Flow of strange and charged particles in pPb and PbPb collisions at LHC energies

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Abstract. Observation of a long-range near-side two-particle correlation (known as the "Ridge") in high-multiplicity pPb and pp collisions opened up new opportunities of exploring novel QCD dynamics in small collision systems. Latest CMS results in pPb and PbPb collisions will be shown: (1) The multi-particle correlation in pPb collisions will be presented for the high multiplicity events, indicating the collective behavior in small collision systems. (2) Identified $p_T$ spectra of $\pi^+/\pi^−$, $K^+/K^−$, and $p/\bar{p}$ in pPb collisions show a strong multiplicity dependence, which indicates radial flow at high multiplicity events. (3) The second-order anisotropy harmonics ($v_2$) of strange particle $K^0_s$ and $\Lambda/\bar{\Lambda}$ are extracted from long-range correlations as a function of particle multiplicity and $p_T$. The mass ordering effect of $v_2$ at low $p_T$ as predicted by hydrodynamics also points to the strong collective nature of expanding medium in small collision systems. Finally, the possible constituent quark number of scaling of $v_2$ between mesons and baryons may indicate the deconfinement in small systems.

1. Introduction
The study of strange and charged particle production and anisotropy harmonics ($v_n$) in high-energy collisions provide deep insights into the nature of the produced systems as well as become an important tool to investigate the properties of soft QCD matter. Earlier studies of the second-order anisotropy harmonics (known as "$v_2$") in AA collisions indicate that the produced systems would undergo a hydrodynamic expansion, and the medium that was created behaves like a fluid [1,2].

However, in recent years, CMS has observed the long-range near side two-particle correlation, known as “ridge” structure, in high multiplicity pPb [3] and pp [4]collisions, which is not expected in small systems. The origin of such structure in smaller collision system is still under intense debate. Even though it is natural to think that the collective flow in hydrodynamics can explain the phenomenon [5–8], other models propose to attribute to the initial gluon correlations [9–11].

From the previous studies of two-particle correlation, one may wonder whether the observed behavior is due to correlation from particle pair or that can be also true for multi-particle, which latter case could indicate the collective nature of the systems. Using the multi-particle cumulant and Lee-Yang zeros (LYZ) method, the $v_2$ from 4, 6, 8 and all particles can be extracted. One of the advantage of using multi-particle correlation is to highly suppress the non-flow contribution to the $v_2$ signal, such as back-to-back jet correlations. In small collision systems, such as pPb, the multi-particle correlation could be an essential study to see whether there is collectivity in small
The feed-down effect would be corrected when applying efficiency corrections. The probability of having particles. If these ratios are similar between the Monte Carlo simulation and measurement, this study of strange particles, the most abundant produced heavy quark generations in heavy-ion collisions, can provide information of formation of strongly interacting medium, where earlier studies have shown the strangeness enhancement, with respect to pp reference, as an indication [14]. The strange hadrons, $K_S^0$ and $\Lambda$ (includes $\bar{\Lambda}$), are useful candidates to calculate the $v_n$ in small systems. In hydrodynamic models, the collective flow would result in a final-state particles distribution with an azimuthal anisotropy and its magnitude would depend on the mass of the particles. The heavier particles, due to the radial boost from the medium, would be more likely to show up at a higher momentum. This mass ordering effect is well studied in AA collisions as one of the evidences of hydrodynamic flow [1, 2]. In this paper, the $v_n$ study of $K_S^0$ and $\Lambda$ in pPb and PbPb collisions is taken from previous CMS published result, which could be found in Ref. [15].

The particles $\pi^+$, $K^+$, $p$, $K_S^0$ and $\Lambda$ candidates could come from weak decay $(\Lambda \to p\pi^0, \Sigma^0 \to \Lambda\pi^0)$ and also could be used to study of $v_n$ in $K_S^0$ reconstruction, while the assumption of $\pi^- p$ is used in $\Lambda$ reconstruction. For $\Lambda$ ($\bar{\Lambda}$), the lower-momentum track is assumed to be the $\pi^-(\pi^+)$.

