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Recent results in small systems from CMS

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Abstract

The observation of a wide variety of physical phenomena in the context of the formation of a strongly interacting QCD matter in heavy-ion nuclear collisions at the LHC has drawn significant attention to the high energy heavy-ion physics community. The appearance of a varieties of similar phenomena as in heavy-ion in the high multiplicity proton-proton and proton-nucleus collisions at the LHC energies has triggered further investigation to understand the dynamics of particle production mechanism in a highly dense and small QCD medium. The CMS collaboration uses many different probes in these studies ranging from the particle production cross section to multi-particle correlations. In this proceeding, I report a few selected recent CMS results from the small systems with the main focus on the measurement of collective phenomena in high multiplicity pp and pPb collisions.

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Recent results in small systems from CMS

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Abstract. The observation of a wide variety of physical phenomena in the context of the formation of a strongly interacting QCD matter in heavy-ion nuclear collisions at the LHC has drawn significant attention to the high energy heavy-ion physics community. The appearance of a varieties of similar phenomena as in heavy-ion in the high multiplicity proton-proton and proton-nucleus collisions at the LHC energies has triggered further investigation to understand the dynamics of particle production mechanism in a highly dense and small QCD medium. The CMS collaboration uses many different probes in these studies ranging from the particle production cross section to multi-particle correlations. In this proceeding, I report a few selected recent CMS results from the small systems with the main focus on the measurement of collective phenomena in high multiplicity pp and pPb collisions.

Keywords: QCD matter, multi-particle correlations, collectivity

1 Introduction

In the context of high energy heavy-ion physics, the collisions between protons or a proton with a nucleus is commonly referred to as small system and they can provide baseline measurements for heavy-ion collisions. Traditionally, it is thought that such small systems do not show characteristics of QGP formation a priori. However, in the recent few years, this simplistic view of a small system has been challenged at the LHC – thanks to the new frontier in energies and state-of-the-art instrumentations. The individual events in a high multiplicity pp and pPb collisions can have very high charged particle multiplicity and energy density which is comparable to that of AA collisions [1].

With the advent of the LHC, high multiplicity pp and pPb collisions show unexpected phenomena which have never been observed before in such small systems. The observation of a long range rapidity ridge in the measurement of two-particle angular correlation in heavy-ion collisions is no surprise to us and this can be well explained by hydrodynamical collective flow of a strongly interacting and expanding medium [3]. However, the appearance of similar structures in a high multiplicity pp and pPb collisions has drawn a lot of attention and prompted studies to understand the cause of such behaviour in small systems. In particular, the discovery of the ridge by CMS collaboration [2] in high multiplicity pp collisions is one of such intriguing results observed in small systems [4].

Long-range, near-side angular correlations in particle production emerged in pp and subsequently in pPb collisions paved the way for a systematic investigation of the existence of the collective phenomena. Much information can also be gained by focusing on collective properties of each event, such as multi-particle correlations, or event-by-event fluctuations of such quantities. We observe signatures traditionally attributed to a collective behaviour not only in PbPb collisions but also in small systems. Since then, a wealth of new, unexpected phenomena has been observed with striking similarities to heavy-ion observations.

2 Transverse energy density

The total transverse energy, E_T , is a measure of the energy liberated by the “stopping” of the colliding nucleons in a heavy-ion or proton-nucleus collision. From Figure 1 it can be seen that $dE_T/d\eta|_{\eta=0} \approx 22$ GeV. This is 1/40 of the value observed for the 2.5% most central PbPb collisions. However, since the cross sectional area of pPb collisions is much smaller than that of central PbPb collisions, this result implies that the maximum energy density in pPb collisions is comparable to that achieved in PbPb collisions [1]. Several modern generators are compared to these results but none is able to capture all aspects of the η and centrality dependence of the data [1].

Fig. 1. (left) Transverse energy density versus η from minimum bias pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. (right) Transverse energy density per participating nucleon-nucleon pair evaluated at various $\sqrt{s_{NN}}$ for minimum bias pAu, pU, dAu, and pPb collisions [1].

3 Collectivity in small systems at the LHC

The p_T distributions of identified hadrons are one of the important tools to probe the collective behaviour of particle production. The p_T distributions in

pp and pPb collisions show a clear evolution, becoming harder as the multiplicity increases [5]. As it is shown in Figure 2, models including hydrodynamics describes the data better for the p_T spectra. Data-to-model agreement is good at higher charged particle multiplicity, N_{ch} . In addition, the evolution of the p_T spectra with multiplicity can be compared more directly by measuring the average transverse kinetic energy, $\langle KE_T \rangle$ [5]. If collective radial flow develops, this would result in a characteristic dependence of the shape of the transverse momentum distribution on the particle mass.

Fig. 2. (left) Simultaneous blast-wave fits of the p_T spectra of K_S^0 and Λ in low- and high-multiplicity pPb events. (right) The extracted kinetic freeze-out temperature, T_{kin} , versus the average radial-flow velocity, $\langle \beta_T \rangle$, from a simultaneous blast-wave fit to the K_S^0 and Λ p_T spectra at $|y_{cm}| < 1$ for different multiplicity intervals in pp, pPb, and PbPb collisions.

