Reconstruction of moments of particle distributions with Identity Method at MPD

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Abstract. Precise determination of the moments of multiplicity distributions of identified particles could be challenging due to the misidentification in detectors. The so-called Identity Method allows one to solve this problem. In this contribution, performance of the Identity Method was tested on the $A-A$ events simulated in the conditions of the MPD experiment at NICA. With this method, moments within a single kinematic window as well as coefficients of forward-backward pseudorapidity correlations are extracted.

1. Introduction
Collisions of relativistic nuclei can produce matter at extremely high temperatures and densities. Studies of the transition between the hadronic and partonic phases of this matter are being performed, in particular, with various combinations of moments of multiplicity distributions, for example, by studying event-by-event fluctuations of net-proton number. This requires identification of different particle species (pions, kaons, protons, electrons). However, precise determination of the moments can be difficult due to misidentification in detectors, for example, due to overlaps of energy loss ($dE/dx$) distributions in a Time-Projection Chamber (TPC). The so-called Identity Method (IM) \cite{1,2,3} allows one to solve this problem by unfolding the moments of the measured multiplicity distributions for each particle species. In IM, “proxies” for particle multiplicities $W_j$ in each event are constructed as $W_j = \sum_{i=1}^{N} \rho_j(x_i)/\rho(x_i) = \sum_{j} \rho_j(x_i)$, where $j$ denotes a particle type, $x$ is a value of $dE/dx$ for a given track $i$ (out of $N$ tracks in an event), and $\rho_j(x_i)$ is the $dE/dx$ distribution of particle type $j$ within a given phase space bin. In contrast to cut-based approach that utilizes signals in TPC and Time-of-Flight detectors, the IM allows one to calculate moments keeping high efficiency of particle registration, which is especially crucial for analysis of higher moments. The IM was recently used in ALICE for studies of $\pi, K, p$ \cite{4} and net-proton \cite{5} fluctuations.

In this contribution, performance of the Identity Method was tested using data simulated in the conditions of the Multi-purpose detector (MPD) at NICA \cite{6}, which currently is under construction in Dubna. The MPD will have the TPC, similarly to STAR and ALICE detectors. In Section 2 details of the simulation, event and track selection are provided. In Section 3 the IM is applied for reconstruction of particle momenta in a single (pseudo)rapidity window, which is the typical use-case of the method. In Section 4 it is proposed to apply the IM to the studies of the forward-backward rapidity correlations \cite{7,8}, and results of a performance test at the MPD are shown. The implementation of the Identity Method, used for the current study, is based on the code available at \cite{9}.
2. Simulated dataset and \( dE/dx \) fits

For the current study, we used a dataset of Bi–Bi collisions at \( \sqrt{s_{NN}} = 9.46 \text{ GeV} \) simulated in SMASH event generator [10], with subsequent simulation of the MPD detector response in GEANT3, digitization of the signals, and the full reconstruction of the events afterwards. Events with position of the vertex along the beam axis \( z \) within \( \pm 20 \text{ cm} \) from the nominal interaction point were taken. Centrality classes were selected by dividing the multiplicity distribution of the tracks observed in the TPC into quantiles, as it is typically done in other experiments. Centrality class 0–20% was used in this study, with 204\( k \) events analyzed.

Tracks for the analysis were selected within pseudorapidity range \( |\eta| < 0.5 \) and transverse momentum \( p_T > 0.15 \text{ GeV}/c \). Additionally, tracks were required to have minimum 30 clusters in TPC with \( \chi^2 \) per cluster less than 5, and the distance of closest approach to the primary vertex along \( z \)-axis less than 2 cm. This selection allows one to reduce contamination by secondary particles from weak decays and detector material, keeping the efficiency at 80–90\% level.

