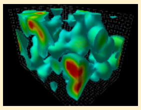
Ultracentral Collisions of Small and Deformed Systems at RHIC

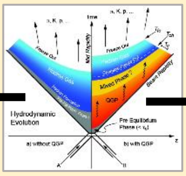
arXiv:1905.13323

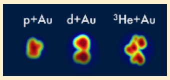
Jacquelyn Noronha-Hostler[1], Noah Paladino[1], Skanda Rao[1],
Matthew D. Sievert[1], Douglas E. Wertepny[2]
[1]Rutgers University, Piscataway, NJ USA [2]University of the Negev, Beer-Sheva, Israel

Possible sources of flow-like signals in small system collisions



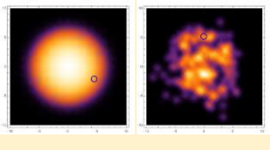
CGC model
Small-x gluons are involved in many-body correlations that give rise to flow-like signals





Hydrodynamic model
Small QGP droplets evolve hydrodynamically to produce flow signals

Significance of distribution function



Examine:
- Effects of introducing sub-nucleon fluctuations
- Changing effective reduced thickness function $f(T_A^\alpha(\overrightarrow{x_\perp}), T_B^\alpha(\overrightarrow{x_\perp}))$ in collision generation

Sharper distribution in initial energy density profile → ***Change in flow signals?***

Flow signals from CGC

- Single-particle distributions are isotropic → two-particle cumulant contains only non-flow correlations
- First approximation for $p_T^2 \gg Q_s^2$ [1]:

n even: $\delta_2(p_1,p_2) = \int d^2x_\perp T_A^2(\overrightarrow{x_\perp})\, T_B^2(\overrightarrow{x_\perp}) f_n(p_1,p_2)$
n odd: $\delta_2(p_1,p_2) = \int d^2x_\perp T_A^3(\overrightarrow{x_\perp})\, T_B^3(\overrightarrow{x_\perp}) g_n(p_1,p_2)$

- Define relevant moments of nuclear density profiles T_A and T_B:

$$\mathfrak{T}_\alpha = \int d^2x_\perp T_A^\alpha(\overrightarrow{x_\perp})\, T_B^\alpha(\overrightarrow{x_\perp})$$

- Initial conditions model determines N_{pairs} dependence on T_A and T_B

$$N_{pairs} \approx N_{tot}^2 \propto [\mathfrak{T}_r]^2$$

where $r = \frac{1}{2}$ or 1 (reduced thickness models)

$$\boxed{\frac{v_n^i\{2\}}{v_n\{2\}} = \sqrt{\frac{\langle(\mathfrak{T}_r)^2\rangle_{0-1\%}}{\langle(\mathfrak{T}_r)^2\rangle_i}\frac{\langle\mathfrak{T}_{v_n}\rangle_i}{\langle\mathfrak{T}_{v_n}\rangle_{0-1\%}}}}$$

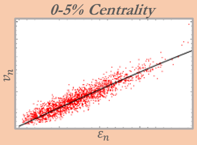
where $v_n = 2$ or 3 (even or odd harmonic)

Flow signals from QGP droplet

- Eccentricities describe initial energy distribution:

$$\varepsilon_n = -\frac{\int r^n e^{in\phi}\epsilon(r,\phi) r dr d\phi}{\int r^n \epsilon(r,\phi) r dr d\phi}$$

0-5% Centrality



- Linear response:

$$v_n = \kappa_n \varepsilon_n$$
$$v_n\{2\} = \sqrt{\langle v_n^2\rangle}$$
$$\boxed{\frac{v_n^i\{2\}}{v_n\{2\}} = \sqrt{\frac{\langle\varepsilon_n^2\rangle_i}{\langle\varepsilon_n^2\rangle_{0-1\%}}}}$$

Method of comparison

1. Select ultra-central events (1% by N_{part})
2. Sub-bin by multiplicity to select geometry
3. Calculate two-particle cumulant $v_n^2\{2\}$ from known values in each bin i:

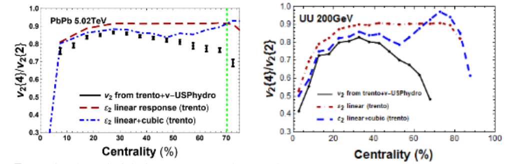
$$v_n\{2\} = \frac{1}{\langle N_{pairs}\rangle}\left\langle \int_{p_1,p_2} e^{in(\phi_1-\phi_2)} \frac{dN}{d^3p_1 d^3p_2}\right\rangle$$

$$\frac{dN}{d^3p_1 d^3p_2} = \frac{dN}{d^3p_1}\frac{dN}{d^3p_2} + \delta_2(p_1,p_2)$$

