XXVIIIth International Conference on Ultrarelativistic Nucleus-Nucleus Collisions
(Quark Matter 2019)

Long-range collectivity in small collision-systems with
two- and four-particle correlations @ STAR

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Abstract
New STAR differential and integral $v_2, v_3$ measurements that explicitly account for non-flow contributions, are reported for $p/d/^{3}$He+Au, collisions at $\sqrt{s_{NN}} = 200$ GeV. The measurements, which leverage the two-particle correlators for $p/d/^{3}$He+Au and minimum-bias $p+p$ collisions in tandem with three well established methods of non-flow subtraction, are observed to be method-independent. For comparable multiplicities, they further indicate system-independent $v_2$ and $v_3$ values that are consistent with the critical role of both size ($N_{ch}$) and the subnucleonic-fluctuations-driven eccentricities $\varepsilon_2, \varepsilon_3$, but are inconsistent with the notion of shape engineering in $p/d/^{3}$He+Au collisions. The scaling function derived from the measurements, confirm the important role of final-state effects across a broad spectrum of collision-system sizes and energies, and suggests an increase in $\eta/s(T, \mu_B)$ for small collision-systems.

Keywords:

1. Introduction
Relativistic heavy-ion collisions can lead to high energy density strongly interacting matter with an anisotropic transverse energy density profile. This matter not only quenches jets, but also expands and hadronize to produce particles with an azimuthal anisotropy that reflects the viscous hydrodynamic response to the initial energy density profile $\rho_e$. The shape of this profile, $\rho_e(r, \phi)$, can be characterized by the complex eccentricity vectors $E_n \equiv e_n e^{i \phi_n}$, where $e_n = \left(\varepsilon_n^2\right)^{1/2}$ and $\phi_n$ denote the magnitude and azimuthal direction of the $n^{th}$-order eccentricity vector which fluctuates from event to event $[2]$. The eccentricity fluctuations are driven by both nucleonic and subnucleonic fluctuations and can be estimated via a quark Glauber model. The quenched jets and the anisotropic flow which derives from the pressure gradients induced by $e_n$, result in an azimuthal anisotropy of the measured single-particle distribution, quantified by the complex anisotropy vectors $V_n \equiv v_n e^{i \Phi_n}$, where $v_n = \left(V_n^2\right)^{1/2}$, and $\Phi_n$ denotes the magnitude and azimuthal direction of the $n^{th}$-order anisotropy vector which also fluctuates from event to
event. Model comparisons to $v_4$ measurements continue to be an important avenue to estimate the transport coefficients for the partonic matter produced in large to moderate-sized collision systems [11, 12, 13].

For the small collision-systems produced in $p/d/^{3}$He+Au and $p$/Pb collisions, collective flow might not develop due to the presence of large gradients that could excite non-hydrodynamic modes or render invalid, the hydrodynamic gradient expansion [5, 6] required to accurately characterize the viscous hydrodynamic response. Indeed, a most vexing question that pervades our field is whether an alternative initial-state-driven mechanism [7] prevails over hydrodynamic expansion for these collision-systems. However, numerical simulations in strongly interacting theories suggest that hydrodynamics remains applicable even when the system size (R) is of $O(1/T)$ – the inverse temperature [8]. Here, subnucleonic fluctuations become crucial.

The current measurements for $p/d/^{3}$He+Au collisions, which supplement earlier measurements at both RHIC [9] and the LHC [10] aim to address the respective influence of collision-system size, $\varepsilon_n$ and its attendant subnucleonic fluctuations and viscous attenuation on the measured non-flow-mitigated $v_4$.

2. Two particle correlators and $v_n$ extraction

The measurements were obtained with the STAR detector, via the two-particle correlation method. The per-trigger yields $Y(\Delta \phi) = 1/N_{\text{Trig}} \times dN/d\Delta \phi$ for $0$ to $2\%$ $p$/Au, $0$ to $10\%$ $d$/Au and $0$ to $10\%$ $^{3}$He+Au collisions are shown as a function of $\Delta \phi$ in Figs. 1(a)-(c); for these correlators, the trigger (Trig$^{\text{+}}$) and the associated (Assoc$^{\text{-}}$) particles are measured in the ranges $0.2 < p_T < 2.0$ GeV/c and $|\eta| < 0.9$. The requirement $|\Delta \eta| > 1.0$ between the Trig$^{\text{+}}$- and the Assoc$^{\text{-}}$-particles was also imposed to suppress possible non-flow contributions from the near-side jet. Figures 1(a)-(c) indicate a near-side “ridge” suggestive of an influence from flow-like contributions to the measured correlators for $p/d/^{3}$He+Au collisions. The absence of this ridge for minimum-bias (MB) $p+p$ collisions (cf Fig. 1), further suggests that the $p+p$ correlator can be leveraged to obtain quantitative estimates of the non-flow contributions to the $p/d/^{3}$He+Au correlators.

