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Observation of prompt J/ψ meson elliptic flow in high-multiplicity pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16\,\mathrm{TeV}$

The CMS Collaboration*

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Abstract

A measurement of the elliptic flow (v_2) of prompt J/ψ mesons in high-multiplicity pPb collisions is reported using data collected by the CMS experiment at a nucleon-nucleon center-of-mass energy $\sqrt{s_{\mathrm{NN}}} = 8.16\,\mathrm{TeV}$. Prompt J/$\psi$ mesons decaying into two muons are reconstructed in the rapidity region in the nucleon-nucleon center-of-mass frame (y_{cm}), corresponding to either $-2.86 < y_{\mathrm{cm}} < -1.86$ or $0.94 < y_{\mathrm{cm}} < 1.94$. The average v_2 result from the two rapidity ranges is reported over the transverse momentum (p_{T}) range from 0.2 to 10 GeV. Positive v_2 values are observed for the prompt J/ψ meson, as extracted from long-range two-particle correlations with charged hadrons, for $2 < p_{\mathrm{T}} < 8\,\mathrm{GeV}$. The prompt J/$\psi$ results are compared with previous CMS measurements of elliptic flow for open charm mesons (D^0) and strange hadrons. From these measurements, constraints can be obtained on the collective dynamics of charm quarks produced in high-multiplicity events arising from small systems.

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1 Introduction

Strong collective behavior is found in the azimuthal correlations of particles emitted in relativistic nucleus-nucleus (AA) collisions at the BNL RHIC [1–4] and at the CERN LHC [5–10]. These correlations, which are long-range in pseudorapidity (η), suggest the formation of a strongly interacting quark-gluon plasma (QGP) that exhibits nearly ideal hydrodynamic behavior [11–13]. The azimuthal correlation structure of emitted particles is typically characterized by its Fourier components [14]. In particular, within a hydrodynamic picture, the second and third Fourier anisotropy components are known as elliptic (v_2) and triangular (v_3) flow, respectively, and reflect the QGP medium response to the initial collision geometry and its fluctuations [15–17]. In recent years, similar long-range collective azimuthal correlations have also been observed in events with high final-state particle multiplicity in proton-proton (pp) [18–21], proton-nucleus (pA) [22–30], and lighter AA collisions [31–33], raising the question of whether a fluid-like QGP is created in these much smaller systems. While experimental measurements in these small systems are consistent with the hydrodynamic expansion of a tiny QGP droplet, alternative scenarios based on gluon saturation in the initial state also claim to capture the main features of the correlation data (recent reviews are provided in Refs. [34, 35]).

Because of their large masses, heavy quarks (charm and bottom) are primarily produced via hard-scattering processes at a very early stage of the collision. Thus, they are largely decoupled from the bulk production of soft gluons and light-flavor quarks at a later stage in AA collisions, and thereby probe the properties and dynamics of the QGP through its entire evolution [36]. A strong elliptic flow (v_2) signal has been observed for open heavy-flavor D^0 mesons in both AuAu collisions at RHIC [37] and PbPb collisions at the LHC [38–40], suggesting that charm quarks may develop strong collective flow behavior. Furthermore, a recent measurement of the elliptic flow of J/ψ mesons in PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$ [41] has provided additional evidence for the collective behavior of charm quarks in the QGP.

In the study of collectivity in small systems, such as that occurring in pp or pPb collisions, a key open question is whether the strong collective behavior observed for bulk constituents in high-multiplicity events also extends to charm and bottom quarks. Long-range correlations involving inclusive muons at high transverse momentum (p_{T}) reveal a hint of heavy-flavor quark collectivity in pPb collisions [42]. Furthermore, the recent observation of a significant elliptic flow signal for prompt D^0 mesons in pPb collisions has provided evidence for charm quark collectivity in a small system [43]. The v_2 signal for D^0 mesons is found to be smaller than that of light-flavor mesons at a given p_{T}, indicating that in these small systems there is a weaker collective motion for charm quarks, as compared to that of the bulk medium. However, as the D^0 meson carries both a light and a charm quark, the relative contribution of these different flavor quarks to the observed v_2 signal is not fully constrained. Without detailed theoretical modeling, a scenario is not excluded where the D^0 meson v_2 signal is entirely carried by the light-flavor quark. The observation of an elliptic flow signal for J/ψ mesons in a small system could provide more direct evidence of charm quark collectivity and could impose new constraints on the collective dynamics of heavy-quark production in such collisions. Furthermore, heavy-quark collectivity may also provide a hint of how, in small systems, hard probes interact with the QGP [36], assuming this is formed. First measurement of inclusive J/ψ (combined charmonia and J/ψ mesons from decay of open beauty hadrons) v_2 in pPb collisions was reported in Ref. [44], where positive v_2 coefficients were found in the range of $3 < p_{\mathrm{T}} < 6\,\mathrm{GeV}$ with center-of-mass rapidities $-4.46 < y_{\mathrm{cm}} < -2.96$ or $2.03 < y_{\mathrm{cm}} < 3.53$. A recent model calculation of J/ψ v_2 in pPb collisions suggests little v_2 signal arising from final-state interactions between charm quarks and the QGP medium [45].

This Letter presents the first measurement of prompt J/ψ meson elliptic flow (excluding contributions from b hadron decays) from long-range two-particle correlations in very high multiplicity pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16\,\mathrm{TeV}$. The v_2 harmonics for prompt J/ψ mesons in the ranges $-2.86 < y_{\mathrm{cm}} < -1.86$ and $0.94 < y_{\mathrm{cm}} < 1.94$ are determined over a wide p_{T} range from 0.2 to 10 GeV. To estimate the possible residual contribution from back-to-back jet-like correlations, the v_2 values are also presented after subtracting correlations obtained from low-multiplicity pPb events (denoted as v_2^{sub}), where jet-like correlations are assumed to dominate. The results are compared to those of the light strange-flavor $\mathrm{K}^0_{\mathrm{S}}$ and Λ hadrons, and the open heavy-flavor prompt D^0 meson, which were previously reported by CMS [43] in the same p_{T} range but in a different rapidity range of $-1.46 < y_{\mathrm{cm}} < 0.54$. In order to explore possible collectivity at the partonic level, a comparison is also presented in terms of the transverse kinetic energy per constituent quark ($KE_{\mathrm{T}}/n_{\mathrm{q}}$, where $KE_{\mathrm{T}} = \sqrt{m^2 + p_{\mathrm{T}}^2} - m$, and n_{q} is the number of constituent quarks).

