbakhsh,[145] R. Rusack,[145] N. Tambe,[145] J. Turkewitz,[145] J. G. Acosta,[146] S. Oliveros,[146] E. Avdeeva,[147] K. Bloom,[147] S. Bose,[147] D. R. Claes,[147] A. Dominguez,[147] C. Fangmeier,[147] R. Gonzalez Suarez,[147] R. Kamalieddin,[147] J. Keller,[147] D. Knowlton,[147] I. Kravchenko,[147] J. Lazo-Flores,[147] F. Meier,[147] J. Monroy,[147] F. Ratnikov,[147] G. R. Snow,[147] M. Alyari,[148] J. Dolen,[148] J. George,[148] A. Godshalk,[148] I. Iashvili,[148] J. Kaisen,[148] A. Kharchilava,[148] A. Kumar,[148] S. Rappoccio,[148] G. Alverson,[149] E. Barberis,[149] D. Baumgartel,[149] M. Chasco,[149] A. Hortiangtham,[149] A. Massironi,[149] D. M. Morse,[149] D. Nash,[149] T. Orimoto,[149] R. Teixeira De Lima,[149] D. Trocino,[149] R.-J. Wang,[149] D. Wood,[149] J. Zhang,[149] K. A. Hahn,[150] A. Kubik,[150] N. Mucia,[150] N. Odell,[150] B. Pollack,[150] A. Pozdnyakov,[150] M. Schmitt,[150] S. Stoynev,[150] K. Sung,[150] M. Trovato,[150] M. Velasco,[150] S. Won,[150] A. Brinkerhoff,[151] N. Dev,[151] M. Hildreth,[151] C. Jessop,[151] D. J. Karmgard,[151] N. Kellams,[151] K. Lannon,[151] S. Lynch,[151] N. Marinelli,[151] F. Meng,[151] C. Mueller,[151] Y. Musienko,[151,af] T. Pearson,[151] M. Planer,[151] R. Ruchti,[151] G. Smith,[151] N. Valls,[151] M. Wayne,[151] M. Wolf,[151] A. Woodard,[151] L. Antonelli,[152] J. Brinson,[152] B. Bylsma,[152] L. S. Durkin,[152] S. Flowers,[152] A. Hart,[152] C. Hill,[152] R. Hughes,[152] K. Kotov,[152] T. Y. Ling,[152] B. Liu,[152] W. Luo,[152] D. Puigh,[152] M. Rodenburg,[152] B. L. Winer,[152] H. W. Wulsin,[152] O. Driga,[153] P. Elmer,[153] J. Hardenbrook,[153] P. Hebda,[153] S. A. Koay,[153] P. Lujan,[153] D. Marlow,[153] T. Medvedeva,[153] M. Mooney,[153] J. Olsen,[153] P. Piroué,[153] X. Quan,[153] H. Saka,[153] D. Stickland,[153] C. Tully,[153] J. S. Werner,[153] A. Zuranski,[153] V. E. Barnes,[154] D. Benedetti,[154] D. Bortoletto,[154] L. Gutay,[154] M. K. Jha,[154] M. Jones,[154] K. Jung,[154] M. Kress,[154] N. Leonardo,[154] D. H. Miller,[154] N. Neumeister,[154] F. Primavera,[154] B. C. Radburn-Smith,[154] X. Shi,[154] I. Shipsey,[154] D. Silvers,[154] J. Sun,[154] A. Svyatkovskiy,[154] F. Wang,[154] W. Xie,[154] L. Xu,[154] J. Zablocki,[154] N. Parashar,[155] J. Stupak,[155] A. Adair,[156] B. Akgun,[156] Z. Chen,[156] K. M. Ecklund,[156] F. J. M. Geurts,[156] W. Li,[156] B. Michlin,[156] M. Northup,[156] B. P. Padley,[156] R. Redjimi,[156] J. Roberts,[156] Z. Tu,[156] J. Zabel,[156] B. Betchart,[157] A. Bodek,[157] P. de Barbaro,[157] R. Demina,[157] Y. Eshaq,[157] T. Ferbel,[157] M. Galanti,[157] A. Garcia-Bellido,[157] P. Goldenzweig,[157] J. Han,[157] A. Harel,[157] O. Hindrichs,[157] A. Khukhunaishvili,[157] G. Petrillo,[157] M. Verzetti,[157] D. Vishnevskiy,[157] L. Demortier,[158] S. Arora,[159] A. Barker,[159] J. P. Chou,[159] C. Contreras-Campana,[159] E. Contreras-Campana,[159] D. Duggan,[159] D. Ferencek,[159] Y. Gershtein,[159] R. Gray,[159] E. Halkiadakis,[159] D. Hidas,[159] E. Hughes,[159] S. Kaplan,[159] R. Kunnawalkam Elayavalli,[159] A. Lath,[159] S. Panwalkar,[159] M. Park,[159] S. Salur,[159] S. Schnetzer,[159] D. Sheffield,[159] S. Somalwar,[159] R. Stone,[159] S. Thomas,[159] P. Thomassen,[159] M. Walker,[159] M. Foerster,[160] K. Rose,[160] S. Spanier,[160] A. York,[160] O. Bouhali,[161,bi] A. Castaneda Hernandez,[161] M. Dalchenko,[161] M. De Mattia,[161] A. Delgado,[161] S. Dildick,[161] R. Eusebi,[161] W. Flanagan,[161] J. Gilmore,[161] T. Kamon,[161,bj] V. Krutelyov,[161] R. Montalvo,[161] R. Mueller,[161] I. Osipenkov,[161] Y. Pakhotin,[161] R. Patel,[161] A. Perloff,[161] J. Roe,[161] A. Rose,[161] A. Safonov,[161] I. Suarez,[161] A. Tatarinov,[161] K. A. Ulmer,[161] N. Akchurin,[162] C. Cowden,[162] J. Damgov,[162] C. Dragoiu,[162] P. R. Dudero,[162] J. Faulkner,[162] K. Kovitanggoon,[162] S. Kunori,[162] K. Lamichhane,[162] S. W. Lee,[162] T. Libeiro,[162] S. Undleeb,[162] I. Volobouev,[162] E. Appelt,[163] A. G. Delannoy,[163] S. Greene,[163] A. Gurrola,[163] R. Janjam,[163] W. Johns,[163] C. Maguire,[163] Y. Mao,[163] A. Melo,[163] P. Sheldon,[163] B. Snook,[163] S. Tuo,[163] J. Velkovska,[163] Q. Xu,[163] M. W. Arenton,[164] S. Boutle,[164] B. Cox,[164] B. Francis,[164] J. Goodell,[164] R. Hirosky,[164] A. Ledovskoy,[164] H. Li,[164] C. Lin,[164] C. Neu,[164] E. Wolfe,[164] J. Wood,[164] F. Xia,[164] C. Clarke,[165] R. Harr,[165] P. E. Karchin,[165] C. Kottachchi Kankanamge Don,[165] P. Lamichhane,[165] J. Sturdy,[165] D. A. Belknap,[166] D. Carlsmith,[166] M. Cepeda,[166] A. Christian,[166] S. Dasu,[166] L. Dodd,[166] S. Duric,[166] E. Friis,[166] R. Hall-Wilton,[166] M. Herndon,[166] A. Hervé,[166] P. Klabbers,[166] A. Lanaro,[166] A. Levine,[166] K. Long,[166] R. Loveless,[166] A. Mohapatra,[166] I. Ojalvo,[166] T. Perry,[166] G. A. Pierro,[166] G. Polese,[166] I. Ross,[166] T. Ruggles,[166] T. Sarangi,[166] A. 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