Methods for anisotropic flow measurements with the MPD Experiment at NICA

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Abstract. The anisotropic collective flow is one of the important observable values sensitive to transport properties of strongly interacting matter created in relativistic heavy-ion collisions. The performance of Multi-Purpose Detector (MPD) at NICA collider for elliptic flow measurements with Monte-Carlo simulations using collisions of Au+Au and Bi+Bi ions employing several state of the art event generators is studied. Different methods for flow measurements as event plane and direct cumulants are used to investigate the contribution of non-flow correlations and flow fluctuations.

1. Introduction
The Multi-Purpose Detector (MPD) experiment will be one of the main scientific pillars of the future Nuclotron-based Ion Collider fAcility (NICA) at JINR, Dubna [1, 2]. The main goal of the MPD research program is to explore the QCD phase diagram in the region of high baryon densities using relativistic heavy-ion collisions at $\sqrt{s_{NN}} = 4 - 11$ GeV. The anisotropic collective flow is one of the most important observable value which is sensitive to the transport properties of the strongly interacting matter and it can be quantified by the Fourier coefficients $v_n$ in the expansion of the particles azimuthal distribution as:

$$dN/d\phi \propto 1 + \sum_{n=1}^{2} 2v_n \cos(n(\phi - \Psi_n))$$

where $n$ is the order of the harmonic, $\phi$ is the azimuthal angle of particle of a given type, and $\Psi_n$ is the azimuthal angle of the $n$th-order event plane. Elliptic flow, $v_2 = \langle \cos[2(\phi - \Psi_n)] \rangle$, is the dominant flow signal at NICA energy regime. In this work, we discuss the anticipated physics performance of MPD detector system for anisotropic flow measurements at NICA energies.

2. The MPD detector system at NICA
The MPD detector system (Fig. 1, a) consists of a barrel part and two endcaps located inside the magnetic field. Time Projection Chamber (TPC) will be the central MPD tracking detector [2]. TPC will provide 3D tracking of charged particles, as well as the measurement of specific ionization energy loss $dE/dx$ for particle identification for $|\eta| < 1.2$. The TPC will be surrounded by a cylindrical barrel of the Time-of-Flight (TOF) detector with a timing resolution of the order of 50 ps. The combined system TPC+TOF will allow the efficient charged pion/kaon separation up to 1.5 GeV/c and protons/meson separation up to 2.5 GeV/c. The Forward Hadronic Calorimeter (FHCal), placed at $2^< |\eta|^ < 5$, will be used for centrality determination as well for the reconstruction of event plane from the directed flow of particles.
In this work, we use two models to simulate the heavy-ion collisions at NICA energies: UrQMD (Ultra-relativistic Quantum Molecular Dynamics) \[7, 8\] and SMASH (Simulating Many Accelerated Strongly-interacting Hadrons) \[9\]. In total, the sample of 120 M of minimum bias Au+Au events at \(\sqrt{s_{NN}} = 7.7\) and 11.5 GeV was used for elliptic flow performance study using different methods of analysis. We used term “generator-level” \(v_2\) data for these results. At the next step, a sample of 10 M UrQMD minimum bias events for each point in collision energy was used as an input for the full chain of the realistic simulations of the MPD detector subsystems’ based on the GEANT4 platform and reconstruction algorithms build in the MPDROOT. The main workflow with the reconstructed data is similar to the one described in the previous works \[10, 11\]. We named these \(v_2\) results as the “reconstructed” \(v_2\) data.

3. Methods for elliptic flow measurements in MPD
In this section we discuss how the event plane and direct cumulant methods can be used for the measurements of elliptic flow of the produced particles with MPD detector system at NICA. The event plane method correlates azimuthal angle \(\phi\) of each particle with the azimuthal angle \(\Psi_n\) of event plane determined from the anisotropic flow itself. The event flow vector \((Q_n)\) and the azimuthal angle of event plane \(\Psi_n\) can be defined for each harmonic, \(n\), of the Fourier expansion by:

\[
Q_{n,x} = \sum_i \omega_i \cos(n\varphi_i), \quad Q_{n,y} = \sum_i \omega_i \sin(n\varphi_i), \quad \Psi_n = \frac{1}{n} \tan^{-1} \left( \frac{Q_{n,y}}{Q_{n,x}} \right),
\]