Due to the assumptions of $\pi$ ($p$) tracks when reconstructing the $K_S^0$ ($\Lambda$) invariant mass, there are non-negligible probabilities of mis-identifying $K_S^0$ or $\Lambda$ candidates. Therefore, using the daughter tracks of $K_S^0$ ($\Lambda$), and assuming it has $p$ ($\pi$) mass, to see whether it could be reconstructed within the mass window of $\Lambda$ ($K_S^0$). Finally, those candidates would be removed. In addition to the mis-identifications, the $\pi^+, p$ and $\Lambda$ candidates could come from weak decay instead of primary collisions known as “feed-down” effect, where $\pi^+$ could be decayed from $K_S^0$, $p$ could come from $\Lambda$ and $\Lambda$ could come from $\Xi^+$. The contributions from weak decay could be up to 10–15% depending on the transverse momentum. However, only the ratios of $\Lambda/p$, $\Lambda/\bar{p}$, $K_S^0/\pi^+$, $K_S^0/\pi^-$ and $\Xi^+/\Lambda$ matter in the study, since the feed-down is given as a fraction of primary particles. If these ratios are similar between the Monte Carlo simulation and measurement, this feed-down effect would be corrected when applying efficiency corrections. The probability of having...
$K^+$ or $K^0_S$ come from weak decay is negligible. The detail descriptions and studies could be found in Ref. [13].

![Figure 1](image1.png)

**Figure 1.** The distribution of $\ln \epsilon$ as a function of total momentum for different particles are presented, where $\epsilon$ is the most probable energy loss rate at a reference path-length $l_0 = 450 \mu m$.

![Figure 2](image2.png)

**Figure 2.** The invariant mass distribution of $K^0_S$ and $\Lambda/\bar{\Lambda}$ are presented at multiplicity range of $220 \leq N_{\text{trk}}^{\text{offline}} < 260$ and transverse momentum 1-3 GeV in pPb collisions. The signal peak is fitted by a double Gaussian function (with a common mean) and the background is described by a 4th-order polynomials.

3. Results

The second-order anisotropy Fourier harmonics, $v_2$, as a function of multiplicity ($N_{\text{trk}}^{\text{offline}}$) is shown in Fig. 3 based on six- and eight-particle cumulants for 2.76 TeV PbPb (left) and 5.02 TeV pPb (right) collisions, averaged over transverse momentum 0.3-3 GeV. The data of $v_2\{2\}$ and $v_2\{4\}$ are taken from the previous measurement from CMS [16], with $\eta$ gap greater than 2 for $v_2\{2\}$ to suppress the non-flow effects. The $v_2$ values from LYZ method that involves all particles correlations

![Figure 3](image3.png)
are also shown. For each multiplicity range, all the $v_2$ values from different number of particles (except $v_2 \{2\}$) agree with each other within 10% for pPb collisions and better agreement as within 2% for PbPb collisions. This result is strongly indicating the collective nature of the produced medium in high multiplicity pPb collisions, where all particles are involved in the correlations. This behavior is not consistent with jet correlation. In the context of hydrodynamics, ratios of $v_2$ values from different orders could follow the universal behavior from fluctuation-driven initial-state conditions [17,18].

The $v_2$ values from 2 particles are consistently higher than other $v_2$ values from multi-particles, which is under expected as event-by-event participant geometry fluctuations of the $v_2$ values could be affected differently by two- and multi-particle cumulants [19,20].

Figure 3. The second-order anisotropy harmonics $v_2$ from different number of particle cumulant are presented in pPb and PbPb collisions. The transverse momentum range is chosen to be 0.3-3 GeV/c and the $v_2 \{2\}$ and $v_2 \{4\}$ are taken from previous CMS published results.

The transverse momentum spectra of $\pi^+$, $K^+$ and $p$ can be well fitted from a function such as $m_T e^{-m_T/T'}$, motivated by the success of Boltzmann-type distributions in nucleus-nucleus collisions [21], which is shown in Fig. 4. The $m_T = \sqrt{p_T^2 + m^2}$ and $T'$ is the inverse slope parameter of the fit function. As particle multiplicity increases, the spectra becomes “harder” as the slope of the spectra becomes more flatten so that $T'$ increases with multiplicity for all particles. The relation between $T'$ and particle mass can be interpreted by using radial flow phenomenon, supported by hydrodynamics. As the system goes to higher multiplicity, the $T'$ becomes more linear with the particle mass. This can be explained if the system has radial flow effect at high multiplicity, the system would provide a common radial flow velocity and kinetic freeze-out temperature to all particles. Therefore, the inverse slope parameter $T'$ would be linear proportional to the particle mass if $T' \propto T_{kin} + m \langle \beta T \rangle$. A similar trend has been observed in PbPb collisions, interpreted as radial flow velocity boost as shown in Ref. [22]. For the lower multiplicity range, this relation is clearly broken.

