Probing novel long-range correlation phenomena in pPb collisions with identified particles at CMS

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Abstract. Observation of a long-range near-side two-particle correlation (known as the "Ridge") in high-multiplicity pp and pPb collisions opened up new opportunities of exploring novel QCD dynamics in small collision systems. To further investigate the origin of this phenomenon, studies of two-particle correlations with identified $K^0_s$ and $\Lambda/\bar{\Lambda}$ trigger particles in 5.02 TeV pPb collisions are presented, and compared to PbPb collisions over a similar multiplicity range. The $K^0_s$ and $\Lambda/\bar{\Lambda}$ are cleanly reconstructed via their secondary decay vertices over a wide pseudorapidity and transverse momentum range. The second-order anisotropy harmonics ($v_2$) of $K^0_s$ and $\Lambda/\bar{\Lambda}$ are extracted from long-range correlations as a function of particle multiplicity and $p_T$. The wide $p_T$ coverage and rich sample of high multiplicity pPb events allow: (1) a precise examination of the mass ordering effect of $v_n$ at low $p_T$ as predicted by hydrodynamics for a collectively expanding medium; (2) exploration of possible constituent quark number scaling of $v_2$ between mesons and baryons as was observed in high-energy nucleus-nucleus collisions.

1. Introduction
Studies of multiparticle correlations provide important insights into the underlying mechanism of particle production in high-energy collisions of both protons and nuclei. The observed long-range (large relative pseudorapidity), two-particle correlations in AA collisions are suggested to mainly arise from the collective flow of a strongly interacting, expanding medium. In hydrodynamic models, the azimuthal correlation structure of emitted particle pairs is typically characterized by its Fourier components, such as the second Fourier components, $v_2$, known as elliptic flow.

Elliptic flow of identified particles measured in AA collisions exhibits a dependence on the particle species [1]. The mass ordering effect of $v_2$ in AA collisions is present in hydrodynamic models due to stronger influence of radial flow for heavier particles. Furthermore, a variety of constituent quark scaling features has been observed in AA collisions for $v_2$ at low and intermediate $p_T$ range ($p_T < 6$ GeV). In particular, $v_2$ as a function of the hadron transverse kinetic energy, $KE_T = \sqrt{m^2 + p_{T}^2} - m$, scales with the number of constituent quarks $n_q$ in the hadron [2].

Similar long-range correlations have been recently discovered by CMS in proton-proton (pp) [3] and proton-lead (pPb) [4] collisions with high final-state particle multiplicity at the CERN LHC. While it is widely accepted that this long-range structure in the large AA systems is a consequence of collective flow, its origin in small collision systems is still unclear.

An analysis of two-particle correlations with identified strange hadrons, $K^0_s$ and $\Lambda/\bar{\Lambda}$, in pPb collisions at a center-of-mass energy per nucleon pair ($\sqrt{s_{NN}}$) of 5.02 TeV is presented [5].

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By associating a $K^0_S$ or $\Lambda/\bar{\Lambda}$ particle with a charged particle, the anisotropy harmonics $v_2$ are extracted from long-range two-particle correlations as a function of strange hadron $p_T$ and event multiplicity. The ratios of $v_2$ to the number of constituent quarks are obtained as a function of hadron transverse kinetic energy per quark for both $K^0_S$ and $\Lambda/\bar{\Lambda}$ to examine the validity of constituent quark number scaling. Results from pPb collisions are directly compared with those from PbPb collisions over a broad range of similar multiplicities.

2. Reconstruction of $K^0_S$ and $\Lambda/\bar{\Lambda}$ candidates

The reconstruction technique for $K^0_S$ and $\Lambda/\bar{\Lambda}$ candidates (generally referred to as $V^0$s) at CMS is described in [5, 6]. The $V^0$ candidates are reconstructed by combining pairs of oppositely charged tracks that displaced from the primary vertex and form a good secondary vertex. Due to the long lifetime of $K^0_S$ and $\Lambda/\bar{\Lambda}$ particles, requirements on the significance of the $V^0$ decay length to be greater than 5 and on the angle $\theta^{\text{point}}$ between the $V^0$ momentum vector and the vector connecting the primary and $V^0$ vertices to satisfy $\cos \theta^{\text{point}} > 0.999$ are applied to reduce background contributions.