2 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume, there are four primary subdetectors including a silicon pixel and strip tracker detector, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Iron and quartz-fiber Cherenkov hadron forward (HF) calorimeters cover the range $3.0 < |\eta| < 5.2$. Muons are measured in the range $|\eta| < 2.4$ in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid, with detection planes made using three technologies: drift tubes, cathode strip chambers, and resistive-plate chambers. The silicon tracker measures charged particles within the range $|\eta| < 2.5$. For charged particles with $1 < p_{\mathrm{T}} < 10\,\mathrm{GeV}$ and $|\eta| < 1.4$, the track resolutions are typically 1.5% in p_{T} and 25–90 (45–150) μm in the transverse (longitudinal) impact parameter [46]. A detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [47].

3 Data selection and J/ψ meson reconstruction

The pPb data at $\sqrt{s_{\mathrm{NN}}} = 8.16\,\mathrm{TeV}$ used in this analysis were collected in 2016, and correspond to an integrated luminosity of $186\,\mathrm{nb}^{-1}$. The beam energies are 6.5 TeV for the protons and 2.56 TeV per nucleon for the lead nuclei. Because of the asymmetric beam conditions, particles selected in the laboratory rapidity range of $1.4 < y_{\mathrm{lab}} < 2.4$ ($-2.4 < y_{\mathrm{lab}} < -1.4$) have a corresponding nucleon-nucleon center-of-mass frame rapidity range of $0.94 < y_{\mathrm{cm}} < 1.94$ ($-2.86 < y_{\mathrm{cm}} < -1.86$), with positive rapidity defined in the proton beam direction. To minimize statistical uncertainties, the quoted J/ψ meson v_2 results combine the individual values obtained for the proton and lead beam directions.

The pPb data are analyzed in different ranges of $N_{\mathrm{trk}}^{\mathrm{offline}}$, where $N_{\mathrm{trk}}^{\mathrm{offline}}$ is the number of primary charged particle tracks [46] with $|\eta| < 2.4$ and $p_{\mathrm{T}} > 0.4\,\mathrm{GeV}$. The main results are obtained with events in the high-multiplicity range $185 \leq N_{\mathrm{trk}}^{\mathrm{offline}} < 250$. To select these events, dedicated triggers were developed, as discussed in Refs. [48, 49]. Events with $N_{\mathrm{trk}}^{\mathrm{offline}} < 35$ are also used to estimate the possible contribution of residual back-to-back jet-like correlations. These lower-multiplicity events are selected online with a hardware-based trigger requiring two muon candidates in the muon detectors with no explicit momentum or rapidity threshold [50]. In the offline analysis, hadronic collisions are selected by requiring at least one HF

calorimeter tower with more than 3 GeV of total energy in each of the two HF detectors. Events must contain a primary vertex close to the nominal interaction point of the beams, within 15 cm along the beam direction, and 0.2 cm in the plane transverse to beam direction. The $N_{\mathrm{trk}}^{\mathrm{offline}}$ range limits correspond to fractional inelastic cross sections from 100 to 57% for $N_{\mathrm{trk}}^{\mathrm{offline}} < 35$, and from 0.33 to 0.01% for $185 \leq N_{\mathrm{trk}}^{\mathrm{offline}} < 250$, respectively.

The offline muon reconstruction algorithm starts either by finding tracks in the muon detectors, which are then fitted together with tracks reconstructed in the silicon tracker (*global muons*), or by extrapolating tracks from the silicon tracker to match a hit on at least one segment of the muon detectors (*tracker muons*). The muon candidates are required to pass the identification criteria of the particle-flow algorithm [51], which suppresses contamination of "punch-through" hadrons misidentified as muons, based on energy deposition in the calorimeters. The *soft* muon selection criteria are also imposed, as defined in Ref. [52], to further improve the purity of muons.

The J/ψ meson candidates are formed from pairs of oppositely charged muons, originating from a common vertex. Based on the vertex probability distributions for signal and background candidates, the probability that the dimuon pair shares a common vertex is required to be larger than 1%, lowering the background from random combinations as well as from semileptonic decays of bottom and charm hadrons. Because of the long lifetime of b hadrons compared to that of J/ψ mesons, the nonprompt J/ψ meson component can be reduced by placing constraints on the pseudo-proper decay length [53]. This is defined by

$$\ell_{\mathrm{J}/\psi}^{\mathrm{3D}} = L_{xyz} \frac{m_{\mathrm{J}/\psi}}{|p_{\mu\mu}|}, \tag{1}$$

where L_{xyz} is the distance between the primary and dimuon vertices, $m_{\mathrm{J}/\psi}$ is the Particle Data Group [54] world average value of the J/ψ meson mass (assumed for all dimuon candidates), and $p_{\mu\mu}$ is the dimuon momentum. The upper limit (decreasing as a function of p_{T}) imposed on the $\ell_{\mathrm{J}/\psi}^{\mathrm{3D}}$ value is based on Monte Carlo (MC) studies with simulated event samples of PYTHIA 8.209 [55, 56], and found to reject 75–90% (from low to high p_{T}) of nonprompt J/ψ mesons, largely independent of multiplicity. The residual nonprompt J/ψ meson fraction in the data is estimated to be approximately 5% across the full p_{T} range, and its effect on the v_2 measurement is propagated as a systematic uncertainty, as described in Section 5.

4 Analysis technique

The azimuthal anisotropy of J/ψ mesons is extracted from the long-range ($|\Delta\eta| > 1$) two-particle azimuthal correlations, following an identical procedure to that described in Refs. [21, 27, 43]. A two-dimensional (2D) correlation function is constructed by pairing each J/ψ candidate with reference primary charged-particle tracks with $0.3 < p_{\mathrm{T}} < 3\,\mathrm{GeV}$ and $|\eta| < 2.4$ (denoted as "ref" particles), and calculating

$$\frac{1}{N_{\mathrm{J}/\psi}} \frac{\mathrm{d}^2 N^{\mathrm{pair}}}{\mathrm{d}\Delta\eta\,\mathrm{d}\Delta\phi} = B(0,0) \frac{S(\Delta\eta,\Delta\phi)}{B(\Delta\eta,\Delta\phi)}, \tag{2}$$

where $\Delta\eta$ and $\Delta\phi$ are the differences in η and in the azimuthal angle (ϕ) of the pair. The same-event pair distribution, $S(\Delta\eta,\Delta\phi)$, represents the yield of particle pairs normalized by the number of J/ψ candidates from the same event. The mixed-event pair yield distribution, $B(\Delta\eta,\Delta\phi)$, is constructed by pairing J/ψ candidates in each event with the reference primary charged-particle tracks from 20 different randomly selected events, from the same $N_{\mathrm{trk}}^{\mathrm{offline}}$ range

