Identification power of the vertex tracking detector of the NICA-MPD setup for decays reconstruction of strange and charmed particles.


MDP-ITS Coordination Meeting, Dubna, 6 February 2020
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Physical motivation of using IT

MPD is being constructed to study the properties of extremely dense nuclear matter formed in relativistic nucleus-nucleus collisions at NICA energies. The yields and spectra of strange and charmed particles are the important observables sensitive to critical phenomena in phase transitions of the QCD-matter. So, vertex detector (IT) is required for highly efficient registration of such short-lived products of nuclear interactions.

Modern vertex detectors consist of a few layers of silicon position-sensitive sensors. This kind of detectors are already used in ALICE, ATLAS, CMS and STAR experiments.
Registration of strange and charmed particles by the vertex detector

\[ \Lambda^0 \rightarrow p + \pi^- \]

\[ \Xi^- \rightarrow \Lambda + \pi^- \]

\[ \Omega^- \rightarrow \Lambda + K^- \]

\[ \Lambda_c \rightarrow p + K^- + \pi^- \]

\[ \tau_c = 68 \text{ \(\mu\)m} \]

\[ D^0 \rightarrow K^- + \pi^+ \]

\[ \tau_c = 123 \text{ \(\mu\)m} \]

Reliable identification of short-lived particles (multistrange hyperons and charmed mesons) is performed by determining the invariant mass of their decay products. So, for high-efficient reconstruction of decay vertices near the interaction point detectors with high pointing resolution are needed.
Monolithic Active Pixel Sensor (MAPS)

Pixel sensors of the new generation - MAPS - have the best spatial resolution at a high counting rate and their high level of segmentation per pixel allows to install detectors of this type at distances of several centimeters from the interaction point without a threat of frequency overload. Combination of the TPC and the MAPS based vertex detector IT will allow to register short-lived products of A-A interactions with maximum efficiency.

Sensitive area: 15×30 mm²
Thickness: 50 μm
Number of pixels: 512×1024
Pixel size: 28×28 μm².
Space resolution:
\( \sigma_{r\phi} = 5 \, \mu m \), \( \sigma_z = 5 \, \mu m \)
IT design on the base of MAPS

Geometric limitations:
• by the size of the beam pipe, the diameter of which can vary from 40 to 65 mm;
• by the dimensions of the TPC, the inner diameter of which is 500 mm

Constructive limitations:
• by the dimensions of the carbon composite support structures;
• by the transverse dimensions of MAPS.

These limitations lead to a 5-layer construction of IT with 12 ladders in the innermost layer.
Model IT5-40 (basic project configuration): 5-layer IT for a beam pipe with the smallest possible diameter of 40 mm with a staggered arrangement of ladders in Outer Barrel (OB) and a fan-like arrangement of ladders in Inner Barrel (IB).

OB: ladders similar to ALICE ITS2
IB: ladders similar to ALICE ITS3

<table>
<thead>
<tr>
<th>Layer</th>
<th>Number of ladders</th>
<th>Number of MAPS</th>
<th>$R_{\text{min}}$, mm</th>
<th>$R_{\text{max}}$, mm</th>
<th>Ladder length, mm</th>
<th>Effective thickness, $\mu$m</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12</td>
<td>288</td>
<td>22.4</td>
<td>26.7</td>
<td>750</td>
<td>100</td>
</tr>
<tr>
<td>2</td>
<td>22</td>
<td>528</td>
<td>40.7</td>
<td>45.9</td>
<td>750</td>
<td>100</td>
</tr>
<tr>
<td>3</td>
<td>32</td>
<td>768</td>
<td>59.8</td>
<td>65.1</td>
<td>750</td>
<td>100</td>
</tr>
<tr>
<td>4</td>
<td>36</td>
<td>3528</td>
<td>144.5</td>
<td>147.9</td>
<td>1526</td>
<td>700</td>
</tr>
<tr>
<td>5</td>
<td>48</td>
<td>4704</td>
<td>194.4</td>
<td>197.6</td>
<td>1526</td>
<td>700</td>
</tr>
</tbody>
</table>
IT pointing resolution for $\pi$, $K$ and $p$

