The Compact Muon Solenoid Experiment

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Probing initial-state fluctuations with p_T -dependent event-plane angle in pPb and PbPb collisions

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Abstract

The technique of two-particle correlations has been widely used in studying flow via azimuthal anisotropy in relativistic heavy-ion collisions. A key assumption imposed in this approach is the factorization of Fourier coefficients extracted from two-particle correlations into a product of single-particle anisotropies of trigger and associated particles. It was recently predicted by hydrodynamics that due to initial-state participant fluctuations, a transverse momentum (p_T) dependence of the event-plane angle would be induced, leading to a breakdown of factorization, even if hydrodynamic flow is the only source of correlations. We present a systematic examination of the factorization assumption in pPb and PbPb collisions at a nucleon-nucleon center-of-mass energy of 5.02 TeV and 2.76 TeV respectively with the CMS experiment. Significant breakdown of factorization (up to 20%) is observed in a large sample of ultra-central (0–0.2%) triggered PbPb events, where initial-state fluctuations play a dominant role. Comparison of data and viscous hydrodynamic predictions, as a function of p_T and centrality, allows new constraints on the modeling of initial condition and shear viscosity to entropy density (η/s) ratio of the medium created in heavy-ion collisions. Furthermore, the measurement is also extended to high-multiplicity pPb collisions. As the initial-state geometry of a pPb collision is expected to be entirely a consequence of fluctuations, quantitative studies of factorization breakdown will help to investigate the nature of the observed long-range correlations in pPb collisions, particularly in the context of hydrodynamic models.

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Abstract

The technique of two-particle correlations has been widely used in studying flow via azimuthal anisotropy in relativistic heavy-ion collisions. A key assumption imposed in this approach is the factorization of Fourier coefficients extracted from two-particle correlations into a product of single-particle anisotropies of trigger and associated particles. It was recently predicted by hydrodynamics that due to initial-state participant fluctuations, a transverse momentum (p_T) dependence of the event-plane angle would be induced, leading to a breakdown of factorization, even if hydrodynamic flow is the only source of correlations. We present a systematic examination of the factorization assumption in pPb and PbPb collisions at a nucleon-nucleon center-of-mass energy of 5.02 TeV and 2.76 TeV respectively with the CMS experiment. Significant breakdown of factorization (up to 20%) is observed in a large sample of ultra-central (0–0.2%) triggered PbPb events, where initial-state fluctuations play a dominant role. Comparison of data and viscous hydrodynamic predictions, as a function of p_T and centrality, allows new constraints on the modeling of initial condition and shear viscosity to entropy density (η/s) ratio of the medium created in heavy-ion collisions. Furthermore, the measurement is also extended to high-multiplicity pPb collisions. As the initial-state geometry of a pPb collision is expected to be entirely a consequence of fluctuations, quantitative studies of factorization breakdown will help to investigate the nature of the observed long-range correlations in pPb collisions, particularly in the context of hydrodynamic models.

Keywords: Dihadron Correlations, Factorization, Initial State Fluctuations

1. Introduction

Collective flow present in the emission of final state particles in heavy-ion collisions can be studied by the method of two-particle correlations. The corresponding two-particle azimuthal distribution can be expanded into a Fourier series given by the following equation,

$$\frac{dN}{d\Delta\phi} \sim 1 + 2V_{2\Delta} \cos 2\Delta\phi + 2V_{3\Delta} \cos 3\Delta\phi + .. \quad (1)$$

with $V_{n\Delta}$ harmonics emerging from spatial anisotropy of formed fireball. A common assumption is that the measured two-particle correlation factorizes into the product of individual single-particle azimuthal distributions. Any breakdown of this factorization relation has been regarded as a consequence of contribution from non-flow effects. However, recent studies from the hydrodynamic models [2, 3, 4] point out that even if collective flow is the only source of correlations, factorization breaking could be induced via p_T -dependent event plane angle. This is directly illustrated by the relation between single and two-particle harmonics,

$$V_{n\Delta}(p_T^{trig}, p_T^{asocc}) = \langle v_n(p_T^{trig}) v_n(p_T^{asocc}) \cos[n(\Psi_n(p_T^{trig}) - \Psi_n(p_T^{asocc}))] \rangle \quad (2)$$

¹ A list of members of the CMS Collaboration and acknowledgements can be found at the end of this issue.