and having a primary vertex falling in the same 2 cm wide range of reconstructed longitudinal, z coordinate. The analysis procedure is performed in each p_{T} and invariant mass (m_{inv}) range of J/ψ candidates. A correction for the acceptance and efficiency of the J/ψ meson yields is applied, but found to have a negligible effect on the measurements. The $\Delta\phi$ correlation functions averaged over $|\Delta\eta| > 1$ (to remove short-range correlations, such as jet fragmentation) are then obtained from the 2D distributions and fitted by the first three terms of a Fourier series (including additional terms has a negligible effect on the fit results):

$$\frac{1}{N_{\mathrm{J}/\psi}}\frac{\mathrm{d}N^{\mathrm{pair}}}{\mathrm{d}\Delta\phi} = \frac{N_{\mathrm{assoc}}}{2\pi}\left[1 + \sum_{n=1}^{3} 2V_{n\Delta}\cos(n\Delta\phi)\right]. \tag{3}$$

Here, $V_{n\Delta}$ are the Fourier coefficients and N_{assoc} represents the total number of same-event pairs per J/ψ candidate for a given invariant mass interval. By assuming that $V_{n\Delta}$ is the product of single-particle anisotropies of J/ψ mesons and reference charged particles [57], $V_{n\Delta}(\mathrm{J}/\psi, \mathrm{ref}) = v_n(\mathrm{J}/\psi) \times v_n(\mathrm{ref})$, the v_n anisotropy harmonics for J/ψ candidates can be extracted as a function of invariant mass, $v_n(\mathrm{J}/\psi) = V_{n\Delta}(\mathrm{J}/\psi, \mathrm{ref}) / \sqrt{V_{n\Delta}(\mathrm{ref}, \mathrm{ref})}$. The $V_{n\Delta}(\mathrm{ref}, \mathrm{ref})$ represents the Fourier coefficients extracted by correlating two reference charged particles. With the current data, only the second order ($n = 2$) elliptic anisotropy harmonic can be measured with meaningful statistical precision.

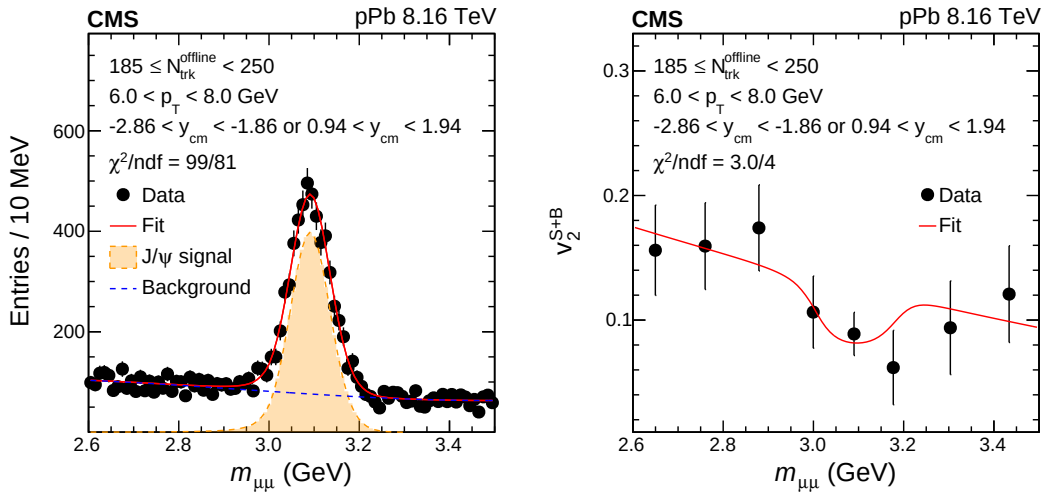

Figure 1: Example of fits to the invariant mass spectrum (left) and the $v_2^{S+B}(m_{\mathrm{inv}})$ distribution (right) in the p_{T} interval 6.0–8.0 GeV for pPb events with $185 \leq N_{\mathrm{trk}}^{\mathrm{offline}} < 250$.

To extract the genuine v_2 values of the J/ψ meson signal (v_2^S), the contribution from background candidates (v_2^B) has to be subtracted from the v_2 values of all J/ψ meson candidates, as obtained in the previous step. The procedure is to first fit the dimuon mass spectrum with a function composed of three components: two Crystal Ball functions [58] with different widths but common mean and tail parameters for the J/ψ signal (the tail parameters are fixed to the values obtained from simulation), $S(m_{\mathrm{inv}})$, and an exponential function to model the background, $B(m_{\mathrm{inv}})$. Then, the signal plus background $v_2^{S+B}(m_{\mathrm{inv}})$ distribution is fitted with:

$$v_2^{S+B}(m_{\mathrm{inv}}) = \alpha(m_{\mathrm{inv}})v_2^S + [1 - \alpha(m_{\mathrm{inv}})]v_2^B(m_{\mathrm{inv}}), \tag{4}$$

where

$$\alpha(m_{\mathrm{inv}}) = \frac{S(m_{\mathrm{inv}})}{S(m_{\mathrm{inv}}) + B(m_{\mathrm{inv}})}. \tag{5}$$

Here, $v_2^B(m_{\mathrm{inv}})$ for the background J/ψ candidates is modeled as an exponential function of the invariant mass, and $\alpha(m_{\mathrm{inv}})$ is the J/ψ signal fraction obtained from the mass spectrum fit. An example of fits to the mass spectrum and $v_2^{S+B}(m_{\mathrm{inv}})$ in the p_{T} interval 6.0–8.0 GeV for the multiplicity range $185 \leq N_{\mathrm{trk}}^{\mathrm{offline}} < 250$ is shown in Fig. 1. The residual contribution of back-to-back dijets to the measured v_2 results is estimated from low-multiplicity pPb events and is removed from the signal after accounting for the jet yield ratio of the selected events, following a jet subtraction procedure similar to that established in Refs. [21, 43, 57]. The Fourier coefficients, $V_{n\Delta}$, extracted from Eq. (3) for $N_{\mathrm{trk}}^{\mathrm{offline}} < 35$, are subtracted from the $V_{n\Delta}$ coefficients obtained in the high-multiplicity region, with

$$V_{n\Delta}^{\mathrm{sub}} = V_{n\Delta} - V_{n\Delta}(N_{\mathrm{trk}}^{\mathrm{offline}} < 35)\,\frac{N_{\mathrm{assoc}}(N_{\mathrm{trk}}^{\mathrm{offline}} < 35)}{N_{\mathrm{assoc}}}\,\frac{Y_{\mathrm{jet}}}{Y_{\mathrm{jet}}(N_{\mathrm{trk}}^{\mathrm{offline}} < 35)}. \tag{6}$$