Panel (a) in figure 1 shows distribution of the \( dE/dx \) signal in TPC versus track momentum. One may see typical trends for pions, kaons and protons (no electrons in SMASH), which start to overlap at high momenta. In order to apply the Identity Method, one has to get \( dE/dx \) projections in narrow momentum slices and fit them by a sum of \( \rho_i(dE/dx) \) functions. As an example, a \( dE/dx \) projection in the momentum bin 0.75–0.76 GeV/c is shown in figure 1 (b). Fits for \( \pi^+ , K^+, p \) yields in this bin are done by the Generalized Gauss function, good quality of the overall fit is obtained. Similar fits are done for \( dE/dx \) distributions of the antiparticles \( (\pi^-, K^-, p) \). It is important to note that in the current work all fit parameters, except relative amplitudes between different species, were obtained using the information about the true type of each particle, which is available in simulations. With real data, if a significant signal overlap between the species is present, a simultaneous fitting for all particle species in a momentum slice is a challenging task. For that, one may use the so-called clean samples of particles with known PID, which can be “marked” using products of V0 decays, taking TOF information, etc. [11].

Fitted functions in each momentum slice and a ROOT tree containing \( dE/dx \) and other event- and track-level information were transferred then to the IM machinery.
3. Reconstruction of moments in single rapidity window
At first, the analysis within a single rapidity window $|\eta| < 0.5$ was performed. The momentum range considered is (0.3, 1.5) GeV/c. The first ($\langle N_i \rangle$, $i$ is a particle type), second ($\langle N_i^2 \rangle$), and cross-moments ($\langle N_i N_j \rangle$) of identified particle yields were recovered with the IM. Statistical uncertainties for the moments were calculated using the subsampling method (with 20 subsamples). Performance of the Identity Method is shown in figure 2 (a–c) in terms of the ratios of the IM-reconstructed moments to the true values. The true moments were calculated using track PID that is explicitly known in simulations. It can be seen that good accuracy of the moment reconstruction is achieved (better than 1%). The uncertainties are the largest for the moments that involve kaons and anti-protons, since their abundances at NICA energies are relatively low. This is visible in panel (d) of the figure 2.

4. Forward-backward correlations of identified particle yields
With the Identity Method, one can also perform more differential studies. Namely, we can select two regions in pseudorapidity and calculate the forward-backward correlations between them, for example, in terms of the Pearson correlation coefficient \[b_{\text{corr}} = \frac{\langle N_{F,i} N_{B,j} \rangle - \langle N_{F,i} \rangle \langle N_{B,j} \rangle}{\sqrt{\langle N_{F,i}^2 \rangle - \langle N_{F,i} \rangle^2} \sqrt{\langle N_{B,j}^2 \rangle - \langle N_{B,j} \rangle^2}}, \]
Cross F–B moments

Figure 3. Ratios of the cross-moments for identified particle yields in forward and backward \( \eta \)-windows \((−0.5, −0.1) – (0.1, 0.5)\), recovered with the Identity Method, to the true values.

where \( F \) and \( B \) denote the forward and the backward windows, respectively, and \( i, j \) are particle species. Figure 3 shows ratios of IM-reconstructed values to the true ones for the cross-moments in a pair of FB windows, where the forward window \( \eta_F \in (0.1, 0.5) \) counts positive particles and the backward window \( \eta_B \in (−0.5, −0.1) \) – negative particles. A good closure of the ratios to unity is observed (the biggest deviations \( \sim 2–3\% \) are, again, for kaons and \( p \) due to their small yields). The correlation coefficient (equation (1)) extracted with the Identity Method for the case of e.g. \( \pi^+ – \pi^- \) FB correlations is \( b_{\text{corr}}^{\text{IM}} = 0.357 \pm 0.002 \), while the true value is \( b_{\text{true}}^{\text{corr}} = 0.3598 \pm 0.0012 \), the results coincide within the uncertainties.

5. Summary
In this work, performance of the Identity Method was tested on realistic \( A-A \) events with GEANT simulation and reconstruction in the MPD detector. The first results showed reasonable quality of the reconstructed moments. Along with the conventional analysis in a single pseudorapidity window, it was suggested also to use the Identity Method for more differential studies, in particular, for forward-backward rapidity correlations. It was shown that the Identity Method allows one to reliably reconstruct the true values of the FB correlation coefficient at MPD.

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