The spatial resolution of the IT5-40 model was evaluated in the framework of the simplified code developed by ALICE collaboration, which performs tracking of charged particles through cylindrical silicon layers with a given radiation thickness.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Mean r, мм</th>
<th>$\sigma(\rho\phi)$, um</th>
<th>$X/X_0$, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam pipe</td>
<td>20.0</td>
<td>-</td>
<td>0.22</td>
</tr>
<tr>
<td>1</td>
<td>24.6</td>
<td>5.0</td>
<td>0.30</td>
</tr>
<tr>
<td>2</td>
<td>43.3</td>
<td>5.0</td>
<td>0.30</td>
</tr>
<tr>
<td>3</td>
<td>62.5</td>
<td>5.0</td>
<td>0.30</td>
</tr>
<tr>
<td>4</td>
<td>146.2</td>
<td>5.0</td>
<td>0.30</td>
</tr>
<tr>
<td>5</td>
<td>196.0</td>
<td>5.0</td>
<td>0.30</td>
</tr>
</tbody>
</table>

Evaluated resolution of IT5-40 provides, for example, the possibility of $D^0$ decay vertex reconstruction in the channel $D^0 \rightarrow K^- + \pi^+ \ (\lambda = 123 \mu m)$ with small $p_T$ up to 300 MeV/c.
MPD IT pointing resolution compared to ALICE ITS

MPD IT pointing resolution with a beam pipe Ø = 40 mm is comparable with ALICE ITS2.
The main simulation tasks include:

- generation of detector responses (Hit Producer);
- reconstruction of particle tracks using generated hits (Track Finder + Track Fitter);
- reconstruction of the primary and secondary interaction vertices (Track Analysis).
Strange particle reconstruction in central Au+Au collisions at \( \sqrt{S_{\text{NN}}} = 9 \text{ GeV} \)

<table>
<thead>
<tr>
<th>Particle</th>
<th>Mass [MeV/c^2]</th>
<th>Mean path c(\tau) [cm]</th>
<th>Decay channel</th>
<th>BR</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\Lambda)</td>
<td>1115.68±0.01</td>
<td>7.89</td>
<td>(\pi^- + p)</td>
<td>63.9%</td>
</tr>
<tr>
<td>(\Xi^-)</td>
<td>1321.71±0.07</td>
<td>4.91</td>
<td>(\pi^- + \Lambda)</td>
<td>99.9%</td>
</tr>
<tr>
<td>(\Omega^-)</td>
<td>1672.45±0.29</td>
<td>2.46</td>
<td>(K^- + \Lambda)</td>
<td>67.8%</td>
</tr>
</tbody>
</table>

To suppress a large combinatorial background in Au+Au collisions it is necessary to use strict criteria for signal selection corresponding to real particle decays.
Selection criteria for two particle decay

Λ selection parameters are dictated by the decay topology:
• distances of closest approach to the collision vertex $DCA_{\pi,p}$,
• two-track separation $DCA_{\pi p}$,
• decay path $\lambda_\Lambda$,
• pointing angle $\theta_\Lambda$.

Selection criteria:
$DCA_\pi > C_1 \& DCA_p > C_2 \& DCA_{\pi p} < C_3 \& \lambda_\Lambda > C_4 \& \theta_\Lambda < C_5$

The parameters $C_i$ (cuts) of the corresponding selection are optimized by maximizing the signal significance:

\[
Sg(C_i) = \int_0^{C_i} \frac{S}{\sqrt{S + B}} dC_i
\]

where $S$ and $B$ are the estimated numbers of the signal and background events.
Λ reconstruction (5·10^3 events):  

\( \Lambda \rightarrow p + \pi \)

dca(p)>0.3 cm & dca(π)>0.3 cm & 
dca(πp)<0.05 cm & \( \lambda(\Lambda) > 3.0 \) cm & \( \theta(\Lambda) < 0.09 \) rad