Here, Y_{jet} represents the jet yield obtained by integrating the difference of the short-range ($|\Delta\eta| < 1$) and long-range event-normalized associated yields for each multiplicity class. The ratio, $Y_{\mathrm{jet}}/Y_{\mathrm{jet}}(N_{\mathrm{trk}}^{\mathrm{offline}} < 35)$, is introduced to account for the enhanced jet correlations resulting from the selection of higher-multiplicity events. For $p_{\mathrm{T}}(\mathrm{J}/\psi) < 4.5$ GeV, the jet yield ratio cannot be directly estimated from the two-particle azimuthal correlations, as the J/ψ candidates tend to have larger η values than the acceptance for charged particles. Therefore, the value is assumed to be the same as that for the high-p_{T} region, where no p_{T} dependence has been observed. It was also previously observed that the values of jet yield ratio for D^0 and strange particle species show little dependence on p_{T} over the full p_{T} range [43].

5 Systematic uncertainties

Sources of systematic uncertainties on the prompt J/ψ meson v_2 measurement include the J/ψ meson yield correction (acceptance and efficiency correction derived from PYTHIA simulation), the nonprompt J/ψ meson contamination, the background $v_2^B(m_{\mathrm{inv}})$ functional form, the signal and background invariant mass PDF, the jet subtraction procedure, the contamination of events containing more than one pPb interaction (pileup), and the trigger bias. In this Letter, the quoted uncertainties in v_2 are absolute values, and are found to have no dependence on p_{T}, except those for the jet subtraction procedure. Systematic uncertainties originating from different sources are added in quadrature to obtain the overall systematic uncertainty shown as boxes in the figures.

To evaluate the uncertainties arising from the efficiency correction to the J/ψ meson yield, the v_2 values are compared to the uncorrected ones, yielding an uncertainty of 0.008. The effect on the measured v_2 due to the residual contribution from nonprompt J/ψ mesons is evaluated by varying the $\ell_{\mathrm{J}/\psi}^{\mathrm{3D}}$ requirement such that the nonprompt J/ψ meson yield is doubled. The v_2 values are found not to change by more than ± 0.004, which is assigned as the systematic uncertainty due to the J/ψ meson yield correction. Possible differences in the rejection efficiency of nonprompt J/ψ mesons between data and simulation are investigated and found to be negligible. The systematic uncertainties from the background v_2 functional form are evaluated by comparing $v_2^B(m_{\mathrm{inv}})$ values based on first-, second-, and third-order polynomial fits to the background distribution. The resulting J/ψ signal v_2 values are found to vary by less than 0.009. Systematic effects related to signal invariant mass PDF are found to be negligible by releasing, one at a time, the fixed tail parameters of the Crystal Ball functions. The variation of v_2, while changing the background invariant mass PDF to a second- or third-order polynomial function is also found to be negligible. In the jet subtraction procedure, the statistical precision of the jet yield ratio is limited. The v_2^{sub} results are found to be consistent within ± 0.002 to ± 0.014

(increasing with p_T) when varying the jet yield ratio by its statistical uncertainty. The systematic uncertainties from the potential pileup effect and the trigger bias are taken to be the same as for inclusive charged particles in Ref. [49], where they can be established with good statistical precision. The pileup and trigger bias uncertainties are negligible compared to the other sources of systematic uncertainties, as the fraction of residual pileup events is only a few % and the trigger efficiency is close to 100%.

6 Results

Figure 2 shows the v_2 results of prompt J/ψ mesons at forward rapidities ($-2.86 < y_{cm} < -1.86$ or $0.94 < y_{cm} < 1.94$) for high-multiplicity ($185 \leq N_{trk}^{offline} < 250$) pPb collisions, covering a p_T range from 0.2 to 10 GeV. Results obtained separately for J/ψ meson rapidity in the Pb- and p-going direction are compared, and found to be consistent within statistical uncertainties. Thus, as mentioned earlier, combined v_2 values are presented for the best statistical precision. The v_2 results for K^0_S and Λ hadrons (light, strange-flavor), and prompt D^0 mesons (open heavy-flavor), reported in a previous CMS publication [43] for the midrapidity region $-1.46 < y_{cm} < 0.54$, are also shown for comparison.

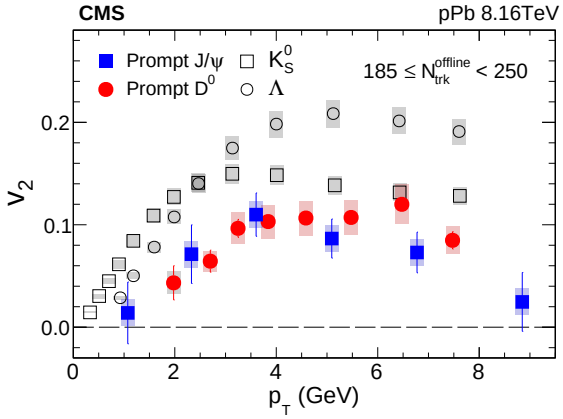

Figure 2: The v_2 results of the prompt J/ψ mesons at forward rapidities ($-2.86 < y_{cm} < -1.86$ or $0.94 < y_{cm} < 1.94$), as a function of p_T in the multiplicity range $185 \leq N_{trk}^{offline} < 250$ for pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV. Data for K^0_S and Λ hadrons, and prompt D^0 mesons at midrapidity ($-1.46 < y_{cm} < 0.54$) from previous CMS measurements [43] are also shown for comparison. The error bars correspond to statistical uncertainties, while the shaded areas denote the systematic uncertainties.

