

Rapidity and multiplicity dependence of charged-particle flow in $p\text{Pb}$ collisions at $\sqrt{s_{\text{NN}}} = 8.16$ TeV



The LHCb collaboration

E-mail: jiayin.sun@cern.ch

ABSTRACT: The elliptic and triangular flow of charged particles are measured using two-particle angular correlations in $p\text{Pb}$ collisions in the pseudorapidity range $2.0 < |\eta| < 4.8$. The data sample was collected by the LHCb experiment in 2016 at a centre-of-mass energy per nucleon pair of $\sqrt{s_{\text{NN}}} = 8.16$ TeV, containing in total approximately 1.5 billion collision events. Non-flow contributions are obtained in low-multiplicity collisions and subtracted to extract the flow harmonics. The results are presented as a function of event multiplicity and hadron transverse momentum. Comparisons with a full (3+1)D dynamic model indicate that it overestimates the measured elliptic flow. A comparison between the forward and backward regions reveals no significant differences in flow parameters, suggesting that final-state effects may dominate over initial-state effects in the origin of flow in small systems.

KEYWORDS: Collective Flow, Heavy Ion Experiments, Particle Correlations and Fluctuations, Relativistic Heavy Ion Physics

ARXIV EPRINT: [2505.09273](https://arxiv.org/abs/2505.09273)

Contents

1	Introduction	1
2	Experimental setup	3
3	Data selection	3
4	Two-particle correlation analysis	5
4.1	Flow coefficients extraction	6
5	Systematic uncertainties	8
6	Results	10
7	Conclusion	13
A	Result tables	19
	The LHCb collaboration	30

1 Introduction

In ultrarelativistic heavy-ion collisions, strongly interacting QCD matter known as the Quark-Gluon Plasma (QGP) can be formed, in which deconfined quarks and gluons constitute a nearly ideal fluid [1–6]. Extensive investigations have been conducted to understand and characterise this exotic form of matter in past and ongoing experiments at the relativistic heavy-ion collider (RHIC) and the LHC. Among the various strategies that have been developed over the years to identify signatures of the deconfined matter, flow analyses [7] have emerged as an important approach to study the thermodynamic properties of the QGP. Since the QGP behaves akin to a quasi-ideal fluid, its evolution can be described using hydrodynamic equations [8]. In a semicentral collision of two nuclei AA at RHIC or the LHC, the overlap of the two colliding nuclei has an almond-shaped initial geometry. The pressure gradients on the short axis and the long axis differ. These differences induce a momentum-space anisotropy which can be measured as a modulation of the azimuthal distribution of the produced particles. The phenomenon is known as collective flow and can be effectively described by hydrodynamic models [9, 10]. This modulated particle azimuthal angular distribution can be described using a Fourier expansion, where the second harmonic coefficient is referred to as the elliptic flow (v_2) and the third harmonic coefficient as the triangular flow (v_3). Significant flow coefficients, even at higher orders, have been observed in many measurements at the LHC and RHIC [11–23]. These coefficients are directly related to the hydrodynamic response of the created matter to the initial collision geometry. For example, by measuring the anisotropic particle flow in PbPb collisions, it becomes possible to estimate hydrodynamic parameters such as the shear viscosity of the QGP [24].

In pp or pA collision systems, referred to as “small systems”, the mean free path of produced partons is large enough that they propagate and fragment without significant interactions with each other [25]. Thus, the presence of a final-state anisotropy in those systems was not anticipated. However, a raised long and narrow (“ridge-like”) structure, characterised by a similar angular modulation as produced in AA collisions, has been observed in high-multiplicity (i.e., a large number of produced particles) pp and pA collisions at the LHCb, ALICE, ATLAS, and CMS experiments at the LHC [26–29] as well as at the STAR and PHENIX experiments at RHIC [30–32]. Recent efforts have been devoted to searching for the smallest system in which anisotropic flow can develop. Measurements of two-particle angular correlations, which serve as a probe of collective flow, are performed in collision systems with even smaller interaction region and different initial states. Studies in electron-positron (e^+e^-) [33–36], electron-proton (ep) [37, 38] and photon-proton (γp) [39] collisions find no conclusive evidence of collective behaviour, however, nonzero values of the second- and third-order flow coefficients are reported in photon-lead (γPb) collisions [40]. More recently, enhanced long-range elliptic anisotropies are also observed inside high-multiplicity jets produced in 13 TeV pp collisions [41]. While the exact origin of the anisotropic flow is still an area of active research and debate, there are several proposed explanations for this observation including hydrodynamic-like behaviour in these smaller collision systems that could exhibit a small-scale version of collective flow [42]. Alternatively, initial-state effects such as gluon saturation [43] could generate long-range correlations that manifest as the ridge in the final-state particle distributions. Other scenarios include final-state correlations that induce collective behaviour through multiple scattering [44, 45]. Colour reconnection by which partons’ colour connections rearrange during the fragmentation process can also lead to a ridge-like structure [46].

The LHCb experiment enables the investigation of initial-state effects in high-energy collisions. Thanks to its unique forward experimental setup, the LHCb detector geometry allows the study of two centre-of-mass rapidity (y^*) regions of pPb collisions: forward (pPb , $1.5 < y^* < 4.0$) and backward ($Pb p$, $-5.0 < y^* < -2.5$). Forward collisions in LHCb provide access to the low- x Bjorken region of the lead nucleus and measurements can be used to constrain nuclear parton distribution functions (nPDFs), where effects related to potential gluon saturation are anticipated. On the other hand, backward collisions are sensitive to higher x values in the nPDFs. This differential sensitivity in the forward and backward collisions enables a comprehensive exploration of the diverse kinematic regions. Comparison of anisotropic flow in the two configurations sheds light on the role of small and intermediate- x physics on the flow development and helps to understand its origin.

This paper reports the first measurement of charged-particle flow harmonic coefficients in pPb collisions at LHCb using two-particle angular correlation functions in the pseudorapidity region $2.0 < |\eta| < 4.8$. The elliptic and triangular flow harmonic coefficients v_2 and v_3 are extracted as functions of transverse momentum (p_T), and charged track density, $dN_{ch}/d\eta$. These studies complement the existing measurements by other experiments in different rapidity intervals covering different initial-state effects. The results are compared to theoretical calculations using a full (3 + 1)D dynamical framework with hydrodynamics and hadronic transport [47, 48].

2 Experimental setup

The LHCb detector [49, 50] is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$. The detector during the LHC Run 2 period includes a high-precision tracking system consisting of a silicon-strip vertex detector (VELO) [51] surrounding the interaction region, a large-area silicon-strip detector located upstream of a dipole magnet with a bending power of about 4 Tm, and three stations of silicon-strip detectors and straw drift tubes placed downstream of the magnet [52, 53]. The tracking system provides a measurement of the momentum, p , of charged particles with a relative uncertainty that varies from 0.5% at low momentum to 1.0% at 200 GeV/ c . The minimum distance of a track to a primary collision vertex (PV), the impact parameter, is measured with a resolution of $(15 + 29/p_T) \mu\text{m}$, where p_T is measured in GeV/ c . Different types of charged hadrons are distinguished using information from two ring-imaging Cherenkov detectors. Photons, electrons and hadrons are identified by a calorimeter system. Muons are identified by a system composed of alternating layers of iron and multiwire proportional chambers.

The online event selection is performed by a trigger. It consists of a hardware stage, which in this analysis randomly selects a predefined fraction of all bunch crossings, followed by a software stage which requires at least one reconstructed track in the VELO.

The analysis is based on the proton and ^{208}Pb ion collision data recorded by LHCb during the LHC heavy-ion run in 2016. The centre-of-mass energy per nucleon pair is $\sqrt{s_{\text{NN}}} = 8.16 \text{ TeV}$. The data were collected in two beam configurations. In the forward configuration, denoted $p\text{Pb}$, the proton beam travels in the direction from the VELO to the tracking system. In the backward configuration, denoted $\text{Pb}p$, the directions of the beams are reversed. After selection the forward and backward data samples contain 0.67 and 0.83 billion events, respectively.

The flow effects are measured using prompt charged particles, which can be hadrons or leptons, with a mean lifetime $\tau > 30 \text{ ps}$, produced directly in the collision or from decays of shorter-lifetime particles. They include all the particles detectable by the tracking system of LHCb (predominately π^- , K^- , p , e^- , μ^- and their antiparticles) and several hyperons which possess a net strangeness content [54]. This translates in the analysis to the use of tracks that come directly from the primary vertex, with the selection discussed in section 3.

Simulation is used to study the detector performance for prompt charged particles. In the simulation, $p\text{Pb}$ and $\text{Pb}p$ collisions are generated using the EPOS-LHC event generator [55]. Decays of unstable particles are described by EVTGEN [56], in which final-state radiation is generated using PHOTOS [57]. The interaction of the generated particles with the detector, and its response, are implemented using the GEANT4 toolkit [58, 59] as described in ref. [60].

3 Data selection

Only events containing fewer than 8000 VELO clusters are recorded for use in this analysis. This causes the loss of the 0.1% highest-multiplicity events in the $\text{Pb}p$ sample while the fraction is negligible in the $p\text{Pb}$ sample. Each collision event is required to contain exactly one reconstructed primary vertex, which is composed of at least five VELO tracks [61]. The position of the PV must be within ± 3 standard deviations of the mean interaction position

along the beam axis. The mean and the standard deviation of the luminous region are estimated from a Gaussian fit to the distributions of the PV position separately for the p Pb and Pbp samples. The standard deviations are found to be around 44 mm for both datasets.

In the measurement, charged particles are reconstructed from tracks that hit all the subdetectors in the tracking system (so-called long tracks). Tracks are required to lie within the kinematic region defined by $2.0 < \eta < 4.8$, $p > 2.0$ GeV/ c , and $0.2 < p_T < 5.0$ GeV/ c . Fake tracks,¹ which are reconstruction artifacts, are suppressed using a multivariate classifier [62]. The impact parameter of the track with respect to the PV must be less than 1.0 mm to select tracks originating directly from the collision.

Simulation is used to study the reconstruction and selection efficiency due to the selection cuts, as well as the fake track and the secondary track contamination rates in the sample. These quantities are estimated as functions of the azimuthal angle ϕ and pseudorapidity, the transverse momentum, and an event multiplicity variable $N_{\text{VELO}}^{\text{hits}}$, which denotes the number of hits in the VELO for a given p Pb or Pbp collision. A weight is calculated for each track in the sample

$$w(\phi, \eta, p_T, N_{\text{VELO}}^{\text{hits}}) = (1 - P_{\text{fake}} - P_{\text{sec}})/\epsilon, \quad (3.1)$$

where P_{fake} and P_{sec} are the contamination rates of fake and secondary tracks in the sample, and ϵ is the combined reconstruction and selection efficiency. The weighted sum of all the selected tracks in a given collision event is denoted as N_{ch} , which stands for the number of produced charged particles in the kinematic region. To estimate the fully corrected charged-particle density without momentum requirements, a momentum extrapolation based on the EPOS-LHC simulation is performed. The charged-particle density, $dN_{\text{ch}}/d\eta$, is obtained by applying a scaling factor

$$\frac{dN_{\text{ch}}}{d\eta} = \frac{N_{\text{ch}}}{\varepsilon_{\text{ch}} \Delta\eta}, \quad (3.2)$$

where ε_{ch} is the fraction of charged particles from simulation which lie within the accepted momentum region and varies from 0.662 to 0.688 depending on N_{ch} , and $\Delta\eta = 2.8$ is the pseudorapidity range.

Five event-multiplicity classes are defined based on N_{ch} , where each contains around 10% of the total collision events in the specific configuration, except for the lowest multiplicity class in the Pbp sample which contains around 20%. In total, the top 50–60% events in multiplicity are included in the measurement. The corresponding mean charged particle densities $\langle dN_{\text{ch}}/d\eta \rangle$ of the classes are estimated and are used to denote the classes. The $\langle dN_{\text{ch}}/d\eta \rangle$ uncertainties are described at the end of section 5. A summary of the event-multiplicity class definitions is shown in table 1. In addition to these five classes, a low-multiplicity class is also defined for each data configuration. This class is used solely for the subtraction of non-flow effects, which is described in section 4.1.

¹Fake tracks are those reconstructed from unrelated hits, which do not correspond to a genuine particle trajectory.

	N_{ch} class range	$\langle dN_{\text{ch}}/d\eta \rangle$
$p\text{Pb}$	$26 < N_{\text{ch}} \leq 31$	15.6 ± 0.5
	$31 < N_{\text{ch}} \leq 37$	18.2 ± 0.6
	$37 < N_{\text{ch}} \leq 44$	21.8 ± 0.8
	$44 < N_{\text{ch}} \leq 54$	25.9 ± 0.9
	$N_{\text{ch}} > 54$	34.5 ± 1.2
$\text{Pb}p$	$24 < N_{\text{ch}} \leq 39$	17.1 ± 0.7
	$39 < N_{\text{ch}} \leq 48$	23.4 ± 0.9
	$48 < N_{\text{ch}} \leq 59$	28.4 ± 1.1
	$59 < N_{\text{ch}} \leq 75$	35.0 ± 1.4
	$N_{\text{ch}} > 75$	47.8 ± 1.9

Table 1. Event-multiplicity class definitions based on N_{ch} and the corresponding mean charged particle density $\langle dN_{\text{ch}}/d\eta \rangle$ for $p\text{Pb}$ and $\text{Pb}p$ configurations. The $\langle dN_{\text{ch}}/d\eta \rangle$ uncertainties are described at the end of section 5.

4 Two-particle correlation analysis

Angular correlation functions of pairs of charged particles, regardless of their charge sign, are constructed separately for each event-multiplicity class. Two particles in the same event, referred to as the trigger and associated particles, are paired to form the angular distribution $S(\Delta\eta, \Delta\phi)$, where $\Delta\eta$ and $\Delta\phi$ are the differences in η and ϕ between the pair. Both trigger and associated particles are from the selected prompt charged particle sample, but they are distinguished by separate p_{T} requirements, which are described later. The mixed event angular distribution, $B(\Delta\eta, \Delta\phi)$, is used to correct for detector effects, which mainly originate from the limited detector acceptance. To construct $B(\Delta\eta, \Delta\phi)$, all trigger particles from an event are paired with all associated particles in ten different random events in the same event-multiplicity class, whose PV positions along the z direction are within 2.2 cm of the original event. The two-particle angular correlation function is defined by

$$C(\Delta\eta, \Delta\phi) \equiv \frac{1}{N_{\text{trig}}} \frac{d^2 N_{\text{pair}}}{d\Delta\eta d\Delta\phi} = B(0, 0) \frac{S(\Delta\eta, \Delta\phi)}{B(\Delta\eta, \Delta\phi)}, \quad (4.1)$$

where N_{pair} is the number of charged particle pairs in the $(\Delta\eta, \Delta\phi)$ bin, N_{trig} is the number of trigger particles within the trigger p_{T} selection and $B(0, 0)$ is a normalisation factor such that the detector pair acceptance is unity for $\Delta\eta = 0, \Delta\phi = 0$, which is expected for two particles travelling along the same direction. The one-dimensional azimuthal correlation function, $C(\Delta\phi)$, is obtained similarly, by projecting $S(\Delta\eta, \Delta\phi)$ and $B(\Delta\eta, \Delta\phi)$ onto the $\Delta\phi$ axis in a common selected $\Delta\eta$ region and taking the ratio between the two.

The trigger and associated particles are selected with independent p_{T} requirements, which can be the same or different. The minimum p_{T} value for both trigger and associated particles is $0.8 \text{ GeV}/c$ to ensure a uniform η acceptance. In this work, the trigger and associated particles are selected with the same p_{T} requirement $0.8 < p_{\text{T}} < 5.0 \text{ GeV}/c$. In addition to

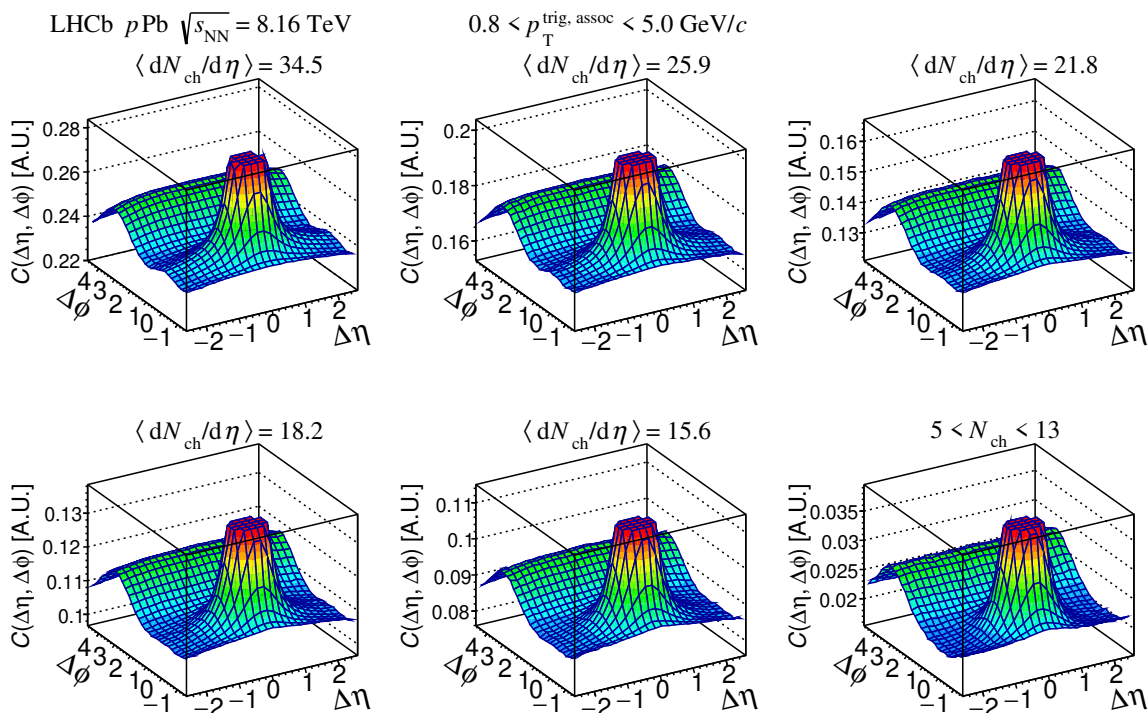


Figure 1. Example angular correlation functions $C(\Delta\eta, \Delta\phi)$ for the five multiplicity classes and the low-multiplicity class in $p\text{Pb}$ collisions. The correlation functions are truncated at the peaks to improve the visibility of the ridge structures.

the full p_T range, the trigger particles are split in 10 smaller p_T intervals in order to study the p_T dependence of flow.

Figures 1 and 2 show examples of the angular correlation functions $C(\Delta\eta, \Delta\phi)$ in $p\text{Pb}$ and PbPb data. The correlation functions are presented in the five multiplicity classes defined in table 1 and in the low-multiplicity class described later in section 4.1. A prominent peak at $(\Delta\eta \simeq 0, \Delta\phi \simeq 0)$, which results from short-range non-flow interactions such as jets and particle decays, is observed in all the correlation functions. The peak is shown truncated to improve visibility of the lower structures in the correlation functions. Ridge structures at $\Delta\phi \simeq 0$ (near-side) and $\Delta\phi \simeq \pi$ (away-side) for the entire $\Delta\eta$ coverage are also observed. While the away-side ridge mainly arises from recoiled particles from the near-side peak, the near-side ridge is a sign of long-range collective flow resulting from modulation of particle ϕ angular distribution. The near-side ridge is most prominent in the highest-multiplicity classes, and its strength decreases with lower event multiplicity. In the last panels of figures 1 and 2, correlation functions are constructed from events in the low-multiplicity class. They are used to subtract the non-flow contribution, which is described in the next section.