Figure 1: Ratio r_2 as a function of the difference $p_T^{trig} - p_T^{assoc}$ for four different trigger p_T selections and different centrality selections in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV

The event plane angle, Ψ_n , instead of having a unique value for the whole event, could be dependent on the particles p_T , causing the $V_{n\Delta}$ harmonics not to factorize. To quantify this effect one can introduce the r_n ratio,

$$r_n = \frac{V_{n\Delta}(p_T^{trig}, p_T^{assoc})}{\sqrt{V_{n\Delta}(p_T^{trig}, p_T^{trig}) V_{n\Delta}(p_T^{assoc}, p_T^{assoc})}} \quad (3)$$

which by definition from hydrodynamics takes on the values $r_n \leq 1$, corresponding to factorization breaking if r_n is below one. As a consequence, a sign of non-flow effect appears when r_n values are above one. Using the r_n ratio we conduct a systematic study of factorization breaking in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the CMS experiment.

Figure 2: Comparison of r_2 ratio in ultra-central PbPb collisions with VISH2+1 hydro model predictions [3] for three values of η/s , as indicated

Figure 3: Ratio r_2 as a function of $p_T^{\text{trig}} - p_T^{\text{assoc}}$ for four different trigger values and for different multiplicity bins for pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, compared to the model from Kozlov et al. [4]

Investigating the origin of the observed ridge-like structure in high-multiplicity pPb collisions [5, 6], that could be due to the collective hydrodynamic expansion of a system with fluctuating initial conditions, this study can shed new light on this long-range correlation. In addition, we compare data with predictions from hydrodynamics, with the aim of obtaining new constraints of the ratio of shear viscosity to entropy density η/s and on recreating more suitable initial-state conditions in heavy-ion collisions.

2. Results

The r_n ratio is presented as a function of the difference $p_T^{\text{trig}} - p_T^{\text{assoc}}$, imposing the inequality $p_T^{\text{assoc}} < p_T^{\text{trig}}$. Fig. 1 shows the r_2 ratio for PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV for four p_T^{trig} bins. Measurements span seven different centrality selections, including 0-0.2%, 0-5%, 5-10%, 10-20%, 20-30%, 30-40% and 40-50%. We see that the effect increases with the rise of p_T^{trig} and $p_T^{\text{trig}} - p_T^{\text{assoc}}$, achieving its maximum (up to 20%) for the highest p_T^{trig} bin in the case of ultra-central collisions. As we move to peripheral collisions, again for the highest $2.5 < p_T^{\text{trig}} < 3.0$ GeV bin, we see a strong decrease in the effect achieving a size of 2-3% for semi-central collisions. In Fig. 2, we compare the PbPb r_2 values for ultra-central collisions with predictions of the VISH2+1 hydro model [3]. The comparison is conducted for different η/s values and two types of initial conditions (Glauber and MC-KLN). The hydro predictions give a good description of CMS data qualitatively for both Glauber and MC-KLN. Roughly, both initial conditions are closest to the experimental data for $\eta/s = 0.12$.

Figure 4: (a) r_2 and (b) r_3 multiplicity dependence, for pPb and PbPb collisions, compared with hydrodynamic predictions [3,4]

Fig. 3 shows r_2 results in pPb collisions. Maintaining the same data structure as in the case of PbPb, we define four multiplicity bins belonging to high multiplicity pPb collisions. We observe a similar pattern as in PbPb, where the effect increases with p_T^{trig} and $p_T^{\text{trig}} - p_T^{\text{assoc}}$. The magnitude of the effect achieves a maximum of around 2 – 3%. We compare the CMS data to predictions of hydrodynamic model from Kozlov et al. [4] represented with blue dashed lines. We see that the model qualitatively describes the data. We summarize the multiplicity dependence of r_2 and r_3 data in figure 4 for pPb and PbPb collisions. The r_n values are averaged for the highest $2.5 < p_T^{\text{trig}} < 3.0$ GeV bin and for $p_T^{\text{trig}} - p_T^{\text{assoc}} \approx 2.0$ GeV. In the case of PbPb r_2 , looking from left to right, we see a very steep drop depicting a strong effect of factorization breaking as we approach very central collisions. Observing the plot from right to left, we see a dramatic decrease of the effect reaching an amplitude on the level of few percent for centralities over 5%. For the higher order r_3 ratio, we see a weak centrality dependence for PbPb, and a very strong one for pPb. This is indicated by pPb r_3 values going above one, representing the presence of non-flow effects. Both hydro models, qualitatively describe CMS data, with larger discrepancies in the case of pPb for lower multiplicity bins and peripheral PbPb data.

3. Conclusions

We conducted extensive measurements on the effect of factorization breaking for two particle correlations using CMS experimental data in pPb and PbPb collisions. We observed a very strong effect in ultra-central PbPb collisions, achieving 20% in amplitude. However, in the case of high multiplicity pPb collisions we see a weak effect around 2-3% comparable in magnitude with peripheral PbPb collisions. All the measurements, qualitatively or even semi-quantitatively are consistent with hydrodynamic models having p_T -dependent event plane angle induced by initial-state fluctuations.

References

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