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Flow measurements at LHCb

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Abstract. The unique geometry and tracking performance of the LHCb detector make it well suited for studying particle correlations in heavy-ion collisions. In particular, it enables measurements of long-range correlations, which serve as probes hydrodynamic behavior, as well as femtoscopic effects such as those arising from Bose–Einstein correlations. The use of asymmetric proton–lead collisions, in both forward (pPb) and backward (Pbp) configurations, provides sensitivity to both initial-state effects, through the two distinct Bjorken-x regions, and final-state effects in particle correlations. These studies also give access to the space-time characteristics of the particle-emitting sources.

1 Introduction

It has been well established, both experimentally and theoretically, that dense heavy-ion collisions such as Pb–Pb at the LHC or Au–Au at RHIC create a hydrodynamic phase, the Quark–Gluon Plasma (QGP). Coupled with the initial collision geometry, this phase gives rise to long-range correlations between particles, often quantified by the elliptic flow (v_2) [1]. However, since the beginning of the LHC era, QGP-like correlations have also been observed in smaller collision systems, where QGP production was not anticipated [2]. This unexpected observation quickly became a central topic in the heavy-ion community, leading to three main (non-exclusive) hypotheses for the origin of such correlations: the formation of a small hydrodynamic phase, initial-state correlations between the partons of the projectiles, or soft-QCD interactions in the final state of the collision. Thanks to the asymmetric acceptance of the LHCb detector [3], it is possible to measure correlations in both the forward (pPb) and backward (Pbp) configurations thanks to the detector being fully instrumented in the pseudorapidity region $2.0 < \eta < 5.0$. This allows access to different initial-state conditions, probing two distinct Bjorken-x regions ($x \sim 10^{-5}$ for the forward configuration and $x \sim 10^{-3}$ for the backward).

In addition to long-range collective correlations, femtoscopic correlations provide complementary information on the particle-emitting sources at much shorter scales. In particular, same-sign pion Bose–Einstein correlations, a key tool of femtoscopy, offer a direct experimental approach to determine the size, shape, and lifetime of the source. When identical pions are produced close together in phase space, their quantum wave functions interfere constructively, enhancing the probability of detecting pion pairs with small relative momentum. Proton–proton (pp) collisions are characterized by significantly shorter lifetimes than their ion–ion counterparts, giving improved experimental access to the early system dynamics and the initial geometry. These correlations are commonly described using the core–halo model,

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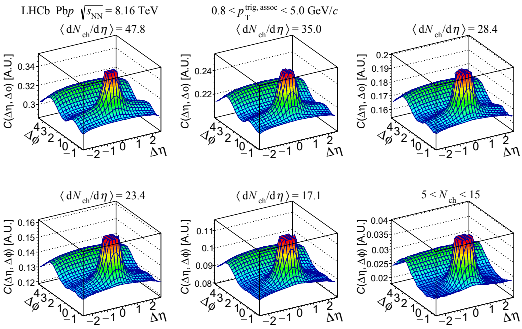

Figure 1. Angular correlation functions $C(\Delta\eta, \Delta\phi)$ for the five multiplicity classes and the low-multiplicity class in Pbp collisions. The correlation functions are truncated at the peaks to improve the visibility of the ridge structures.

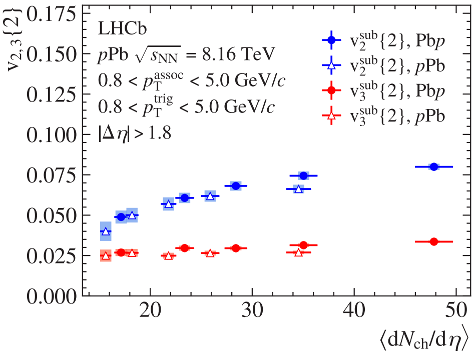

Figure 2. Results for $v_2^{sub}\{2\}$ and $v_3^{sub}\{2\}$ for the pPb and Pbp samples as functions of $\langle dN_{\mathrm{ch}}/d\eta \rangle$, presented after the non-flow subtraction procedure.

which provides an interpretation of the results to obtain spatial and temporal properties of the emitting sources.

2 Rapidity an multiplicity dependence of charged particle flow in pPb collisions

The flow analysis in pPb and Pbp collisions [4] is done using two-particle correlations. The correlation function, defined in terms of $\Delta\eta$ (pseudorapidity difference) and $\Delta\phi$ (azimuthal difference), shows at large $|\Delta\eta|$ a ridge-like structure whose strength grows with charged-particle multiplicity ($dN_{\mathrm{ch}}/d\eta$), as illustrated in Fig. 1.

The anisotropy is quantified by projecting onto $\Delta\phi$, excluding the near-side jet peak ($|\Delta\eta| > 1.8$) from jets and resonance decays, and decomposing the distribution into a Fourier series. Residual non-flow is further reduced using a subtraction method based on the measurement of flow in low multiplicity events.

The resulting second (v_2) and third (v_3) harmonics flow coefficients versus multiplicity are shown in Fig. 2. Despite probing different initial-state conditions in forward (pPb) and backward (Pbp) configurations, v_2 and v_3 are consistent at similar multiplicities. These results suggest that final-state collectivity dominates over initial-state effects. Small differences in the p_T-differential results (Fig. 3) may reflect initial-state effects at higher Q^2 or residual non-flow.