where the sum runs over all particles \(i\) used in the event plane calculation, and \(\varphi_i\) and \(\omega_i\) are the laboratory azimuthal angle and the weight for the particle \(i\). For \(v_2\) measurements in MPD we can use both event planes from elliptic \((\Psi_{2,TPC})\) and directed flow \((\Psi_{1,FHCal})\):

\[
v_2\{\Psi_{2,TPC}\} = \frac{\langle \cos(2(\phi_i - \Psi_{2,TPC})) \rangle}{R_2(\Psi_{2,TPC})}, \tag{2}
\]

\[
v_2\{\Psi_{1,FHCal}\} = \frac{\langle \cos(2(\phi_i - \Psi_{1,FHCal})) \rangle}{R_2(\Psi_{1,FHCal})}, \tag{3}
\]

where \(R_2(\Psi_{2,TPC})\) and \(R_2(\Psi_{1,FHCal})\) represent the resolution of the event planes. Here, the first order event plane \(\Psi_{1,FHCal}\) determined from the directed flow \((n=1)\) of particles detected in

![Figure 1. The schematic view of the MPD detector in Stage 1 (a). Centrality dependence of event plane resolution \(R_2(\Psi_{2,FHCal})\) for \(v_2\) measurements in Au+Au collisions at \(\sqrt{s_{NN}} = 4.5, 7.7\) and 11 GeV (b).](image-url)
the FHCal (2 < |η| < 5) and the second order event plane Ψ_{2,TPC} determined from the elliptic flow (n=2) of produced particles detected in the TPC (|η| < 1.5). As an example the right part of Fig. 1 shows the centrality dependence of event plane resolution R_{2}(Ψ_{1,FHCal}) for v_{2} measurements in Au+Au collisions at √s_{NN} = 4.5, 7.7 and 11 GeV. The results are based on the analysis of the fully reconstructed UrQMD events. In order to suppress nonflow effects, due to Bose-Einstein correlations, resonance decays, and the fragments of individual jets, an additional η-gap of Δη > 0.1 was implemented between the two sub-events in v_{2}{Ψ_{2,TPC}} event plane method using the procedure in Ref [12]. The v_{2}{Ψ_{1,FHCal}} results are expected to be less affected by nonflow due to larger η-gap between tracks in TPC and particles used for the event plane reconstruction in FHCal: Δη > 0.5.

In the Q-cumulant method the two- and four- particle cumulants can be calculated directly from a Q vector, constructed using particles from the TPC acceptance |η| < 1.5, Q_n ≡ ∑_{i}^{M} exp (inφ_i):

\begin{equation}
(2)_n = \frac{|Q_n|^2 - M}{M(M - 1)},
\end{equation}

(4)_n = \frac{|Q_n|^4 + |Q_{2n}|^2 - 2\Re |Q_{2n}Q_n^{*}Q_n^{*} - 4(M - 2)|Q_n|^2 - 2M(M - 3)}{M(M - 1)(M - 2)(M - 3)}.

M denotes the multiplicity in each event used in the analysis. Since nonflow effects are mainly due to few particle correlations, estimates of v_{2} flow coefficients based on multi-particle cumulants have the advantage of significant reduction of contribution δ_{2} from nonflow effects:

\begin{equation}
\langle 2 \rangle_2 = v_{2}^2 + δ_{2}, \quad \langle 4 \rangle_2 = v_{2}^4 + 4v_{2}^2δ_{2} + 2 δ_{2}.
\end{equation}

Finaly, the elliptic flow (n = 2) can be defined via the Q-cumulant method as follows:

\begin{equation}
v_{2}\{2\} = \sqrt{\langle 2 \rangle} = \sqrt{\langle 2 \rangle}, \quad v_{2}\{4\} = \sqrt{\langle 4 \rangle} = \sqrt{\langle 4 \rangle},
\end{equation}

where \langle \langle k \rangle \rangle means \langle k \rangle, averaged over all events. Equations for the p_{T}-differential elliptic flow can be found in [4]. For v_{2}\{2\} method we used the η-gap of Δη > 0.1 in order to reduce nonflow contribution.