4.1 Flow coefficients extraction

Considering a large number of collisions, the two-particle azimuthal anisotropy can be described with a Fourier transform [63, 64] such that the azimuthal angle distribution of

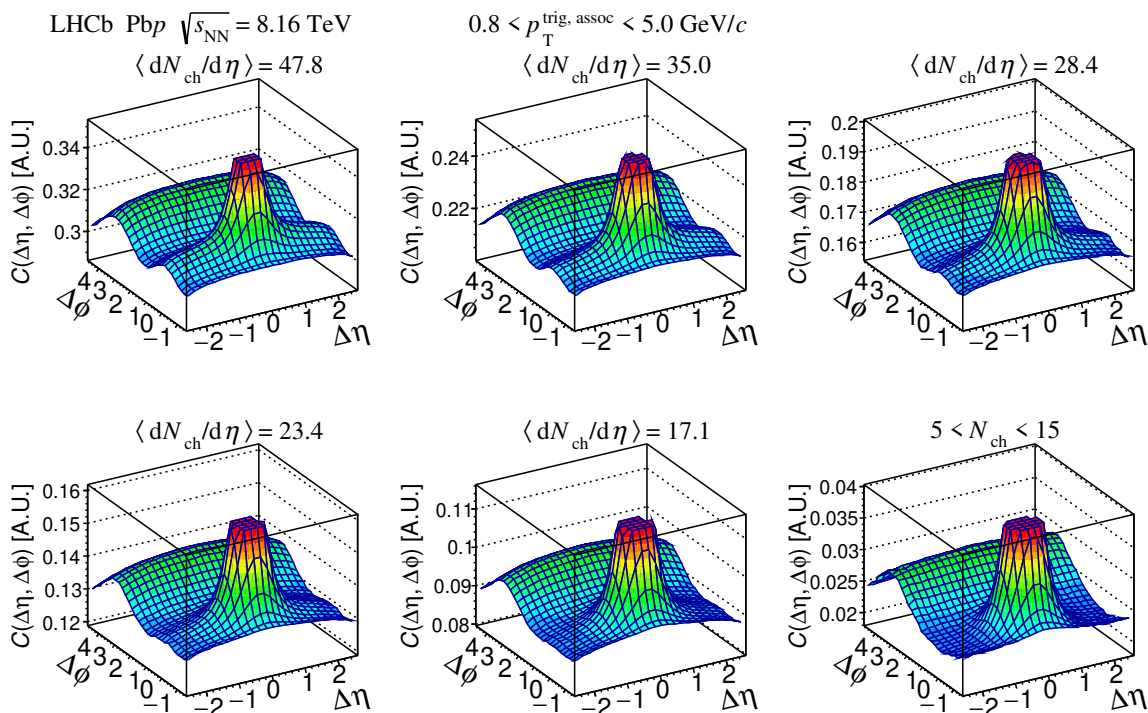


Figure 2. Example angular correlation functions $C(\Delta\eta, \Delta\phi)$ for the five multiplicity classes and the low-multiplicity class in PbP collisions. The correlation functions are truncated at the peaks to improve the visibility of the ridge structures.

the produced pair of charged particles is written as:

$$\frac{dN_{\text{pair}}}{d\Delta\phi} = A \left(1 + 2 \sum_{n=1}^{\infty} V_{n\Delta} \cos[n(\Delta\phi)] \right), \quad (4.2)$$

where $V_{n\Delta}$ is the Fourier coefficient of the pair distribution, and A is a normalisation factor. Furthermore, the Fourier coefficient of a pair of particles can be written in terms of the harmonic flow coefficients

$$V_{n\Delta}(p_T^{\text{trig}}, p_T^{\text{assoc}}) = v_n(p_T^{\text{trig}})v_n(p_T^{\text{assoc}}). \quad (4.3)$$

Therefore, the flow coefficients of particles with a specific p_T^{trig} are given by

$$v_n(p_T^{\text{trig}}) = \frac{V_{n\Delta}(p_T^{\text{trig}}, p_T^{\text{assoc}})}{\sqrt{V_{n\Delta}(p_T^{\text{assoc}}, p_T^{\text{assoc}})}}. \quad (4.4)$$

The coefficients $V_{n\Delta}$ are extracted using a binned maximum-likelihood fit to the correlation functions projected onto the $\Delta\phi$ variable, using the function defined in eq. (4.2) up to the fourth order. The parameters $V_{n\Delta}$ and the normalisation A are left to vary in the fit. Examples of Fourier fits to the correlation functions in high- and low-multiplicity in pPb and PbP collisions are shown in figure 3. In addition to the contributions due to collective flow effects, the two-particle correlations also receive significant contributions from other

correlation sources, such as resonances, minijets, and quantum correlations [65–70]. Such non-flow contributions are usually short-ranged. Therefore, to limit the influence of those additional effects, the measurements aiming to study collective flow phenomena focus on long-range correlations.

One obvious origin of the non-flow is the jet contribution that is clearly visible for $\Delta\phi \approx 0$ and $\Delta\eta \approx 0$. A way to avoid this contamination is to exclude the short range (SR) region defined by $|\Delta\eta| < 1.8$. Hence the fit is performed in the long range (LR) region, $|\Delta\eta| > 1.8$. Additional non-flow effects, less obvious, are present at $\Delta\phi \approx \pi$. Therefore, methods have been developed to quantify these effects.

The method used here is taken from ref. [71]. It is based on the assumption that the correlation coefficients ($V_{n\Delta}$) are a linear combination of flow (c_n) and non-flow (d_n) contributions such that $V_{n\Delta} = c_n + d_n$. Equation 4.2 can then be rewritten as

$$C(\Delta\phi) = G \left(1 + 2 \sum_{n=1}^{\infty} (c_n + d_n) \cos[n(\Delta\phi)] \right), \quad (4.5)$$

where G is a normalisation factor. In this analysis the objective is to extract the c_n coefficients. Thus d_n must be subtracted from the results from the direct Fourier fit. The strategy to estimate d_n is to exploit a low-multiplicity interval where no flow is expected. Under the assumption that the shape of the non-flow correlation does not change with varying the multiplicity, d_n can be written as

$$d_n^{\text{HM}} = J_{\text{LM}}^{\text{HM}} d_n^{\text{LM}}, \quad (4.6)$$

where LM stands for low multiplicity and HM for high multiplicity, and $J_{\text{LM}}^{\text{HM}}$ is the scaling factor from LM to HM. At low multiplicity flow effects are negligible, thus $d_n^{\text{LM}} = V_{n\Delta}^{\text{LM}}$. The factor $J_{\text{LM}}^{\text{HM}}$ can be interpreted as the relative jet yields between low and high multiplicities, expressed as

$$J_{\text{LM}}^{\text{HM}} = \frac{N^{\text{LM}} \int_{-1}^1 (C_{\text{SR}}^{\text{HM}}(\Delta\phi) - C_{\text{LR}}^{\text{HM}}(\Delta\phi)) d\Delta\phi}{N^{\text{HM}} \int_{-1}^1 (C_{\text{SR}}^{\text{LM}}(\Delta\phi) - C_{\text{LR}}^{\text{LM}}(\Delta\phi)) d\Delta\phi}, \quad (4.7)$$

where $N^{\text{LM(HM)}}$ is the total integral of $C^{\text{LM(HM)}}$. In this analysis, the HM events are taken from the five event-multiplicity classes defined in table 1. The LM class events are selected with the criterion $5 < N_{\text{ch}} < 13$ for the $p\text{Pb}$ and $5 < N_{\text{ch}} < 15$ for the $\text{Pb}p$ sample. The mean charged particle density $\langle dN_{\text{ch}}/d\eta \rangle$ is 5.2 ± 0.2 and 5.9 ± 0.2 for the $p\text{Pb}$ and $\text{Pb}p$ LM class, respectively. Figure 4 displays the short range $C(\Delta\phi)$ for $|\Delta\eta| < 1$ and the root mean square of the near and away side in the $\text{Pb}p$ configuration, showing that the jet widths are similar for the five event-multiplicity classes, and $C(\Delta\phi)$ reaches the minimum at approximately $\Delta\phi = 1.2$. Therefore the jet region is restricted to $\Delta\eta \in [-1.0, 1.0]$ and $\Delta\phi \in [-1.2, 1.2]$. The final subtracted results of elliptic and triangular flow of charged particles are named $v_2^{\text{sub}\{2\}}$ and $v_3^{\text{sub}\{2\}}$, respectively. The symbol $\{2\}$ indicates that the $v_{2,3}^{\text{sub}}$ coefficients are measured from the two-particle correlation method, while ‘sub’ indicates that the results are jet subtracted.

5 Systematic uncertainties

Several sources of systematic uncertainty are considered in the final results, primarily related to the various elements of the method defined in section 4.1. In particular, these include

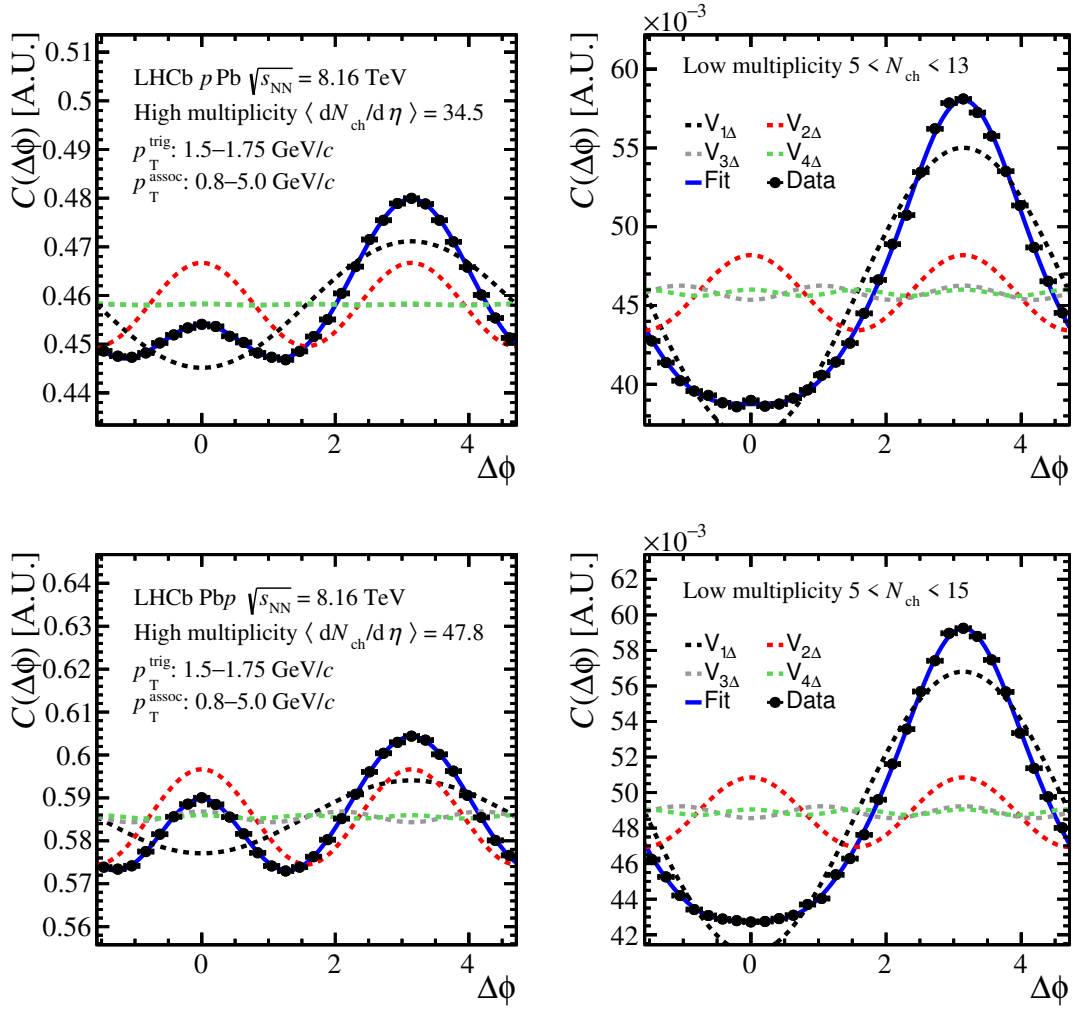


Figure 3. Examples of Fourier fits of the (top left) high- and (top right) low-multiplicity bins in $p\text{Pb}$ collisions for $1.5 < p_T^{\text{trig}} < 1.75$ GeV/ c , and of the (bottom left) high- and (bottom right) low-multiplicity bins in Pbp collisions for $1.5 < p_T^{\text{trig}} < 1.75$ GeV/ c . The different harmonics n of the fits are labelled $V_{n\Delta}$.

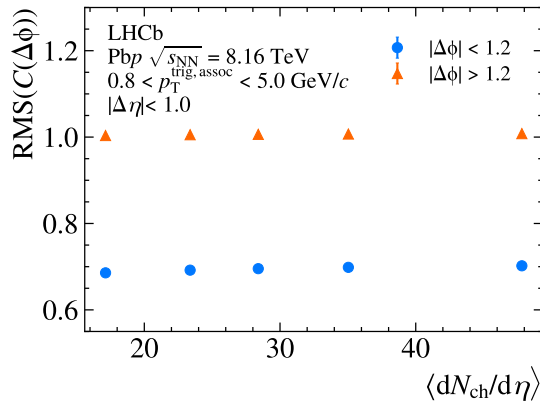


Figure 4. Root mean square of short-range $C(\Delta\phi)$ in the near and away side in different Pbp multiplicity bins.

the effects of the low-multiplicity class definition, the long-range $|\Delta\eta|$ cut, the $|\Delta\phi|$ range used for jet normalisation, the correction of track efficiency and contamination of fake and secondary tracks, and the uncertainty in the N_{ch} determination. A summary of the systematic uncertainties is presented in table 2 for $p\text{Pb}$ and in table 3 for $\text{Pb}p$. The total systematic uncertainty is obtained by summing the individual components in quadrature.

To assess the impact of the low-multiplicity bin definition, alternative ranges of N_{ch} are considered. For $\text{Pb}p$ the N_{ch} ranges tested are [5,10], [10,15], [15,20], and [10,20], with the baseline range being [5,15]. For $p\text{Pb}$, the tested ranges are [5,15], [7,15], [5,10], and [10,15], with the baseline range being [5,13]. The systematic uncertainty is quantified as the standard deviation of the results obtained across these different ranges.

The effect of the $\Delta\eta$ jet exclusion cut is tested using $|\Delta\eta| > 1.6$ and $|\Delta\eta| > 2.0$. The uncertainty is calculated by taking the largest difference observed in the $v_n^{\text{sub}}\{2\}$ results relative to the baseline value of $|\Delta\eta| > 1.8$.

The track efficiency and contamination correction is expected to have little effect on the measurement. However, a test is performed with and without the correction, and a systematic uncertainty is assigned as the full shift under the two alternative approaches.

The $|\Delta\phi|$ range used to normalise the low-multiplicity jets for the subtraction method is varied, showing very little effect on the final results. Similarly, no significant effects are observed on the final results when modifying the fake track rejection criteria.

The dominant systematic uncertainty in the N_{ch} determination arises from the efficiency and purity correction applied to the tracks. A closure test using the $p\text{Pb}$ simulation is performed to compare the N_{ch} value estimated with the efficiency and purity correction to the number of generated charged particles. The maximum difference of 3% is assigned as an uncertainty to the mean N_{ch} values in all multiplicity classes. In the track-matching algorithm used to remove background candidates from simulated samples, occasionally a correctly reconstructed track may be mistaken for a fake track. A systematic uncertainty of 1.9% for $p\text{Pb}$ and 2.5% for $\text{Pb}p$ collisions is assigned to account for this effect. The total systematic uncertainty of N_{ch} is 3.5% and 3.9% for $p\text{Pb}$ and $\text{Pb}p$ collisions, respectively.

6 Results

The $v_2^{\text{sub}}\{2\}$ results for the $p\text{Pb}$ and $\text{Pb}p$ samples versus p_{T} in different $\langle dN_{\text{ch}}/d\eta \rangle$ bins are presented in figures 5 and 6, respectively. The results are displayed before and after the non-flow subtraction procedure. For the $v_2\{2\}$ values before the subtraction, the effect arising from jets is visible as a clear increase at higher p_{T} . The subtraction takes care of removing the high- p_{T} non-flow contribution, and gives the expected trend of the elliptic flow coming from soft QCD effects, whereby $v_2^{\text{sub}}\{2\}$ first increases at low p_{T} and starts to decrease for p_{T} greater than around 2.5 GeV/c. Moreover, a decrease of the flow coefficient $v_2^{\text{sub}}\{2\}$ at smaller $\langle dN_{\text{ch}}/d\eta \rangle$ values is clearly observed as expected. The detailed numerical tables of results can be found in tables 4–17 in appendix A.

The results of $v_2\{2\}$ versus $\langle dN_{\text{ch}}/d\eta \rangle$ for the integrated p_{T} range $0.8 < p_{\text{T}} < 5.0$ GeV/c are presented in figures 7 and 8 for the $p\text{Pb}$ and $\text{Pb}p$ data, respectively. There is a clear increase of $v_2^{\text{sub}}\{2\}$ values with higher event multiplicity, while $v_2\{2\}$ without the subtraction

Systematic uncertainty	$\langle dN_{\text{ch}}/d\eta \rangle$	$v_2^{\text{sub}}\{2\}$	$v_2^{\text{sub}}\{2\}$	$v_3^{\text{sub}}\{2\}$
		vs. p_T (%)	int. p_T (%)	int. p_T (%)
Low-multiplicity bin definition	34.5	1.1–6.8	1.5	2.9
	25.9	1.6–13.2	2.3	3.9
	21.8	2.1–25.0	3.2	5.2
	18.2	2.7–87.9	5.0	5.3
	15.6	11.1–132.6	9.3	7.0
$\Delta\eta$ jet exclusion	34.5	0.6–17.5	0.9	1.1
	25.9	0.4–50.2	0.7	1.3
	21.8	0.6–82.7	0.5	2.1
	18.2	0.9–32.5	0.6	1.6
	15.6	1.3–63.9	0.1	2.7
Track efficiency and contamination correction	34.5	1.8–7.7	3.6	2.4
	25.9	0.5–9.6	5.2	3.2
	21.8	0.6–10.6	6.4	4.1
	18.2	0.6–16.5	7.5	3.1
	15.6	7.7–22.2	11.8	2.7
Total	34.5	3.5–18.8	4.0	4.0
	25.9	4.4–51.9	5.7	5.2
	21.8	5.8–86.4	7.2	7.0
	18.2	6.5–93.7	9.0	6.4
	15.6	8.9–148.2	15.0	8.0

Table 2. Summary of the different systematic uncertainty sources and total systematic uncertainty on the $v_{2,3}^{\text{sub}}\{2\}$ determination in the $p\text{Pb}$ sample in bins of the mean charged-particle density $\langle dN_{\text{ch}}/d\eta \rangle$ for differential and integrated p_T^{trig} . The numeric values are shown in percentage with respect to the central values.

reaches a plateau for the observed $\langle dN_{\text{ch}}/d\eta \rangle$ range in the measurement. Again it is evident that the non-flow subtraction procedure has an important effect on $v_2^{\text{sub}}\{2\}$.

