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# Collective behavior in small systems

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**Abstract**

The presence of correlations between particles significantly separated in pseudorapidity in proton-proton and proton-nucleus collisions has raised questions about whether collective effects are observed in small collision systems as well as in heavy-ion collisions. The quantification of these long-range correlations by $v_n$ coefficients is of particular interest. A selection of the latest $v_n$ measurements is presented, including results from the recent $d$+Au beam energy scan at RHIC where a significant non-zero $v_2$ is measured down to low center-of-mass energies ($\sqrt{s_{\mathrm{NN}}} = 39$ GeV). Results from a collision system scan – comprising $p$+Au, $d$+Au, and $^3$He+Au collisions – are also shown to address the role of the initial nuclear geometry in the final state anisotropy. Finally, the challenge of measuring multi-particle cumulants, particularly $c_2\{4\}$, in $p$+$p$ collisions is discussed, and new methods for reducing the effects of non-flow are shown to produce a more robust measurement of $v_2\{4\}$ in $p$+$p$ collisions.

*Keywords:* small systems, collective behavior, heavy-ion collisions

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## 1. Introduction

The surprising discovery of the "ridge" – a correlation between particles which are significantly separated in pseudorapidity ($\eta$) – in $p$+$p$ and $p$+$A$ collisions opened many questions about the interpretation of these correlation structures both in heavy-ion collisions and in smaller systems. Causality arguments suggest that correlations between particles separated in $\eta$ should originate at early times in the evolution of the collision, either in the initial state or in the initial energy distribution. It is suggested that collective interactions are needed to transform the early spatial correlations into the observed final-state momentum-space correlations. In heavy-ion collisions, the presence of long-range ridges has typically been attributed to the collective hydrodynamic behavior of the medium produced in such collisions, but it is unclear whether the ridges in small systems imply hydrodynamics or if there are other physical mechanisms which produce similar structures. In this proceedings, to avoid making reference to a specific physical explanation for the ridge, collectivity is defined as multiple particles correlated across rapidity due to a common source.

The ridge in small systems was first observed in an analysis of two-particle angular correlations in high multiplicity $p$+$p$ collisions at $\sqrt{s} = 7$ TeV [1], where it appears as a correlation in azimuthal angle ($\varphi$) between particles across large ranges of pseudorapidity. The nearside ridge was also observed in $p$+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV [2], and after subtraction of jet-like structures a symmetric "double ridge" was observed on the awayside [3, 4]. The double ridge structure has been quantified by $v_n$ coefficients, analogous to those studied in heavy-ion collisions. Since then, the ridge and $v_n$ have been studied in other

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collision systems and differentially with respect to momentum, particle species, pseudorapidity, etc. A selection of the latest results is discussed in these proceedings.

## 2. Observables and analysis methods

There are several analysis techniques currently employed for studying ridges in small (and large) collision systems. The first is the direct analysis of two-particle correlation functions. The correlation function, $C(\Delta\varphi, \Delta\eta)$, is defined as the distribution in relative azimuthal angle ($\Delta\varphi = \varphi_{assoc} - \varphi_{trig}$) and relative pseudorapidity ($\Delta\eta = \eta_{assoc} - \eta_{trig}$) for particle pairs consisting of a trigger and associated particle. In order to study various physical effects, correlation functions can be constructed differentially with respect to properties of the trigger and associated particles (such as their transverse momenta $p_{\mathrm{T}}$, species, and pseudorapidity) and event properties (such as the centrality or multiplicity of the collision). Correlation functions in $p$+$p$ collisions are dominated by features characteristic of (mini-)jet production: a nearside peak localized around $(\Delta\varphi, \Delta\eta) = (0, 0)$, representing pairs of particles where the trigger and associated particles are fragments of the same jet, and the awayside peak localized around $\Delta\varphi = \pi$ but extended in $\Delta\eta$, representing pairs in which the trigger and associated particles are in back-to-back jets. In heavy-ion collisions, the same jet structures are observed, on top of additional correlations in $\Delta\varphi$ which are extended in $\Delta\eta$. These long-range structures in the two-particle correlation function are typically quantified by the coefficients, $v_n$, of a Fourier cosine series in $\Delta\varphi$,

$$\frac{dN}{d\Delta\varphi} \propto 1 + 2v_1^{trig} v_1^{assoc} \cos(\Delta\varphi) + 2v_2^{trig} v_2^{assoc} \cos(2\Delta\varphi) + 2v_3^{trig} v_3^{assoc} \cos(3\Delta\varphi) + ... \tag{1}$$

The magnitudes of the $v_n$ coefficients can be extracted directly by fitting the long-range part of $C(\Delta\varphi, \Delta\eta)$ with Eq. 1 (truncated at some order $n$). Measuring $v_2$ and the other $v_n$ components has been critical to determining the properties and dynamics of the medium created in heavy-ion collisions, and likewise the measurement of $v_n$ in small systems is of particular interest.

One of the challenges in characterizing the bulk dynamics with $v_n$ coefficients is reducing the influence of non-flow effects, such as jet production or resonance decays. This must be handled with particular care in small collision systems where multiplicities are significantly lower than in heavy-ion collisions and a significant proportion of the particle production is from (mini-)jet fragmentation. It should be emphasized here that while correlations between particles which do not have a collective origin are commonly called "non-flow," a term which has been adopted from large collision systems into small ones, the use of the word "non-flow" does not imply the existence of flow in small systems.

While fitting the correlation function at large $|\Delta\eta|$ makes it possible to avoid the nearside jet peak, the awayside jet peak can still contribute to the measured $v_n$ coefficients (predominantly to $v_1$). For this reason, several methods have been utilized to further reduce the effects of non-flow on the measured $v_n$ coefficients.

One technique for removing correlations due to jet and minijet fragmentation is to subtract the correlations in low-multiplicity events from the high-multiplicity correlation functions. This procedure relies on the assumption that jet structures (both on the nearside and awayside) are independent of multiplicity, which was shown to be a reasonable approximation in $p$+Pb collisions [5]. The "template fit" procedure [6] is similar but allows the yields of the jet peaks to vary with multiplicity. In this method, the correlation function is fit with the following function,

$$Y^{\mathrm{templ}}(\Delta\varphi) = F Y^{\mathrm{periph}}(\Delta\varphi) + G(1 + 2v_{2,2} \cos 2\Delta\varphi), \tag{2}$$

where $Y^{\mathrm{periph}}(\Delta\varphi)$ is the correlation function in a selected low-multiplicity bin and $F$, $G$, and $v_{2,2}$ are fit parameters. Essentially, the template fit method assumes that the shape of the hard (jet-like) component is independent of multiplicity but allows the yield to vary (although note that the yields of the nearside and awayside peaks must scale together by the same factor $F$). Residual shapes in the correlation function are fit by a cosine series up to order $n = 2$.

It is necessary to determine whether the observed correlation structures arise from interactions between only a few particles, or whether they are a true collective effect involving a global correlation among many