The second-order anisotropy harmonics $v_2$ is shown as a function of $p_T$ for $K_S^0$ (filled squares), $\Lambda$ (filled circles) and previously published result of inclusive charge particles(open crosses) in Fig. 5. The four different panels are corresponding to the four high multiplicity ranges in pPb collisions. In the range of $p_T < 2$ GeV, the $v_2$ of the heavier particle $\Lambda$, is lower than that of $K_S^0$ particles, while
Figure 4. The inverse slope parameter $T'$ is shown as a function of particle mass at different multiplicities in pPb collisions, where $T'$ is extracted from fit function $m_T e^{-m_T/T'}$ of the $m_T$ spectra of $\pi^+$, $K^+$ and $p$. The lines that connect the data point is used as guiding lines to see the linear relation between $T'$ and particle mass.

Both $K_S^0$ and $\Lambda$ are below the inclusive charged hadron. In hydrodynamics, this mass ordering effect can be an indication of collective radial flow, which pushes the heavier particles to a higher momentum if the system has a common radial flow velocity. Interestingly, if we compare Fig. 6, which is also $v_2$ as function of $p_T$ of $K_S^0$ and $\Lambda$ in PbPb collisions, the mass ordering effect at low $p_T$ is smaller in PbPb than that in pPb at the same multiplicities. This might indicate the strength of the flow effect in small systems is larger than that of large systems has been predicted by hydrodynamic models such as Ref. [23].

The scaling behavior of $v_2$ value divided by number of quarks, as a function of kinetic energy of each particle divided by the number of quarks in their bound states, is also investigated in high multiplicity pPb events. As shown in the middle row of Fig. 5, the $K_S^0$ and $\Lambda$ are in a good agreement except $KE_T/n_q < 0.2$ GeV, which has a deviation of 20%. This could be understood as the impact of radial flow at very low $p_T$ [15]. In PbPb collisions, this approximate scaling behavior can be related to the quark recombination models, which states that the collective flow is developed among constituent quarks before hadronizations [24–26].

The third-order anisotropy harmonics $v_3$, known as the triangular flow, is also shown in Fig. 7 as a function of $p_T$ for $K_S^0$ (filled squares), $\Lambda$ (filled circles), and previously published result of inclusive charge particles(open crosses) [15]. Similar scaling trend can be seen in $v_3$ results.

4. Summary

From the latest CMS results, the multi-particle correlation of charged hadron in high multiplicity pPb collisions indicates the collective nature of the produced medium in small systems. The identified particle spectra, $\pi^+/\pi^−$, $K^+/K^−$ and $p/\bar{p}$, show a strong dependence of particle multiplicity in pPb collisions, indicating radial flow phenomenon at high multiplicity. The strange
Figure 5. Top row: The $v_2$ as a function of $p_T$ for four different high multiplicity ranges for $K^0_S$ (filled squares), $\Lambda$ (filled circles) and inclusive charge particles(open crosses) are shown in pPb collisions. Middle row: $v_2/n_q$ is plotted as a function $K E_T/n_q$ for the same multiplicity ranges as the top row, along with a polynomial fit function of $K^0_S$. Bottom row: the fit to data ratio of $K^0_S$ and $\Lambda$ are presented as function of $K E_T/n_q$. The error bar corresponds to statistical uncertainties and the boxes denote systematic uncertainties.

Figure 6. Top row: The $v_2$ as a function of $p_T$ for four different high multiplicity ranges for $K^0_S$ (filled squares), $\Lambda$ (filled circles) and inclusive charge particles(open crosses) are shown in PbPb collisions. Middle row: $v_2/n_q$ is plotted as a function $K E_T/n_q$ for the same multiplicity ranges as the top row, along with a polynomial fit function of $K^0_S$. Bottom row: the fit to data ratio of $K^0_S$ and $\Lambda$ are presented as function of $K E_T/n_q$. The error bar corresponds to statistical uncertainties and the boxes denote systematic uncertainties.
Figure 7. Top row: The $v_3$ as a function of $p_T$ for four different high multiplicity ranges for $K_S^0$ (filled squares), $\Lambda$ (filled circles) and inclusive charge particles(open crosses) are shown in pPb collisions. Middle row: $v_3/n_q$ is plotted as a function $KE_T/n_q$ for the same multiplicity ranges as the top row, along with a polynomial fit function of $K_S^0$. Bottom row: the fit to data ratio of $K_S^0$ and $\Lambda$ are presented as function of $KE_T/n_q$. The error bar corresponds to statistical uncertainties and the boxes denote systematic uncertainties.

hadron $K_S^0$ and $\Lambda/\bar{\Lambda}$ have shown comparable values of $v_2$ and $v_3$ in pPb and PbPb collisions, while in the low $p_T$ regime, the mass ordering effect is larger in pPb than that in PbPb collisions. In addition, the number of constituent quark scaling have been observed in pPb and PbPb collisions.
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