Obtained values of significance level 112.6 and signal-to-noise ratio 11.3 indicate a high quality of charged particle tracking in the MPD tracking system.
The use of optimized selection criteria allows to reconstruct $\Xi^-$ with an efficiency of 1.3% at sufficiently high level of significance of 43.4.
Ω⁻ reconstruction (10⁶ events):

\[ \Omega^- \rightarrow \Lambda + K^- \]
\[ \Lambda \rightarrow p + \pi^- \]

\[ dca(\pi) > 0.05 \text{ cm} \]
\[ dca(p) > 0.05 \text{ cm} \]
\[ dca(K) > 0.1 \text{ cm} \]
\[ dca(\Lambda) > 0.1 \text{ cm} \]
\[ dca(\pi p) < 0.3 \text{ cm} \]
\[ dca(\Lambda K) < 0.1 \text{ cm} \]
\[ \theta(\Lambda) > 0.01 \text{ rad} \]
\[ \theta(\Omega) < 0.015 \text{ rad} \]
\[ \lambda(\Lambda) > 5 \text{ cm} \]
\[ \lambda(\Omega) < 8 \text{ cm} \]

Increasing the statistics to 1M events allows to reconstruct Ω⁻ with an efficiency of 1.5% at a significance level of 30.2
Charmed particle reconstruction in central Au+Au collisions at $\sqrt{S_{NN}} = 9$ GeV

<table>
<thead>
<tr>
<th>Particle</th>
<th>Mass [MeV/c$^2$]</th>
<th>Mean path $c\tau$ [mm]</th>
<th>Decay channel</th>
<th>BR</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^+$</td>
<td>1869.62±0.20</td>
<td>0.312</td>
<td>$\pi^+ + \pi^+ + K^-$</td>
<td>9.13%</td>
</tr>
<tr>
<td>$D^0$</td>
<td>1864.84±0.17</td>
<td>0.123</td>
<td>$\pi^+ + K^-$</td>
<td>3.89%</td>
</tr>
</tbody>
</table>

Background simulation - using QGSM generator (100K events)
Signal simulation – using thermal generator (1M events)

Two methods are used for signal selection:
1) Method of topological cuts (TC)
2) Method of multivariate data analysis (MVA)
D⁰ reconstruction by TC method: cut selection

All topological cuts are selected according to the maximum of significance functions

\[ \text{dca}(K) > 0.012 \text{ cm} & \]
\[ \text{dca}(\pi) > 0.012 \text{ cm} & \]
\[ \text{dca}(\pi K) < 0.019 \text{ cm} & \]
\[ \lambda(D⁰) > 0.044 \text{ cm} & \]
\[ \theta(D⁰) < 0.15 \text{ rad} \]
D⁰ reconstruction (10⁸ events): invariant mass spectra

Signal after applying cuts in 10⁸ events

Background before applying cuts in 10⁵ events

M(πK): signal(100M) with cuts

M(πK): background(100K) without cut

M(πK): background(100K) with cuts

M(πK): signal+background(100M)

Background after applying cuts in 10⁵ events

Signal + background after applying cuts in 10⁸ events
D mesons reconstruction by TC method: invariant mass spectra

$D^0 \rightarrow K^- + \pi^+$

$D^+ \rightarrow K^- + \pi^+ + \pi^+$

Using the method of topological cuts allows to reconstruct $D^0$ and $D^+$ with an efficiency of 0.8% and 0.5% respectively.
TMVA is a ROOT package for training, testing and performances evaluation of multivariate classification techniques.

Analysis is generally organized in 2 steps:

- **Training phase**
  At this stage the variables from the signal and background samples are trained according the classifier chosen by the user. The results of the classification is written into weight files, traducing the initial \( N \) input variables \( V \) to one dimensional variable \( R \) (response):
  \[
  V^N \rightarrow R
  \]

- **Application phase**
  At this stage the data classification, reading from the weight files, is applied to the data to be analyzed.