The results are compared to full (3+1)D dynamical calculations coupled with a hydrodynamic and hadronic transport hybrid framework to simulate the entire dynamics of relativistic nuclear collisions [47, 48]. An important ingredient is the link made between the initial-state conditions and the later hydrodynamic evolution including energy-momentum and baryon-number conservation through Glauber-model and string-like formalism. The model has been calibrated using various measurements at mid-rapidity region. The hydrodynamic parameters associated with the multiplicity distributions are determined by fitting to the multiplicity distribution data from proton-proton collisions at 7 TeV, as measured by the ALICE collaboration [72]. The parameters related to the QGP viscosities are constrained by

Systematic uncertainty	$\langle dN_{\text{ch}}/d\eta \rangle$	$v_2^{\text{sub}}\{2\}$	$v_2^{\text{sub}}\{2\}$	$v_3^{\text{sub}}\{2\}$
		vs. p_T (%)	int. p_T (%)	int. p_T (%)
Low-multiplicity bin definition	47.8	0.1–2.9	0.1	2.9
	35.0	0.3–5.3	0.2	4.7
	28.4	0.4–8.8	0.3	6.9
	23.4	0.6–17.2	0.5	8.7
	17.1	1.3–60.2	1.0	14.7
$\Delta\eta$ jet exclusion	47.8	0.4–2.9	0.7	0.2
	35.0	0.1–2.4	0.1	0.9
	28.4	0.2–3.6	0.2	0.9
	23.4	0.6–10.4	0.3	1.4
	17.1	0.7–20.6	0.7	1.5
Track efficiency and contamination correction	47.8	2.1–5.9	2.3	1.6
	35.0	1.5–3.9	3.6	1.2
	28.4	1.8–4.1	4.3	0.2
	23.4	1.2–5.9	5.3	0.5
	17.1	2.1–8.8	8.1	1.0
Total	47.8	2.4–6.0	2.4	3.3
	35.0	2.9–5.8	3.6	5.0
	28.4	4.2–9.7	4.3	7.0
	23.4	5.9–20.1	5.3	8.8
	17.1	8.0–63.7	8.2	14.8

Table 3. Summary of the different systematic uncertainty sources and total systematic uncertainty on the $v_{2,3}^{\text{sub}}\{2\}$ determination in the $\text{Pb}p$ sample in bins of the mean charged-particle density $\langle dN_{\text{ch}}/d\eta \rangle$ for differential and integrated p_T^{trig} . The numeric values are shown in percentage with respect to the central values.

fits to the flow measurements in proton-lead collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV from the ATLAS collaboration [73], as well as to the mean transverse momentum ($\langle p_T \rangle$) in $p\text{Pb}$ collisions at the LHC reported by the ALICE collaboration [74]. Collective flow in the model is developed through initial geometry from Glauber model and the subsequent hydrodynamical evolution. The 3D model is calculated for $2.0 < |\eta| < 4.8$, where the predicted flow coefficients mostly agree between the $p\text{Pb}$ and $\text{Pb}p$ configurations at comparable multiplicity, with larger $p\text{Pb}$ values at high multiplicity. The theoretical calculations, which must be compared with the jet subtracted results, are generally above the $v_2^{\text{sub}}\{2\}$ data points, although the values are in agreement with the measured $v_2\{2\}$ before the non-flow subtraction. The comparison suggests that the collective flow developed in the forward rapidity region may be weaker than hydrodynamical expectations based on parametrisation tuned to data in the mid-rapidity re-

gion. The forward data can provide unique experimental constraints in longitudinal direction to improve the full 3D model.

A direct comparison of $v_2^{\text{sub}}\{2\}$ integrated in the $0.8 < p_T < 5.0 \text{ GeV}/c$ range versus the event multiplicity of the collisions in both forward and backward configurations is presented in figure 9. The forward and backward rapidity regions at LHCb correspond to different partonic Bjorken- x regions. Based on a recent LHCb publication [75], in the forward region, the prompt charged hadron data probe the small Bjorken- x region at approximately $10^{-6} < x < 10^{-4}$ depending on the particle p_T , where gluon saturation may theoretically take place. In the backward region, the data cover the large Bjorken- x region at approximately $10^{-3} < x < 10^{-1}$, where gluon saturation is not expected. The comparison in figure 9 shows that the $v_2^{\text{sub}}\{2\}$ values from forward and backward rapidity regions are compatible within 2.2 standard deviations at similar event multiplicity $\langle dN_{\text{ch}}/d\eta \rangle$, although the particles may be affected by different initial-state effects. This suggests that final-state effects may be dominant over initial-state effects in the origin of flow in small systems.

Figure 10 compares $v_2^{\text{sub}}\{2\}$ as a function of $\langle dN_{\text{ch}}/d\eta \rangle$ in forward and backward rapidities for different trigger p_T ranges. In the lower p_T bins, the $v_2^{\text{sub}}\{2\}$ values in the forward and backward regions are consistent at similar $\langle dN_{\text{ch}}/d\eta \rangle$. However, at higher p_T , the difference between $p\text{Pb}$ and $\text{Pb}p$ grows significantly, reaching around five standard deviations at $3.5 < p_T < 5.0 \text{ GeV}/c$ and $\langle dN_{\text{ch}}/d\eta \rangle \sim 35$. In the backward data the $v_2^{\text{sub}}\{2\}$ values are systematically larger than those in the forward data. This could indicate some initial-state effect showing up only for high- Q^2 processes or the presence of some remaining non-flow effects.

The results corresponding to the triangular flow harmonic $v_3\{2\}$ and $v_3^{\text{sub}}\{2\}$ from the $p\text{Pb}$ and $\text{Pb}p$ samples for the integrated p_T range $0.8 < p_T < 5.0 \text{ GeV}/c$ are presented in figures 11 and 12, respectively. While the $v_3\{2\}$ values before the non-flow subtraction differ substantially in the forward and backward data, the subtracted $v_3^{\text{sub}}\{2\}$ values are similar in both rapidity regions. The change of sign of $v_3\{2\}$ reflects the type of correlation: an anticorrelation originating from jets and a positive correlation from flow effects. As the multiplicity increases, the contribution from pure flow correlations becomes more dominant. In contrast to the $v_2^{\text{sub}}\{2\}$ case, $v_3^{\text{sub}}\{2\}$ does not exhibit strong dependence on the event multiplicity. Both $p\text{Pb}$ and $\text{Pb}p$ $v_3^{\text{sub}}\{2\}$ results are compatible with a flat trend across the observed $\langle dN_{\text{ch}}/d\eta \rangle$ ranges, while the $\text{Pb}p$ data show a hint of increase at high multiplicity with a positive slope of $(1.9 \pm 0.5) \times 10^{-4}$.

7 Conclusion

The elliptic and triangular flow of charged particles has been measured in $p\text{Pb}$ collisions recorded by the LHCb experiment in both forward and backward configurations. The measurements are performed as a function of charged-particle multiplicity and transverse momentum for the elliptic flow. As expected, the elliptic flow increases with multiplicity. However, for a given multiplicity no significant differences are observed between the forward and backward configurations. This suggests that initial-state correlations do not play a significant role in the development of the elliptic flow. The triangular flow remains constant across multiplicities and is compatible between the two configurations. The measured elliptic flow is in general smaller than calculations using a full (3+1)D dynamical framework. The

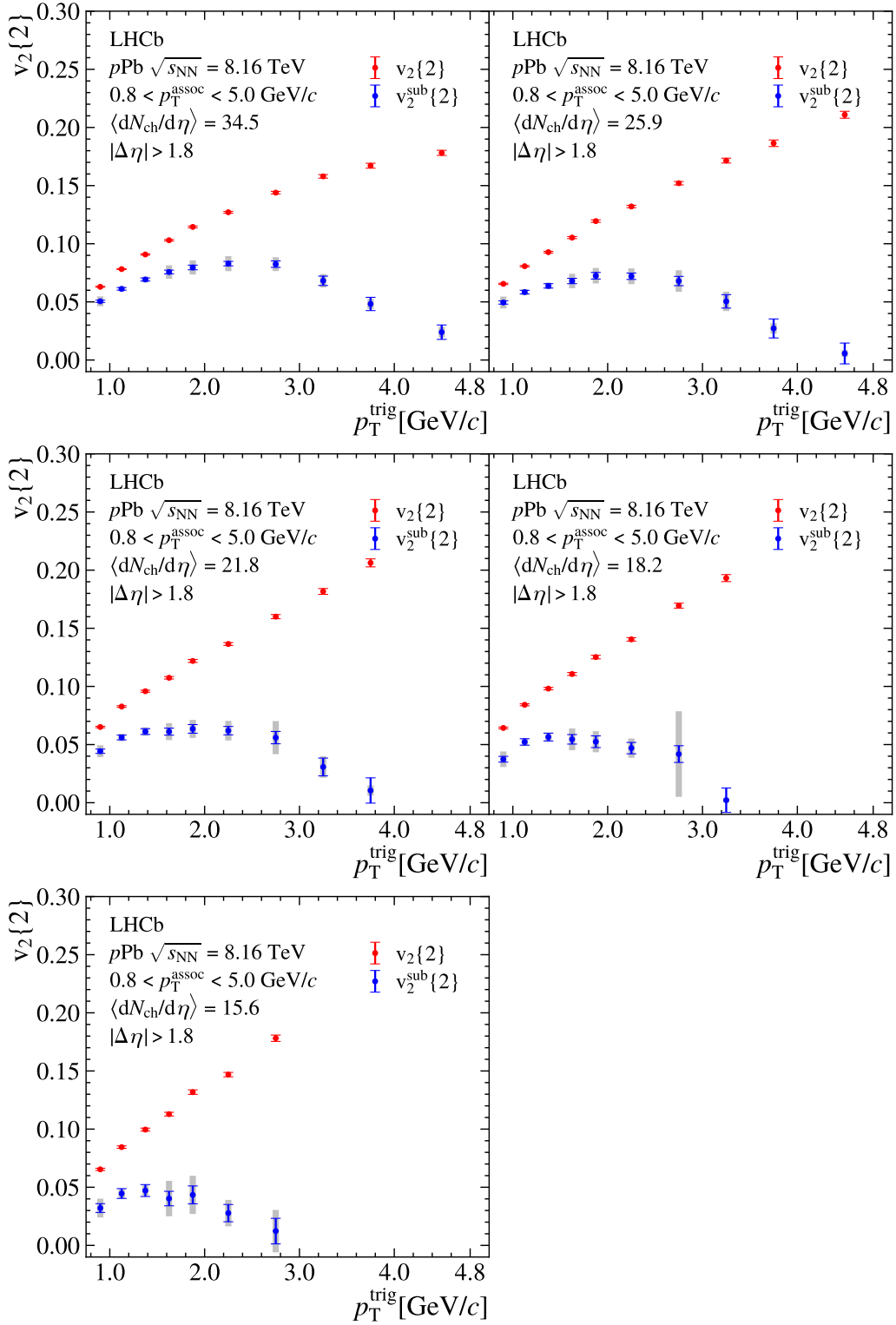


Figure 5. Results for $v_2\{2\}$ as a function of p_T for the pPb sample in different $\langle dN_{ch}/d\eta \rangle$ bins, presented before (red) and after (blue) the non-flow subtraction procedure. The vertical error bars represent statistical uncertainties while the shaded boxes represent systematic uncertainties.

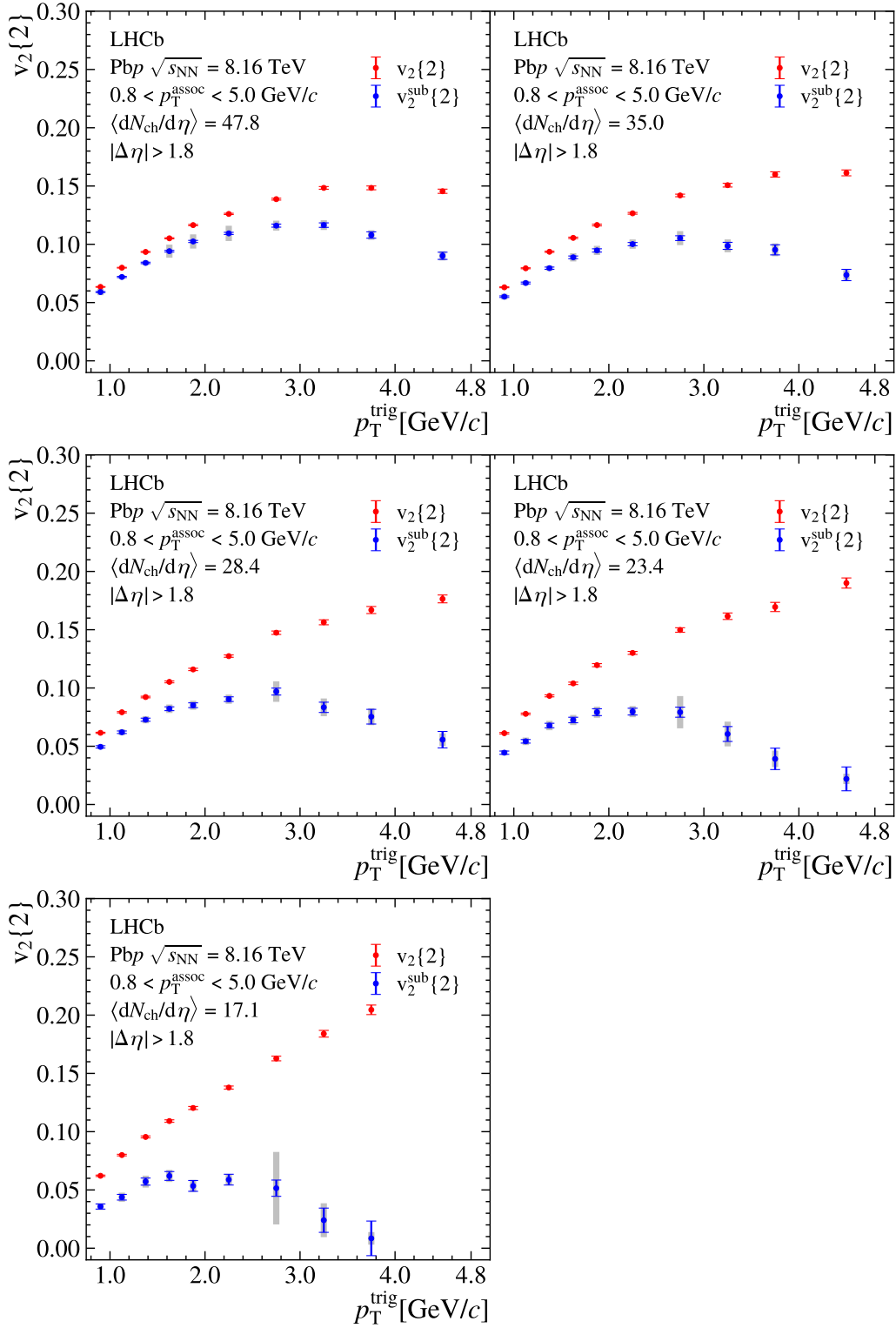


Figure 6. Results for $v_2\{2\}$ as a function of p_T for the PbPb sample in different $\langle dN_{\text{ch}}/d\eta \rangle$ bins, presented before (red) and after (blue) the non-flow subtraction procedure. The vertical error bars represent statistical uncertainties while the shaded boxes represent systematic uncertainties.

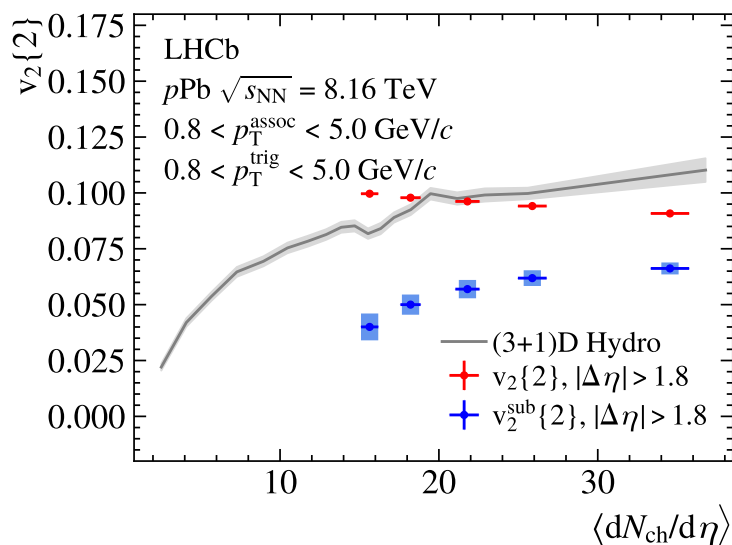


Figure 7. Results for $v_2\{2\}(|\Delta\eta| > 1.8)$ as functions of $\langle dN_{ch}/d\eta \rangle$ for the pPb sample, presented before and after the non-flow subtraction procedure. The vertical error bars represent statistical uncertainties, which are hidden by the data points. The shaded boxes represent systematic uncertainties. The results are compared with theoretical predictions based on refs. [47, 48] for $2.0 < |\eta| < 4.8$. The shaded band represents theoretical uncertainties.

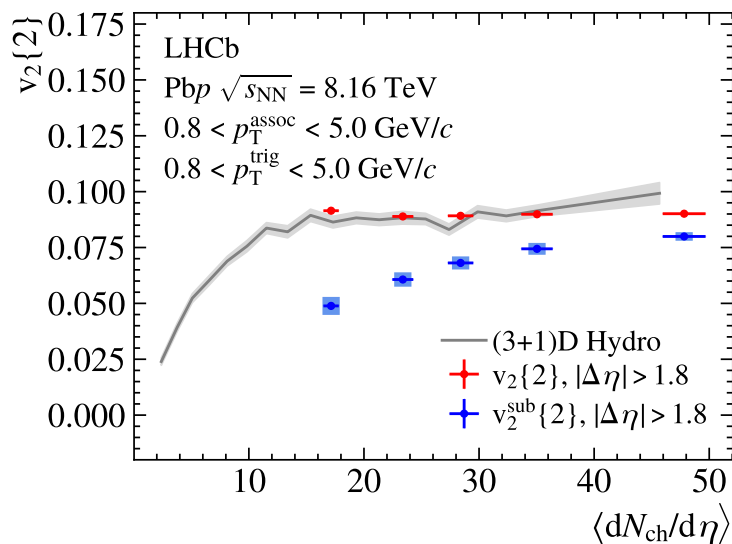


Figure 8. Results for $v_2\{2\}(|\Delta\eta| > 1.8)$ as functions of $\langle dN_{ch}/d\eta \rangle$ for the $PbPb$ sample, presented before and after the non-flow subtraction procedure. The vertical error bars represent statistical uncertainties, which are hidden by the data points. The shaded boxes represent systematic uncertainties. The results are compared with theoretical predictions based on refs. [47, 48] for $2.0 < |\eta| < 4.8$. The shaded band represents theoretical uncertainties.

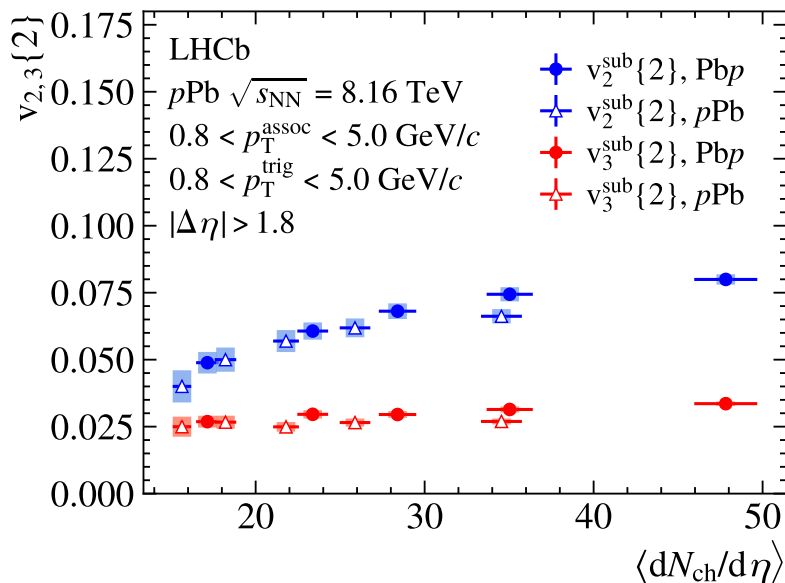


Figure 9. Results for $v_2^{\text{sub}}\{2\}$ and $v_3^{\text{sub}}\{2\}$ for the $p\text{Pb}$ and $\text{Pb}p$ sample as functions of $\langle dN_{\text{ch}}/d\eta \rangle$, presented after the non-flow subtraction procedure. The vertical error bars represent statistical uncertainties, which are hidden by the data points. The shaded boxes represent systematic uncertainties.

data can also be compared to models incorporating a 3D gluon saturation initial state framework in the future. The result in the forward rapidity region helps to understand the origin of particle flow in small systems, and provides experimental inputs to three-dimensional theoretical models that include longitudinal dynamics.

