Anisotropic flow measurements from NA61/SHINE and NA49 scans at SPS

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For the NA61/SHINE and NA49 Collaborations

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Collective flow at different energies

- NA49 and NA61/SHINE Pb-ion beam energy scan ($p_{\text{LAB}} = 13-158A$ GeV/c):
  - complementary to STAR@RHIC and NICA
  - bridge to FAIR/GSI beam energies
- Advantage of NA61/SHINE (NA49) fixed target setup
  - forward rapidity tracking with TPC
  - projectile spectators (forward calorimeter – PSD (VCAL))

**Directed flow (slope)**

**Elliptic flow**

![Graphs showing directed and elliptic flow](image)

- **STAR Collaboration**
  - PRL 112 (2014) 162301
- **HADES Collaboration**
  - JPCS 742 (2016) 012008
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Collision geometry and the anisotropic transverse flow

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

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

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

\( \Psi_s \) can be estimated with produced particles \( \Psi_{pp} \) or with projectile (target) spectators \( \Psi_{proj} \) or projectile spectators \( \Psi_{proj} \) or projectile spectators \( \Psi_{spec} \).

Needed components to calculate \( v_n \):
- momentum (\( \phi, y, p_T \))
- centrality estimation
- particle identification
- \( \Psi_s \) estimation
Pb beam energy scan with NA49 and NA61/SHINE

- Four large-acceptance TPC-s
- Full coverage of forward hemisphere
- Tracking + identification down to $p_T \sim 0$ GeV/c

Forward rapidity calorimeter
NA49: Ring (RCAL) + Veto (VCAL) calorimeters
NA61/Shine: Projectile spectator detector (PSD)

- Pb+Pb beam energy (momentum) scan:
  NA49: 20A, 30A, 40A, 80A, 158A GeV data
  NA61/Shine: 13A, 30A, 150A GeV/c
Event & tracks selection, centrality estimation

Event Selection:

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

Centrality estimated using energy in PSD

Track selection:

Number of clusters:

\[ N_{\text{clusters}}^{[\text{VTPC1+VTPC2}]} > 15 \]
\[ N_{\text{clusters}}^{[\text{Total}]} > 30 \]
\[ 0.55 < \frac{N_{\text{clusters}}^{[\text{Total}]} / N_{\text{clusters}}^{[\text{Total, Pot}]} }{1.1} \]

Distance of closest approach to vertex

\[ |b_x| < 2 \text{ cm}; \ |b_y| < 1 \text{ cm} \]

Negative pions and protons identified using track energy losses (dE/dx)
Scalar product method with 1\textsuperscript{st} harmonic Q-vector

**TPC u-vector**

\[ u_n = (u_x, u_y) = (\cos n \phi, \sin n \phi) \]

**Directed flow:**

\[ v_{1,i} = \frac{2\langle u_{1,i} Q_{1,i}^A \rangle}{R_{1,i}^A} \quad \text{6 combinations} \]

R\textsubscript{1}^A – resolution correction factor

**PSD subevents Q-vector**

\[ Q_{1,i}^A = \frac{1}{E_A} \sum_{j=1}^{N_A} E_j u_{1,i}^j, \quad i = [x,y] \]

A,B,C – PSD subevents

**Elliptic flow:**

\[ v_2 = \frac{4\langle u_{2,i} Q_{1,j}^A Q_{1,k}^B \rangle}{R_{1,j}^A R_{1,k}^B} \quad \text{12 combinations} \]
Corrections for detector azimuthal non-uniformity

QnVector Corrections Framework

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

- QnVector Corrections Framework (used by ALICE)
  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

QnTools Framework

- Extended flow-vector corrections for $p_T$/$y$-differential
- Multi-dimensional correlations of flow-vectors
  L. Kreis (GSI / Heidelberg) and I. Selyuzhenkov (GSI / MEPhI)
  https://github.com/HeavyIonAnalysis/QnTools
3 PSD + 1 TPC subevents resolution

PSD subevents EP resolution factors

\[ R_{P1} = \frac{\langle Q_{P1} Q_{P3} \rangle}{\langle Q_{T} Q_{P3} \rangle} R_T \]

\[ R_{P2} = \frac{\langle Q_{P2} Q_T \rangle}{R_T} \]

\[ R_{P3} = \frac{\langle Q_{P3} Q_{P1} \rangle}{\langle Q_{P3} Q_{P3} \rangle} R_T \]

TPC subevent EP resolution factor

\[ R_T[Q_{P1}, Q_{P3}] = \sqrt{2 \frac{\langle Q_T Q_{P1} \rangle \langle Q_T Q_{P3} \rangle}{\langle Q_{P3} Q_{P1} \rangle}} \]

protons \( 0.8 < y < 1.2 \)
“Systematics” for directed flow ($v_1$) negative pions

Consistent results for PSD subevents

x/y components are consistent
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 (VCAL) acceptance)

The results are corrected only for azimuthal detector non-uniformity. No \( p_t / Y \) dependent efficiency correction applied. 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
Negative pion $v_1$ vs transverse momentum

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

- Significant mass dependence of $v_1(p_T)$
Slope of $v_1$ at midrapidity: comparison with STAR

* Proton and $\pi^-$ selection is tuned to fit STAR fxt acceptance

- Clear mass dependence
- Slope of $v_1(y)$ changes sign at $\sim70\%$ centrality (protons) and $\sim20\%$ centrality ($\pi^-$)
- $v_1(y)$ slope extraction is sensitive to fitting function and rapidity range
Pion and proton $v_2(p_T)$ vs STAR FXT

