Methods for anisotropic flow measurements with the MPD Experiment at NICA

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Outline

• Anisotropic flow at NICA energies
• Description of direct cumulant and event plane methods
• Sensitivity of different orders of cumulants to elliptic flow fluctuations
• Feasibility study for elliptic flow of charged hadrons:
  – for Au+Au, Bi+Bi collisions at $\sqrt{s_{NN}} = 7.7$ and 11.5 GeV in UrQMD model
  – for reconstructed UrQMD events in MPD detector at NICA
  – Comparison Bi+Bi with Au+Au collisions at $\sqrt{s_{NN}} = 7.7$ GeV
• Summary and outlook
Elliptic flow at NICA energies

\[
\frac{dN}{N_0 d(\phi - \psi_R)} = \frac{1}{2\pi} \left( 1 + \sum_{n=1}^{\infty} 2v_n \cos(n(\phi - \psi_R)) \right)
\]

- \(v_1\) - direct flow
- \(v_2\) - elliptic flow

- At \(\sqrt{s_{NN}}=4.5\) GeV pure string/hadronic cascade models give similar \(v_2\) signal compared to STAR data
- At \(\sqrt{s_{NN}}=7.7\) GeV pure string/hadronic cascade models underpredict \(v_2\)
- \(v_2\) is sensitive to the properties of strongly interacted matter
Description of event plane method

\[ Q_n = \sum_{j=1}^{N} w_n(j) e^{in\phi_j} = |Q_n| e^{in\Phi_n} \]  

(1)

\[ Q_n \cos(n\Psi_n) = X_n = \sum_i w_i \cos(n\phi_i), \]

\[ Q_n \sin(n\Psi_n) = Y_n = \sum_i w_i \sin(n\phi_i), \]

\[ \Psi_n = \left( \frac{\tan^{-1} \sum_i w_i \sin(n\phi_i)}{\sum_i w_i \cos(n\phi_i)} \right) / n \]  

(2)

• \( \eta \)-sub EP method: resolution of the reaction plane \( \Psi_2 \) obtained from 2 sub-events

Left half (\( \eta < -0.05 \)) \( \rightarrow \eta \)

Right half (\( \eta > 0.05 \)) \( \rightarrow \eta_+ \)

\[ \nu_2{\eta\text{-sub,EP}} = \frac{\langle \cos[n(\phi_{\eta_\pm} - \Psi_{2,\eta_\mp})]\rangle}{\sqrt{\langle \cos[n(\Psi_{2,\eta_+} - \Psi_{2,\eta_-})]\rangle}} \]  

(3)

Description of direct cumulant method for flow measurements

2 and 4 particle azimuthal correlations

\[ \langle 2 \rangle_n = \frac{\left| Q_n \right|^2 - M}{M(M-1)} \] (1) where \( Q_n = \sum_{i=1}^{M} e^{in\phi_i} \) (2)

\[ \langle 4 \rangle_n = \frac{|Q_n|^4 + |Q_{2n}|^2 - 2|Q_{2n}Q_{2n}^*| - 4M(M-2)|Q_n|^2 + 2M(M-3)}{M(M-1)(M-2)(M-3)} \] (3)

Elliptic flow estimate with direct cumulant method

\[ \langle 2 \rangle_n = v_n^2 + \delta_n \] \[ \langle 4 \rangle_n = v_n^4 + 4v_n^2\delta_n + 2\delta_n^2 \] (4)

\( v_n\{2\} = \sqrt{\langle 2 \rangle} \) \( v_n\{4\} = \sqrt{2\langle 2 \rangle^2 - \langle 4 \rangle} \) (5)

This method was introduced by Ante Bilandzic in Phys. Rev. C83:044913, 2011
Sensitivity of different orders cumulants to elliptic flow fluctuations

- How fluctuations affect the measured values of $v_n$. The effect of the fluctuations on $v_n$ estimates can be obtained from

$$\langle v_n^2 \rangle = \bar{v}_n^2 + \sigma_{v_n}^2, \quad \langle v_n^4 \rangle = \bar{v}_n^4 + 6\sigma_{v_n}^2 \bar{v}_n^2$$

$$v_n\{2\} = \sqrt{\langle v_n^2 \rangle}, \quad v_n\{4\} = 4\sqrt{2\langle v_n^2 \rangle^2 - \langle v_n^4 \rangle}$$