Acknowledgments

We express our gratitude to our colleagues in the CERN accelerator departments for the excellent performance of the LHC. We thank the technical and administrative staff at the LHCb institutes. We acknowledge support from CERN and from the national agencies: ARC (Australia); CAPES, CNPq, FAPERJ and FINEP (Brazil); MOST and NSFC (China); CNRS/IN2P3 (France); BMBF, DFG and MPG (Germany); INFN (Italy); NWO (Netherlands); MNiSW and NCN (Poland); MCID/IFA (Romania); MICIU and AEI (Spain); SNSF and SER (Switzerland); NASU (Ukraine); STFC (United Kingdom); DOE NP and NSF (U.S.A.). We acknowledge the computing resources that are provided by ARDC (Australia), CBPF (Brazil), CERN, IHEP and LZU (China), IN2P3 (France), KIT and DESY (Germany), INFN (Italy), SURF (Netherlands), Polish WLCG (Poland), IFIN-HH (Romania), PIC (Spain), CSCS (Switzerland), and GridPP (United Kingdom). We are indebted to the communities behind the multiple open-source software packages on which we depend. Individual groups or members have received support from Key Research Program of Frontier Sciences of CAS, CAS PIFI, CAS CCEPP, Fundamental Research Funds for the Central Universities, and Sci. & Tech. Program of Guangzhou (China); Minciencias (Colombia); EPLANET, Marie Skłodowska-Curie Actions, ERC and NextGenerationEU (European Union); A*MIDEX, ANR, IPhU and Labex P2IO, and Région Auvergne-Rhône-Alpes (France); Alexander-von-Humboldt

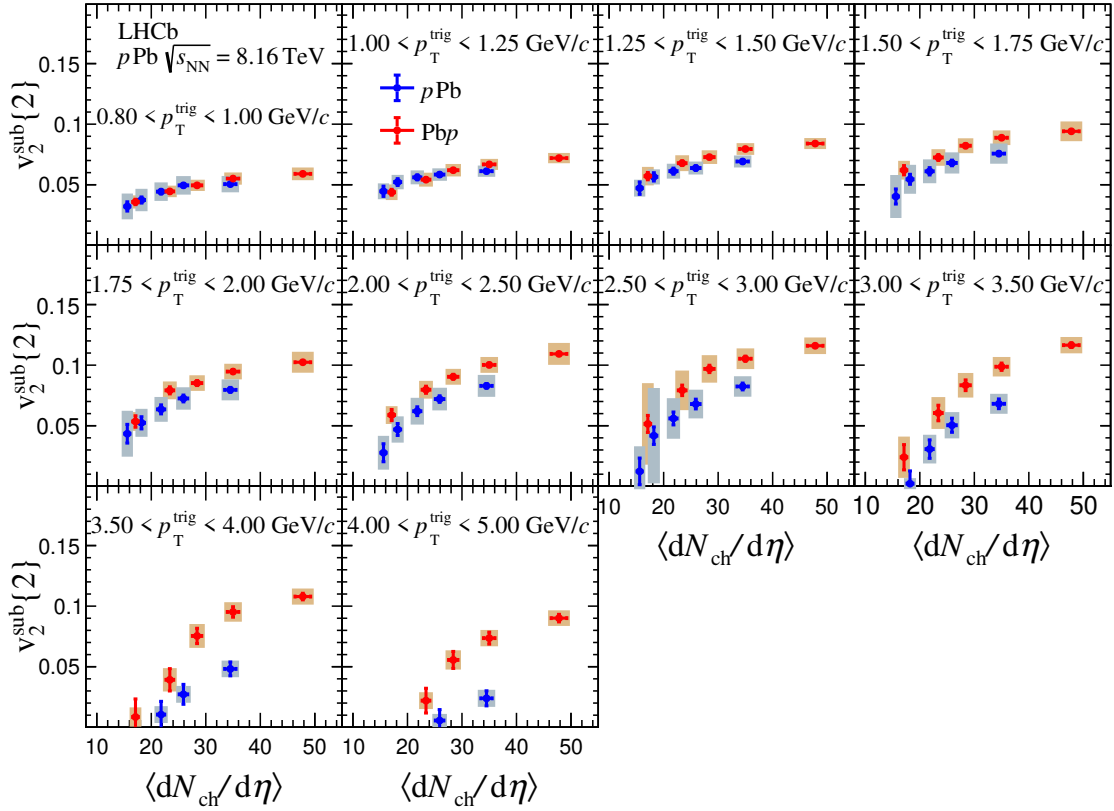


Figure 10. Results for $v_2^{\text{sub}}\{2\}$ ($|\Delta\eta| > 1.8$) for the $p\text{Pb}$ and $\text{Pb}p$ samples as functions of $\langle dN_{\text{ch}}/d\eta \rangle$ in different p_T^{trig} ranges, presented after the non-flow subtraction procedure. The vertical error bars represent statistical uncertainties while the shaded boxes represent systematic uncertainties.

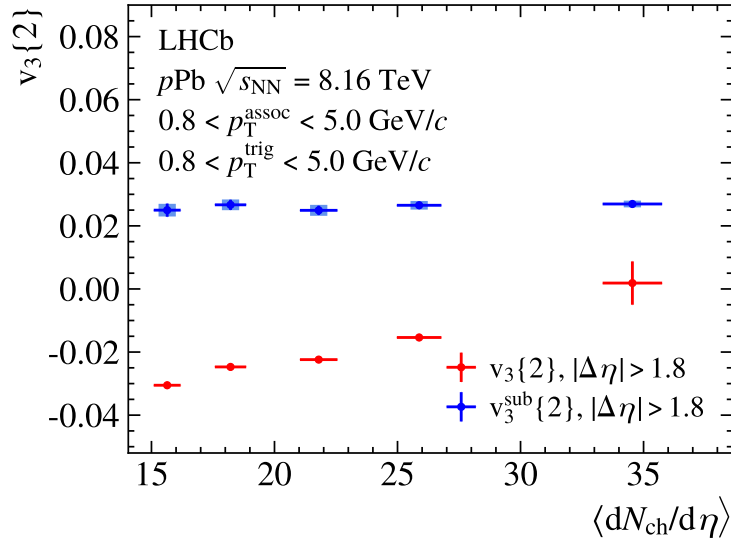


Figure 11. Results for $v_3\{2\}$ ($|\Delta\eta| > 1.8$) for the $p\text{Pb}$ sample as functions of $\langle dN_{\text{ch}}/d\eta \rangle$, presented before (red) and after (blue) the non-flow subtraction procedure. The vertical error bars represent statistical uncertainties while the shaded boxes represent systematic uncertainties.

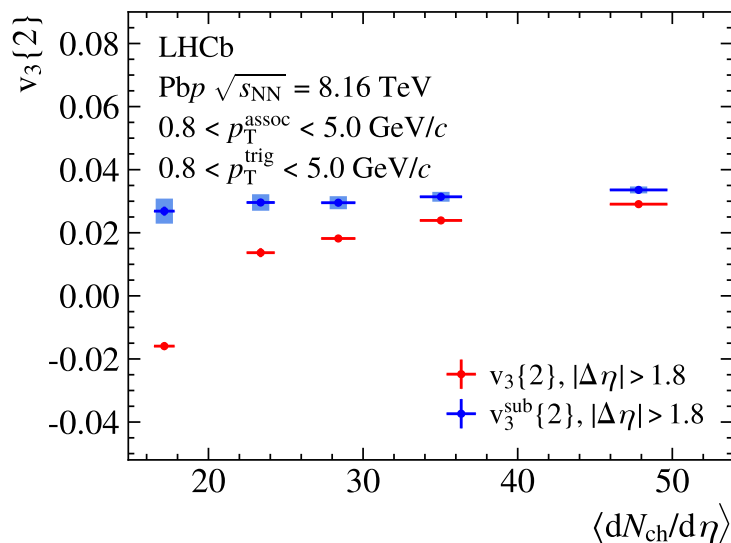


Figure 12. Results for $v_3\{2\}(|\Delta\eta| > 1.8)$ for the PbPb sample as functions of $\langle dN_{ch}/d\eta \rangle$, presented before (red) and after (blue) the non-flow subtraction procedure. The vertical error bars represent statistical uncertainties, which are hidden by the data points. The shaded boxes represent systematic uncertainties.

$p_T^{trig} [\text{GeV}/c]$	$v_2^{sub}\{2\} \pm \text{stat} \pm \text{syst}$
0.80–1.00	$0.0590 \pm 0.0004 \pm 0.0027$
1.00–1.25	$0.0720 \pm 0.0005 \pm 0.0017$
1.25–1.50	$0.0840 \pm 0.0006 \pm 0.0020$
1.50–1.75	$0.0941 \pm 0.0008 \pm 0.0056$
1.75–2.00	$0.1024 \pm 0.0009 \pm 0.0061$
2.00–2.50	$0.1093 \pm 0.0009 \pm 0.0065$
2.50–3.00	$0.1160 \pm 0.0013 \pm 0.0043$
3.00–3.50	$0.1165 \pm 0.0019 \pm 0.0042$
3.50–4.00	$0.1079 \pm 0.0027 \pm 0.0041$
4.00–5.00	$0.0901 \pm 0.0031 \pm 0.0039$

Table 4. Results of $v_2^{sub}\{2\}$ from the PbPb samples for the bin $\langle dN_{ch}/d\eta \rangle = 47.8$.

Foundation (Germany); ICSC (Italy); Severo Ochoa and María de Maeztu Units of Excellence, GVA, XuntaGal, GENCAT, InTalent-Inditex and Prog. Atracción Talento CM (Spain); SRC (Sweden); the Leverhulme Trust, the Royal Society and UKRI (United Kingdom).

A Result tables

Numeric values of $v_2^{sub}\{2\}$ and $v_3^{sub}\{2\}$ in p_T and $\langle dN_{ch}/d\eta \rangle$ bins for pPb and PbPb samples are presented in tables 4 to 17.

$p_T^{\text{trig}}[\text{GeV}/c]$	$v_2^{\text{sub}}\{2\} \pm \text{stat} \pm \text{syst}$
0.80–1.00	$0.0551 \pm 0.0007 \pm 0.0025$
1.00–1.25	$0.0668 \pm 0.0008 \pm 0.0020$
1.25–1.50	$0.0795 \pm 0.0009 \pm 0.0023$
1.50–1.75	$0.0888 \pm 0.0011 \pm 0.0035$
1.75–2.00	$0.0947 \pm 0.0014 \pm 0.0039$
2.00–2.50	$0.1002 \pm 0.0014 \pm 0.0040$
2.50–3.00	$0.1053 \pm 0.0021 \pm 0.0060$
3.00–3.50	$0.0987 \pm 0.0030 \pm 0.0055$
3.50–4.00	$0.0952 \pm 0.0043 \pm 0.0055$
4.00–5.00	$0.0736 \pm 0.0049 \pm 0.0042$

Table 5. Results of $v_2^{\text{sub}}\{2\}$ from the Pb p samples for the bin $\langle dN_{\text{ch}}/d\eta \rangle = 35.0$.

$p_T^{\text{trig}}[\text{GeV}/c]$	$v_2^{\text{sub}}\{2\} \pm \text{stat} \pm \text{syst}$
0.80–1.00	$0.0495 \pm 0.0010 \pm 0.0021$
1.00–1.25	$0.0620 \pm 0.0011 \pm 0.0026$
1.25–1.50	$0.0728 \pm 0.0013 \pm 0.0031$
1.50–1.75	$0.0822 \pm 0.0016 \pm 0.0036$
1.75–2.00	$0.0852 \pm 0.0020 \pm 0.0039$
2.00–2.50	$0.0904 \pm 0.0020 \pm 0.0040$
2.50–3.00	$0.0969 \pm 0.0030 \pm 0.0088$
3.00–3.50	$0.0834 \pm 0.0044 \pm 0.0076$
3.50–4.00	$0.0754 \pm 0.0063 \pm 0.0073$
4.00–5.00	$0.0556 \pm 0.0070 \pm 0.0054$

Table 6. Results of $v_2^{\text{sub}}\{2\}$ from the Pb p samples for the bin $\langle dN_{\text{ch}}/d\eta \rangle = 28.4$.

$p_T^{\text{trig}} [\text{GeV}/c]$	$v_2^{\text{sub}}\{2\} \pm \text{stat} \pm \text{syst}$
0.80–1.00	$0.0445 \pm 0.0014 \pm 0.0022$
1.00–1.25	$0.0542 \pm 0.0015 \pm 0.0032$
1.25–1.50	$0.0678 \pm 0.0019 \pm 0.0040$
1.50–1.75	$0.0725 \pm 0.0024 \pm 0.0043$
1.75–2.00	$0.0792 \pm 0.0029 \pm 0.0048$
2.00–2.50	$0.0797 \pm 0.0029 \pm 0.0048$
2.50–3.00	$0.0792 \pm 0.0043 \pm 0.0138$
3.00–3.50	$0.0605 \pm 0.0064 \pm 0.0106$
3.50–4.00	$0.0392 \pm 0.0092 \pm 0.0071$
4.00–5.00	$0.0220 \pm 0.0102 \pm 0.0044$

Table 7. Results of $v_2^{\text{sub}}\{2\}$ from the Pb p samples for the bin $\langle dN_{\text{ch}}/d\eta \rangle = 23.4$.

$p_T^{\text{trig}} [\text{GeV}/c]$	$v_2^{\text{sub}}\{2\} \pm \text{stat} \pm \text{syst}$
0.80–1.00	$0.0358 \pm 0.0022 \pm 0.0029$
1.00–1.25	$0.0438 \pm 0.0024 \pm 0.0039$
1.25–1.50	$0.0571 \pm 0.0030 \pm 0.0051$
1.50–1.75	$0.0620 \pm 0.0038 \pm 0.0052$
1.75–2.00	$0.0535 \pm 0.0047 \pm 0.0052$
2.00–2.50	$0.0588 \pm 0.0046 \pm 0.0048$
2.50–3.00	$0.0515 \pm 0.0070 \pm 0.0311$
3.00–3.50	$0.0240 \pm 0.0104 \pm 0.0145$
3.50–4.00	$0.0085 \pm 0.0149 \pm 0.0054$

Table 8. Results of $v_2^{\text{sub}}\{2\}$ from the Pb p samples for the bin $\langle dN_{\text{ch}}/d\eta \rangle = 17.1$.

$p_T^{\text{trig}} [\text{GeV}/c]$	$v_2^{\text{sub}}\{2\} \pm \text{stat} \pm \text{syst}$
0.80–1.00	$0.0505 \pm 0.0010 \pm 0.0042$
1.00–1.25	$0.0612 \pm 0.0011 \pm 0.0021$
1.25–1.50	$0.0692 \pm 0.0013 \pm 0.0024$
1.50–1.75	$0.0757 \pm 0.0016 \pm 0.0058$
1.75–2.00	$0.0796 \pm 0.0020 \pm 0.0061$
2.00–2.50	$0.0829 \pm 0.0019 \pm 0.0065$
2.50–3.00	$0.0824 \pm 0.0028 \pm 0.0059$
3.00–3.50	$0.0681 \pm 0.0040 \pm 0.0057$
3.50–4.00	$0.0482 \pm 0.0057 \pm 0.0043$
4.00–5.00	$0.0239 \pm 0.0062 \pm 0.0045$

Table 9. Results of $v_2^{\text{sub}}\{2\}$ from the $p\text{Pb}$ samples $\langle dN_{\text{ch}}/d\eta \rangle = 34.5$.

$p_T^{\text{trig}} [\text{GeV}/c]$	$v_2^{\text{sub}}\{2\} \pm \text{stat} \pm \text{syst}$
0.80–1.00	$0.0495 \pm 0.0014 \pm 0.0051$
1.00–1.25	$0.0584 \pm 0.0015 \pm 0.0026$
1.25–1.50	$0.0638 \pm 0.0019 \pm 0.0028$
1.50–1.75	$0.0680 \pm 0.0023 \pm 0.0062$
1.75–2.00	$0.0725 \pm 0.0028 \pm 0.0067$
2.00–2.50	$0.0720 \pm 0.0027 \pm 0.0068$
2.50–3.00	$0.0679 \pm 0.0040 \pm 0.0093$
3.00–3.50	$0.0504 \pm 0.0058 \pm 0.0083$
3.50–4.00	$0.0272 \pm 0.0082 \pm 0.0044$
4.00–5.00	$0.0056 \pm 0.0090 \pm 0.0029$

Table 10. Results of $v_2^{\text{sub}}\{2\}$ from the $p\text{Pb}$ samples for the bin $\langle dN_{\text{ch}}/d\eta \rangle = 25.9$.

$p_T^{\text{trig}} [\text{GeV}/c]$	$v_2^{\text{sub}}\{2\} \pm \text{stat} \pm \text{syst}$
0.80–1.00	$0.0443 \pm 0.0018 \pm 0.0051$
1.00–1.25	$0.0561 \pm 0.0020 \pm 0.0032$
1.25–1.50	$0.0612 \pm 0.0025 \pm 0.0036$
1.50–1.75	$0.0611 \pm 0.0030 \pm 0.0073$
1.75–2.00	$0.0635 \pm 0.0037 \pm 0.0077$
2.00–2.50	$0.0620 \pm 0.0036 \pm 0.0085$
2.50–3.00	$0.0560 \pm 0.0053 \pm 0.0142$
3.00–3.50	$0.0307 \pm 0.0076 \pm 0.0093$
3.50–4.00	$0.0105 \pm 0.0109 \pm 0.0044$

Table 11. Results of $v_2^{\text{sub}}\{2\}$ from the $p\text{Pb}$ samples for the bin $\langle dN_{\text{ch}}/d\eta \rangle = 21.8$.

$p_T^{\text{trig}} [\text{GeV}/c]$	$v_2^{\text{sub}}\{2\} \pm \text{stat} \pm \text{syst}$
0.80–1.00	$0.0374 \pm 0.0025 \pm 0.0067$
1.00–1.25	$0.0522 \pm 0.0028 \pm 0.0034$
1.25–1.50	$0.0565 \pm 0.0034 \pm 0.0037$
1.50–1.75	$0.0545 \pm 0.0041 \pm 0.0094$
1.75–2.00	$0.0524 \pm 0.0050 \pm 0.0090$
2.00–2.50	$0.0469 \pm 0.0049 \pm 0.0083$
2.50–3.00	$0.0418 \pm 0.0072 \pm 0.0368$
3.00–3.50	$0.0022 \pm 0.0105 \pm 0.0020$

Table 12. Results of $v_2^{\text{sub}}\{2\}$ from the $p\text{Pb}$ samples for the bin $\langle dN_{\text{ch}}/d\eta \rangle = 18.2$.

$p_T^{\text{trig}} [\text{GeV}/c]$	$v_2^{\text{sub}}\{2\} \pm \text{stat} \pm \text{syst}$
0.80–1.00	$0.0321 \pm 0.0038 \pm 0.0081$
1.00–1.25	$0.0446 \pm 0.0042 \pm 0.0040$
1.25–1.50	$0.0472 \pm 0.0051 \pm 0.0044$
1.50–1.75	$0.0403 \pm 0.0062 \pm 0.0152$
1.75–2.00	$0.0434 \pm 0.0077 \pm 0.0164$
2.00–2.50	$0.0277 \pm 0.0074 \pm 0.0114$
2.50–3.00	$0.0123 \pm 0.0110 \pm 0.0182$

Table 13. Results of $v_2^{\text{sub}}\{2\}$ from the $p\text{Pb}$ samples for the bin $\langle dN_{\text{ch}}/d\eta \rangle = 15.6$.

$\langle dN_{\text{ch}}/d\eta \rangle$	$v_2^{\text{sub}}\{2\} \pm \text{stat} \pm \text{syst}$
47.8	$0.0799 \pm 0.0002 \pm 0.0019$
35.0	$0.0744 \pm 0.0002 \pm 0.0027$
28.4	$0.0681 \pm 0.0003 \pm 0.0029$
23.4	$0.0607 \pm 0.0005 \pm 0.0032$
17.1	$0.0489 \pm 0.0008 \pm 0.0040$

Table 14. Results of $v_2^{\text{sub}}\{2\}$ from the PbP samples for different bins of $\langle dN_{\text{ch}}/d\eta \rangle$.