Anisotropic flow can fluctuate from event to event. We define the elliptic flow fluctuations by σ_{v_{2}}^2 = \langle v_{2}^2 \rangle - \langle v_{2} \rangle^2. Here, the resulting flow signal, averaged over all events is denoted as \langle v_{2} \rangle. Different methods of flow measurements have different sensitivity to the v_{2} fluctuations σ_{v_{2}}. In the case of the Q-cumulants (v_{2}\{2\} and v_{2}\{4\}), for a Gaussian model of fluctuations and in the limit σ_{v_{2}} \ll \langle v_{2} \rangle one can write [5, 6]:

\begin{equation}
v_{2}\{2\} = \langle v_{2} \rangle + \frac{1}{2}\frac{σ_{v_{2}}^2}{\langle v_{2} \rangle}, \quad v_{2}\{4\} = \langle v_{2} \rangle - \frac{1}{2}\frac{σ_{v_{2}}^2}{\langle v_{2} \rangle}.
\end{equation}

One of the important sources of v_{2} flow fluctuations are participant eccentricity fluctuations in the initial geometry of the overlapping region of two colliding nuclei. Therefore, the v_{2}{Ψ_{1,FHCal}} values measured with respect to the reaction plane Ψ_{1,FHCal} will be always smaller than v_{2}{Ψ_{2,TPC}} measured with respect to the participant plane Ψ_{2,TPC} [5, 6]:

\begin{equation}
v_{2}{Ψ_{1,FHCal}} \simeq \langle v_{2} \rangle, \quad v_{2}{Ψ_{2,TPC}} \simeq \langle v_{2} \rangle + \frac{1}{2}\frac{σ_{v_{2}}^2}{\langle v_{2} \rangle}.
\end{equation}

4. Results
The ratio v_{2}\{4\}/v_{2}\{2\} depends on the event-by-event fluctuations of v_{2} and often used as a measure of the relative fluctuations of v_{2} [13]: the larger the fluctuations of v_{2} are, the smaller
the ratio $v_2\{4\}/v_2\{2\}$ is. Figure 2 shows the centrality dependence of the ratio $v_2\{4\}/v_2\{2\}$ for charged hadrons from Au+Au collisions at $\sqrt{s_{NN}} = 7.7$ and 11.5 GeV. The results from the analysis of the Au+Au collisions generated by UrQMD and SMASH heavy-ion event generators were compared to the experimental data from the STAR experiment [12]. The comparison shows that both UrQMD and SMASH models can reproduce the ratio $v_2\{4\}/v_2\{2\}$ from the STAR experiment reasonably well.

![Figure 2](image-url).

**Figure 2.** Centrality dependence of the ratio $v_2\{4\}/v_2\{2\}$ of charged hadrons from Au+Au collisions at $\sqrt{s_{NN}} = 11.5$ (a) and 7.7 GeV (b). The closed star symbols correspond to the experimental data from the STAR experiment [12], closed circles to the results from UrQMD model and open boxes from SMASH model.

![Figure 3](image-url).

**Figure 3.** $p_T$-dependence of $v_2$ of charged hadrons (a), pions (b) and protons (c) from 10-40% midcentral Au+Au collisions at $\sqrt{s_{NN}} = 7.7$ GeV obtained using the event plane ($v_2\{\Psi_{1,FHCAL}\}$, $v_2\{\Psi_{2,TPC}\}$) and Q-cumulant ($v_2\{2\}$, $v_2\{4\}$) methods for analysis of UrQMD events. Lower raw shows the ratio $v_2$ (method)/$v_2\{2\}$.

Figure 3 shows the $p_T$ dependence of $v_2$ of charged hadrons (left panels), charged pions (middle panels) and protons (right panels) from 10-40% midcentral Au+Au collisions at $\sqrt{s_{NN}} = 7.7$ GeV. Different symbols correspond to the the $v_2$ results obtained by event plane...
\((v_2\{\Psi_{1,FHCale}\}, v_2\{\Psi_{2,TPC}\})\) and Q-cumulant \((v_2\{2\}, v_2\{4\})\) methods of analysis of events from UrQMD model. The ratios of \(v_2\) signal to the \(v_2\{2\}\) are shown on the bottom panels. The \(v_2\) results obtained using \(\eta\)-sub event plane \(v_2\{\Psi_{2,TPC}\}\) method are in a good agreement with results obtained by \(v_2\{2\}\) method. Both \(v_2\{4\}\) and \(v_2\{\Psi_{1,FHCale}\}\) methods give a smaller \(v_2\) signal as one expect from elliptic flow fluctuations and nonflow effects. The \(v_2\) results obtained using \(\eta\)-sub event plane \(v_2\{\Psi_{2,TPC}\}\) method are in a good agreement with results obtained by \(v_2\{2\}\) method. Both \(v_2\{4\}\) and \(v_2\{\Psi_{1,FHCale}\}\) methods give a smaller \(v_2\) signal as one expect from elliptic flow fluctuations and nonflow effects. The event plane \((v_n\{\Psi_{1,FHCale}\}, v_n\{\Psi_{2,TPC}\})\) and Q-cumulant \((v_n\{2\}, v_n\{4\})\) methods were implemented in the MPDROOT framework. Figure 4 shows the \(p_T\) dependence of \(v_2\) of charged hadrons from 10-40\% midcentral Au+Au collisions at \(\sqrt{s_{NN}} = 7.7\) GeV (upper panels) and \(\sqrt{s_{NN}} = 11.5\) GeV (lower panels). The perfect agreement between \(v_2\) results from the analysis of fully reconstructed ("Reco") and generated ("True") UrQMD events is observed.