Positive prompt J/ψ meson v_2 values are observed over a wide p_T range from about 2 to 8 GeV. The prompt J/ψ meson v_2 results show a trend of first increasing up to $p_T \sim 4$ GeV and then decreasing toward higher p_T. This observed trend appears to be in common with the other hadron species shown. In the p_T range below 5 GeV, the v_2 values for J/ψ and D^0 mesons are consistent with each other within the uncertainties, while an indication of smaller v_2 values for J/ψ mesons than that for D^0 mesons is seen for $p_T > 5$ GeV, although the difference is not significant within current experimental uncertainties. Over the full p_T range, the v_2 signal values for both J/ψ and D^0 hadrons are smaller than those for K^0_S and Λ hadrons. This observation is consistent with the earlier conclusion that charm quarks develop a weaker collective dynamics than light quarks in small systems [43]. Because of experimental limitation, v_2 values for the prompt J/ψ meson and the other meson species are not compared within the same rapidity range, possibly affecting their comparison. The rapidity dependence of v_2 values for charged

particles in pPb collisions has been measured [59, 60], suggesting up to around 15% variation from $|y_{\mathrm{lab}}| \sim 0$ to 2.4.

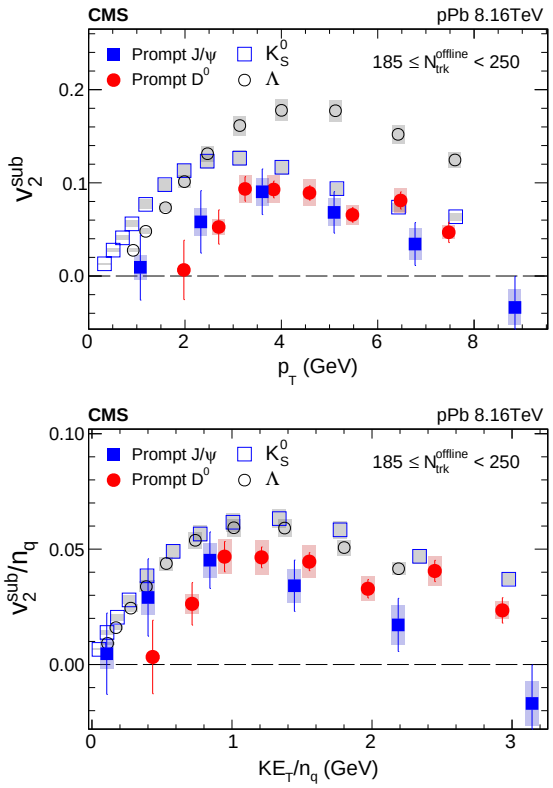

Figure 3: Upper: the v_2^{sub} values for prompt J/ψ mesons at forward rapidities ($-2.86 < y_{\mathrm{cm}} < -1.86$ or $0.94 < y_{\mathrm{cm}} < 1.94$), as well as for $\mathrm{K}^0_{\mathrm{S}}$ and Λ hadrons, and prompt D^0 mesons at midrapidity ($-1.46 < y_{\mathrm{cm}} < 0.54$), as a function of p_{T} for pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV with $185 \leq N_{\mathrm{trk}}^{\mathrm{offline}} < 250$. Lower: the n_{q}-normalized v_2^{sub} results. The $\mathrm{K}^0_{\mathrm{S}}$, Λ and D^0 v_2^{sub} data are taken from Ref. [43]. The error bars correspond to statistical uncertainties, while the shaded areas denote the systematic uncertainties.

To better study the elliptic flow signal coming purely from long-range collective correlations, the J/ψ v_2 results are corrected for residual jet correlations. The resulting (v_2^{sub}) values are shown in Fig. 3 (upper) for prompt J/ψ mesons as a function of p_{T} with $185 \leq N_{\mathrm{trk}}^{\mathrm{offline}} < 250$, and compared to similarly corrected $\mathrm{K}^0_{\mathrm{S}}$, Λ, and D^0 hadron results [43]. The effect of the correction for all particle species is most noticeable at very high p_{T}, while the overall p_{T} dependence of the v_2 data remains unchanged. The $\mathrm{K}^0_{\mathrm{S}}$ mesons have a larger correction applied to their v_2 values (possibly because $\mathrm{K}^0_{\mathrm{S}}$ mesons are more correlated with the bulk multiplicity, and thus are biased toward stronger jet correlations due to the selection of high multiplicities) and their v_2^{sub} values after the correction tend to converge to those of the prompt J/ψ and D^0 mesons at high p_{T}.

A recent model calculation of J/ψ v_2 in minimum bias pPb collisions, based on final-state interactions between produced charm quarks and a QGP medium, suggests a very small v_2 signal of less than 0.01 [45]. This calculation indicates that additional contributions, e.g., those from initial-state interactions, may be needed to account for the observed v_2 signal of prompt J/ψ mesons for high-multiplicity pPb events reported in this Letter.

Motivated by the possible formation of a hydrodynamically expanding QGP medium in small systems, the elliptic flow signals for $\mathrm{K}^0_{\mathrm{S}}$, Λ, J/ψ and D^0 hadrons are compared as a function

of transverse kinetic energy (KE_T) in Fig. 3 (lower), to account for the mass difference among the four hadron species [61, 62]. Here, the values of v_2^{sub} and KE_T are both divided by the number of constituent quarks, n_q, to represent the collective flow signal at the partonic level in the context of the quark coalescence model [63–65], which postulates that the elliptic flow signal of a hadron is a sum of contributions from individual constituent quark flow values. As was previously reported in pPb collisions [27, 43], a scaling of n_q-normalized v_2^{sub} values is observed between the K^0_S meson and Λ baryon, shown in Fig. 3 (lower). This scaling between light baryon and meson species systems produced in the collision (known as the number-of-constituent-quark or NCQ scaling) was first discovered in AA colliding systems [61, 62, 66], indicating that collectivity is first developed among the partons, which later recombine into final-state hadrons. The elliptic flow signal per quark (v_2^{sub}/n_q) for prompt J/ψ mesons at low KE_T/n_q range is consistent with those of K^0_S, Λ, and prompt D^0 hadrons within large statistical uncertainties for the current data. There is a hint that the prompt J/ψ meson data tend to fall on the same trend as those of K^0_S and Λ baryons, all of which are above the prompt D^0 meson data. However, the difference between the present prompt D^0 and J/ψ meson results deviates from 0 with a significance of only about 1.2 standard deviations at $KE_T/n_q \approx 0.4$ GeV. A more definitive conclusion could be drawn with future high precision data. For $KE_T/n_q > 1$ GeV, the v_2^{sub}/n_q for prompt D^0 and J/ψ mesons are consistently below that of the K^0_S meson. An indication of smaller v_2^{sub}/n_q values for J/ψ mesons than for D^0 mesons is seen for $KE_T/n_q > 1$ GeV. As J/ψ mesons contain two charm quarks, while D^0 mesons contain a charm and a light-flavor quark, this observation would be consistent with a weaker collective behavior of heavy-flavor quarks than light quarks, possibly a consequence of the much smaller size of the collision system. Future data with improved precision will provide crucial insights to fully constrain the collective behavior of light- and heavy-flavor quarks in high-multiplicity, small systems.