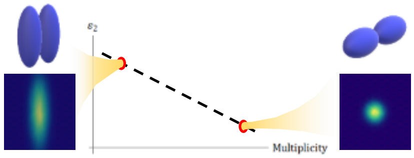
flow
non-flow

Using deformed nuclei (^{238}U, ^{9}Be) as discriminators between QGP and CGC

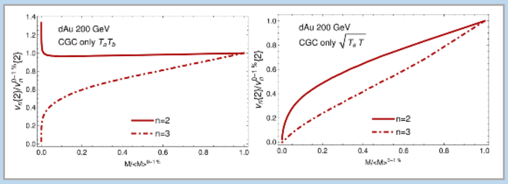
Lower flow fluctuations in ultra-central UU collisions due to driving geometry



Pure hydro (initial geometry dependence):
→ **negative correlation** of elliptic flow signals with multiplicity
Pure CGC (multiplicity dependence):
→ **positive correlation** of elliptic flow signals with multiplicity [2]



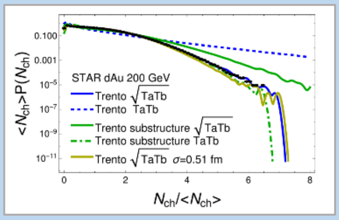
Models used to produce events: Collisions for both CGC and QGP calculations are generated with TRENTo software [3] modified with new ions and to include a new scaling in the effective reduced thickness function $f(A,B)$. Multiplicity is calculated in TRENTo as $\boldsymbol{S = c\int d^2x_\perp f(T_A^\alpha(\overrightarrow{x_\perp}), T_B^\alpha(\overrightarrow{x_\perp}))}$ where c is a scaling constant. By default TRENTo includes a scaling as $f(A,B) = \sqrt{AB}$ ($r = \frac{1}{2}$ above). $f(A,B) = AB$ ($r = 1$) is include to match theory predictions of the expected behavior of flow with multiplicity [1]. TRENTo is also modified to output the moments $\mathfrak{T}_\alpha$ for CGC calculations. To evolve these distributions hydrodynamically for QGP calculations, the software v-USPhydro [4] was used with parameters from [5].

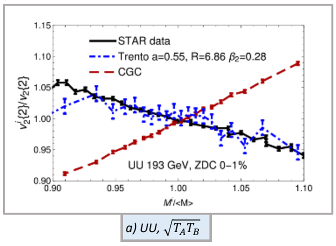


Calculated multiplicity dependence across all centrality classes

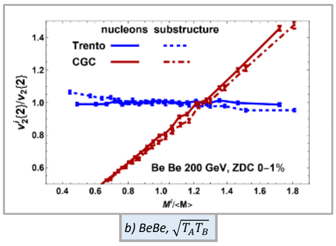
Accuracy of initial conditions model

- Changes to TRENTo model tested:
    - Effective reduced thickness function: $\sqrt{T_AT_B} \to T_AT_B$
    - Turning on and off sub-nucleon fluctuations
    - Varying cross-sectional area σ: 0.3 fm→ 0.51 fm
- $\sqrt{T_AT_B} \to T_AT_B$ agrees well with predictions in [6] of scaling of elliptic flow in semidilute-dense systems:
    - $v_2 \propto M^0$
    - $v_3 \propto M^{1/2}$
- As predicted by [7], cross section of 0.3 fm fits STAR data better
- T_AT_B scaling does not do well; parameter retuning needed

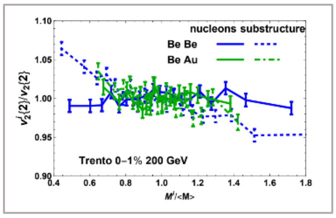




a) UU, $\sqrt{T_AT_B}$



b) BeBe, $\sqrt{T_AT_B}$



Results of CGC-QGP comparison

- QGP picture fares far better in UU collisions, ultracentral small deformed ions still need to be investigated
- BeBe collisions as an intermediate between small systems collisions like dAu and large systems like UU known to form QGP
    - Predict similar opposite correlation, though hydro response is flatter
- Multiplicity fluctuations → Discernable difference between BeBe results

→ propose experiments with symmetric and asymmetric Be collisions

References

[1] Y. V. Kovchegov and D. E. Wertepny, Nucl. Phys. A906, 50 (2013), arXiv:1212.1195 [hep-ph].
[2] Y. V. Kovchegov and D. E. Wertepny, Nucl. Phys. A925, 254 (2014), arXiv:1310.6701 [hep-ph].
[3] J. S. Moreland, J. E. Bernhard, and S. A. Bass, Phys. Rev. C92, 011901 (2015), arXiv:1412.4708 [nucl-th].
[4] J. Noronha-Hostler et al, Phys. Rev. C88, 044916 (2013), arXiv:1305.1981 [nucl-th].
[5] Alba et al, Phys.Rev. C98 (2018) no.3, 034909
[6] M. Mace, V. V. Skokov, P. Tribedy, and R. Venugopalan, (2018), arXiv:1807.00825 [hep-ph].
[7] G. Giacalone, J. Noronha-Hostler, and J.-Y. Ollitrault, Phys. Rev. C95, 054910 (2017), arXiv:1702.01730 [nuclth].