Three separate methods were utilized to estimate and subtract the non-flow contributions to the measured differential correlation functions $Y(\Delta \phi, p_T, \text{cent})$ used to extract $v_2, v_3, v_2, v_3 (N_{\text{ch}})$. One is based on the template-fit method [11]. The other two are based on Fourier expansion fits to the measured correlators [12]. The template fitting procedure [11] is illustrated in Fig. 1. It assumes that the central $p/d/^{3}$He+Au $Y(\Delta \phi)$ distributions are a superposition of a scaled MB $Y(\Delta \phi)$ distribution for $p+p$ collisions and a constant modulated by the ridge $\sum_{n=2}^{4} c_{n}^\text{sub} \cos(n \Delta \phi)$ as: $Y(\Delta \phi)^{\text{templ}} = FY(\Delta \phi)^{pp} + Y(\Delta \phi)^{\text{ridge}}$, where $Y(\Delta \phi)^{\text{ridge}} = G \left[ 1 + 2 \sum_{n=2}^{4} c_{n}^\text{sub} \cos(n \Delta \phi) \right]$, with free parameters $F$ and $c_{n}^\text{sub}$. The coefficient $G$, which represents the magnitude of the combinatoric component of $Y(\Delta \phi)^{\text{ridge}}$, is fixed by requiring that $\int_{0}^{\pi} \Delta \phi \ Y^{\text{templ}} = \int_{0}^{\pi} \Delta \phi \ Y^{\text{MB}}$. Fig. 1 shows that the template fit accounts for the data quite well.

Methods two and three rely on Fourier fits to the measured two particle correlators; $Y(\Delta \phi) = c_{0}(1 + \sum_{n=1}^{4} 2c_{n} \cos(n \Delta \phi))$. Method two assumes that the non-flow contributions to $p/d/^{3}$He+Au is a superposition of several proton-proton collisions. This leads to non-flow contributions that are equal to $c_{2}^{2}$, but diluted by the pair-yield coefficient ($c_{0}$) difference between $p+p$ and $p/d/^{3}$He+Au. The subtracted coefficients $c_{n}^\text{sub}$...
for \( p/d^3 \)He+Au are then obtained as: \( \varepsilon_n^{\text{sub}} = \varepsilon_n - \varepsilon_n^{pp} \times \frac{\varepsilon_n^{T}}{\varepsilon_n^{pp}} \), where \( \varepsilon_n = \varepsilon_n^{\text{Trig}} \times \varepsilon_n^{\text{Assoc}} \), the product of the flow coefficients \( \varepsilon_n \) for trigger- and associated-particles. Then \( \varepsilon_n^{\text{Trig}} = \varepsilon_n^{\text{Assoc}} \) and \( \varepsilon_n^{\text{sub,Trig}} = \varepsilon_n^{\text{sub,Assoc}} \). Method three assumes that \( c_1 \) is dominated by the away-side jet. This leads to the estimate that the ratio of the non-flow between \( p + p \) and \( p/d^3 \)He+Au is proportional to the ratio of the \( c_1 \) values for \( p + p \) and \( p/d^3 \)He+Au respectively. Thus, \( \varepsilon_n^{\text{sub}} \) can be obtained as: \( \varepsilon_n^{\text{sub}} = \varepsilon_n - \varepsilon_n^{pp} \times \frac{\varepsilon_n}{\varepsilon_n^{pp}} \), and used to extract \( \varepsilon_n^{\text{sub}} \) as described for method two. It is noteworthy that closure tests were performed with simulated events from the AMPT model to aid validation of the efficacy of the respective methods for non-flow mitigation.

3. Results

The \( v_2(p_T) \) and \( v_3(p_T) \) values for \( p/d^3 \)He+Au before and after non-flow subtraction, are compared for all three methods in the left panel of Fig. 2. They indicate non-flow contributions that are system-dependent, but the non-flow mitigated \( v_2(p_T) \) (top panels) and \( v_3(p_T) \) (bottom panels) are method-independent within the indicated uncertainties. Here, it is noteworthy that the un-subtracted \( v_3(p_T) \) is a lower limit since non-flow subtraction leads to higher \( v_3(p_T) \) values. The uncertainties for \( v_2(p_T) \) and \( v_3(p_T) \) reflect statistical, as well as systematic uncertainties linked to (i) track related backgrounds, (ii) pileup effects and (iii) the methods of non-flow subtraction. The right panel of Fig. 2 indicates magnitudes and trends for the \( p_T \)-integrated \( v_2(2) \) and \( v_2(4) \) for \( d+Au \) and \( 3^1 \)He+Au, that are consistent with an important influence from both subnucleonic eccentricity fluctuations and size-driven \( (N_{ch}) \) viscous attenuation. Note that the statistics available for the \( p+Au \) data precluded a statistically significant measurement of \( c_3(4) \) and hence, \( v_3(4) \).