7 Summary

In summary, the elliptic flow harmonic (v_2) for prompt J/ψ mesons in high-multiplicity proton-lead (pPb) collisions at $\sqrt{s_{NN}} = 8.16$ TeV is presented as a function of transverse momentum (p_T). Positive v_2 values are observed for prompt J/ψ mesons at forward rapidity ($-2.86 < y_{cm} < -1.86$ or $0.94 < y_{cm} < 1.94$) over a wide p_T range ($2 < p_T < 8$ GeV). This observation provides evidence for charm quark collectivity in high-multiplicity pPb collisions, similar to that first observed for light-flavor hadrons. The observed ordering of v_2 among light-flavor, open and hidden heavy-flavor hadrons at intermediate and high-p_T regions (e.g., above 4 GeV) adds support to the earlier conclusion that heavy quarks exhibit weaker collective behavior than light quarks or gluons in small systems. For particle transverse kinetic energy per constituent quark values less than 1 GeV, the v_2 of prompt J/ψ mesons is consistent with prompt D^0, K^0_S and Λ hadrons, within current uncertainties. A model calculation based on final-state interactions between charm quarks and a QGP medium in pPb collisions significantly underestimates the measured prompt J/ψ v_2 signal. The new prompt J/ψ meson results, together with previous results for light-flavor and open heavy-flavor hadrons, provide novel insights into the dynamics of the heavy quarks produced in small systems that lead to high final-state multiplicities.

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References

[1] PHOBOS Collaboration, "System size dependence of cluster properties from two-particle angular correlations in Cu+Cu and Au+Au collisions at $\sqrt{s_{\mathrm{NN}}} = 200\,\mathrm{GeV}$", *Phys. Rev. C* **81** (2010) 024904, doi:10.1103/PhysRevC.81.024904, arXiv:0812.1172.

[2] STAR Collaboration, "Distributions of charged hadrons associated with high transverse momentum particles in pp and Au+Au collisions at $\sqrt{s_{\mathrm{NN}}} = 200\,\mathrm{GeV}$", *Phys. Rev. Lett.* **95**

(2005) 152301, doi:10.1103/PhysRevLett.95.152301, arXiv:nucl-ex/0501016.

[3] STAR Collaboration, "Long range rapidity correlations and jet production in high energy nuclear collisions", *Phys. Rev. C* **80** (2009) 064912, doi:10.1103/PhysRevC.80.064912, arXiv:0909.0191.

[4] PHOBOS Collaboration, "High transverse momentum triggered correlations over a large pseudorapidity acceptance in Au+Au collisions at $\sqrt{s_{\mathrm{NN}}} = 200\,\mathrm{GeV}$", *Phys. Rev. Lett.* **104** (2010) 062301, doi:10.1103/PhysRevLett.104.062301, arXiv:0903.2811.

[5] CMS Collaboration, "Long-range and short-range dihadron angular correlations in central PbPb collisions at a nucleon-nucleon center of mass energy of 2.76 TeV", *JHEP* **07** (2011) 076, doi:10.1007/JHEP07(2011)076, arXiv:1105.2438.

[6] CMS Collaboration, "Centrality dependence of dihadron correlations and azimuthal anisotropy harmonics in PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV", *Eur. Phys. J. C* **72** (2012) 2012, doi:10.1140/epjc/s10052-012-2012-3, arXiv:1201.3158.

[7] ALICE Collaboration, "Elliptic flow of charged particles in Pb-Pb collisions at 2.76 TeV", *Phys. Rev. Lett.* **105** (2010) 252302, doi:10.1103/PhysRevLett.105.252302, arXiv:1011.3914.

[8] ATLAS Collaboration, "Measurement of the azimuthal anisotropy for charged particle production in $\sqrt{s_{\mathrm{NN}}} = 2.76\,\mathrm{TeV}$ lead-lead collisions with the ATLAS detector", *Phys. Rev. C* **86** (2012) 014907, doi:10.1103/PhysRevC.86.014907, arXiv:1203.3087.

[9] CMS Collaboration, "Measurement of the elliptic anisotropy of charged particles produced in PbPb collisions at nucleon-nucleon center-of-mass energy = 2.76 TeV", *Phys. Rev. C* **87** (2013) 014902, doi:10.1103/PhysRevC.87.014902, arXiv:1204.1409.

[10] CMS Collaboration, "Studies of azimuthal dihadron correlations in ultra-central PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76\,\mathrm{TeV}$", *JHEP* **02** (2014) 088, doi:10.1007/JHEP02(2014)088, arXiv:1312.1845.

[11] J.-Y. Ollitrault, "Anisotropy as a signature of transverse collective flow", *Phys. Rev. D* **46** (1992) 229, doi:10.1103/PhysRevD.46.229.

[12] U. Heinz and R. Snellings, "Collective flow and viscosity in relativistic heavy-ion collisions", *Ann. Rev. Nucl. Part. Sci.* **63** (2013) 123, doi:10.1146/annurev-nucl-102212-170540, arXiv:1301.2826.

[13] C. Gale, S. Jeon, and B. Schenke, "Hydrodynamic modeling of heavy-ion collisions", *Int. J. Mod. Phys. A* **28** (2013) 1340011, doi:10.1142/S0217751X13400113, arXiv:1301.5893.

[14] S. Voloshin and Y. Zhang, "Flow study in relativistic nuclear collisions by Fourier expansion of azimuthal particle distributions", *Z. Phys. C* **70** (1996) 665, doi:10.1007/s002880050141, arXiv:hep-ph/9407282.

[15] B. H. Alver, C. Gombeaud, M. Luzum, and J.-Y. Ollitrault, "Triangular flow in hydrodynamics and transport theory", *Phys. Rev. C* **82** (2010) 034913, doi:10.1103/PhysRevC.82.034913, arXiv:1007.5469.

[16] B. Schenke, S. Jeon, and C. Gale, "Elliptic and triangular flow in event-by-event D=3+1 viscous hydrodynamics", *Phys. Rev. Lett.* **106** (2011) 042301, doi:10.1103/PhysRevLett.106.042301, arXiv:1009.3244.

