Importance of Multiplicity Fluctuations in Entropy Scaling

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One of the greatest uncertainties in heavy-ion collisions is the description of the initial state. Different models predict a wide range of initial energy density distributions based on their underlying assumptions. Final flow harmonics are sensitive to these differences in the initial state due to the nearly linear mapping between eccentricities and anisotropic flow harmonics. The Trento code uses a model-agnostic approach by phenomenologically parameterizing the initial state and constraining those parameters from a Bayesian analysis. There the multiplicity fluctuations were determined by a one parameter Γ distribution. However, initial-state models arising from the Color-Glass Condensate (CGC) framework lead to an initial energy density which is outside the functional form considered in Trento and its later Bayesian analyses because they rely on log-normal multiplicity fluctuations. We compare $T_A T_B$ scaling (CGC-like) to $\sqrt{T_A T_B}$ scaling (preferred from a Trento Bayesian analysis) and find that the $T_A T_B$ form together with log-normal fluctuations is a reasonable candidate to describe the multiplicity fluctuations but leads to larger eccentricities, which would affect the extraction of viscosity in small systems.

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1. Introduction

Understanding the initial state of heavy-ion collisions requires real-time non-perturbative calculations in Quantum Chromodynamics that cannot be done on the lattice. The initial condition affects the final state, which affects the extraction of viscosities from comparisons to experimental measurements of flow harmonics v_n. The initial state can be quantified using eccentricities $\varepsilon_n = |\langle e^{in\phi}\rangle|$, which are strongly correlated with v_n [1, 2]. The extraction of viscosity is directly correlated with the model's ε_n [3]. Thus, the correct description of the initial state is crucial to extract properties of the Quark Gluon Plasma. Recently a Bayesian analysis used a phenomenologically based initial state, TRENTO, and demonstrated a preference for the initial entropy density $s \propto \sqrt{T_A T_B}$ where T_A, T_B are the nuclear thickness functions [4]. The Bayesian analysis assumed a Γ functional form for the event-by-event multiplicity fluctuations [4]. This choice restricts the range of models considered, excluding potentially viable models such as a Color-Glass Condensate (CGC) description of the initial state [5–8]. In Ref. [5] the authors investigated a CGC-like linear scaling of the initial energy density $\epsilon \propto T_A T_B$ and considered a log-normal distribution for the functional form of the multiplicity fluctuations. Here, we systematically study the impact of these two initial-state models and choices of multiplicity fluctuations on the initial-state eccentricities.

2. Methods

The initial state in Trento is characterized by thickness functions of the form $T_{A,B} = \omega_{A,B} \int dz\, \rho$ where ρ is the number density of individual nucleons and ω is a multiplicity weight which fluctuates event by event. The weights ω are sampled from a distribution whose mean in 1 but allow for high-multiplicity fluctuations within a given nucleon. In Trento, that distribution is chosen to be a one-parameter Γ distribution of the form

$$P_k(\omega) = \frac{k^k}{\Gamma(k)} \omega^{k-1} e^{-k\omega},\tag{1}$$

with the parameter k controlling the shape of the distribution [4]. In the limit $k \to \infty$, the distribution Eq. (1) approaches a delta function $\delta(\omega)$; it becomes wider as $k \to 1$; and blows up at 0 when $k < 1$. Given this assumed functional form, the Bayesian analysis found that the initial-state model $s \propto \sqrt{T_A T_B}$ was preferred. Other models [5], using instead a log-normal distribution

$$P_k(\omega) = \frac{2}{\omega k \sqrt{2\pi}} e^{-\frac{\ln^2(\omega^2)}{2k^2}},\tag{2}$$

in conjunction with the linear scaling $\epsilon \propto T_A T_B$ can also describe the data. The log-normal distribution Eq. (2) becomes a delta function $\delta(\omega)$ in the limit $k \to 0$, while large values $k \sim O(1)$ correspond to a wider distribution.

To systematically study the effects of these different choices, we have added both linear scaling and the log-normal distribution to Trento. The effect of these choices can be seen in the multiplicity distributions shown in Fig. 1, where k, for each distribution and functional form, is tuned to best reproduce STAR data for dAu at 200 GeV. Below $N_{ch}/\langle N_{ch}\rangle = 4$, there is good agreement with the data in all four cases. The high-multiplicity tail of the distribution is where the curves start to depart
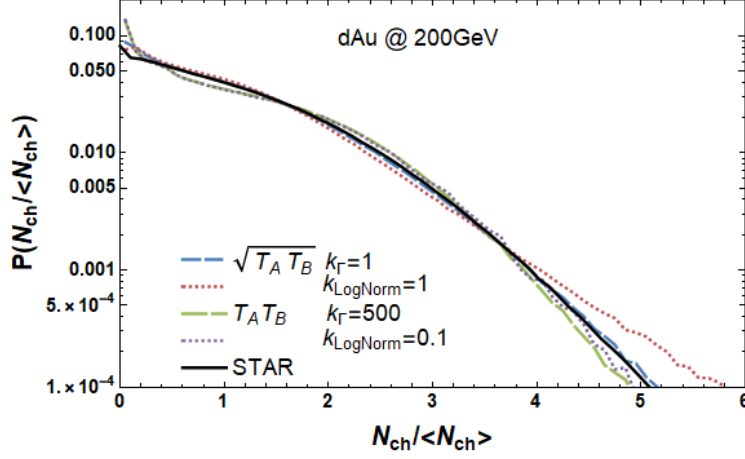
Figure 1: Multiplicity Distribution of dAu for functional forms $\sqrt{T_A T_B}$ and $T_A T_B$ using best fits for Γ and lognormal multiplicity fluctuation distributions.