$\langle dN_{\text{ch}}/d\eta \rangle$	$v_3^{\text{sub}}\{2\} \pm \text{stat} \pm \text{syst}$
47.8	$0.0336 \pm 0.0004 \pm 0.0011$
35.0	$0.0314 \pm 0.0006 \pm 0.0016$
28.4	$0.0295 \pm 0.0008 \pm 0.0021$
23.4	$0.0296 \pm 0.0010 \pm 0.0026$
17.1	$0.0269 \pm 0.0014 \pm 0.0040$

Table 15. Results of $v_3^{\text{sub}}\{2\}$ from the PbP samples for different bins of $\langle dN_{\text{ch}}/d\eta \rangle$.

$\langle dN_{\text{ch}}/d\eta \rangle$	$v_2^{\text{sub}}\{2\} \pm \text{stat} \pm \text{syst}$
34.5	$0.0662 \pm 0.0003 \pm 0.0027$
25.9	$0.0619 \pm 0.0005 \pm 0.0035$
21.8	$0.0569 \pm 0.0006 \pm 0.0041$
18.2	$0.0500 \pm 0.0009 \pm 0.0045$
15.6	$0.0400 \pm 0.0013 \pm 0.0060$

Table 16. Results of $v_2^{\text{sub}}\{2\}$ from the pPb samples for different bins of $\langle dN_{\text{ch}}/d\eta \rangle$.

$\langle dN_{\text{ch}}/d\eta \rangle$	$v_3^{\text{sub}}\{2\} \pm \text{stat} \pm \text{syst}$
34.5	$0.0269 \pm 0.0008 \pm 0.0011$
25.9	$0.0265 \pm 0.0011 \pm 0.0014$
21.8	$0.0249 \pm 0.0015 \pm 0.0017$
18.2	$0.0267 \pm 0.0016 \pm 0.0017$
15.6	$0.0250 \pm 0.0021 \pm 0.0020$

Table 17. Results of $v_3^{\text{sub}}\{2\}$ from the pPb samples for different bins of $\langle dN_{\text{ch}}/d\eta \rangle$.

Data Availability Statement. Data associated to the plots in this publication as well as in supplementary materials are made available on the CERN document server at <http://cdsweb.cern.ch/record/2932151>.

Code Availability Statement. This article has no associated code or the code will not be deposited.

Open Access. This article is distributed under the terms of the Creative Commons Attribution License ([CC-BY4.0](https://creativecommons.org/licenses/by/4.0/)), which permits any use, distribution and reproduction in any medium, provided the original author(s) and source are credited.

References

- [1] ALICE collaboration, *The ALICE experiment: a journey through QCD*, *Eur. Phys. J. C* **84** (2024) 813 [[arXiv:2211.04384](https://arxiv.org/abs/2211.04384)] [[INSPIRE](#)].
- [2] STAR collaboration, *Experimental and theoretical challenges in the search for the quark gluon plasma: the STAR collaboration's critical assessment of the evidence from RHIC collisions*, *Nucl. Phys. A* **757** (2005) 102 [[nucl-ex/0501009](https://arxiv.org/abs/nuc1-ex/0501009)] [[INSPIRE](#)].
- [3] PHENIX collaboration, *Formation of dense partonic matter in relativistic nucleus-nucleus collisions at RHIC: experimental evaluation by the PHENIX collaboration*, *Nucl. Phys. A* **757** (2005) 184 [[nucl-ex/0410003](https://arxiv.org/abs/nuc1-ex/0410003)] [[INSPIRE](#)].
- [4] W. Busza, K. Rajagopal and W. van der Schee, *Heavy ion collisions: the big picture, and the big questions*, *Ann. Rev. Nucl. Part. Sci.* **68** (2018) 339 [[arXiv:1802.04801](https://arxiv.org/abs/1802.04801)] [[INSPIRE](#)].
- [5] A. Jaiswal and V. Roy, *Relativistic hydrodynamics in heavy-ion collisions: general aspects and recent developments*, *Adv. High Energy Phys.* **2016** (2016) 9623034 [[arXiv:1605.08694](https://arxiv.org/abs/1605.08694)] [[INSPIRE](#)].
- [6] J.E. Bernhard, J.S. Moreland and S.A. Bass, *Bayesian estimation of the specific shear and bulk viscosity of quark-gluon plasma*, *Nature Phys.* **15** (2019) 1113 [[INSPIRE](#)].
- [7] P. Foka and M.A. Janik, *An overview of experimental results from ultra-relativistic heavy-ion collisions at the CERN LHC: bulk properties and dynamical evolution*, *Rev. Phys.* **1** (2016) 154 [[arXiv:1702.07233](https://arxiv.org/abs/1702.07233)] [[INSPIRE](#)].
- [8] J.-Y. Ollitrault, *Relativistic hydrodynamics for heavy-ion collisions*, *Eur. J. Phys.* **29** (2008) 275 [[arXiv:0708.2433](https://arxiv.org/abs/0708.2433)] [[INSPIRE](#)].

- [9] J.-Y. Ollitrault, *Anisotropy as a signature of transverse collective flow*, *Phys. Rev. D* **46** (1992) 229 [INSPIRE].
- [10] J.-Y. Ollitrault and F.G. Gardim, *Hydro overview*, *Nucl. Phys. A* **904-905** (2013) 75c [arXiv:1210.8345] [INSPIRE].
- [11] NA49 collaboration, *Directed and elliptic flow of charged pions and protons in Pb+Pb collisions at 40 A-GeV and 158 A-GeV*, *Phys. Rev. C* **68** (2003) 034903 [nucl-ex/0303001] [INSPIRE].
- [12] STAR collaboration, *Elliptic flow in Au+Au collisions at $\sqrt{s_{NN}} = 130$ GeV*, *Phys. Rev. Lett.* **86** (2001) 402 [nucl-ex/0009011] [INSPIRE].
- [13] STAR collaboration, *Elliptic flow from two and four particle correlations in Au+Au collisions at $\sqrt{s_{NN}} = 130$ GeV*, *Phys. Rev. C* **66** (2002) 034904 [nucl-ex/0206001] [INSPIRE].
- [14] STAR collaboration, *Multi-strange baryon elliptic flow in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV*, *Phys. Rev. Lett.* **95** (2005) 122301 [nucl-ex/0504022] [INSPIRE].
- [15] PHENIX collaboration, *Elliptic flow of identified hadrons in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV*, *Phys. Rev. Lett.* **91** (2003) 182301 [nucl-ex/0305013] [INSPIRE].
- [16] PHENIX collaboration, *Scaling properties of azimuthal anisotropy in Au+Au and Cu+Cu collisions at $\sqrt{s_{NN}} = 200$ GeV*, *Phys. Rev. Lett.* **98** (2007) 162301 [nucl-ex/0608033] [INSPIRE].
- [17] PHOBOS collaboration, *Non-flow correlations and elliptic flow fluctuations in gold-gold collisions at $\sqrt{s_{NN}} = 200$ GeV*, *Phys. Rev. C* **81** (2010) 034915 [arXiv:1002.0534] [INSPIRE].
- [18] ALICE collaboration, *Higher harmonic anisotropic flow measurements of charged particles in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV*, *Phys. Rev. Lett.* **107** (2011) 032301 [arXiv:1105.3865] [INSPIRE].
- [19] ALICE collaboration, *Directed flow of charged particles at midrapidity relative to the spectator plane in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV*, *Phys. Rev. Lett.* **111** (2013) 232302 [arXiv:1306.4145] [INSPIRE].
- [20] ALICE collaboration, *Charge-dependent flow and the search for the chiral magnetic wave in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV*, *Phys. Rev. C* **93** (2016) 044903 [arXiv:1512.05739] [INSPIRE].
- [21] ALICE collaboration, *Anisotropic flow of charged particles in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV*, *Phys. Rev. Lett.* **116** (2016) 132302 [arXiv:1602.01119] [INSPIRE].
- [22] ALICE collaboration, *Anisotropic flow and flow fluctuations of identified hadrons in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV*, *JHEP* **05** (2023) 243 [arXiv:2206.04587] [INSPIRE].
- [23] ATLAS collaboration, *Measurement of the pseudorapidity and transverse momentum dependence of the elliptic flow of charged particles in lead-lead collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the ATLAS detector*, *Phys. Lett. B* **707** (2012) 330 [arXiv:1108.6018] [INSPIRE].
- [24] S. Plumari, *Anisotropic flows and the shear viscosity of the QGP within an event-by-event massive parton transport approach*, *Eur. Phys. J. C* **79** (2019) 2 [INSPIRE].
- [25] J.F. Grosse-Oetringhaus and U.A. Wiedemann, *A decade of collectivity in small systems*, submitted to World Scientific Annual Review of Particle Physics (2024) [arXiv:2407.07484] [INSPIRE].
- [26] LHCb collaboration, *Measurements of long-range near-side angular correlations in $\sqrt{s_{NN}} = 5$ TeV proton-lead collisions in the forward region*, *Phys. Lett. B* **762** (2016) 473 [arXiv:1512.00439] [INSPIRE].

- [27] CMS collaboration, *Observation of long-range near-side angular correlations in proton-lead collisions at the LHC*, *Phys. Lett. B* **718** (2013) 795 [[arXiv:1210.5482](#)] [[INSPIRE](#)].
- [28] ATLAS collaboration, *Observation of associated near-side and away-side long-range correlations in $\sqrt{s_{NN}} = 5.02$ TeV proton-lead collisions with the ATLAS detector*, *Phys. Rev. Lett.* **110** (2013) 182302 [[arXiv:1212.5198](#)] [[INSPIRE](#)].
- [29] ALICE collaboration, *Long-range angular correlations on the near and away side in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV*, *Phys. Lett. B* **719** (2013) 29 [[arXiv:1212.2001](#)] [[INSPIRE](#)].
- [30] PHENIX collaboration, *Measurements of multiparticle correlations in d+Au collisions at 200, 62.4, 39, and 19.6 GeV and p+Au collisions at 200 GeV and implications for collective behavior*, *Phys. Rev. Lett.* **120** (2018) 062302 [[arXiv:1707.06108](#)] [[INSPIRE](#)].
- [31] PHENIX collaboration, *Creation of quark–gluon plasma droplets with three distinct geometries*, *Nature Phys.* **15** (2019) 214 [[arXiv:1805.02973](#)] [[INSPIRE](#)].
- [32] STAR collaboration, *Measurements of the elliptic and triangular azimuthal anisotropies in central $^3\text{He}+\text{Au}$, d+Au and p+Au collisions at $\sqrt{s_{NN}} = 200$ GeV*, *Phys. Rev. Lett.* **130** (2023) 242301 [[arXiv:2210.11352](#)] [[INSPIRE](#)].
- [33] A. Badea et al., *Measurements of two-particle correlations in e^+e^- collisions at 91 GeV with ALEPH archived data*, *Phys. Rev. Lett.* **123** (2019) 212002 [[arXiv:1906.00489](#)] [[INSPIRE](#)].
- [34] Y.-C. Chen et al., *Long-range near-side correlation in e^+e^- collisions at 183–209 GeV with ALEPH archived data*, *Phys. Lett. B* **856** (2024) 138957 [[arXiv:2312.05084](#)] [[INSPIRE](#)].
- [35] BELLE collaboration, *Measurement of two-particle correlations of hadrons in e^+e^- collisions at Belle*, *Phys. Rev. Lett.* **128** (2022) 142005 [[arXiv:2201.01694](#)] [[INSPIRE](#)].
- [36] BELLE collaboration, *Two-particle angular correlations in e^+e^- collisions to hadronic final states in two reference coordinates at Belle*, *JHEP* **03** (2023) 171 [[arXiv:2206.09440](#)] [[INSPIRE](#)].
- [37] ZEUS collaboration, *Two-particle azimuthal correlations as a probe of collective behaviour in deep inelastic ep scattering at HERA*, *JHEP* **04** (2020) 070 [[arXiv:1912.07431](#)] [[INSPIRE](#)].
- [38] ZEUS collaboration, *Azimuthal correlations in photoproduction and deep inelastic ep scattering at HERA*, *JHEP* **12** (2021) 102 [[arXiv:2106.12377](#)] [[INSPIRE](#)].
- [39] CMS collaboration, *Two-particle azimuthal correlations in γp interactions using pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV*, *Phys. Lett. B* **844** (2023) 137905 [[arXiv:2204.13486](#)] [[INSPIRE](#)].
- [40] ATLAS collaboration, *Two-particle azimuthal correlations in photonuclear ultraperipheral Pb+Pb collisions at 5.02 TeV with ATLAS*, *Phys. Rev. C* **104** (2021) 014903 [[arXiv:2101.10771](#)] [[INSPIRE](#)].
- [41] CMS collaboration, *Observation of enhanced long-range elliptic anisotropies inside high-multiplicity jets in pp collisions at $\sqrt{s} = 13$ TeV*, *Phys. Rev. Lett.* **133** (2024) 142301 [[arXiv:2312.17103](#)] [[INSPIRE](#)].
- [42] H. Song, Y. Zhou and K. Gajdošová, *Collective flow and hydrodynamics in large and small systems at the LHC*, *Nucl. Sci. Tech.* **28** (2017) 99 [[arXiv:1703.00670](#)] [[INSPIRE](#)].
- [43] B. Schenke, P. Tribedy and R. Venugopalan, *Fluctuating glasma initial conditions and flow in heavy ion collisions*, *Phys. Rev. Lett.* **108** (2012) 252301 [[arXiv:1202.6646](#)] [[INSPIRE](#)].
- [44] S.A. Bass et al., *Microscopic models for ultrarelativistic heavy ion collisions*, *Prog. Part. Nucl. Phys.* **41** (1998) 255 [[nucl-th/9803035](#)] [[INSPIRE](#)].

- [45] L.A. Tarasovičová et al., *Flow and equation of state of nuclear matter at $E_{kin}/A = 0.25-1.5$ GeV with the SMASH transport approach*, *Eur. Phys. J. A* **60** (2024) 232 [[arXiv:2405.09889](#)] [[INSPIRE](#)].
- [46] A. Ortiz Velasquez et al., *Color reconnection and flowlike patterns in pp collisions*, *Phys. Rev. Lett.* **111** (2013) 042001 [[arXiv:1303.6326](#)] [[INSPIRE](#)].
- [47] W. Zhao, C. Shen and B. Schenke, *Collectivity in ultraperipheral Pb+Pb collisions at the Large Hadron Collider*, *Phys. Rev. Lett.* **129** (2022) 252302 [[arXiv:2203.06094](#)] [[INSPIRE](#)].
- [48] C. Shen and B. Schenke, *Longitudinal dynamics and particle production in relativistic nuclear collisions*, *Phys. Rev. C* **105** (2022) 064905 [[arXiv:2203.04685](#)] [[INSPIRE](#)].
- [49] LHCb collaboration, *The LHCb detector at the LHC*, 2008 *JINST* **3** S08005 [[INSPIRE](#)].
- [50] LHCb collaboration, *LHCb detector performance*, *Int. J. Mod. Phys. A* **30** (2015) 1530022 [[arXiv:1412.6352](#)] [[INSPIRE](#)].
- [51] R. Aaij et al., *Performance of the LHCb vertex locator*, 2014 *JINST* **9** P09007 [[arXiv:1405.7808](#)] [[INSPIRE](#)].
- [52] R. Arink et al., *Performance of the LHCb outer tracker*, 2014 *JINST* **9** P01002 [[arXiv:1311.3893](#)] [[INSPIRE](#)].
- [53] R. Arink et al., *Improved performance of the LHCb outer tracker in LHC run 2*, 2017 *JINST* **12** P11016 [[arXiv:1708.00819](#)] [[INSPIRE](#)].
- [54] ALICE collaboration, *The ALICE definition of primary particles*, ALICE-PUBLIC-2017-005, CERN, Geneva, Switzerland (2017).
- [55] T. Pierog et al., *EPOS LHC: test of collective hadronization with data measured at the CERN Large Hadron Collider*, *Phys. Rev. C* **92** (2015) 034906 [[arXiv:1306.0121](#)] [[INSPIRE](#)].
- [56] D.J. Lange, *The EvtGen particle decay simulation package*, *Nucl. Instrum. Meth. A* **462** (2001) 152 [[INSPIRE](#)].
- [57] N. Davidson, T. Przedzinski and Z. Was, *PHOTOS interface in C++: technical and physics documentation*, *Comput. Phys. Commun.* **199** (2016) 86 [[arXiv:1011.0937](#)] [[INSPIRE](#)].
- [58] J. Allison et al., *GEANT4 developments and applications*, *IEEE Trans. Nucl. Sci.* **53** (2006) 270 [[INSPIRE](#)].
- [59] GEANT4 collaboration, *GEANT4 — a simulation toolkit*, *Nucl. Instrum. Meth. A* **506** (2003) 250 [[INSPIRE](#)].
- [60] LHCb collaboration, *The LHCb simulation application, Gauss: design, evolution and experience*, *J. Phys. Conf. Ser.* **331** (2011) 032023 [[INSPIRE](#)].
- [61] M. Kucharczyk, P. Morawski and M. Witek, *Primary vertex reconstruction at LHCb*, LHCb-PUB-2014-044, CERN, Geneva, Switzerland (2014).
- [62] M. De Cian, S. Farry, P. Seyfert and S. Stahl, *Fast neural-net based fake track rejection in the LHCb reconstruction*, LHCb-PUB-2017-011, CERN, Geneva, Switzerland (2017).
- [63] S. Voloshin and Y. Zhang, *Flow study in relativistic nuclear collisions by Fourier expansion of Azimuthal particle distributions*, *Z. Phys. C* **70** (1996) 665 [[hep-ph/9407282](#)] [[INSPIRE](#)].
- [64] ALICE collaboration, *Harmonic decomposition of two-particle angular correlations in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV*, *Phys. Lett. B* **708** (2012) 249 [[arXiv:1109.2501](#)] [[INSPIRE](#)].
- [65] LHCb collaboration, *Study of the Bose-Einstein correlations of same-sign pions in proton-lead collisions*, *JHEP* **09** (2023) 172 [[arXiv:2306.09755](#)] [[INSPIRE](#)].

- [66] K. Kajantie, P.V. Landshoff and J. Lindfors, *Minijet production in high-energy nucleus-nucleus collisions*, *Phys. Rev. Lett.* **59** (1987) 2527 [[INSPIRE](#)].
- [67] L. Pang, Q. Wang and X.-N. Wang, *Relics of minijets amid anisotropic flows in high-energy heavy-ion collisions*, *Phys. Rev. C* **89** (2014) 064910 [[arXiv:1309.6735](#)] [[INSPIRE](#)].
- [68] R. Hanbury Brown and R.Q. Twiss, *A new type of interferometer for use in radio astronomy*, *Phil. Mag. Ser. 7* **45** (1954) 663 [[INSPIRE](#)].
- [69] R.H. Brown and R.Q. Twiss, *Correlation between photons in two coherent beams of light*, *Nature* **177** (1956) 27 [[INSPIRE](#)].
- [70] R. Hanbury Brown and R.Q. Twiss, *A test of a new type of stellar interferometer on Sirius*, *Nature* **178** (1956) 1046 [[INSPIRE](#)].
- [71] CMS collaboration, *Evidence for collectivity in pp collisions at the LHC*, *Phys. Lett. B* **765** (2017) 193 [[arXiv:1606.06198](#)] [[INSPIRE](#)].
- [72] ALICE collaboration, *Pseudorapidity distributions of charged particles as a function of mid- and forward rapidity multiplicities in pp collisions at $\sqrt{s} = 5.02, 7$ and 13 TeV*, *Eur. Phys. J. C* **81** (2021) 630 [[arXiv:2009.09434](#)] [[INSPIRE](#)].
- [73] ATLAS collaboration, *Measurements of long-range azimuthal anisotropies and associated Fourier coefficients for pp collisions at $\sqrt{s} = 5.02$ and 13 TeV and p+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with the ATLAS detector*, *Phys. Rev. C* **96** (2017) 024908 [[arXiv:1609.06213](#)] [[INSPIRE](#)].
- [74] ALICE collaboration, *Multiplicity dependence of pion, kaon, proton and lambda production in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV*, *Phys. Lett. B* **728** (2014) 25 [[arXiv:1307.6796](#)] [[INSPIRE](#)].
- [75] LHCb collaboration, *Measurement of the nuclear modification factor and prompt charged particle production in p-Pb and pp collisions at $\sqrt{s_{NN}} = 5$ TeV*, *Phys. Rev. Lett.* **128** (2022) 142004 [[arXiv:2108.13115](#)] [[INSPIRE](#)].