[17] Z. Qiu, C. Shen, and U. Heinz, "Hydrodynamic elliptic and triangular flow in Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 2.76 TeV", *Phys. Lett. B* **707** (2012) 151, doi:10.1016/j.physletb.2011.12.041, arXiv:1110.3033.

[18] CMS Collaboration, "Observation of long-range near-side angular correlations in proton-proton collisions at the LHC", *JHEP* **09** (2010) 091, doi:10.1007/JHEP09(2010)091, arXiv:1009.4122.

[19] ATLAS Collaboration, "Observation of long-range elliptic azimuthal anisotropies in $\sqrt{s}$ =13 and 2.76 TeV pp collisions with the ATLAS detector", *Phys. Rev. Lett.* **116** (2016) 172301, doi:10.1103/PhysRevLett.116.172301, arXiv:1509.04776.

[20] CMS Collaboration, "Measurement of long-range near-side two-particle angular correlations in pp collisions at $\sqrt{s}$ =13 TeV", *Phys. Rev. Lett.* **116** (2016) 172302, doi:10.1103/PhysRevLett.116.172302, arXiv:1510.03068.

[21] CMS Collaboration, "Evidence for collectivity in pp collisions at the LHC", *Phys. Lett. B* **765** (2017) 193, doi:10.1016/j.physletb.2016.12.009, arXiv:1606.06198.

[22] CMS Collaboration, "Observation of long-range near-side angular correlations in proton-lead collisions at the LHC", *Phys. Lett. B* **718** (2013) 795, doi:10.1016/j.physletb.2012.11.025, arXiv:1210.5482.

[23] ALICE Collaboration, "Long-range angular correlations on the near and away side in pPb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV", *Phys. Lett. B* **719** (2013) 29, doi:10.1016/j.physletb.2013.01.012, arXiv:1212.2001.

[24] ATLAS Collaboration, "Observation of associated near-side and away-side long-range correlations in $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV proton-lead collisions with the ATLAS detector", *Phys. Rev. Lett.* **110** (2013) 182302, doi:10.1103/PhysRevLett.110.182302, arXiv:1212.5198.

[25] LHCb Collaboration, "Measurements of long-range near-side angular correlations in $\sqrt{s_{\mathrm{NN}}}$ = 5 TeV proton-lead collisions in the forward region", *Phys. Lett. B* **762** (2016) 473, doi:10.1016/j.physletb.2016.09.064, arXiv:1512.00439.

[26] ALICE Collaboration, "Long-range angular correlations of π, K and p in p–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV", *Phys. Lett. B* **726** (2013) 164, doi:10.1016/j.physletb.2013.08.024, arXiv:1307.3237.

[27] CMS Collaboration, "Long-range two-particle correlations of strange hadrons with charged particles in pPb and PbPb collisions at LHC energies", *Phys. Lett. B* **742** (2015) 200, doi:10.1016/j.physletb.2015.01.034, arXiv:1409.3392.

[28] CMS Collaboration, "Evidence for collective multi-particle correlations in pPb collisions", *Phys. Rev. Lett.* **115** (2015) 012301, doi:10.1103/PhysRevLett.115.012301, arXiv:1502.05382.

[29] ATLAS Collaboration, "Measurement of multi-particle azimuthal correlations in pp, p+Pb and low-multiplicity Pb+Pb collisions with the ATLAS detector", *Eur. Phys. J. C* **77** (2017) 428, doi:10.1140/epjc/s10052-017-4988-1, arXiv:1705.04176.

[30] ATLAS Collaboration, "Measurement of long-range multiparticle azimuthal correlations with the subevent cumulant method in pp and p+Pb collisions with the ATLAS detector at the CERN Large Hadron Collider", *Phys. Rev. C* **97** (2018) 024904, doi:10.1103/PhysRevC.97.024904, arXiv:1708.03559.

[31] STAR Collaboration, "Long-range pseudorapidity dihadron correlations in d+Au collisions at $\sqrt{s_{\rm NN}}$ = 200 GeV", *Phys. Lett. B* **747** (2015) 265, doi:10.1016/j.physletb.2015.05.075, arXiv:1502.07652.

[32] PHENIX Collaboration, "Measurements of elliptic and triangular flow in high-multiplicity ^{3}He+Au collisions at $\sqrt{s_{\rm NN}}$ = 200 GeV", *Phys. Rev. Lett.* **115** (2015) 142301, doi:10.1103/PhysRevLett.115.142301, arXiv:1507.06273.

[33] 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, doi:10.1103/PhysRevLett.120.062302, arXiv:1707.06108.

[34] K. Dusling, W. Li, and B. Schenke, "Novel collective phenomena in high-energy protonproton and protonnucleus collisions", *Int. J. Mod. Phys. E* **25** (2016) 1630002, doi:10.1142/S0218301316300022, arXiv:1509.07939.

[35] J. L. Nagle and W. A. Zajc, "Small system collectivity in relativistic hadron and nuclear collisions", (2018). arXiv:1801.03477.

[36] P. Braun-Munzinger, "Quarkonium production in ultra-relativistic nuclear collisions: Suppression versus enhancement", *J. Phys. G* **34** (2007) S471, doi:10.1088/0954-3899/34/8/S36, arXiv:nucl-th/0701093.

[37] STAR Collaboration, "Measurement of D^{0}azimuthal anisotropy at midrapidity in Au + Au collisions at $\sqrt{s_{\rm NN}}$ = 200 GeV", *Phys. Rev. Lett.* **118** (2017) 212301, doi:10.1103/PhysRevLett.118.212301, arXiv:1701.06060.

[38] ALICE Collaboration, "Azimuthal anisotropy of D meson production in Pb-Pb collisions at $\sqrt{s_{\rm NN}}$ = 2.76 TeV", *Phys. Rev. C* **90** (2014) 034904, doi:10.1103/PhysRevC.90.034904, arXiv:1405.2001.

[39] ALICE Collaboration, "D-meson azimuthal anisotropy in midcentral Pb-Pb collisions at $\sqrt{\mathbf{s}_{\rm NN}}$ = **5.02** TeV", *Phys. Rev. Lett.* **120** (2018) 102301, doi:10.1103/PhysRevLett.120.102301, arXiv:1707.01005.

[40] CMS Collaboration, "Measurement of prompt D^0 meson azimuthal anisotropy in Pb-Pb collisions at $\sqrt{s_{\rm NN}}$ = 5.02 TeV", *Phys. Rev. Lett.* **120** (2018) 202301, doi:10.1103/PhysRevLett.120.202301, arXiv:1708.03497.