- The difference between $v_n\{2\}$ and $v_n\{4\}$ is sensitive to not only nonflow but also to the event-by-event $v_n$ fluctuations.

$$v_n\{2\} = \bar{v}_n + \frac{1}{2} \frac{\sigma_{v_n}^2}{\bar{v}_n}, \quad v_n\{4\} = \bar{v}_n - \frac{1}{2} \frac{\sigma_{v_n}^2}{\bar{v}_n}$$

Comparison of models results with STAR data for Au+Au collisions at 11.5 GeV and 7.7 GeV


- Fluctuation driven difference between $v_2(4)$ and $v_2(2)$ is reproduced in UrQMD and SMASH models
- Flow measurements for models were done using STAR-like analysis method
Results for $v_2$ from UrQMD model of Au+Au collisions at $\sqrt{s_{NN}} = 7.7$ GeV

- $v_2\{2\}$ is in a good agreement with $v_2(\psi_{2,TPC})$ at 10-40% centrality
- $v_2\{4\}$ is smaller than $v_2\{2\}$ due to fluctuations and nonflow
• $v_2(\psi, TPC)$ and $v_2(\psi_1, FHCal)$ are in a good agreement

• $v_2(4)$ and $v_2(\psi_1, FHCal)$ are smaller than $v_2(2)$ due to fluctuation and nonflow
Flow performance study with MPD (NICA)

- Total number of reconstructed Au+Au, Bi+Bi minimum bias events - 9 M, at 7.7 and 11.5 GeV
- Full reconstruction procedure was done using GEANT4 simulation
- Particle selection:
  - charged hadrons
  - $0.2 < p_T < 3$ GeV/c
  - $|\eta| < 1.5$ (TPC), $2 < |\eta| < 5$ (FHCal)
  - Number of TPC hits >16
  - Primary tracks selected
- Same methods ($v_2(2)$, $v_2(4)$, $v_2(\eta\text{-sub,EP})$) were used for reconstructed data
Performance study of $v_2$ for Au+Au at 7.7 and 11.5 GeV in MPD

Reconstructed and generated $v_2$ values are in a good agreement for all methods.
Au+Au vs. Bi+Bi collisions for reconstructed data in MPD

Expected small difference between colliding systems
Au+Au vs. Bi+Bi collisions for reconstructed data in MPD

FHCal event plane

Expected small difference between colliding systems
Summary and outlook

• Comparison of models with STAR data shows that at NICA energies $v_2$ grows non-monotonically with increasing beam energy

• UrQMD, SMASH models reproduce $v_2(4) / v_2(2)$ ratio for centrality range 0-60%.

• $v_2$ in UrQMD model for Au + Au collisions at 7.7 GeV:
  - $v_2(2)$ have good agreement with $v_2(\psi_{2,TPC})$ at 10-40% centrality.
  - $v_2(4)$ and $v_2(\psi_{1,FHCAL})$ are smaller than $v_2(2)$ due to fluctuation and nonflow

• Measurement of elliptic flow $v_2$ of charged hadrons using direct cumulant and event plane methods was implemented in MPD.
  - $v_2$ reconstructed and model data are in a good agreement.

• Comparison of results for Au+Au and Bi+Bi collisions shows expected small difference between colliding systems.
Thank you for you attention
Backup
Flow performance study with MPD (NICA)

- Total number of reconstructed Au+Au, Bi+Bi minimum bias events - 9 M, at 7.7 and 11.5 GeV
- Full reconstruction procedure was done using GEANT4 simulation
- Particle selection:
  - charged hadrons
  - $0.2 < p_T < 3$ GeV/c
  - $|\eta| < 1.5$ (TPC), $2 < |\eta| < 5$ (FHCal)
  - Number of TPC hits $>16$
  - Primary tracks selected
- Same methods ($v_2\{2\}$, $v_2\{4\}$, $v_2\{\eta\text{-sub,EP}\}$) were used for reconstructed data
Eccentricity: Bi+Bi vs Au+Au

