Anisotropic flow measurement from NA61/SHINE experiment at CERN SPS

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Collision geometry and anisotropic transverse flow

Asymmetry in coordinate space due to interaction is transformed into momentum asymmetry with respect to the symmetry plane:

\[ \rho(\phi) = \frac{1}{2\pi} \left[ 1 + 2 \sum_{n=1}^{\infty} v_n \cos(n(\phi - \Psi_s)) \right] \]

\[ v_n = \langle \cos(n(\phi - \Psi_s)) \rangle \]

Components needed for \( v_n \) calculation:
- particle type and momentum (\( \phi, y, p_T \))
- centrality estimation
- \( \Psi_s \) estimation

\( \Psi_s \) can be estimated using produced particles \( \Psi_{pp} \) or projectile (target) spectators \( \Psi_{proj} (\Psi_{spec}) \)
Collective flow at SPS / RHIC energies

NA61/SHINE Pb-ion beam energy scan $p_{\text{LAB}} = 13-150\,\text{A GeV/c}$:
- extend existing NA49 data
- complementary to STAR@RHIC
- bridge to FAIR and NICA energies

Advantage of NA49 & NA61/SHINE fixed target setup:
- tracking and particle identification over wide rapidity range with TPCs
- projectile spectators’ measurements with forward calorimeters

STAR Collaboration
PRL 112 (2014) 162301

HADES Collaboration
JPCS 742 (2016) 012008
NA61/SHINE setup for Pb-ion beam energy scan (2016-2018)

- Successor of the NA49 experiment
- Full coverage of forward hemisphere with TPCs
- High-granularity forward calorimeter (PSD)
- Pb+Pb beam momentum scan:
  - 13A, **30A GeV/c** recorded in 2016 (pilot run at 150A GeV/c)
  - 150A GeV/c scheduled for November, 2018
Event selection & Centrality Estimation

- Event has fitted vertex
- Good reconstructed vertex position
- Good beam position
- No overlap events / beam particles

Statistics per trigger:
1.1M **minimum bias (T4)**
600k **central (T2)**
Track selection & Corrections for detector non-uniformity in $p_T/y$

Example of $p_T/y$ correction map

Number of clusters:
- $N_{\text{clusters}} [ \text{VTPC1+VTPC2} ] > 15$
- $N_{\text{clusters}} [ \text{Total} ] > 30$
- $0.55 < N_{\text{cl}} [ \text{Total} ] / N_{\text{cl}} [ \text{Total, Pot} ] < 1$

Distance of closest approach to the fitted vertex
- $|b_x| < 2 \text{ cm}$
- $|b_y| < 1 \text{ cm}$

TPC energy loss (dE/dx)
- charged pions & proton identification

Tracking efficiency
- GEANT4 Monte-Carlo with DCM-QGSM
Corrections for detector azimuthal non-uniformity

**QnVector Corrections Framework**

Data driven corrections for azimuthal non-uniformity
I. Selyuzhenkov and S. Voloshin [PRC77 034904 (2008)]

- QnVector Corrections Framework
  J. Onderwaater, V. Gonzalez, I. Selyuzhenkov
  https://github.com/FlowCorrections/FlowVectorCorrections

- Recentering, twist, and rescaling corrections applied
  time dependent (run-by-run) and as a function of centrality

**Flow Analysis Framework**

Extended flow-vector for $p_T/y$-differential corrections

- Multi-dimensional correlations of flow-vectors
  L. Kreis (GSI / Heidelberg) and I. Selyuzhenkov (GSI / MEPhI)

Framework has been tested and used in:
ALICE@LHC, NA49 and NA61/SHINE@SPS, CBM@FAIR and HADES@SIS18
Scalar product method for flow measurement with 1\textsuperscript{st} harmonic $Q$-vector

$u_n$ and $Q_n$ vectors:

\[
u_n = \begin{pmatrix} \cos n \phi \\ \sin n \phi \end{pmatrix}, \quad Q_n = \sum_j w_j u_n^j\]

Directed flow:

\[
v_1 = \frac{2 \langle u_{1,i} Q_{1,i}^A \rangle}{R_{1,i}^A}, \quad i, j, k = [x, y]\]

Elliptic flow:

\[
v_2 = \frac{4 \langle u_{2,i} Q_{1,i}^A Q_{1,j}^B \rangle}{R_{1,i}^A R_{1,j}^B}\]

First harmonic resolution correction factor:

\[
R_{1,i}^A = \sqrt{2 \frac{\langle Q_{1,i}^A Q_{1,i}^B \rangle \langle Q_{1,i}^A Q_{1,i}^C \rangle}{\langle Q_{1,i}^B Q_{1,i}^C \rangle}}\]
“Systematics” for directed flow ($v_1$) components

Consistent results for PSD subevents

$x/y$ components show consistent results, while results for $y$-component shows larger stat. errors

For preliminary results: only $x$-component is used and PSD subevents are combined.
NA61/SHINE preliminary results

Results are presented for correlations between charged pions and protons* (in the TPC acceptance) and all hadrons at forward rapidity (in the PSD acceptance)

The results are corrected for detector non-uniformity. No corrections for secondary interactions and weak decays are done yet. Only statistical uncertainties are shown.