The LHCb collaboration

R. Aaij³⁸, A.S.W. Abdelmotteleb⁵⁷, C. Abellan Beteta⁵¹, F. Abudinén⁵⁷, T. Ackernley⁶¹, A. A. Adefisoye⁶⁹, B. Adeva⁴⁷, M. Adinolfi⁵⁵, P. Adlarson⁸⁴, C. Agapopoulou¹⁴, C.A. Aidala⁸⁶, Z. Ajaltouni¹¹, S. Akar¹¹, K. Akiba³⁸, P. Albicocco²⁸, J. Albrecht^{19,e}, F. Alessio⁴⁹, M. Alexander⁶⁰, Z. Aliouche⁶³, P. Alvarez Cartelle⁵⁶, R. Amalric¹⁶, S. Amato³, J.L. Amey⁵⁵, Y. Amhis¹⁴, L. An⁶, L. Anderlini²⁷, M. Andersson⁵¹, A. Andreianov⁴⁴, P. Andreola⁵¹, M. Andreotti²⁶, D. Andreou⁶⁹, A. Anelli^{31,n,49}, D. Ao⁷, F. Archilli^{37,t}, M. Argenton²⁶, S. Arguedas Cuendis^{9,49}, A. Artamonov⁴⁴, M. Artuso⁶⁹, E. Aslanides¹³, R. Ataíde Da Silva⁵⁰, M. Atzeni⁶⁵, B. Audurier¹², D. Bacher⁶⁴, I. Bachiller Perea⁵⁰, S. Bachmann²², M. Bachmayer⁵⁰, J.J. Back⁵⁷, P. Baladron Rodriguez⁴⁷, V. Balagura¹⁵, A. Balboni²⁶, W. Baldini²⁶, L. Balzani¹⁹, H. Bao⁷, J. Baptista de Souza Leite⁶¹, C. Barbero Pretel^{47,12}, M. Barbetti²⁷, I. R. Barbosa⁷⁰, R.J. Barlow⁶³, M. Barnyakov²⁵, S. Barsuk¹⁴, W. Barter⁵⁹, J. Bartz⁶⁹, S. Bashir⁴⁰, B. Batsukh⁵, P. B. Battista¹⁴, A. Bay⁵⁰, A. Beck⁶⁵, M. Becker¹⁹, F. Bedeschi³⁵, I.B. Bediaga², N. A. Behling¹⁹, S. Belin⁴⁷, K. Belous⁴⁴, I. Belov²⁹, I. Belyaev³⁶, G. Benane¹³, G. Bencivenni²⁸, E. Ben-Haim¹⁶, A. Berezhnoy⁴⁴, R. Bernet⁵¹, S. Bernet Andres⁴⁵, A. Bertolin³³, C. Betancourt⁵¹, F. Betti⁵⁹, J. Bex⁵⁶, Ia. Bezshyiko⁵¹, O. Bezshyiko³⁵, J. Bhom⁴¹, M.S. Bieker¹⁸, N.V. Biesuz²⁶, P. Billoir¹⁶, A. Biolchini³⁸, M. Birch⁶², F.C.R. Bishop¹⁰, A. Bitadze⁶³, A. Bizzeti¹⁶, T. Blake⁵⁷, F. Blanc⁵⁰, J.E. Blank¹⁹, S. Blusk⁶⁹, V. Bocharnikov⁴⁴, J.A. Boelhaeve¹⁹, O. Boente Garcia¹⁵, T. Boettcher⁶⁸, A. Bohare⁵⁹, A. Boldyrev⁴⁴, C.S. Bolognani⁸¹, R. Bolzonella²⁶, R. B. Bonacci¹, N. Bondar^{44,49}, A. Bordelius⁴⁹, F. Borgato^{33,49}, S. Borghi⁶³, M. Borsato^{31,n}, J.T. Borsuk⁸², E. Bottalico⁶¹, S.A. Bouchiba⁵⁰, M. Bovill⁶⁴, T.J.V. Bowcock⁶¹, A. Boyer⁴⁹, C. Bozzi²⁶, J. D. Brandenburg⁸⁷, A. Brea Rodriguez⁵⁰, N. Breer¹⁹, J. Brodzicka⁴¹, A. Brossa Gonzalo^{47,†}, J. Brown⁶¹, D. Brundu³², E. Buchanan⁵⁹, L. Buonincontri^{33,o}, M. Burgos Marcos⁸¹, A.T. Burke⁶³, C. Burr⁴⁹, J.S. Butter⁵⁶, J. Buytaert⁴⁹, W. Byczynski⁴⁹, S. Cadeddu³², H. Cai⁷⁴, A. Caillet¹⁶, R. Calabrese^{26,j}, S. Calderon Ramirez⁹, L. Calefice⁴⁶, S. Cali²⁸, M. Calvi^{31,n}, M. Calvo Gomez⁴⁵, P. Camargo Magalhaes^{2,y}, J. I. Cambon Bouzas⁴⁷, P. Campana²⁸, D.H. Campora Perez⁸¹, A.F. Campoverde Quezada⁷, S. Capelli³¹, L. Capriotti²⁶, R. Caravaca-Mora⁹, A. Carbone^{25,h}, L. Carcedo Salgado⁴⁷, R. Cardinale^{29,l}, A. Cardini³², P. Carniti^{31,n}, L. Carus²², A. Casais Vidal⁶⁵, R. Caspary²², G. Casse⁶¹, M. Cattaneo⁴⁹, G. Cavallero^{26,49}, V. Cavallini^{26,j}, S. Celani²², S. Cesare^{30,m}, A.J. Chadwick⁶¹, I. Chahrouh⁸⁶, H. Chang^{4,b}, M. Charles¹⁶, Ph. Charpentier⁴⁹, E. Chatzianagnostou³⁸, M. Chefdeville¹⁰, C. Chen⁵⁶, S. Chen⁵, Z. Chen⁷, A. Chernov⁴¹, S. Chernyshenko⁵³, X. Chiotopoulos⁸¹, V. Chobanova⁸³, M. Chrzaszcz⁴¹, A. Chubykin⁴⁴, V. Chulikov^{28,36}, P. Ciambone²⁸, X. Cid Vidal⁴⁷, G. Ciezarek⁴⁹, P. Cifra⁴⁹, P.E.L. Clarke⁵⁹, M. Clemencic⁴⁹, H.V. Cliff⁵⁶, J. Closier⁴⁹, C. Cocha Toapaxi²², V. Coco⁴⁹, J. Cogan¹³, E. Cogneras¹¹, L. Cojocariu⁴³, S. Collaviti⁵⁰, P. Collins⁴⁹, T. Colombo⁴⁹, M. Colonna¹⁹, A. Comerma-Montells⁴⁶, L. Congedo²⁴, A. Contu³², N. Cooke⁶⁰, C. Coronel⁶⁶, I. Corredoira¹², A. Correia¹⁶, G. Corti⁴⁹, J. Cottee Meldrum⁵⁵, B. Couturier⁴⁹, D.C. Craik⁵¹, M. Cruz Torres², E. Curras Rivera⁵⁰, R. Currie⁵⁹, C.L. Da Silva⁶⁸, S. Dadabaev⁴⁴, L. Dai⁷¹, X. Dai⁴,

E. Dall’Occo [ID](#)⁴⁹, J. Dalseno [ID](#)⁸³, C. D’Ambrosio [ID](#)⁶², J. Daniel [ID](#)¹¹, P. d’Argent [ID](#)²⁴, G. Darze [ID](#)³, A. Davidson [ID](#)⁵⁷, J.E. Davies [ID](#)⁶³, O. De Aguiar Francisco [ID](#)⁶³, C. De Angelis [ID](#)^{32,i}, F. De Benedetti [ID](#)⁴⁹, J. de Boer [ID](#)³⁸, K. De Bruyn [ID](#)⁸⁰, S. De Capua [ID](#)⁶³, M. De Cian [ID](#)²², U. De Freitas Carneiro Da Graca [ID](#)^{2,a}, E. De Lucia [ID](#)²⁸, J.M. De Miranda [ID](#)², L. De Paula [ID](#)³, M. De Serio [ID](#)^{24,f}, P. De Simone [ID](#)²⁸, F. De Vellis [ID](#)¹⁹, J.A. de Vries [ID](#)⁸¹, F. Debernardis [ID](#)²⁴, D. Decamp [ID](#)¹⁰, S. Dekkers [ID](#)¹, L. Del Buono [ID](#)¹⁶, B. Delaney [ID](#)⁶⁵, H.-P. Dembinski [ID](#)¹⁹, J. Deng [ID](#)⁸, V. Denysenko [ID](#)⁵¹, O. Deschamps [ID](#)¹¹, F. Dettori [ID](#)^{32,i}, B. Dey [ID](#)⁷⁸, P. Di Nezza [ID](#)²⁸, I. Diachkov [ID](#)⁴⁴, S. Didenko [ID](#)⁴⁴, S. Ding [ID](#)⁶⁹, L. Dittmann [ID](#)²², V. Dobishuk [ID](#)⁵³, A. D. Docheva [ID](#)⁶⁰, C. Dong [ID](#)^{4,b}, A.M. Donohoe [ID](#)²³, F. Dordei [ID](#)³², A.C. dos Reis [ID](#)², A. D. Dowling [ID](#)⁶⁹, W. Duan [ID](#)⁷², P. Duda [ID](#)⁸², M.W. Dudek [ID](#)⁴¹, L. Dufour [ID](#)⁴⁹, V. Duk [ID](#)³⁴, P. Durante [ID](#)⁴⁹, M. M. Duras [ID](#)⁸², J.M. Durham [ID](#)⁶⁸, O. D. Durmus [ID](#)⁷⁸, A. Dziurda [ID](#)⁴¹, A. Dzyuba [ID](#)⁴⁴, S. Easo [ID](#)⁵⁸, E. Eckstein [ID](#)¹⁸, U. Egede [ID](#)¹, A. Egorychev [ID](#)⁴⁴, V. Egorychev [ID](#)⁴⁴, S. Eisenhardt [ID](#)⁵⁹, E. Ejopu [ID](#)⁶³, L. Eklund [ID](#)⁸⁴, M. Elashri [ID](#)⁶⁶, J. Ellbracht [ID](#)¹⁹, S. Ely [ID](#)⁶², A. Ene [ID](#)⁴³, J. Eschle [ID](#)⁶⁹, S. Esen [ID](#)²², T. Evans [ID](#)³⁸, F. Fabiano [ID](#)³², S. Faghih [ID](#)⁶⁶, L.N. Falcao [ID](#)², B. Fang [ID](#)⁷, L. Fantini [ID](#)^{34,p,49}, M. Faria [ID](#)⁵⁰, K. Farmer [ID](#)⁵⁹, D. Fazzini [ID](#)^{31,n}, L. Felkowski [ID](#)⁸², M. Feng [ID](#)^{5,7}, M. Feo [ID](#)², A. Fernandez Casani [ID](#)⁴⁸, M. Fernandez Gomez [ID](#)⁴⁷, A.D. Fernez [ID](#)⁶⁷, F. Ferrari [ID](#)^{25,h}, F. Ferreira Rodrigues [ID](#)³, M. Ferrillo [ID](#)⁵¹, M. Ferro-Luzzi [ID](#)⁴⁹, S. Filippov [ID](#)⁴⁴, R.A. Fini [ID](#)²⁴, M. Fiorini [ID](#)^{26,j}, M. Firlej [ID](#)⁴⁰, K.L. Fischer [ID](#)⁶⁴, D.S. Fitzgerald [ID](#)⁸⁶, C. Fitzpatrick [ID](#)⁶³, T. Fiutowski [ID](#)⁴⁰, F. Fleuret [ID](#)¹⁵, M. Fontana [ID](#)²⁵, L. F. Foreman [ID](#)⁶³, R. Forty [ID](#)⁴⁹, D. Foulds-Holt [ID](#)⁵⁶, V. Franco Lima [ID](#)³, M. Franco Sevilla [ID](#)⁶⁷, M. Frank [ID](#)⁴⁹, E. Franzoso [ID](#)^{26,j}, G. Frau [ID](#)⁶³, C. Frei [ID](#)⁴⁹, D.A. Friday [ID](#)⁶³, J. Fu [ID](#)⁷, Q. Fühling [ID](#)^{19,e,56}, Y. Fujii [ID](#)¹, T. Fulghesu [ID](#)¹³, E. Gabriel [ID](#)³⁸, G. Galati [ID](#)²⁴, M.D. Galati [ID](#)³⁸, A. Gallas Torreira [ID](#)⁴⁷, D. Galli [ID](#)^{25,h}, S. Gambetta [ID](#)⁵⁹, M. Gandelman [ID](#)³, P. Gandini [ID](#)³⁰, B. Ganie [ID](#)⁶³, H. Gao [ID](#)⁷, R. Gao [ID](#)⁶⁴, T.Q. Gao [ID](#)⁵⁶, Y. Gao [ID](#)⁸, Y. Gao [ID](#)⁶, Y. Gao [ID](#)⁸, L.M. Garcia Martin [ID](#)⁵⁰, P. Garcia Moreno [ID](#)⁴⁶, J. García Pardiñas [ID](#)⁶⁵, P. Gardner [ID](#)⁶⁷, K. G. Garg [ID](#)⁸, L. Garrido [ID](#)⁴⁶, C. Gaspar [ID](#)⁴⁹, A. Gavrikov [ID](#)³³, L.L. Gerken [ID](#)¹⁹, E. Gersabeck [ID](#)²⁰, M. Gersabeck [ID](#)²⁰, T. Gershon [ID](#)⁵⁷, S. Ghizzo [ID](#)^{29,l}, Z. Ghorbanimoghaddam [ID](#)⁵⁵, L. Giambastiani [ID](#)^{33,o}, F. I. Giasemis [ID](#)^{16,d}, V. Gibson [ID](#)⁵⁶, H.K. Gienza [ID](#)⁴², A.L. Gilman [ID](#)⁶⁴, M. Giovannetti [ID](#)²⁸, A. Gioventù [ID](#)⁴⁶, L. Girardey [ID](#)^{63,58}, C. Giugliano [ID](#)^{26,j}, M.A. Giza [ID](#)⁴¹, F.C. Glaser [ID](#)^{14,22}, V.V. Gligorov [ID](#)¹⁶, C. Göbel [ID](#)⁷⁰, L. Golinka-Bezshyyko [ID](#)⁸⁵, E. Golobardes [ID](#)⁴⁵, D. Golubkov [ID](#)⁴⁴, A. Golutvin [ID](#)^{62,49}, S. Gomez Fernandez [ID](#)⁴⁶, W. Gomulka [ID](#)⁴⁰, F. Goncalves Abrantes [ID](#)⁶⁴, M. Goncerz [ID](#)⁴¹, G. Gong [ID](#)^{4,b}, J. A. Gooding [ID](#)¹⁹, I.V. Gorelov [ID](#)⁴⁴, C. Gotti [ID](#)³¹, E. Govorkova [ID](#)⁶⁵, J.P. Grabowski [ID](#)¹⁸, L.A. Granado Cardoso [ID](#)⁴⁹, E. Graugés [ID](#)⁴⁶, E. Graverini [ID](#)^{50,r}, L. Grazette [ID](#)⁵⁷, G. Graziani [ID](#), A. T. Grecu [ID](#)⁴³, L.M. Greeven [ID](#)³⁸, N.A. Grieser [ID](#)⁶⁶, L. Grillo [ID](#)⁶⁰, S. Gromov [ID](#)⁴⁴, C. Gu [ID](#)¹⁵, M. Guarise [ID](#)²⁶, L. Guerry [ID](#)¹¹, V. Guliaeva [ID](#)⁴⁴, P. A. Günther [ID](#)²², A.-K. Guseinov [ID](#)⁵⁰, E. Gushchin [ID](#)⁴⁴, Y. Guz [ID](#)^{6,49}, T. Gys [ID](#)⁴⁹, K. Habermann [ID](#)¹⁸, T. Hadavizadeh [ID](#)¹, C. Hadjivasiliou [ID](#)⁶⁷, G. Haefeli [ID](#)⁵⁰, C. Haen [ID](#)⁴⁹, G. Hallett [ID](#)⁵⁷, P.M. Hamilton [ID](#)⁶⁷, J. Hammerich [ID](#)⁶¹, Q. Han [ID](#)³³, X. Han [ID](#)^{22,49}, S. Hansmann-Menzemer [ID](#)²², L. Hao [ID](#)⁷, N. Harnew [ID](#)⁶⁴, T. H. Harris [ID](#)¹, M. Hartmann [ID](#)¹⁴, S. Hashmi [ID](#)⁴⁰, J. He [ID](#)^{7,c}, F. Hemmer [ID](#)⁴⁹, C. Henderson [ID](#)⁶⁶, R.D.L. Henderson [ID](#)^{1,57}, A.M. Hennequin [ID](#)⁴⁹, K. Hennessy [ID](#)⁶¹, L. Henry [ID](#)⁵⁰, J. Herd [ID](#)⁶², P. Herrero Gascon [ID](#)²², J. Heuel [ID](#)¹⁷, A. Hicheur [ID](#)³, G. Hijano Mendizabal [ID](#)⁵¹, J. Horswill [ID](#)⁶³, R. Hou [ID](#)⁸, Y. Hou [ID](#)¹¹, N. Howarth [ID](#)⁶¹, J. Hu [ID](#)⁷², W. Hu [ID](#)⁷, X. Hu [ID](#)^{4,b}, W. Hulsbergen [ID](#)³⁸, R.J. Hunter [ID](#)⁵⁷, M. Hushchyn [ID](#)⁴⁴, D. Hutchcroft [ID](#)⁶¹, M. Idzik [ID](#)⁴⁰, D. Ilin [ID](#)⁴⁴, P. Ilten [ID](#)⁶⁶, A. Inglessi [ID](#)⁴⁴,

