Characterizing the Initial Stages of a Heavy-Ion Collision for Determining Final State Evolution: Including Conserved Charges, Momentum, and Stress

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Introduction

- Heavy-ion collision: complicated process represented as
  \[ V_n = \kappa_n \epsilon_n \]
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Final State
Introduction

- Heavy-ion collision: complicated process represented as $V_n = \kappa_n \epsilon_n$

  - Final State
  - Initial State

Response

Until now: only energy density is considered

Goal: include $T_{\mu\nu}$ components and conserved currents

Motivation: determine relevant aspects, importance of the contributions, importance in other collision systems
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$$V_n = \kappa_n \epsilon_n$$

Final State \quad Response \quad Initial State
Heavy-ion collision: complicated process represented as

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Final State \hspace{10cm} Response \hspace{10cm} Initial State

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Final State \( \rightarrow \) Response \( \rightarrow \) Initial State

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Cumulants expansion
Including Baryon density

\[ \rho(\vec{x}) = T^{\tau\tau}(\vec{x}) \]
Cumulants expansion
Including Baryon density

$$\rho(\vec{x}) = T^{\tau\tau}(\vec{x})$$

$$\epsilon_n = -\frac{W_{n,n}}{\left(W_{0,2}\right)^{n/2}}$$

$$V_n = \kappa_n \epsilon_n$$
Cumulants expansion

Including Baryon density

\[ \rho(\vec{x}) = T^{\tau\tau}(\vec{x}) + \gamma B(\vec{x}) \]

\[ \epsilon_n(\gamma) = - \frac{W_{n,n}}{\left( W_{0,2} \right)^{n/2}} \]

\[ V_n = \kappa_n \epsilon_n(\gamma) \]
Cumulants expansion
Including Baryon density

- **Charge conjugation**

  \[ B(\vec{x}) \rightarrow -B(\vec{x}) \]

  \[ V_{n}^{(net)} \equiv V_{n}^{+p} - V_{n}^{-p} \]

- **Antisymmetrizing the eccentricity** \( \epsilon_{n}(\gamma) \)

  \[
  \epsilon_{n}^{(net)}(\gamma) \equiv \epsilon_{n}(\gamma) - \epsilon_{n}(-\gamma)
  \]
Cumulants expansion

Including Baryon density

- Charge conjugation

\[ B(\vec{x}) \rightarrow -B(\vec{x}) \]

\[ V_{n}^{(\text{net})} \equiv V_{n}^{+p} - V_{n}^{-p} \]

\[ \rho(\vec{x}) \]

\[ T^{\tau\tau}(\vec{x}) + \gamma B(\vec{x}) \rightarrow T^{\tau\tau}(\vec{x}) - \gamma B(\vec{x}) \]

- Antisymmetrizing the eccentricity \( \epsilon_{n}(\gamma) \)

\[ \epsilon_{n}^{(\text{net})}(\gamma) \equiv \epsilon_{n}(\gamma) - \epsilon_{n}(-\gamma) \]

\[ V_{n}^{(\text{net})} = \kappa_{n}\epsilon_{n}^{(\text{net})}(\gamma) \]
Numerical tests

\[ T^\tau (\vec{x}) = Ae^{-\frac{r^2}{2\sigma^2}} \]

\[ B(\vec{x}) = r^2 Re^{-\frac{r^2}{2\sigma^2}} \cos 2\phi \]

\[ B(\vec{x}) = r^2 Re^{-\frac{r^2}{2\sigma^2}} \cos 3\phi \]
\[ V_{2}^{\text{net}} = V_{2}^{+p} - V_{2}^{-p} \]

\[ B(\vec{x}) = r^2 \text{Re} \left( -\frac{r^2}{2\rho^2} \right) \cos 2\phi \]

\[
\begin{array}{c|c|c|c|c|c|c|c}
R (\text{fm}^{-1}) & 0.0 & 0.05 & 0.1 & 0.0 & 0.05 & 0.1 & 0.0 & 0.05 & 0.1 \\
\{0.0 - 0.1\} & \{0.0 - 0.1\} & \{0.0 - 0.1\} & \{0.0 - 0.1\} & \{0.0 - 0.1\} & \{0.0 - 0.1\} & \{0.0 - 0.1\} & \{0.0 - 0.1\} & \{0.0 - 0.1\} & \{0.0 - 0.1\} \\
\end{array}
\]
\[ V_{3}^{\text{net}} = V_{3}^{+p} - V_{3}^{-p} \]

\[ B(\vec{x}) = r^2 \text{Re} \left( -\frac{r^2}{2\rho^2} \cos 3\phi \right) \]

\[
\begin{array}{c|c}
R \text{ (fm}^{-1}) & \\
\hline
\{0.0 - 0.1\} & \\
\end{array}
\]
Conclusions

- Include other aspects of initial conditions in the eccentricity ($\epsilon_n$)
- Numerical tests
- How treat the charge conjugation (Baryon density)
Extra: Cumulants expansion

\[ \rho(\vec{x}) = T^{\tau \tau}(\vec{x}) \]

\[ e^{W(\vec{k})} = \int d^2 x \rho(\vec{x}) e^{-i \vec{k} \cdot \vec{x}} \]

\[ W(\vec{k}) = \sum_{n=-\infty}^{\infty} \sum_{m=-|n|}^{\infty} W_{n,m} k^m e^{-in\phi_k} \]

\[ \epsilon_n = -\frac{W_{n,n}}{\left(W_{0,2}\right)^{\frac{n}{2}}} \]

\[ V_n = \kappa_n \epsilon_n \]
Extra: Including Momentum and Stress

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\[ V_n = \kappa_n \epsilon_n \]
Extra: Including Momentum and Stress

\[ \rho(\vec{x}) = T^{\tau\tau}(\vec{x}) + \alpha \partial_i T^{\tau i}(\vec{x}) + \beta \partial_i \partial_j T^{ij}(\vec{x}) \]

\[ e^{W(\vec{k})} = \int d^2x \rho(\vec{x}) e^{-i\vec{k} \cdot \vec{x}} \]

\[ W(\vec{k}) = \sum_{n=-\infty}^{\infty} \sum_{m=-|n|}^{\infty} W_{n,m} k^m e^{-in\phi_k} \]

\[ \epsilon_n(\alpha, \beta) = -\frac{W_{n,n}}{\left(W_{0,2}\right)^{\frac{n}{2}}} \]

\[ V_n = \kappa_n \epsilon_n(\alpha, \beta) \]