Examples of invariant mass distributions of reconstructed $K^0_S$ and $\Lambda/\bar{\Lambda}$ candidates are shown in Fig. 1 for pPb data. The $V^0$ peaks can be clearly identified with little background. The true $V^0$ signal peak is well described by a double Gaussian function (with a common mean), while the background is modeled by a 4th-order polynomial function. The mass window of $\pm 2\sigma$ wide around the center of the peak is defined as the “peak region”, where $\sigma$ represents the root mean square of the two standard deviations of the double Gaussian functions weighted by the yields. A “sideband region” is chosen that includes $V^0$ candidates from outside the $\pm 3\sigma$ mass range around the $V^0$ mass to the limit of the mass distributions shown in Fig. 1.

3. Results

The method of extracting $v_n$ from the two-particle correlation functions is described in [4, 7]. The $v_n$ values are first extracted for $V^0$ candidates from the peak region and sideband region, denoted as $v_n^{\text{obs}}$ and $v_n^{\text{bkg}}$, respectively. The $v_n$ signal of true $V^0$ particles is denoted by $v_n^{\text{sig}}$ and is obtained by:

$$v_n^{\text{sig}} = \frac{v_n^{\text{obs}} - (1 - f^{\text{sig}}) \times v_n^{\text{bkg}}}{f^{\text{sig}}}.$$ 

Here, $f^{\text{sig}}$ represents the signal yield fraction in the peak region determined by the fits to the mass distribution shown in Fig. 1. This fraction exceeds 80% for $\Lambda/\bar{\Lambda}$ candidates at $p_T > 1$ GeV and is above 95% for $K^0_S$ candidates over the entire $p_T$ range.
Λ particles are extracted in [5]. In Fig. 2, the values of inclusive charged particles (mostly pions). The data indicate a mass ordering behavior where lighter particle species exhibit a stronger azimuthal anisotropy signal, consistent with expectations in hydrodynamic models. At higher $p_T$ the $v_2$ values of Λ/Λ particles are larger than those for K/Λ particles divided by the number of constituent quarks as a function of $p_T$ in the $p_T < 2$ GeV region for all high-multiplicity ranges. Both of them are consistently below the $v_2$ values of inclusive charged particles (mostly pions). The data indicate a mass ordering behavior where lighter particle species exhibit a stronger azimuthal anisotropy signal, consistent with expectations in hydrodynamic models. At higher $p_T$ the $v_2$ values of Λ/Λ particles are larger than those of K/Λ.

The scaling behavior of $v_2$ divided by the number of constituent quarks as a function of transverse kinetic energy per quark, $KE_T/n_q$, is investigated for high-multiplicity pPb events in the middle row of Fig. 2. The $v_2$ distributions for K/Λ and Λ/Λ particles are found to be in agreement after scaling by the number of quarks. The result of fitting a polynomial function to the K/Λ data is shown in the middle row of Fig. 2. The bottom row of Fig. 2 shows the $n_q$-scaled $v_2$ results for K/Λ and Λ/Λ particles divided by this polynomial function fit. The data/fit ratios indicate that the scaling is valid to better than 10% over most of the $KE_T/n_q$ range. In AA collisions, this approximate scaling behavior is conjectured to be related to quark recombination which postulates that collective flow is developed among constituent quarks before they combine to form final-state hadrons.