The \( v_2(p_T) \) and \( v_3(p_T) \) measurements for \( p/d^3 \)He+Au are compared to published PHENIX measurements \( [9] \) in Fig. 3. The comparisons for \( v_2(p_T) \) (left panel) show that, within the indicated uncertainties,
the $v_2(p_T)$ data from both experiments are in reasonable agreement, albeit with modest $p_T$-dependent differences for $p_T > 1$ GeV/c ($d+Au$) and $p_T < 1$ GeV/c ($p+Au$). The $v_3(p_T)$ data for $^3$He$+Au$ (right panel) are also in reasonably good agreement. However, the $v_3(p_T)$ measurements for $p+Au$ and $d+Au$ are about a factor of 3-4 larger than those reported by PHENIX, and lie well outside the statistical and systematic uncertainties of the current measurements. The STAR results indicate that the fluctuations-driven $v_3(p_T)$ is system-independent which contrasts with the earlier report of a system-dependent $v_3(p_T)$ [9].

The non-flow mitigated $v_n$ measurements shown in Fig. 2 can be checked for the respective influence of collision-system size ($N_{ch}$), $\epsilon_n$ and its attendant subnucleonic fluctuations and viscous attenuation, via an anisotropy scaling function [13]. The scaling function $S_{FS}(v_n/\epsilon_n, p_T, N_{ch}, \eta/s, q)$: $v_n/\epsilon_n = \exp (\frac{1}{1-2\epsilon_n(p_T)} \frac{1}{1+2\epsilon_n(p_T)} \frac{n[p_T]}{N_{ch}(p_T)})$, which incorporates the physics of jet suppression: $R_{\Lambda}(p_T, L) = \exp \left( \frac{2n[L]}{\sqrt{N_{ch}}} \frac{1}{\sqrt{\epsilon_n(p_T)}} \right) + \frac{1}{\sqrt{\epsilon_n(p_T)}} \frac{R_{\Lambda}(0, p_T)}{R_{\Lambda}(0, p_T)} = \frac{1-2\epsilon_n(p_T)}{1+2\epsilon_n(p_T)}$, and hydrodynamic viscous attenuation: $v_n/\epsilon_n \propto \exp (\frac{-n[p_T]}{N_{ch}(p_T)} \frac{1}{\sqrt{\epsilon_n(p_T)}} \frac{RT}{\epsilon_n(p_T)} \frac{\sigma_{blue}}{\sigma_{red}})$, which incorporates the physics of $\eta/s(T, \mu_B)$, confers these dependences via a collapse of diverse measurements of $v_n$ on to a single curve, for fully constrained scaling coefficients. In turn, the coefficients give insight on the magnitude of the associated transport coefficients. The scaling function shown in Fig. 2 indicates that the measurements are consistent with the final-state (FS) effects which account for the broad spectrum of collision-system sizes and energies summarized in the figure. Note the jet quenching(viscous attenuation) branch for $p_T > 4(p_T < 4)$ GeV/c.

The resulting scaling coefficients not only suggest an increase in the magnitude of the specific viscosity $\eta/s(T, \mu_B)$, from RHIC to LHC energies, but also an increase for relatively small collision-systems.

4. Summary

New STAR differential and integral $v_n$ measurements that explicitly account for non-flow contributions, are reported for $p/d/^{3}$He$+Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV. The measurements which are compared to published PHENIX results, indicate system-independent values of $v_2$ and $v_3$ for comparable charged hadron multiplicity, that are consistent with the critical influence of both size ($N_{ch}$) and the subnucleonic-fluctuations-driven eccentricities, $\epsilon_{2,3}$. However, they are inconsistent with the notion of shape engineering in $p/d/^{3}$He$+Au$ collisions. The scaling function derived from the measurements, confirm the important role of final-state effects across a broad spectrum of collision-system sizes and energies, and suggests an increase in $\eta/s(T, \mu_B)$ for small collision-systems. Future supplemental measurements at RHIC and the LHC, for systems such as O$+O$, could provide additional constraints and insights.

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