A. Iniukhin [ID](#)⁴⁴, A. Ishteev [ID](#)⁴⁴, K. Ivshin [ID](#)⁴⁴, H. Jage [ID](#)¹⁷, S.J. Jaimes Elles [ID](#)^{76,49,48},
 S. Jakobsen [ID](#)⁴⁹, E. Jans [ID](#)³⁸, B.K. Jashal [ID](#)⁴⁸, A. Jawahery [ID](#)⁶⁷, V. Jevtic [ID](#)¹⁹, E. Jiang [ID](#)⁶⁷,
 X. Jiang [ID](#)^{5,7}, Y. Jiang [ID](#)⁷, Y. J. Jiang [ID](#)⁶, M. John [ID](#)⁶⁴, A. John Rubesh Rajan [ID](#)²³,
 D. Johnson [ID](#)⁵⁴, C.R. Jones [ID](#)⁵⁶, T.P. Jones [ID](#)⁵⁷, S. Joshi [ID](#)⁴², B. Jost [ID](#)⁴⁹, J. Juan Castella [ID](#)⁵⁶,
 N. Jurik [ID](#)⁴⁹, I. Juszczyk [ID](#)⁴¹, D. Kaminaris [ID](#)⁵⁰, S. Kandybei [ID](#)⁵², M. Kane [ID](#)⁵⁹, Y. Kang [ID](#)^{4,b},
 C. Kar [ID](#)¹¹, M. Karacson [ID](#)⁴⁹, D. Karpenkov [ID](#)⁴⁴, A. Kauniskangas [ID](#)⁵⁰, J.W. Kautz [ID](#)⁶⁶,
 M.K. Kazanecki [ID](#)⁴¹, F. Keizer [ID](#)⁴⁹, M. Kenzie [ID](#)⁵⁶, T. Ketel [ID](#)³⁸, B. Khanji [ID](#)⁶⁹, A. Kharisova [ID](#)⁴⁴,
 S. Kholodenko [ID](#)^{35,49}, G. Khreich [ID](#)¹⁴, T. Kirn [ID](#)¹⁷, V.S. Kirsebom [ID](#)^{31,n}, O. Kitouni [ID](#)⁶⁵,
 S. Klaver [ID](#)³⁹, N. Kleijne [ID](#)^{35,q}, K. Klimaszewski [ID](#)⁴², M.R. Kmiec [ID](#)⁴², S. Koliev [ID](#)⁵³, L. Kolk [ID](#)¹⁹,
 A. Konoplyannikov [ID](#)⁶, P. Kopciewicz [ID](#)⁴⁹, P. Koppenburg [ID](#)³⁸, A. Korchin [ID](#)⁵², M. Korolev [ID](#)⁴⁴,
 I. Kostiuk [ID](#)³⁸, O. Kot [ID](#)⁵³, S. Kotriakhova [ID](#), A. Kozachuk [ID](#)⁴⁴, P. Kravchenko [ID](#)⁴⁴, L. Kravchuk [ID](#)⁴⁴,
 M. Kreps [ID](#)⁵⁷, P. Krokovny [ID](#)⁴⁴, W. Krupa [ID](#)⁶⁹, W. Krzemien [ID](#)⁴², O. Kshyvanskyi [ID](#)⁵³, S. Kubis [ID](#)⁸²,
 M. Kucharczyk [ID](#)⁴¹, V. Kudryavtsev [ID](#)⁴⁴, E. Kulikova [ID](#)⁴⁴, A. Kupsc [ID](#)⁸⁴, V. Kushnir [ID](#)⁵², B. K.
 Kutsenko [ID](#)¹³, I. Kyrillin [ID](#)⁵², D. Lacarrere [ID](#)⁴⁹, P. Laguarda Gonzalez [ID](#)⁴⁶, A. Lai [ID](#)³²,
 A. Lampis [ID](#)³², D. Lancierini [ID](#)⁶², C. Landesa Gomez [ID](#)⁴⁷, J.J. Lane [ID](#)¹, G. Lanfranchi [ID](#)²⁸,
 C. Langenbruch [ID](#)²², J. Langer [ID](#)¹⁹, O. Lantwin [ID](#)⁴⁴, T. Latham [ID](#)⁵⁷, F. Lazzari [ID](#)^{35,r,49},
 C. Lazzeroni [ID](#)⁵⁴, R. Le Gac [ID](#)¹³, H. Lee [ID](#)⁶¹, R. Lefèvre [ID](#)¹¹, A. Leflat [ID](#)⁴⁴, S. Legotin [ID](#)⁴⁴,
 M. Lehuraux [ID](#)⁵⁷, E. Lemos Cid [ID](#)⁴⁹, O. Leroy [ID](#)¹³, T. Lesiak [ID](#)⁴¹, E. D. Lesser [ID](#)⁴⁹,
 B. Leverington [ID](#)²², A. Li [ID](#)^{4,b}, C. Li [ID](#)^{4,b}, C. Li [ID](#)¹³, H. Li [ID](#)⁷², J. Li [ID](#)⁸, K. Li [ID](#)⁷⁵, L. Li [ID](#)⁶³,
 M. Li [ID](#)⁸, P. Li [ID](#)⁷, P.-R. Li [ID](#)⁷³, Q. Li [ID](#)^{5,7}, S. Li [ID](#)⁸, T. Li [ID](#)⁷¹, T. Li [ID](#)⁷², Y. Li [ID](#)⁸, Y. Li [ID](#)⁵,
 Z. Lian [ID](#)^{4,b}, X. Liang [ID](#)⁶⁹, S. Libralon [ID](#)⁴⁸, C. Lin [ID](#)⁷, T. Lin [ID](#)⁵⁸, R. Lindner [ID](#)⁴⁹, H. Linton [ID](#)⁶²,
 V. Lisovskyi [ID](#)⁵⁰, R. Litvinov [ID](#)^{32,49}, D. Liu [ID](#)⁸, F. L. Liu [ID](#)¹, G. Liu [ID](#)⁷², K. Liu [ID](#)⁷³, S. Liu [ID](#)^{5,7}, W.
 Liu [ID](#)⁸, Y. Liu [ID](#)⁵⁹, Y. Liu [ID](#)⁷³, Y. L. Liu [ID](#)⁶², G. Loachamin Ordonez [ID](#)⁷⁰, A. Lobo Salvia [ID](#)⁴⁶,
 A. Loi [ID](#)³², T. Long [ID](#)⁵⁶, J.H. Lopes [ID](#)³, A. Lopez Huertas [ID](#)⁴⁶, S. López Soliño [ID](#)⁴⁷, Q. Lu [ID](#)¹⁵,
 C. Lucarelli [ID](#)^{27,k}, D. Lucchesi [ID](#)^{33,o}, M. Lucio Martinez [ID](#)⁴⁸, Y. Luo [ID](#)⁶, A. Lupato [ID](#)^{33,g},
 E. Luppi [ID](#)^{26,j}, K. Lynch [ID](#)²³, X.-R. Lyu [ID](#)⁷, G. M. Ma [ID](#)^{4,b}, S. Maccolini [ID](#)¹⁹, F. Machefer [ID](#)¹⁴,
 F. Maciuc [ID](#)⁴³, B. Mack [ID](#)⁶⁹, I. Mackay [ID](#)⁶⁴, L. M. Mackey [ID](#)⁶⁹, L.R. Madhan Mohan [ID](#)⁵⁶, M. J.
 Madurai [ID](#)⁵⁴, D. Magdalinski [ID](#)³⁸, D. Maisuzenko [ID](#)⁴⁴, J.J. Malczewski [ID](#)⁴¹, S. Malde [ID](#)⁶⁴,
 L. Malentacca [ID](#)⁴⁹, A. Malinin [ID](#)⁴⁴, T. Maltsev [ID](#)⁴⁴, G. Manca [ID](#)^{32,i}, G. Mancinelli [ID](#)¹³,
 C. Mancuso [ID](#)¹⁴, R. Manera Escalero [ID](#)⁴⁶, F. M. Manganella [ID](#)³⁷, D. Manuzzi [ID](#)²⁵,
 D. Marangotto [ID](#)³⁰, J.F. Marchand [ID](#)¹⁰, R. Marchevski [ID](#)⁵⁰, U. Marconi [ID](#)²⁵, E. Mariani [ID](#)¹⁶,
 S. Mariani [ID](#)⁴⁹, C. Marin Benito [ID](#)⁴⁶, J. Marks [ID](#)²², A.M. Marshall [ID](#)⁵⁵, L. Martel [ID](#)⁶⁴,
 G. Martelli [ID](#)^{34,p}, G. Martellotti [ID](#)³⁶, L. Martinazzoli [ID](#)⁴⁹, M. Martinelli [ID](#)^{31,n}, D.
 Martinez Gomez [ID](#)⁸⁰, D. Martinez Santos [ID](#)⁸³, F. Martinez Vidal [ID](#)⁴⁸, A. Martorell i Granollers [ID](#)⁴⁵,
 A. Massafferri [ID](#)², R. Matev [ID](#)⁴⁹, A. Mathad [ID](#)⁴⁹, V. Matiunin [ID](#)⁴⁴, C. Matteuzzi [ID](#)⁶⁹,
 K.R. Mattioli [ID](#)¹⁵, A. Mauri [ID](#)⁶², E. Maurice [ID](#)¹⁵, J. Mauricio [ID](#)⁴⁶, P. Mayencourt [ID](#)⁵⁰,
 J. Mazorra de Cos [ID](#)⁴⁸, M. Mazurek [ID](#)⁴², M. McCann [ID](#)⁶², T.H. McGrath [ID](#)⁶³, N.T. McHugh [ID](#)⁶⁰,
 A. McNab [ID](#)⁶³, R. McNulty [ID](#)²³, B. Meadows [ID](#)⁶⁶, G. Meier [ID](#)¹⁹, D. Melnychuk [ID](#)⁴², F. M.
 Meng [ID](#)^{4,b}, M. Merk [ID](#)^{38,81}, A. Merli [ID](#)⁵⁰, L. Meyer Garcia [ID](#)⁶⁷, D. Miao [ID](#)^{5,7}, H. Miao [ID](#)⁷,
 M. Mikhasenko [ID](#)⁷⁷, D.A. Milanese [ID](#)^{76,w}, A. Minotti [ID](#)^{31,n}, E. Minucci [ID](#)²⁸, T. Miralles [ID](#)¹¹,
 B. Mitreska [ID](#)¹⁹, D.S. Mitzel [ID](#)¹⁹, A. Modak [ID](#)⁵⁸, L. Moeser [ID](#)¹⁹, R.A. Mohammed [ID](#)⁶⁴,
 R.D. Moise [ID](#)¹⁷, E. F. Molina Cardenas [ID](#)⁸⁶, T. Mombächer [ID](#)⁴⁹, M. Monk [ID](#)^{57,1}, S. Monteil [ID](#)¹¹,
 A. Morcillo Gomez [ID](#)⁴⁷, G. Morello [ID](#)²⁸, M.J. Morello [ID](#)^{35,q}, M.P. Morgenthaler [ID](#)²², J. Moron [ID](#)⁴⁰, W.

Morren [ID](#)³⁸, A.B. Morris [ID](#)⁴⁹, A.G. Morris [ID](#)¹³, R. Mountain [ID](#)⁶⁹, H. Mu [ID](#)^{4,b}, Z. M. Mu [ID](#)⁶,
 E. Muhammad [ID](#)⁵⁷, F. Muheim [ID](#)⁵⁹, M. Mulder [ID](#)⁸⁰, K. Müller [ID](#)⁵¹, F. Muñoz-Rojas [ID](#)⁹,
 R. Murta [ID](#)⁶², V. Mytrochenko [ID](#)⁵², P. Naik [ID](#)⁶¹, T. Nakada [ID](#)⁵⁰, R. Nandakumar [ID](#)⁵⁸, T. Nanut [ID](#)⁴⁹,
 I. Nasteva [ID](#)³, M. Needham [ID](#)⁵⁹, E. Nekrasova [ID](#)⁴⁴, N. Neri [ID](#)^{30,m}, S. Neubert [ID](#)¹⁸, N. Neufeld [ID](#)⁴⁹,
 P. Neustroev [ID](#)⁴⁴, J. Nicolini [ID](#)⁴⁹, D. Nicotra [ID](#)⁸¹, E.M. Niel [ID](#)⁴⁹, N. Nikitin [ID](#)⁴⁴, Q. Niu [ID](#)⁷³,
 P. Nogarolli [ID](#)³, P. Nogga [ID](#)¹⁸, C. Normand [ID](#)⁵⁵, J. Novoa Fernandez [ID](#)⁴⁷, G. Nowak [ID](#)⁶⁶,
 C. Nunez [ID](#)⁸⁶, H. N. Nur [ID](#)⁶⁰, A. Oblakowska-Mucha [ID](#)⁴⁰, V. Obraztsov [ID](#)⁴⁴, T. Oeser [ID](#)¹⁷,
 S. Okamura [ID](#)^{26,j}, A. Okhotnikov [ID](#)⁴⁴, O. Okhrimenko [ID](#)⁵³, R. Oldeman [ID](#)^{32,i}, F. Oliva [ID](#)⁵⁹,
 M. Olocco [ID](#)¹⁹, C.J.G. Onderwater [ID](#)⁸¹, R.H. O’Neil [ID](#)⁴⁹, D. Osthues [ID](#)¹⁹, J.M. Otalora Goicochea [ID](#)³,
 P. Owen [ID](#)⁵¹, A. Oyanguren [ID](#)⁴⁸, O. Ozcelik [ID](#)⁵⁹, F. Paciolla [ID](#)^{35,u}, A. Padee [ID](#)⁴², K.O. Padeken [ID](#)¹⁸,
 B. Pagare [ID](#)⁵⁷, T. Pajero [ID](#)⁴⁹, A. Palano [ID](#)²⁴, M. Palutan [ID](#)²⁸, X. Pan [ID](#)^{4,b}, S. Panebianco [ID](#)¹²,
 G. Panshin [ID](#)⁵, L. Paolucci [ID](#)⁵⁷, A. Papanestis [ID](#)^{58,49}, M. Pappagallo [ID](#)^{24,f}, L.L. Pappalardo [ID](#)²⁶,
 C. Pappenheimer [ID](#)⁶⁶, C. Parkes [ID](#)⁶³, D. Parmar [ID](#)⁷⁷, B. Passalacqua [ID](#)^{26,j}, G. Passaleva [ID](#)²⁷,
 D. Passaro [ID](#)^{35,q,49}, A. Pastore [ID](#)²⁴, M. Patel [ID](#)⁶², J. Patoc [ID](#)⁶⁴, C. Patrignani [ID](#)^{25,h}, A. Paul [ID](#)⁶⁹,
 C.J. Pawley [ID](#)⁸¹, A. Pellegrino [ID](#)³⁸, J. Peng [ID](#)^{5,7}, M. Pepe Altarelli [ID](#)²⁸, S. Perazzini [ID](#)²⁵,
 D. Pereima [ID](#)⁴⁴, H. Pereira Da Costa [ID](#)⁶⁸, A. Pereiro Castro [ID](#)⁴⁷, P. Perret [ID](#)¹¹, A. Perrevoort [ID](#)⁸⁰,
 A. Perro [ID](#)^{49,13}, M.J. Peters [ID](#)⁶⁶, K. Petridis [ID](#)⁵⁵, A. Petrolini [ID](#)^{29,l}, J. P. Pfaller [ID](#)⁶⁶, H. Pham [ID](#)⁶⁹,
 L. Pica [ID](#)³⁵, M. Piccini [ID](#)³⁴, L. Piccolo [ID](#)³², B. Pietrzyk [ID](#)¹⁰, G. Pietrzyk [ID](#)¹⁴, R. N. Pilato [ID](#)⁶¹,
 D. Pinci [ID](#)³⁶, F. Pisani [ID](#)⁴⁹, M. Pizzichemi [ID](#)^{31,n,49}, V. Placinta [ID](#)⁴³, M. Plo Casasus [ID](#)⁴⁷,
 T. Poeschl [ID](#)⁴⁹, F. Polci [ID](#)¹⁶, M. Poli Lener [ID](#)²⁸, A. Poluektov [ID](#)¹³, N. Polukhina [ID](#)⁴⁴, I. Polyakov [ID](#)⁶³,
 E. Polycarpo [ID](#)³, S. Ponce [ID](#)⁴⁹, D. Popov [ID](#)^{7,49}, S. Poslavskii [ID](#)⁴⁴, K. Prasanth [ID](#)⁵⁹, C. Prouve [ID](#)⁸³,
 D. Provenzano [ID](#)^{32,i}, V. Pugatch [ID](#)⁵³, G. Punzi [ID](#)^{35,r}, S. Qasim [ID](#)⁵¹, Q. Q. Qian [ID](#)⁶, W. Qian [ID](#)⁷,
 N. Qin [ID](#)^{4,b}, S. Qu [ID](#)^{4,b}, R. Quagliani [ID](#)⁴⁹, R.I. Rabadan Trejo [ID](#)⁵⁷, J.H. Rademacker [ID](#)⁵⁵,
 M. Rama [ID](#)³⁵, M. Ramírez García [ID](#)⁸⁶, V. Ramos De Oliveira [ID](#)⁷⁰, M. Ramos Pernas [ID](#)⁵⁷,
 M.S. Rangel [ID](#)³, F. Ratnikov [ID](#)⁴⁴, G. Raven [ID](#)³⁹, M. Rebollo De Miguel [ID](#)⁴⁸, F. Redi [ID](#)^{30,g},
 J. Reich [ID](#)⁵⁵, F. Reiss [ID](#)²⁰, Z. Ren [ID](#)⁷, P.K. Resmi [ID](#)⁶⁴, M. Ribalda Galvez [ID](#)⁴⁶, R. Ribatti [ID](#)⁵⁰,
 G. Ricart [ID](#)^{15,12}, D. Riccardi [ID](#)^{35,q}, S. Ricciardi [ID](#)⁵⁸, K. Richardson [ID](#)⁶⁵, M. Richardson-Slipper [ID](#)⁵⁹,
 K. Rinnert [ID](#)⁶¹, P. Robbe [ID](#)^{14,49}, G. Robertson [ID](#)⁶⁰, E. Rodrigues [ID](#)⁶¹, A. Rodriguez Alvarez [ID](#)⁴⁶,
 E. Rodriguez Fernandez [ID](#)⁴⁷, J.A. Rodriguez Lopez [ID](#)⁷⁶, E. Rodriguez Rodriguez [ID](#)⁴⁹, J. Roensch [ID](#)¹⁹,
 A. Rogachev [ID](#)⁴⁴, A. Rogovskiy [ID](#)⁵⁸, D.L. Rolf [ID](#)¹⁹, P. Roloff [ID](#)⁴⁹, V. Romanovskiy [ID](#)⁶⁶,
 A. Romero Vidal [ID](#)⁴⁷, G. Romolini [ID](#)²⁶, F. Ronchetti [ID](#)⁵⁰, T. Rong [ID](#)⁶, M. Rotondo [ID](#)²⁸, S. R.
 Roy [ID](#)²², M.S. Rudolph [ID](#)⁶⁹, M. Ruiz Diaz [ID](#)²², R.A. Ruiz Fernandez [ID](#)⁴⁷, J. Ruiz Vidal [ID](#)⁸¹, J.
 J. Saavedra-Arias [ID](#)⁹, J.J. Saborido Silva [ID](#)⁴⁷, R. Sadek [ID](#)¹⁵, N. Sagidova [ID](#)⁴⁴, D. Sahoo [ID](#)⁷⁸,
 N. Sahoo [ID](#)⁵⁴, B. Saitta [ID](#)^{32,i}, M. Salomoni [ID](#)^{31,49,n}, I. Sanderswood [ID](#)⁴⁸, R. Santacesaria [ID](#)³⁶,
 C. Santamarina Rios [ID](#)⁴⁷, M. Santimaria [ID](#)²⁸, L. Santoro [ID](#)², E. Santovetti [ID](#)³⁷, A. Saputi [ID](#)^{26,49},
 D. Saranin [ID](#)⁴⁴, A. Sarnatskiy [ID](#)⁸⁰, G. Sarpis [ID](#)⁵⁹, M. Sarpis [ID](#)⁷⁹, C. Satriano [ID](#)^{36,s}, A. Satta [ID](#)³⁷,
 M. Saur [ID](#)⁷³, D. Savrina [ID](#)⁴⁴, H. Sazak [ID](#)¹⁷, F. Sborzacchi [ID](#)^{49,28}, A. Scarabotto [ID](#)¹⁹, S. Schael [ID](#)¹⁷,
 S. Scherl [ID](#)⁶¹, M. Schiller [ID](#)⁶⁰, H. Schindler [ID](#)⁴⁹, M. Schmelling [ID](#)²¹, B. Schmidt [ID](#)⁴⁹, S. Schmitt [ID](#)¹⁷,
 H. Schmitz [ID](#)¹⁸, O. Schneider [ID](#)⁵⁰, A. Schopper [ID](#)⁶², N. Schulte [ID](#)¹⁹, S. Schulte [ID](#)⁵⁰, M.H. Schune [ID](#)¹⁴,
 G. Schwering [ID](#)¹⁷, B. Sciascia [ID](#)²⁸, A. Sciucati [ID](#)⁴⁹, I. Segal [ID](#)⁷⁷, S. Sellam [ID](#)⁴⁷, A. Semennikov [ID](#)⁴⁴,
 T. Senger [ID](#)⁵¹, M. Senghi Soares [ID](#)³⁹, A. Sergi [ID](#)^{29,l}, N. Serra [ID](#)⁵¹, L. Sestini [ID](#)²⁷, A. Seuthe [ID](#)¹⁹, B.
 Sevilla Sanjuan [ID](#)⁴⁵, Y. Shang [ID](#)⁶, D.M. Shangase [ID](#)⁸⁶, M. Shapkin [ID](#)⁴⁴, R. S. Sharma [ID](#)⁶⁹,
 I. Shchemerov [ID](#)⁴⁴, L. Shchutska [ID](#)⁵⁰, T. Shears [ID](#)⁶¹, L. Shekhtman [ID](#)⁴⁴, Z. Shen [ID](#)³⁸, S. Sheng [ID](#)^{5,7},