The classifier BDT (Boosted Decision Trees) has been chosen for the analysis phase when reconstructing D mesons.
D⁰ reconstruction by MVA method: cut selection

dca(π), dca(K), dca(πK), λ(D⁰), θ(D⁰)

To separate the signal and background the optimal value of the resulting cut of the classifier BDTD_response>0.3 was selected and applied to 1M signal and 100K background events generated using the thermal and QGSM generator.
D mesons reconstruction by MVA method: invariant mass spectra

\[ D^0 \rightarrow K^- + \pi^+ \]

\[ D^+ \rightarrow K^- + \pi^+ + \pi^+ \]

Using the optimal BDT cut allows to reconstruct \( D^0 \) and \( D^+ \) with an efficiency of 0.85\% and 1.0\% respectively.
Reconstruction parameters of strange and charmed particles in central Au+Au collisions at $\sqrt{S_{\text{NN}}} = 9$ GeV

<table>
<thead>
<tr>
<th>Particle</th>
<th>$\Lambda$</th>
<th>$\Xi^-$</th>
<th>$\Omega^-$</th>
<th>$D^0$</th>
<th>$D^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Method</td>
<td>TC</td>
<td>TC</td>
<td>TC</td>
<td>TC</td>
<td>TC</td>
</tr>
<tr>
<td>Multiplicity</td>
<td>20</td>
<td>1.2</td>
<td>$10^{-1}$</td>
<td>$10^{-2}$</td>
<td>$10^{-2}$</td>
</tr>
<tr>
<td>Number of events</td>
<td>$5 \cdot 10^3$</td>
<td>$10^5$</td>
<td>$10^6$</td>
<td>$10^8$</td>
<td>$10^8$</td>
</tr>
<tr>
<td>Efficiency, %</td>
<td>8.0</td>
<td>1.3</td>
<td>1.5</td>
<td>0.80</td>
<td>0.85</td>
</tr>
<tr>
<td>Significance $S/\sqrt{S+B}$</td>
<td>112.6</td>
<td>43.4</td>
<td>30.2</td>
<td>5.3</td>
<td>5.5</td>
</tr>
<tr>
<td>$S/B(2\sigma)$ ratio</td>
<td>11.3</td>
<td>24.4</td>
<td>7.6</td>
<td>0.10</td>
<td>0.10</td>
</tr>
<tr>
<td>Yield per month</td>
<td>$2 \cdot 10^9$</td>
<td>$3 \cdot 10^7$</td>
<td>$2 \cdot 10^6$</td>
<td>$6 \cdot 10^3$</td>
<td>$7 \cdot 10^3$</td>
</tr>
</tbody>
</table>

If $D^0$ reconstruction efficiencies by MVA and TC are similar, then the use of MVA in the case of $D^+$ allows doubling the efficiency with a higher level of significance.
Conclusion

Quality assessment of the MPD tracking system, which includes TPC and MAPS based IT has been studied when reconstructing strange and charmed particles formed in AA collisions at NICA energies.

Simulation shows:
- reliable reconstruction of hyperons $\Lambda, \Xi^-, \Omega^-$
- possibility of D-mesons reconstruction in central Au + Au collisions at $\sqrt{S_{NN}} = 9$ GeV, which opens up prospects for studying the heavy flavors physics at the NICA-MPD facility.
Thank you for your attention!
Back up slides
Effective thickness of ITS2 layers

Outer barrel

Effective Si thickness $t=760 \, \mu m$

Inner barrel

Effective Si thickness $t=260 \, \mu m$
Thermal generator: $p_t$ – spectrum of $D^0$ in Au+Au collisions at NICA energies

Abdel Nasser TAWFIK† and Ehab ABBAS
Thermal Description of Particle Production in Au-Au Collisions at STAR Energies
QGSM generator: $p_t$ – spectra of strange particles in 100K central Au+Au collisions at $\sqrt{S_{NN}} = 9$ GeV
Input variables distributions for signal and background events after the decorrelation, gaussianisation and principal component decomposition.
MC and reconstructed $p_t$-spectra of $D^0$-mesons and they decay products

D$^0$ mesons

Pions

Kaons
MC and reconstructed $p_t$-spectra of $D^+$-mesons and they decay products

![Plt spectrum of generated and reconstructed D+](image)

D+ mesons

![Plt spectrum of generated and reconstructed $\pi^+$](image)

Pions

![Plt spectrum of generated and reconstructed $K^-$](image)

Kaons