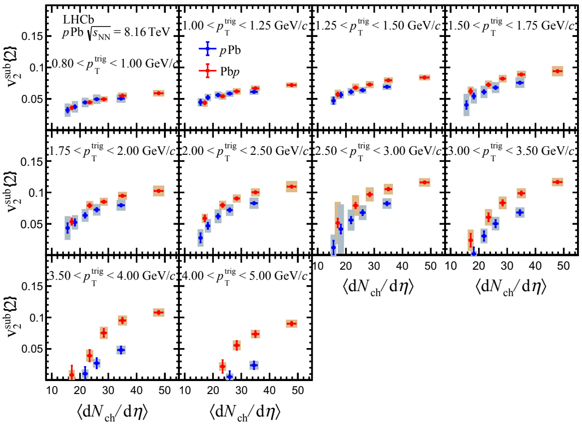

Figure 3. Results for $v_2^{sub}\{2\}$ for the pPb and Pbp samples as functions of $\langle dN_{\mathrm{ch}}/d\eta\rangle$ in different p_{T}^{trig} ranges, presented after the non-flow subtraction procedure.

3 Three-pion Bose–Einstein correlations in proton–proton collisions

The three-pion Bose–Einstein in proton-proton collisions analysis [6] extends the two-pion study presented in [5], in which pion pairs are constructed in each events and studied as a function of their four-momentum differences. Detector effects are corrected using a mixed-event normalization technique. The three-pion correlation can be expressed as a convolution of the two-pion correlations. The measured functions, shown in Fig. 4, are fitted with a Lévy parametrization:

$$C_3^{\mathrm{fit}} = C_{\mathrm{bkg}}(Q_{12}, Q_{13}, Q_{23})\Big(1 + \lambda_3 e^{-0.5(|Q_{12}R|+|Q_{13}R|+|Q_{23}R|)^{\alpha}} + \lambda_2\big(e^{-|Q_{12}R|} + e^{-|Q_{13}R|} + e^{-|Q_{23}R|}\big)\Big) \quad (1)$$

where Q_{mn} is the four-momentum difference between particles m and n, R is a parameter related to the source size (taken from the two-pion analysis), and λ_2 and λ_3 define the two- and three-particle correlation strength.

The results are interpreted within the core–halo model [7], which describes pion emission as a dense central core surrounded by a dilute halo. From the fits, two parameters are extracted: the fraction of particles produced by the core (f_c) and the fraction produced coherently (p_c). Their dependence on charged-particle multiplicity, measured with the VELO, is shown in Fig. 5. The core fraction f_c decreases only slightly with increasing activity, indicating that the relative contribution from the core remains stable. In contrast, the coherence parameter p_c rises significantly, suggesting an increasing degree of partial coherence in pion emission.

4 Conclusion

The forward geometry of LHCb enables unique correlation studies in small systems. The comparison of elliptic flow in pPb and Pbp collisions, probing two distinct Bjorken-x regions, shows that v_2 and v_3 are consistent at similar multiplicities, indicating a limited role of initial-state effects in partice anisotropy. In addition, the first measurement of three-pion Bose–Einstein correlations in proton–proton collisions reveals hints of partial coherence in pion emission within the core–halo framework. These results highlight the distinctive contribution of the LHCb collaboration to the study of collective phenomena.

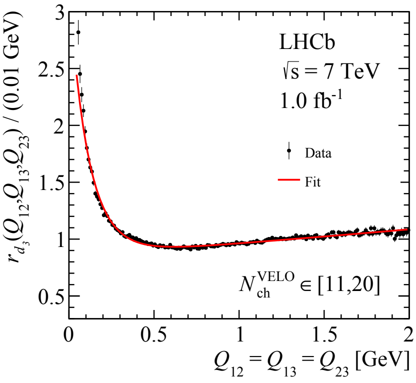

Figure 4. Results of the fit to the three-particle double ratio (r_{d3}) for same-sign pion triplets in a bin of VELO track multiplicity in proton-proton collisions. The red line illustrates the fit performed using the parametrization from 1.

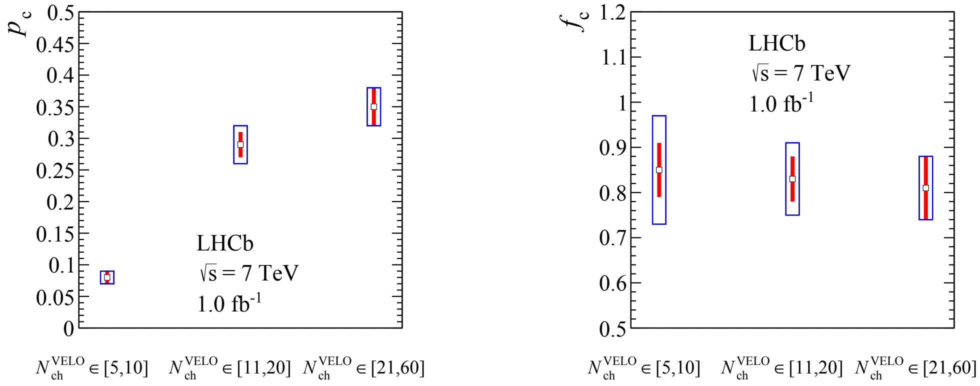

Figure 5. Values of the parameters of the core-halo model determined in three bins of VELO track multiplicity in proton-proton collisions.

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