The particle species dependence of $v_2$ and its scaling behavior is also studied in PbPb data over the same multiplicity ranges as for the pPb data, as shown in Fig. 3. For all multiplicity ranges of inclusive charged particles are plotted as a function of $p_T$ for four high multiplicity ranges. Middle row: the $v_2/n_q$ ratios for K/Λ and Λ/Λ as a function of $KE_T/n_q$, along with a fit to the K/Λ results using a polynomial function. Bottom row: ratios of $v_2/n_q$ for K/Λ and Λ/Λ to the fitted polynomial function as a function of $KE_T/n_q$. The error bars correspond to statistical uncertainties, while the shaded areas denote the systematic uncertainties.

The elliptic ($v_2$) flow harmonics of K/Λ and Λ/Λ particles are extracted in [5]. In Fig. 2, the $v_2$ values of K/Λ and Λ/Λ particles are plotted as a function of $p_T$ for four multiplicity ranges pPb collisions. A separation of the $v_2$ values between K/Λ and Λ/Λ particles as a function of $p_T$ is observed. The previously CMS published $v_2$ results [8] for inclusive charged particles are shown as open cross markers for comparison. The $v_2$ values of K/Λ particles are larger than those for Λ/Λ particles in the $p_T < 2$ GeV region for all high-multiplicity ranges. Both of them are consistently below the $v_2$ values of inclusive charged particles (mostly pions). The data indicate a mass ordering behavior where lighter particle species exhibit a stronger azimuthal anisotropy signal, consistent with expectations in hydrodynamic models. At higher $p_T$ the $v_2$ values of Λ/Λ particles are larger than those of K/Λ.

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Figure 3. Top row: the $v_2$ results for $K_0^0$, $\Lambda/\bar{\Lambda}$, and inclusive charged particles (open crosses) as a function of $p_T$ for four multiplicity ranges. Middle row: the $v_2/n_q$ ratios for $K_0^0$ and $\Lambda/\bar{\Lambda}$ as a function of $KE_T/n_q$. Bottom row: ratios of $v_2/n_q$ for $K_0^0$ and $\Lambda/\bar{\Lambda}$ to the fitted polynomial function as a function of $KE_T/n_q$. The error bars correspond to statistical uncertainties, while the shaded areas denote the systematic uncertainties.

ranges, the mass ordering effect of $v_2$ for different particle species is found to be less evident in PbPb data than in pPb data. This may indicate, in hydrodynamic models, a stronger radial flow is developed in the pPb system than that of a PbPb system at the same multiplicity. Moreover, compared to pPb data, the $n_q$-scaled $v_2$ data in PbPb at similar multiplicities suggest a stronger violation of constituent quark number scaling, up to 25%.

References
[1] 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, vol. 757, p. 102, 2005.
[2] PHENIX Collaboration, “Scaling properties of azimuthal anisotropy in Au+Au and Cu+Cu collisions at $\sqrt{s_{NN}} = 200$ GeV,” Phys. Rev. Lett., vol. 98, p. 162301, 2007.
[3] CMS Collaboration, “Observation of long-range near-side angular correlations in proton-proton collisions at the LHC,” JHEP, vol. 09, p. 091, 2010.
[4] CMS Collaboration, “Observation of long-range near-side angular correlations in pPb collisions at the LHC,” Phys. Lett. B, vol. 718, p. 795, 2013.
[5] CMS Collaboration, “Long-range two-particle correlations of strange hadrons with charged particles in pPb and PbPb collisions at LHC energies.” Submitted to Phys. Lett. B, arXiv:1409.3392, 2014.
[6] CMS Collaboration, “Strange particle production in pp collisions at $\sqrt{s} = 0.9$ and 7 TeV,” JHEP, vol. 05, p. 064, 2011.
[7] CMS Collaboration, “Long-range and short-range dihadron angular correlations in central PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV,” JHEP, vol. 07, p. 076, 2011.
[8] CMS Collaboration, “Multiplicity and transverse momentum dependence of two- and four-particle correlations in pPb and PbPb collisions,” Phys. Lett. B, vol. 724, p. 213, 2013.