![Figure 4](image_url)

**Figure 4.** Comparison of \(v_2(p_T)\) obtained by Q-cumulant and event plane methods of analysis of fully reconstructed UrQMD events ("Reco") and generated UrQMD events ("True").

![Figure 5](image_url)

**Figure 5.** (a) Centrality dependence of the event plane resolution factor \(R_2(\Psi_{2,TPC})\) and (b) \(p_T\)-dependence of \(v_2(\Psi_{2,TPC})\) of \(\pi^+\) and protons from 10-40\% midcentral Au+Au (open symbols) and Bi+Bi (filled symbols) collisions.

Figures 5 and 6 show the MPD detector system performance for the elliptic flow \((v_2)\) measurements of charged pions and protons from 10-40\% midcentral Au+Au (open symbols) and Bi+Bi (filled symbols) collisions at \(\sqrt{s_{NN}} = 7.7\) GeV. The \(v_2\) results were obtained by event
Figure 6. (a) Centrality dependence of the event plane resolution factor $R_2(\Psi_{1,FHcal})$ and (b) $p_T$-dependence of $v_2(\Psi_{1,FHcal})$ of $\pi^+$ and protons from 10-40% midcentral Au+Au (open symbols) and Bi+Bi (filled symbols) collisions.

plane method: using the second order event plane ($\Psi_{2,TPC}$) from TPC and the first order event plane ($\Psi_{1,FHcal}$) from FHCal. In both cases, one can see the expected small difference between results for the event plane resolution and $v_2$ between two colliding systems.

5. Summary
In summary, the MPD detector system performance for the elliptic flow measurements $v_2$ of charged hadrons is studied with Monte-Carlo simulations using collisions of Au+Au and Bi+Bi ions employing UrQMD and SMASH heavy-ion event generators. We have shown how the various experimental measures of elliptic flow are affected by fluctuations and nonflow correlations at NICA energies. The detailed comparison of the $v_2$ results obtained from the analysis of the fully reconstructed data and generator-level data allows to conclude that MPD system will allow reconstruction of $v_2$ coefficients with high precision.

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References
[1] Kekelidze V D 2018 Phys. Part. Nucl. 49 no.4 457
[2] Kisiel A (MPD collaboration) 2020 J. Phys. Conf. Ser. 1602 no.1 012021
[3] Ollitrault J Y, Poskanzer A M and Voloshin S A 2009 Phys. Rev. C 80 014904
[4] Bilandzic A, Snellings R and Voloshin S 2011 Phys. Rev. C 83 044913
[5] Voloshin S A, Poskanzer A M, Tang A and Wang G 2008 Phys. Lett. B 659 537-41
[6] Voloshin S A, Poskanzer A M and Snellings R 2010 Landolt-Bornstein 23 293-333
[7] Bleicher M et al. 1999 J. Phys. G 25, 1859-96
[8] S. A. Bass S A et al. 1998 Prog. Part. Nucl. Phys. 41 255-369
[9] Weil J et al. 2016 Phys. Rev. C 94 no.5 054905
[10] Parfenov P, Selyuzhenkov I, Taranenko A and Trutse A 2018 KnE Energ. Phys. 3, 352-6
[11] Parfenov P, Taranenko A, Selyuzhenkov I and Senger P 2019 EPJ Web Conf. 204 07010
[12] Adamczyk L et al. (STAR collaboration) 2012 Phys. Rev. C 86 054908
[13] Giacalone G, Noronha-Hostler J and Ollitrault J Y 2017 Phys. Rev. C 95 no.5 054910