The $\langle KE_T \rangle$ for K_S^0 , Λ and Ξ particles as a function of multiplicity are shown in Figure 3. For all particle species, $\langle KE_T \rangle$ increases with increasing multiplicity. A theoretical Blast-wave model [6] fits have also been performed to the p_T spectra of strange particles in several multiplicity bins as shown in Figure 2. The interpretation of the parameters of these fits, such as kinetic freeze-out temperature, T_{kin} and transverse radial flow velocity, β_T , are model dependent. In the context of the Blast-Wave model, when comparing the parameters of different systems at similar $dN_{ch}/d\eta$, it was found that β_T is larger for small systems i.e., $\beta_T(\text{pp}) > \beta_T(\text{pPb}) > \beta_T(\text{PbPb})$. This could be an indication of a larger radial flow in small systems as a consequence of stronger pressure gradients due to a more explosive system. However, a similar decreasing trend is observed for T_{kin} and β_T as a function of multiplicity in all three collision systems. One of the key questions about the nature of the ridge and its collectivity is whether the two-particle azimuthal correlation structures observed at large relative pseudorapidity in pp and pPb collisions result from correlations exclusively between particle pairs, or if it is a multi-particle genuine collective effect, needs to be further understood. A strong hint for multi-particle correlations in high multiplicity pp and pPb collisions

Fig. 3. The average transverse kinetic energy for K_s^0 , Λ and Ξ particles as a function of multiplicity in pp, pPb, and PbPb collisions [5].

was reported by the CMS collaboration [7, 15]. Figure 4 shows the second-order azimuthal anisotropy Fourier harmonics (v_2) measured in pp, pPb and PbPb collisions over a wide pseudorapidity range based on correlations calculated up to eight particles. The v_2 values stay high and show similar trends in all three systems. The v_2 computed from two-particle correlations is found to be larger than that obtained with four-, six- and eight-particle correlations, as well as the Lee-Yang zeroes method. However, the v_2 obtained from multi-particle correlations, all yield to similar v_2 values i.e., $v_2\{4\} \approx v_2\{6\} \approx v_2\{8\} \approx v_2\{\text{LYZ}\}$ [7]. These observations support the interpretation of a collective origin for the observed long-range correlations in high-multiplicity pp and pPb collisions. An-

Fig. 4. Second-order azimuthal anisotropy Fourier harmonics, v_2 measured by CMS in pp, pPb and PbPb collisions based on multi-particle correlations [7].

other useful observable in the study of collectivity is the event-by-event corre-

lation between Fourier harmonics of different order flow coefficients. The CMS Collaboration has measured these normalized symmetric cumulants, $SC(m, n)$, where m and n are different order flow coefficients, in pp, pPb and PbPb collisions, as a function of track multiplicity [8]. Similar observations are made in all three systems. In the case of $SC(2, 3)$, which gauges the correlation between v_2 and v_3 , an anti-correlation is found at high track multiplicity, as shown in Figure 5. On the contrary, $SC(2, 4) > 0$: the v_2 and v_4 values are positively correlated event-by-event. Similar trends are observed in pPb and PbPb collisions, and high multiplicity pp collisions, regarding the trend of these observables as a function of track multiplicity. A long-range near-side two-particle correlation involving an identified particle is also observed [7, 9]. Results for both pPb and pp collisions are shown in Figure 6. Moving to high-multiplicity events for both systems, a particle species dependence of v_2 is observed. The mass ordering of v_2 was first seen in AA collisions at RHIC and LHC energies [10, 11], which can be understood as the effect of radial flow pushing heavier particles towards higher p_T . This behavior is found to be qualitatively consistent with both hydrodynamic models [12] and an alternative initial state interpretation [13]. A measurement

Fig. 5. The normalized symmetric cumulant for the second and third coefficients (left) and the second and fourth coefficients (right) are shown for pp (black cross), pPb (red circle), and PbPb (blue square). Tracks with transverse momentum between 0.3 and 3.0 GeV are used [8].

of the elliptic flow of prompt J/Ψ meson in high-multiplicity pPb collisions is reported by the CMS experiment [14]. The prompt J/Ψ results are compared with the v_2 values for open charm mesons (D^0) and strange hadrons. As shown in Figure 6, positive v_2 values are observed for the prompt J/Ψ meson, as extracted from long-range two-particle correlations with charged hadrons, for $2 < p_T < 8$ GeV. The prompt J/Ψ meson results, together with 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.

Fig. 6. The v_2 results for K_s^0 , and Λ , prompt D^0 and prompt J/ψ in high-multiplicity pPb (left) events. (right) The v_2 results for inclusive charged particles, K_s^0 , and Λ as a function of p_T in pp collisions at $\sqrt{s} = 13$ TeV.

4 Conclusions

Several effects, such as mass-dependent hardening of p_T distributions, near-side long-range correlations, multi-particle azimuthal correlations, etc, which in nuclear collisions are typically attributed to the formation of a strongly-interacting collectively-expanding quark-gluon medium, have been observed in high-multiplicity pp and pPb collisions at the LHC. The study of small collision systems at high multiplicity is undoubtedly of considerable interest. While a lot of progress has been made towards understanding the long-range correlation phenomena in small colliding systems, there are still many open questions to be addressed by the experimental and theoretical communities.

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