from the data, with $\sqrt{T_A T_B}$ and log-normal fluctuations overpredicting the data by a significant amount. Γ multiplicity fluctuations work well with Trento's $\sqrt{T_A T_B}$ and log normal fluctuations do not. Across both fluctuation distributions, $T_A T_B$ favors a narrow distribution providing few fluctuations while $\sqrt{T_A T_B}$ prefers a wider distribution leading to a lot of fluctuations, suggesting linear scaling is able to match data by mean field while $\sqrt{T_A T_B}$ requires many fluctuations to reach the same result.

3. Results

The effect of these choices in functional form and multiplicity fluctuations can be seen in the plots of $\varepsilon_2\{2\}$ (left), that describes the ellipticity of the initial state, and $\varepsilon_3\{2\}$ (right), which characterizes the triangular geometry, shown in Fig. (2). Despite agreement in multiplicity
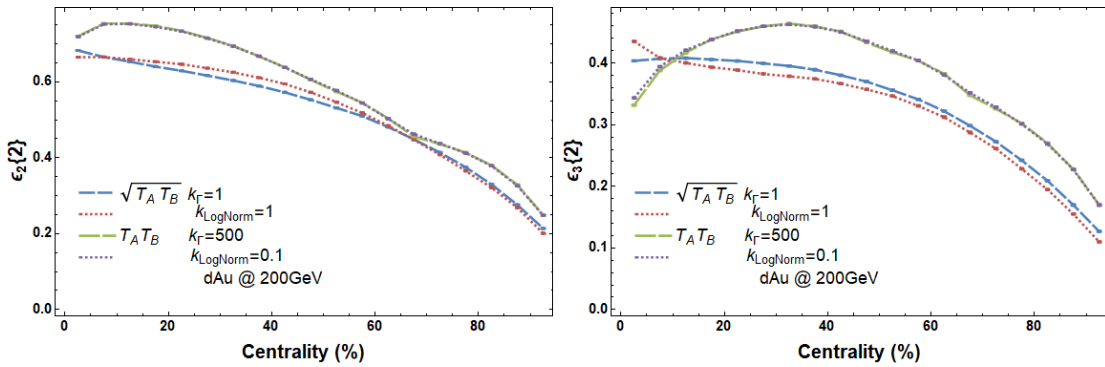

Figure 2: Two particle eccentricities of dAu for functional forms $\sqrt{T_A T_B}$ and $T_A T_B$ using best fits for Γ and lognormal multiplicity fluctuation distributions.

distribution below $N_{ch}/\langle N_{ch}\rangle = 4$, the eccentricities differ significantly. Linear scaling leads

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to larger eccentricities than $\sqrt{T_A T_B}$, except for a dip in $\varepsilon_3\{2\}$ in central events. This could be a mean field effect, $\sqrt{T_A T_B}$ spreads out the energy more than $T_A T_B$ and slightly washes out the geometry. The difference in choice of multiplicity fluctuations is negligible except for $\sqrt{T_A T_B}$ at low centralities, where the Γ fluctuations trend downward or level off while the log normal trend upward. The effect of the differences in the eccentricities of the two functional forms will be seen in the extraction of shear viscosity with $T_A T_B$ needing a larger viscosity.

4. Conclusion

Trento's preferred functional form $T_R = \sqrt{T_A T_B}$ works best with a Γ multiplicity fluctuation distribution, suggesting the choice of functional form is correlated with the multiplicity fluctuation distribution. The linear functional form $T_R \propto T_A T_B$, which is outside the scope considered in the Trento Bayesian analysis, is also able to reproduce the experimental dAu multiplicity distributions with fewer multiplicity fluctuations. This may suggest that the parameter space considered in Trento's Bayesian was overly restrictive, excluding some viable models in small systems. Between the two models, there is a noticeable difference in the magnitude of the eccentricities $\varepsilon_2\{2\}, \varepsilon_3\{2\}$, although the trends are qualitatively similar. The difference in eccentricities suggests that there is systematic uncertainty in the Trento Bayesian extraction of QGP viscosities in small systems, which could be controlled by increasing the functional space of the Bayesian analysis.

Acknowledgements

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