Methods for event plane determination in flow measurements with HADES at SIS18

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Anisotropic flow & spectators

spatial asymmetry of the initial energy distribution transforms via interaction into anisotropic emission of produced particles

The azimuthal angle distribution is decomposed in a Fourier series relative to reaction plane angle:

$$\rho(\varphi - \Psi_{RP}) = \frac{1}{2\pi} \left( 1 + 2 \sum_{n=1}^{\infty} v_n \cos n(\varphi - \Psi_{RP}) \right)$$

directed flow:

$$v_1 = \langle \cos (\varphi - \Psi_{RP}) \rangle$$
$v_n$ of protons, deuterons and tritons in Au+Au collisions with HADES

HADES Collaboration, arxiv:2005.12217
Flow vectors

From momentum of each measured particle define a \( u_n \)-vector in transverse plane:

\[
u_n = e^{in\phi}\]

where \( \phi \) is the azimuthal angle

Sum over a group of \( u_n \)-vectors in one event forms \( Q_n \)-vector:

\[
Q_n = \frac{\sum_{k=1}^{N} w_n^k w_n^k}{\sum_{k=1}^{N} w_n^k} = |Q_n| e^{in\Psi_{EP}^n}
\]

\( \Psi_{EP}^n \) is the event plane angle
Flow methods for $v_n$ calculation

Event plane (EP) method:

$$v_1 = \frac{\langle \cos (\phi - \Psi_1^{EP}) \rangle}{R_1}$$

Resolution correction from random subevent (RND):

$$R_1^{sub} = \sqrt{\langle \cos (\Psi_a^n - \Psi_b^n) \rangle}$$

Extrapolation to full event plane is implemented following J.Y. Ollitrault [arXiv:nucl-ex/9711003]

Scalar product (SP) method:

$$v_1 = \frac{\langle u_1^a Q_1^a \rangle}{R_1}$$

Where

$$R_1^a = \frac{\sqrt{\langle Q_1^a Q_1^b \rangle \langle Q_1^a Q_1^c \rangle}}{\sqrt{\langle Q_1^b Q_1^c \rangle}}$$
The HADES experiment

Tracking system (0.09 < \( \eta \) < 1.84)
- Multi-wire drift chambers (MDC)
- Magnet coil

Particle identification (0.09 < \( \eta \) < 1.84)
- Time Of Flight (TOF)
- Resistive Plate Chambers (RPC)

Event plane reconstruction
- Forward Wall (FW)
  \( 2.68 < \eta < 5.38 \)
Q-vectors for protons and charged fragments

Protons with $p_T < 2 \text{ GeV}/c$

for 2 rapidity regions:

- $\eta$ from $W_1$:
  - $3.77 < \eta < 5.38$

- $\eta$ from $W_2$:
  - $3.28 < \eta < 3.88$

- $\eta$ from $W_3$:
  - $2.68 < \eta < 3.35$

Charged fragments from FW:

- $W_1$: $3.77 < \eta < 5.38$
- $W_2$: $3.28 < \eta < 3.88$
- $W_3$: $2.68 < \eta < 3.35$

Full FW (sum over all modules) $2.68 < \eta < 5.38$

RND-sub: all modules randomly split into 2 groups
QnTools framework

Corrections are based on method in:
I. Selyuzhenkov and S. Voloshin PRC77, 034904 (2008)

Originally implemented as QnCorrections framework for ALICE experiment at CERN:
J. Onderwaater, I. Selyuzhenkov, V. Gonzalez

QnTools analysis package:
https://github.com/HeavyIonAnalysis/QnTools

QnTools configuration

<table>
<thead>
<tr>
<th>Q-vector</th>
<th>$Q_n$ weight</th>
<th>Correction axes</th>
<th>Correction steps</th>
<th>Error calculation</th>
<th>$Q_n$ Normalization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protons</td>
<td>1</td>
<td>$p_T$ [0.0, 2.00], 10 bins $y_{cm}$[-0.75, 0.75], 15 bins Centrality, 8 bins</td>
<td>Recentering Twist Rescaling</td>
<td>Bootstrapping, 100 samples</td>
<td>Sum of Weights</td>
</tr>
<tr>
<td>Charged Fragments</td>
<td>Module charge</td>
<td>Centrality, 8 bins</td>
<td>Recentering</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Resolution estimates with rapidity-separated subevents are consistent with each other within 3-5%. Other combinations deviate by up to ~30% in central collisions.

1. Rapidity-separated and unseparated combinations split on two branches.
Resolution estimates with rapidity-separated subevents are consistent with each other within 3-5%. Other combinations deviate by up to ~30% in central collisions.
Quantifying non-flow correlations in $R_1$

1. Rapidity-separated and unseparated combinations split on two branches

2. Rapidity-separated combinations are consistent with each other

3. Combinations with no rapidity separation deviate from each other

Resolution estimates with rapidity-separated subevents are consistent with each other within 3-5%.
Other combinations deviate by up to ~30% in central collisions
Systematic uncertainty of directed flow, $v_1$

Proton $v_1$ vs. centrality

$y_{cm}$ [-0.25; -0.15]

$p_T$ [ 0.0; 2.0] GeV/c

Rapidity separated only are shown.

Results for event plane and scalar production (with rapidity separated subevents) are consistent within stat. uncertainties.
Summary of systematic uncertainty for $v_1$

proton $v_1$ vs. centrality
$y_{cm}$ [-0.25; -0.15]
$p_T$ [ 0.0; 2.0] GeV/c

Overall difference between $v_1$ with event plane (RND-sub) and scalar product (with rapidity separated combinations) is ~10% in central events and below 5% in mid-central

Rapidity separated only are shown
Summary

- Investigated systematic uncertainties in directed flow of protons measurement relatively to the spectators symmetry plane
- Implemented scalar product, 3-subevents technique for flow measurement
- From the comparison of event plane (random subevents) and scalar product (three subevents) methods, the systematic uncertainties due to non-flow effects of spectator symmetry plane estimation was evaluated: ~ 10% for proton $v_1$ in most central and < 5% in mid-central collisions

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Backup
Data Selection

Data: Au+Au collisions at 1.23GeV (subsample of 10M events)

Event selection:
- Minimum bias trigger
- vertex on Z: [-60;0] mm
- vertex on XY < 3 mm
- Good Vertex Cluster
- Good Vertex Candidate
- Good START
- No Pile Up in START
- Good START VETO
- Good START META
- No VETO

Proton selection:
- DCA-z<15mm
- DCA-xy<15mm
- Standard HADES TOF selection

Charged fragment (FW modules) selection
- Wall Ring: 0-4:
  - wallHitCharge > 80
  - wallHitBeta [0.84, 1]
- Wall Ring: 5-6:
  - wallHitCharge > 85
  - wallHitBeta [0.85, 1]
- Wall Ring: 0-4:
  - wallHitCharge > 88
  - wallHitBeta [0.8, 1]

Centrality is determined with selected TOF+RPC hits
HADES event display & subsystem’s acceptance

Au+Au collisions at 1.23GeV (subsample of 10M events)
Minimum bias trigger (PT2), 0-40% centrality

Tracking (MDC) and PID (TOF+RPC)
$0.09 < \eta < 1.84$

Charged fragments (FW)
$2.68 < \eta < 5.38$

Centrality determined from TOF+RPC hits