V. Shevchenko [ID](#)⁴⁴, B. Shi [ID](#)⁷, Q. Shi [ID](#)⁷, Y. Shimizu [ID](#)¹⁴, E. Shmanin [ID](#)²⁵, R. Shorkin [ID](#)⁴⁴, J.D. Shupperd [ID](#)⁶⁹, R. Silva Coutinho [ID](#)⁶⁹, G. Simi [ID](#)^{33,o}, S. Simone [ID](#)^{24,f}, M. Singha [ID](#)⁷⁸, N. Skidmore [ID](#)⁵⁷, T. Skwarnicki [ID](#)⁶⁹, M.W. Slater [ID](#)⁵⁴, E. Smith [ID](#)⁶⁵, K. Smith [ID](#)⁶⁸, M. Smith [ID](#)⁶², L. Soares Lavra [ID](#)⁵⁹, M.D. Sokoloff [ID](#)⁶⁶, F.J.P. Soler [ID](#)⁶⁰, A. Solomin [ID](#)⁵⁵, A. Solovev [ID](#)⁴⁴, I. Solovvey [ID](#)⁴⁴, N. S. Sommerfeld [ID](#)¹⁸, R. Song [ID](#)¹, Y. Song [ID](#)⁵⁰, Y. Song [ID](#)^{4,b}, Y. S. Song [ID](#)⁶, F.L. Souza De Almeida [ID](#)⁶⁹, B. Souza De Paula [ID](#)³, E. Spadaro Norella [ID](#)^{29,l}, E. Spedicato [ID](#)²⁵, J.G. Speer [ID](#)¹⁹, E. Spiridenkov [ID](#)⁴⁴, P. Spradlin [ID](#)⁶⁰, V. Sriskaran [ID](#)⁴⁹, F. Stagni [ID](#)⁴⁹, M. Stahl [ID](#)⁷⁷, S. Stahl [ID](#)⁴⁹, S. Stanislaus [ID](#)⁶⁴, M. Stefaniak [ID](#)⁸⁷, E.N. Stein [ID](#)⁴⁹, O. Steinkamp [ID](#)⁵¹, O. Stenyakin [ID](#)⁴⁴, H. Stevens [ID](#)¹⁹, D. Strelakina [ID](#)⁴⁴, Y. Su [ID](#)⁷, F. Suljik [ID](#)⁶⁴, J. Sun [ID](#)³², L. Sun [ID](#)⁷⁴, D. Sundfeld [ID](#)², W. Sutcliffe [ID](#)⁵¹, K. Swientek [ID](#)⁴⁰, F. Swystun [ID](#)⁵⁶, A. Szabelski [ID](#)⁴², T. Szumlak [ID](#)⁴⁰, Y. Tan [ID](#)^{4,b}, Y. Tang [ID](#)⁷⁴, Y. T. Tang [ID](#)⁷, M.D. Tat [ID](#)²², A. Terentev [ID](#)⁴⁴, F. Terzuoli [ID](#)^{35,u,49}, F. Teubert [ID](#)⁴⁹, U. Thoma [ID](#)¹⁸, E. Thomas [ID](#)⁴⁹, D.J.D. Thompson [ID](#)⁵⁴, H. Tilquin [ID](#)⁶², V. Tisserand [ID](#)¹¹, S. T’Jampens [ID](#)¹⁰, M. Tobin [ID](#)⁵, L. Tomassetti [ID](#)^{26,j}, G. Tonani [ID](#)^{30,m}, X. Tong [ID](#)⁶, T. Tork [ID](#)³⁰, D. Torres Machado [ID](#)², L. Toscano [ID](#)¹⁹, D.Y. Tou [ID](#)^{4,b}, C. Trippi [ID](#)⁴⁵, G. Tuci [ID](#)²², N. Tuning [ID](#)³⁸, L.H. Uecker [ID](#)²², A. Ukleja [ID](#)⁴⁰, D.J. Unverzagt [ID](#)²², A. Upadhyay [ID](#)⁷⁸, B. Urbach [ID](#)⁵⁹, A. Usachov [ID](#)³⁹, A. Ustyuzhanin [ID](#)⁴⁴, U. Uwer [ID](#)²², V. Vagnoni [ID](#)²⁵, V. Valcarce Cadenas [ID](#)⁴⁷, G. Valenti [ID](#)²⁵, N. Valls Canudas [ID](#)⁴⁹, J. van Eldik [ID](#)⁴⁹, H. Van Hecke [ID](#)⁶⁸, E. van Herwijnen [ID](#)⁶², C.B. Van Hulse [ID](#)^{47,x}, R. Van Laak [ID](#)⁵⁰, M. van Veghel [ID](#)³⁸, G. Vasquez [ID](#)⁵¹, R. Vazquez Gomez [ID](#)⁴⁶, P. Vazquez Regueiro [ID](#)⁴⁷, C. Vázquez Sierra [ID](#)⁸³, S. Vecchi [ID](#)²⁶, J.J. Velthuis [ID](#)⁵⁵, M. Veltri [ID](#)^{27,v}, A. Venkateswaran [ID](#)⁵⁰, M. Verdoglia [ID](#)³², M. Vesterinen [ID](#)⁵⁷, D. Vico Benet [ID](#)⁶⁴, P. Vidrier Villalba [ID](#)⁴⁶, M. Vieites Diaz [ID](#)⁴⁷, X. Vilasis-Cardona [ID](#)⁴⁵, E. Vilella Figueras [ID](#)⁶¹, A. Villa [ID](#)²⁵, P. Vincent [ID](#)¹⁶, B. Vivacqua [ID](#)³, F.C. Volle [ID](#)⁵⁴, D. vom Bruch [ID](#)¹³, N. Voropaev [ID](#)⁴⁴, K. Vos [ID](#)⁸¹, C. Vrahas [ID](#)⁵⁹, J. Wagner [ID](#)¹⁹, J. Walsh [ID](#)³⁵, E.J. Walton [ID](#)^{1,57}, G. Wan [ID](#)⁶, A. Wang [ID](#)⁷, C. Wang [ID](#)²², G. Wang [ID](#)⁸, H. Wang [ID](#)⁷³, J. Wang [ID](#)⁶, J. Wang [ID](#)⁵, J. Wang [ID](#)^{4,b}, J. Wang [ID](#)⁷⁴, M. Wang [ID](#)⁴⁹, N. W. Wang [ID](#)⁷, R. Wang [ID](#)⁵⁵, X. Wang [ID](#)⁸, X. Wang [ID](#)⁷², X. W. Wang [ID](#)⁶², Y. Wang [ID](#)⁷⁵, Y. Wang [ID](#)⁶, Y. W. Wang [ID](#)⁷³, Z. Wang [ID](#)¹⁴, Z. Wang [ID](#)^{4,b}, Z. Wang [ID](#)³⁰, J.A. Ward [ID](#)^{57,1}, M. Waterlaat [ID](#)⁴⁹, N.K. Watson [ID](#)⁵⁴, D. Websdale [ID](#)⁶², Y. Wei [ID](#)⁶, J. Wendel [ID](#)⁸³, B.D.C. Westhenry [ID](#)⁵⁵, C. White [ID](#)⁵⁶, M. Whitehead [ID](#)⁶⁰, E. Whiter [ID](#)⁵⁴, A.R. Wiederhold [ID](#)⁶³, D. Wiedner [ID](#)¹⁹, G. Wilkinson [ID](#)^{64,49}, M.K. Wilkinson [ID](#)⁶⁶, M. Williams [ID](#)⁶⁵, M. J. Williams [ID](#)⁴⁹, M.R.J. Williams [ID](#)⁵⁹, R. Williams [ID](#)⁵⁶, Z. Williams [ID](#)⁵⁵, F.F. Wilson [ID](#)⁵⁸, M. Winn [ID](#)¹², W. Wislicki [ID](#)⁴², M. Witek [ID](#)⁴¹, L. Witola [ID](#)¹⁹, G. Wormser [ID](#)¹⁴, S.A. Wotton [ID](#)⁵⁶, H. Wu [ID](#)⁶⁹, J. Wu [ID](#)⁸, X. Wu [ID](#)⁷⁴, Y. Wu [ID](#)^{6,56}, Z. Wu [ID](#)⁷, K. Wyllie [ID](#)⁴⁹, S. Xian [ID](#)⁷², Z. Xiang [ID](#)⁵, Y. Xie [ID](#)⁸, T. X. Xing [ID](#)³⁰, A. Xu [ID](#)³⁵, L. Xu [ID](#)^{4,b}, L. Xu [ID](#)^{4,b}, M. Xu [ID](#)⁵⁷, Z. Xu [ID](#)⁴⁹, Z. Xu [ID](#)⁷, Z. Xu [ID](#)⁵, K. Yang [ID](#)⁶², X. Yang [ID](#)⁶, Y. Yang [ID](#)^{29,l}, Z. Yang [ID](#)⁶, V. Yeroshenko [ID](#)¹⁴, H. Yeung [ID](#)⁶³, H. Yin [ID](#)⁸, X. Yin [ID](#)⁷, C. Y. Yu [ID](#)⁶, J. Yu [ID](#)⁷¹, X. Yuan [ID](#)⁵, Y. Yuan [ID](#)^{5,7}, E. Zaffaroni [ID](#)⁵⁰, M. Zavertyaev [ID](#)²¹, M. Zdybal [ID](#)⁴¹, F. Zenesini [ID](#)²⁵, C. Zeng [ID](#)^{5,7}, M. Zeng [ID](#)^{4,b}, C. Zhang [ID](#)⁶, D. Zhang [ID](#)⁸, J. Zhang [ID](#)⁷, L. Zhang [ID](#)^{4,b}, R. Zhang [ID](#)⁸, S. Zhang [ID](#)⁷¹, S. Zhang [ID](#)⁶⁴, Y. Zhang [ID](#)⁶, Y. Z. Zhang [ID](#)^{4,b}, Z. Zhang [ID](#)^{4,b}, Y. Zhao [ID](#)²², A. Zhelezov [ID](#)²², S. Z. Zheng [ID](#)⁶, X. Z. Zheng [ID](#)^{4,b}, Y. Zheng [ID](#)⁷, T. Zhou [ID](#)⁶, X. Zhou [ID](#)⁸, Y. Zhou [ID](#)⁷, V. Zhovkovska [ID](#)⁵⁷, L. Z. Zhu [ID](#)⁷, X. Zhu [ID](#)^{4,b}, X. Zhu [ID](#)⁸, Y. Zhu [ID](#)¹⁷, V. Zhukov [ID](#)¹⁷, J. Zhuo [ID](#)⁴⁸, Q. Zou [ID](#)^{5,7}, D. Zuliani [ID](#)^{33,o}, G. Zunica [ID](#)⁵⁰

¹ School of Physics and Astronomy, Monash University, Melbourne, Australia

² Centro Brasileiro de Pesquisas Físicas (CBPF), Rio de Janeiro, Brazil

³ Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil

- ⁴ *Department of Engineering Physics, Tsinghua University, Beijing, China*
- ⁵ *Institute Of High Energy Physics (IHEP), Beijing, China*
- ⁶ *School of Physics State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China*
- ⁷ *University of Chinese Academy of Sciences, Beijing, China*
- ⁸ *Institute of Particle Physics, Central China Normal University, Wuhan, Hubei, China*
- ⁹ *Consejo Nacional de Rectores (CONARE), San Jose, Costa Rica*
- ¹⁰ *Université Savoie Mont Blanc, CNRS, IN2P3-LAPP, Annecy, France*
- ¹¹ *Université Clermont Auvergne, CNRS/IN2P3, LPC, Clermont-Ferrand, France*
- ¹² *Université Paris-Saclay, Centre d'Etudes de Saclay (CEA), IRFU, Saclay, France, Gif-Sur-Yvette, France*
- ¹³ *Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France*
- ¹⁴ *Université Paris-Saclay, CNRS/IN2P3, IJCLab, Orsay, France*
- ¹⁵ *Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France*
- ¹⁶ *LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris, France*
- ¹⁷ *I. Physikalisches Institut, RWTH Aachen University, Aachen, Germany*
- ¹⁸ *Universität Bonn — Helmholtz-Institut für Strahlen und Kernphysik, Bonn, Germany*
- ¹⁹ *Fakultät Physik, Technische Universität Dortmund, Dortmund, Germany*
- ²⁰ *Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany*
- ²¹ *Max-Planck-Institut für Kernphysik (MPIK), Heidelberg, Germany*
- ²² *Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany*
- ²³ *School of Physics, University College Dublin, Dublin, Ireland*
- ²⁴ *INFN Sezione di Bari, Bari, Italy*
- ²⁵ *INFN Sezione di Bologna, Bologna, Italy*
- ²⁶ *INFN Sezione di Ferrara, Ferrara, Italy*
- ²⁷ *INFN Sezione di Firenze, Firenze, Italy*
- ²⁸ *INFN Laboratori Nazionali di Frascati, Frascati, Italy*
- ²⁹ *INFN Sezione di Genova, Genova, Italy*
- ³⁰ *INFN Sezione di Milano, Milano, Italy*
- ³¹ *INFN Sezione di Milano-Bicocca, Milano, Italy*
- ³² *INFN Sezione di Cagliari, Monserrato, Italy*
- ³³ *INFN Sezione di Padova, Padova, Italy*
- ³⁴ *INFN Sezione di Perugia, Perugia, Italy*
- ³⁵ *INFN Sezione di Pisa, Pisa, Italy*
- ³⁶ *INFN Sezione di Roma La Sapienza, Roma, Italy*
- ³⁷ *INFN Sezione di Roma Tor Vergata, Roma, Italy*
- ³⁸ *Nikhef National Institute for Subatomic Physics, Amsterdam, Netherlands*
- ³⁹ *Nikhef National Institute for Subatomic Physics and VU University Amsterdam, Amsterdam, Netherlands*
- ⁴⁰ *AGH — University of Krakow, Faculty of Physics and Applied Computer Science, Kraków, Poland*
- ⁴¹ *Henryk Niewodniczanski Institute of Nuclear Physics Polish Academy of Sciences, Kraków, Poland*
- ⁴² *National Center for Nuclear Research (NCBJ), Warsaw, Poland*
- ⁴³ *Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest-Magurele, Romania*
- ⁴⁴ *Authors affiliated with an institute formerly covered by a cooperation agreement with CERN.*
- ⁴⁵ *DS4DS, La Salle, Universitat Ramon Llull, Barcelona, Spain*
- ⁴⁶ *ICCUB, Universitat de Barcelona, Barcelona, Spain*
- ⁴⁷ *Instituto Galego de Física de Altas Enerxías (IGFAE), Universidade de Santiago de Compostela, Santiago de Compostela, Spain*
- ⁴⁸ *Instituto de Física Corpuscular, Centro Mixto Universidad de Valencia — CSIC, Valencia, Spain*
- ⁴⁹ *European Organization for Nuclear Research (CERN), Geneva, Switzerland*
- ⁵⁰ *Institute of Physics, Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland*
- ⁵¹ *Physik-Institut, Universität Zürich, Zürich, Switzerland*
- ⁵² *NSC Kharkiv Institute of Physics and Technology (NSC KIPT), Kharkiv, Ukraine*
- ⁵³ *Institute for Nuclear Research of the National Academy of Sciences (KINR), Kyiv, Ukraine*

- ⁵⁴ *School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom*
- ⁵⁵ *H.H. Wills Physics Laboratory, University of Bristol, Bristol, United Kingdom*
- ⁵⁶ *Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom*
- ⁵⁷ *Department of Physics, University of Warwick, Coventry, United Kingdom*
- ⁵⁸ *STFC Rutherford Appleton Laboratory, Didcot, United Kingdom*
- ⁵⁹ *School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom*
- ⁶⁰ *School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom*
- ⁶¹ *Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom*
- ⁶² *Imperial College London, London, United Kingdom*
- ⁶³ *Department of Physics and Astronomy, University of Manchester, Manchester, United Kingdom*
- ⁶⁴ *Department of Physics, University of Oxford, Oxford, United Kingdom*
- ⁶⁵ *Massachusetts Institute of Technology, Cambridge, MA, United States*
- ⁶⁶ *University of Cincinnati, Cincinnati, OH, United States*
- ⁶⁷ *University of Maryland, College Park, MD, United States*
- ⁶⁸ *Los Alamos National Laboratory (LANL), Los Alamos, NM, United States*
- ⁶⁹ *Syracuse University, Syracuse, NY, United States*
- ⁷⁰ *Pontifícia Universidade Católica do Rio de Janeiro (PUC-Rio), Rio de Janeiro, Brazil, associated to ³*
- ⁷¹ *School of Physics and Electronics, Hunan University, Changsha City, China, associated to ⁸*
- ⁷² *Guangdong Provincial Key Laboratory of Nuclear Science, Guangdong-Hong Kong Joint Laboratory of Quantum Matter, Institute of Quantum Matter, South China Normal University, Guangzhou, China, associated to ⁴*
- ⁷³ *Lanzhou University, Lanzhou, China, associated to ⁵*
- ⁷⁴ *School of Physics and Technology, Wuhan University, Wuhan, China, associated to ⁴*
- ⁷⁵ *Henan Normal University, Xinxiang, China, associated to ⁸*
- ⁷⁶ *Departamento de Física, Universidad Nacional de Colombia, Bogota, Colombia, associated to ¹⁶*
- ⁷⁷ *Ruhr Universitaet Bochum, Fakultae f. Physik und Astronomie, Bochum, Germany, associated to ¹⁹*
- ⁷⁸ *Eotvos Lorand University, Budapest, Hungary, associated to ⁴⁹*
- ⁷⁹ *Vilnius University, Vilnius, Lithuania, associated to ²⁰*
- ⁸⁰ *Van Swinderen Institute, University of Groningen, Groningen, Netherlands, associated to ³⁸*
- ⁸¹ *Universiteit Maastricht, Maastricht, Netherlands, associated to ³⁸*
- ⁸² *Tadeusz Kosciuszko Cracow University of Technology, Cracow, Poland, associated to ⁴¹*
- ⁸³ *Universidade da Coruña, A Coruña, Spain, associated to ⁴⁵*
- ⁸⁴ *Department of Physics and Astronomy, Uppsala University, Uppsala, Sweden, associated to ⁶⁰*
- ⁸⁵ *Taras Schevchenko University of Kyiv, Faculty of Physics, Kyiv, Ukraine, associated to ¹⁴*
- ⁸⁶ *University of Michigan, Ann Arbor, MI, United States, associated to ⁶⁹*
- ⁸⁷ *Ohio State University, Columbus, United States, associated to ⁶⁸*

^a *Centro Federal de Educação Tecnológica Celso Suckow da Fonseca, Rio De Janeiro, Brazil*

^b *Center for High Energy Physics, Tsinghua University, Beijing, China*

^c *Hangzhou Institute for Advanced Study, UCAS, Hangzhou, China*

^d *LIP6, Sorbonne Université, Paris, France*

^e *Lamarr Institute for Machine Learning and Artificial Intelligence, Dortmund, Germany*

^f *Università di Bari, Bari, Italy*

^g *Università di Bergamo, Bergamo, Italy*

^h *Università di Bologna, Bologna, Italy*

ⁱ *Università di Cagliari, Cagliari, Italy*

^j *Università di Ferrara, Ferrara, Italy*

^k *Università di Firenze, Firenze, Italy*

^l *Università di Genova, Genova, Italy*

^m *Università degli Studi di Milano, Milano, Italy*

ⁿ *Università degli Studi di Milano-Bicocca, Milano, Italy*

^o *Università di Padova, Padova, Italy*

^p *Università di Perugia, Perugia, Italy*

^q *Scuola Normale Superiore, Pisa, Italy*

^r *Università di Pisa, Pisa, Italy*

^s *Università della Basilicata, Potenza, Italy*

^t *Università di Roma Tor Vergata, Roma, Italy*

^u *Università di Siena, Siena, Italy*

^v *Università di Urbino, Urbino, Italy*

^w *Universidad de Ingeniería y Tecnología (UTEC), Lima, Peru*

^x *Universidad de Alcalá, Alcalá de Henares, Spain*

^y *Facultad de Ciencias Físicas, Madrid, Spain*

[†] *Deceased*