[41] ALICE Collaboration, "J/ψ elliptic flow in Pb-Pb collisions at $\sqrt{s_{\rm NN}}$ = 5.02 TeV", *Phys. Rev. Lett.* **119** (2017) 242301, doi:10.1103/PhysRevLett.119.242301, arXiv:1709.05260.

[42] ALICE Collaboration, "Forward-central two-particle correlations in p-Pb collisions at $\sqrt{s_{\rm NN}}$ = 5.02 TeV", *Phys. Lett. B* **753** (2016) 126, doi:10.1016/j.physletb.2015.12.010, arXiv:1506.08032.

[43] CMS Collaboration, "Elliptic flow of charm and strange hadrons in high-multiplicity pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV", *Phys. Rev. Lett.* (2018) doi:10.3204/PUBDB-2018-02206, arXiv:1804.09767.

[44] ALICE Collaboration, "Search for collectivity with azimuthal J/ψ-hadron correlations in high multiplicity p-Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 and 8.16 TeV", *Phys. Lett. B* **780** (2018) 7, doi:10.1016/j.physletb.2018.02.039, arXiv:1709.06807.

[45] X. Du and R. Rapp, "In-medium charmonium production in proton-nucleus collisions", (2018). arXiv:1808.10014.

[46] CMS Collaboration, "Description and performance of track and primary-vertex reconstruction with the CMS tracker", *JINST* **9** (2014) P10009, doi:10.1088/1748-0221/9/10/P10009, arXiv:1405.6569.

[47] CMS Collaboration, "The CMS experiment at the CERN LHC", *JINST* **3** (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.

[48] CMS Collaboration, "Constraints on the chiral magnetic effect using charge-dependent azimuthal correlations in pPb and PbPb collisions at the CERN Large Hadron Collider", *Phys. Rev. C* **97** (2018) 044912, doi:10.1103/PhysRevC.97.044912, arXiv:1708.01602.

[49] CMS Collaboration, "Observation of correlated azimuthal anisotropy fourier harmonics in pp and pPb collisions at the LHC", *Phys. Rev. Lett.* **120** (2018) 092301, doi:10.1103/PhysRevLett.120.092301, arXiv:1709.09189.

[50] CMS Collaboration, "Event activity dependence of Y(nS) production in $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV pPb and $\sqrt{s}$ = 2.76 TeV pp collisions", *JHEP* **04** (2014) 103, doi:10.1007/JHEP04(2014)103, arXiv:1312.6300.

[51] CMS Collaboration, "Particle-flow reconstruction and global event description with the CMS detector", *JINST* **12** (2017) P10003, doi:10.1088/1748-0221/12/10/P10003, arXiv:1706.04965.

[52] CMS Collaboration, "Performance of CMS muon reconstruction in pp collision events at $\sqrt{s} = 7$ TeV", *JINST* **7** (2012) P10002, doi:10.1088/1748-0221/7/10/P10002, arXiv:1206.4071.

[53] ALEPH Collaboration, "Measurement of the B^0 and B^- meson lifetimes", *Phys. Lett. B* **307** (1993) 194, doi:10.1016/0370-2693(93)90211-Y. [Erratum: doi:10.1016/0370-2693(94)90054-X].

[54] Particle Data Group, M. Tanabashi et al., "Review of particle physics", *Phys. Rev. D* **98** (2018) 030001, doi:10.1103/PhysRevD.98.030001.

[55] T. Sjöstrand, S. Mrenna, and P. Skands, "A brief introduction to PYTHIA 8.1", *Comp. Phys. Comm.* **178** (2008) 852, doi:10.1016/j.cpc.2008.01.036, arXiv:0710.3820.

[56] CMS Collaboration, "Event generator tunes obtained from underlying event and multiparton scattering measurements", *Eur. Phys. J. C* **76** (2016) 155, doi:10.1140/epjc/s10052-016-3988-x, arXiv:1512.00815.

[57] CMS Collaboration, "Multiplicity and transverse momentum dependence of two- and four-particle correlations in pPb and PbPb collisions", *Phys. Lett. B* **724** (2013) 213, doi:10.1016/j.physletb.2013.06.028, arXiv:1305.0609.

[58] M. J. Oreglia, "A study of the reactions $\psi' \to \gamma\gamma\psi$". PhD thesis, Stanford University, 1980. SLAC Report SLAC-R-236, see Appendix D.

[59] CMS Collaboration, "Pseudorapidity dependence of long-range two-particle correlations in pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV", *Phys. Rev. C* **96** (2017) 014915, doi:10.1103/PhysRevC.96.014915, arXiv:1604.05347.

[60] CMS Collaboration, "Pseudorapidity and transverse momentum dependence of flow harmonics in pPb and PbPb collisions", (2017). arXiv:1710.07864.

[61] STAR Collaboration, "Mass, quark-number, and $\sqrt{s_{\mathrm{NN}}}$ dependence of the second and fourth flow harmonics in ultra-relativistic nucleus-nucleus collisions", *Phys. Rev. C* **75** (2007) 054906, doi:10.1103/PhysRevC.75.054906, arXiv:nucl-ex/0701010.

[62] PHENIX Collaboration, "Scaling properties of azimuthal anisotropy in Au+Au and Cu+Cu collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV", *Phys. Rev. Lett.* **98** (2007) 162301, doi:10.1103/PhysRevLett.98.162301, arXiv:nucl-ex/0608033.

[63] D. Molnar and S. A. Voloshin, "Elliptic flow at large transverse momenta from quark coalescence", *Phys. Rev. Lett.* **91** (2003) 092301, doi:10.1103/PhysRevLett.91.092301, arXiv:nucl-th/0302014.

[64] V. Greco, C. M. Ko, and P. Levai, "Parton coalescence and anti-proton/pion anomaly at RHIC", *Phys. Rev. Lett.* **90** (2003) 202302, doi:10.1103/PhysRevLett.90.202302, arXiv:nucl-th/0301093.

[65] R. J. Fries, B. Muller, C. Nonaka, and S. A. Bass, "Hadronization in heavy ion collisions: recombination and fragmentation of partons", *Phys. Rev. Lett.* **90** (2003) 202303, doi:10.1103/PhysRevLett.90.202303, arXiv:nucl-th/0301087.

[66] STAR Collaboration, "Particle type dependence of azimuthal anisotropy and nuclear modification of particle production in Au + Au collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV", *Phys. Rev. Lett.* **92** (2004) 052302, doi:10.1103/PhysRevLett.92.052302, arXiv:nucl-ex/0306007.

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