* Proton and $\pi$ selection is tuned to fit STAR fxt acceptance

- Clear mass dependence of $v_2(p_T)$

Directed and elliptic flow energy dependence

- strong energy dependence
- change of sign moves to high-$p_T$ with increasing energy
Summary

- Obtained preliminary results on directed and elliptic flow relative to spectator plane from NA49 and NA61/Shine Pb+Pb beam energy (momentum) scan data. Results are presented differentially vs transverse momentum, rapidity and centrality.
  - Negative pions and protons $v_1$ and $v_2$ for collisions at 13A GeV/c (NA61/Shine, 2015)
  - Charged pions and protons $v_1$ and $v_2$ for collisions at 30A GeV/c (NA61/Shine, 2016)
  - Negative pions $v_1$ for collisions at $E_{\text{beam}} = 40$A GeV (NA49)
- New results are compared to STAR@RHIC beam energy scan program
- Energy dependence of $v_1$ and $v_2$ is presented
BACKUP
Pb-ion beam energy scan with NA49 (1996-2002)

- Large acceptance hadron spectrometer (TPC)
- Full coverage of forward hemisphere
- Tracking + identification down to $p_T \sim 0$ GeV/c
- Forward rapidity calorimeters
- Pb+Pb beam energy scan 20A, 30A, 40A, 80A, 158A GeV data
PSD Energy vs Charged tracks multiplicity

Clear anti-correlation – mostly spectators in PSD
QnTools setup for \( u \)- and \( Q \)-vectors

<table>
<thead>
<tr>
<th></th>
<th>( u )-vector</th>
<th>( Q )-vector</th>
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<tbody>
<tr>
<td><strong>Subevents</strong></td>
<td>Protons (TPC)</td>
<td>PSD1</td>
</tr>
<tr>
<td></td>
<td>Negative pions (TPC)</td>
<td>PSD2</td>
</tr>
<tr>
<td></td>
<td>Positive pions (TPC)</td>
<td>PSD3</td>
</tr>
<tr>
<td><strong>Weights</strong></td>
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<td>Energy in PSD module</td>
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<tr>
<td><strong>Correction steps</strong></td>
<td>Recentering</td>
<td>Recentering</td>
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<tr>
<td></td>
<td>Twist</td>
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<td>Rescale</td>
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<tr>
<td><strong>Correction axes</strong></td>
<td>( P_T ): ([0.0, 3.0]) GeV/c, 10 bins</td>
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<td>( Y ): ([-0.8, 1.6]) 20 bins</td>
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<td>Centrality: 8 bins</td>
<td>Centrality: 8 bins</td>
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<tr>
<td><strong>Total amount of ( u )- and ( Q )-vectors</strong></td>
<td>(10 \times 20 \times 8 \times 3 = 4800)</td>
<td>(8 \times 3 = 24)</td>
</tr>
</tbody>
</table>
Resolution is biased due to self correlations: hadronic shower sharing between PSD subevents.
“Systematics” for directed flow ($v_1$) protons

Consistent results for PSD subevents

X/Y difference: protons seen in TPC deflected in the same direction as spectators in the PSD

Preliminary results for $\pi$ and $p$: only X-component, PSD subevents are combined
Proton $v_1(y)$ vs with STAR FXT (13A GeV/c)

Au+Au @ 4.5 GeV ($p_{LAB} = 9.8A$ GeV/c)

Proton selection is tuned to fit STAR fxt acceptance

Slope of $v_1$ at midrapidity vs. centrality (13A GeV/c)

Slope extraction procedure:

- 1st order polynomial fit with 2 parameters (slope and offset):
  - Offset for protons is below $6 \times 10^{-3}$ for centrality 0-60% and increasing up to $3 \times 10^{-2}$ for centrality >60%.

Observations:

- Slope of proton $v_1$ changes sign at about 70% centrality
- Slope of pions $v_1$ changes sign at about 20% centrality

Slope extraction is sensitive to fit function and rapidity range
Slope of $v_1$ at midrapidity vs. centrality (30A GeV/c)

Slope extraction is sensitive to fit function and rapidity range

Preliminary results for centrality dependence presented by STAR Collaboration: NPA 956 (2016) 260
Elliptic flow $v_2(p_T)$: particle type dependence

NA61/SHINE preliminary
Pb+Pb @ 13A GeV/c

$\pi^-$

$p$

0 < $y$ < 1.2
PSD centrality 15-35%

Clear mass dependence
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)
Backup: Pb+Pb flow results in NA49 & NA61/SHINE

- 13A GeV/c:  
  - preliminary  
  - published  
  - in progress/to be done
  Present talk

- 30A GeV/c:
  - NA61/SHINE measurements of anisotropic flow relative to the spectator plane in Pb-Pb collisions over a wide rapidity range (QM2018 talk) link
  - NA61/SHINE measurements of anisotropic flow relative to the spectator plane in Pb+Pb collisions at 30A GeV/c link

- 40A GeV (NA49)
  - (TPC only analysis) Directed and elliptic flow of charged pions and protons in Pb+Pb collisions at 40A and 158A GeV (2003) link
  - Anisotropic flow measured in Pb-Pb collisions with the NA49 experiment at the CERN SPS (QM2018 poster) link

- 150A GeV/c

- 158A GeV (NA49)
  - (TPC only analysis) Directed and elliptic flow of charged pions and protons in Pb+Pb collisions at 40A and 158A GeV (2003) link
Negative pion $v_1$ vs rapidity: comparison with STAR FXT Au+Au @ 4.5 GeV ($p_{\text{LAB}} = 9.8A$ GeV/c)

D. Cebra, EMMI Workshop 2019, GSI