*hadrons produced by strong interaction processes and their electromagnetic decays

NA61/SHINE acceptance:
TPC https://edms.cern.ch/document/1549298/1
PSD https://edms.cern.ch/document/1867336/1
Charged pion $v_1$ vs transverse momentum

- Strong centrality dependence of $v_1$
- $v_1(p_T \sim 0\text{ GeV/c}) = 0$
- $v_1$ changes sign at $p_T \sim 1\text{ GeV/c}$

- Significant mass dependence of $v_1$
- Difference between $\pi^+$ and $\pi^-$ $v_1$ is sensitive to the electromagnetic effects*

Similar flow results relative to the spectator plane using data from NA49 and NA61/SHINE
Slope of $v_1$ at midrapidity vs centrality
Comparison with STAR results

Slope extraction is sensitive to fit function and rapidity range
Elliptic flow vs transverse momentum
Comparison with STAR

- Clear mass dependence
- Difference between $\pi^+$ and $\pi^-$ $v_2$ is small

Tension for mid-central collisions could be due to different centrality estimators:
- Particle multiplicity at midrapidity (STAR)
- Projectile spectators (NA61/SHINE)
Summary

- Preliminary results for anisotropic flow relative to spectator plane from NA61/SHINE are presented differentially (vs. centrality, rapidity, $p_T$) for:
  - charged pions and protons directed and elliptic flow for Pb+Pb collisions at 30A GeV/c recorded in 2016 by the NA61/SHINE experiment

- New results are compared to:
  - Existing data for $v_1$, $v_2$ from STAR@RHIC Beam Energy Scan
  - New analysis of flow wrt spectator plane for 40A GeV data by NA49

Outlook

- Complete systematic analysis of the Pb ion beam energy scan data: 13A (2016) and 150A GeV/c (November, 2018)

- Study collective effects in smaller collision systems available from NA61/SHINE system size (Be+Be, Ar+Sc, Xe+La) and beam energy (13A-158A GeV/c) scan
NA49 setup for Pb-ion beam energy scan (1996-2002)

- Large acceptance hadron spectrometer (TPC)
- ~ 2 units of rapidity coverage
- tracking + identification down to $p_T \sim 0 \text{ GeV/c}$
- Forward rapidity calorimeters (RCAL & VCAL):
  - sensitivity to spectator symmetry plane
- Beam energies:
  - 20A, 30A, 80A GeV (central)
  - **40A**, 158A GeV (minimum bias)
Good performance of the Projectile Spectator Detector at lowest SPS energy
- very close to the top energy of CBM @ FAIR which
will have a similar forward calorimeter for centrality and spectator plane determination
## Backup: Event selection

<table>
<thead>
<tr>
<th>Pb-Pb@30A GeV/c (NA61)</th>
<th>Pb-Pb@40A GeV (NA49)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Vertex Fit</strong></td>
<td><strong>Vertex Fit</strong></td>
</tr>
<tr>
<td>(-0.35 &lt; x &lt; 0.3)</td>
<td>(-0.05 &lt; x &lt; 0.95)</td>
</tr>
<tr>
<td>(-0.37 &lt; y &lt; 0.8)</td>
<td>(-0.50 &lt; y &lt; 0.50)</td>
</tr>
<tr>
<td>(-594 &lt; z &lt; -590)</td>
<td>(579.5 &lt; z &lt; -578.5)</td>
</tr>
<tr>
<td>good vertex fit</td>
<td>good vertex fit</td>
</tr>
</tbody>
</table>

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<thead>
<tr>
<th><strong>Beam Position</strong></th>
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</tr>
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<tbody>
<tr>
<td><strong>Detector</strong></td>
<td><strong>Detector</strong></td>
</tr>
<tr>
<td>BPD1</td>
<td>BPD1</td>
</tr>
<tr>
<td>(x [-0.4, 0.0]) (y [-0.6, 0.8])</td>
<td>(x [-0.4, 0.0]) (y [-0.6, 0.8])</td>
</tr>
<tr>
<td>BPD2</td>
<td>BPD2</td>
</tr>
<tr>
<td>(x [-0.2, 0.1]) (y [-0.3, 0.3])</td>
<td>(x [-0.2, 0.1]) (y [-0.3, 0.3])</td>
</tr>
<tr>
<td>BPD3</td>
<td>BPD3</td>
</tr>
<tr>
<td>(x [-0.34, 0.22]) (y [-0.35, 0.05])</td>
<td>(x [-0.34, 0.22]) (y [-0.35, 0.05])</td>
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<thead>
<tr>
<th><strong>Trigger</strong></th>
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<tbody>
<tr>
<td>Minbias T4, Central T2</td>
<td>Minbias, Midcentral, Central</td>
</tr>
</tbody>
</table>

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<tr>
<th><strong>WFA</strong></th>
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<tbody>
<tr>
<td>Beam: 4000ns</td>
<td>Beam: 4000ns</td>
</tr>
<tr>
<td>Interaction: 25000ns</td>
<td>Interaction: 25000ns</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Minimum number of selected tracks</strong></th>
<th><strong>Minimum number of selected tracks</strong></th>
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<tbody>
<tr>
<td>10</td>
<td>10</td>
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</table>
NA49 results: spectator (new) vs participant (published) plane

Observed difference between results relative to participant and spectator symmetry planes

Results relative to participant plane are corrected for global momentum conservation (following procedure in N. Borghini et al. Phys.Rev. C66 (2002) 014901)