UrQMD model predicts small difference between $\varepsilon_n$ of Au+Au and Bi+Bi
Sensitivity of different orders cumulants to elliptic flow fluctuations

- How fluctuations affect the measured values of $v_n$. The effect of the fluctuations on $v_n$ estimates can be obtained from

\[
\langle v_n^2 \rangle = \bar{v}_n^2 + \sigma_{v_n}^2, \quad \langle v_n^4 \rangle = \bar{v}_n^4 + 6\sigma_{v_n}^2 \bar{v}_n^2
\]

\[
v_n\{2\} = \sqrt{\langle v_n^2 \rangle}, \quad v_n\{4\} = 4\sqrt{2\langle v_n^2 \rangle^2 - \langle v_n^4 \rangle}
\]

- The difference between $v_n\{2\}$ and $v_n\{4\}$ is sensitive to not only nonflow but also to the event-by-event $v_n$ fluctuations.

\[
v_n\{2\} = \bar{v}_n + \frac{1}{2} \frac{\sigma_{v_n}^2}{\bar{v}_n}, \quad v_n\{4\} = \bar{v}_n - \frac{1}{2} \frac{\sigma_{v_n}^2}{\bar{v}_n}
\]

Cumulant results from Beam Energy Scans


- The magnitude and trend of the fluctuations, have weak beam energy dependence
  - Methods of flow measurements have different sensitivity to flow fluctuations
Cumulant results from Beam Energy Scans

Comprasssion of (a) $v_2\{2\}$ vs. $\langle N_{ch} \rangle$, (b) $v_2\{4\}$ vs. $\langle N_{ch} \rangle$ and (c) thir ratio for Au+Au collisions

arXiv:1807.07638

$\langle b_{geo} \rangle = 2.9$ fm
$-0.2 < y^{(0)} < 0.$

$\nu_2$ versus transverse momentum for protons measured in semi-central events and around mid-rapidity.

arXiv:nucl-ex/0504002
Results for $v_2$ from UrQMD model of Au+Au collisions at $\sqrt{s_{NN}} = 7.7$ GeV

- Total number of generated minimum bias events - 88 M

- Particle selection: charged hadrons, $0.2 < p_T < 3$ GeV/c

- Configuration of cumulant method:
  1. RFP and POI: charged hadrons;
  2. calculations were performed taking into account the effect of autocorrelation

- All 3 methods have the same kinematical cuts

\[ \begin{array}{c|c}
\text{Left} & \text{Right} \\
-1.5 < \eta < -0.05 & 0.05 < \eta < 1.5 \\
\end{array} \]

Left half ($\eta < 0.05$) → $\eta_-$
Right half ($\eta > 0.05$) → $\eta_+$
Results for $v_2$ for reconstructed events of MPD

$v_2\{2\}$ and $v_2\{4\}$ are in good agreement with $v_2\{\eta\text{-sub,EP}\}$ at 10-40% centrality.
2 and 4 particle azimuthal correlations

\[
\langle v^2_n \rangle \approx \langle e^{i n (\phi_1 - \phi_2)} \rangle + \delta_n \quad (1)
\]

\[
\langle v^4_n \rangle \approx \langle e^{i n (\phi_1 + \phi_2 - \phi_3 - \phi_4)} \rangle - 2 \cdot \langle e^{i n (\phi_1 - \phi_3)} \rangle \langle e^{i n (\phi_2 - \phi_4)} \rangle \quad (2)
\]

Elliptic flow estimate with direct cumulant method

\[
\langle v^2_n \rangle = \frac{|Q_n|^2 - M}{M (M - 1)} \quad (3) \quad \text{where} \quad Q_n = \sum_{i=1}^{M} e^{i n \phi_i} \quad (4)
\]

\[
\langle v^4_n \rangle = \frac{|Q_n|^4 + |Q_{2n}|^2 - 2 |Q_{2n} Q_n^* Q_n^*| - 4M (M - 2) |Q_n|^2 + 2M (M - 3)}{M (M - 1)(M - 2)(M - 3)} - 2 \cdot \langle v^2_n \rangle^2 \quad (5)
\]

This method was introduced by Ante Bilandzic in Phys. Rev. C83:044913, 2011