Collective flow measurements in Gold-Gold collisions at 1.23 AGeV with HADES

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for the HADES Collaboration

Dense Nuclear Matter Equation of State from Heavy-Ion Collisions
INT WORKSHOP INT-22-84W

6th December, 2022
Outline

- Dense nuclear matter and collective phenomena
- HADES and Au+Au data at 1.23 AGeV
- Directed $v_1$, elliptic $v_2$, and higher flow harmonics ($v_3, v_4, v_5, v_6$) of protons, deuterons and tritons
- Scaling properties of flow harmonics
- Model comparisons

Talk based on following publication:
HADES, arXiv:2208.02740 submitted to EPJ A
Motivation

Nuclear and Neutron Star Matter

**Neutron Star Merger**
Observation via gravitational waves
**GW170817**: B.P. Abott et al. (LIGO + VIRGO)
PRL **119** (2017) 1611001

Sensitivity to equation-of-state

Matter at super nuclear density in the universe

**Heavy-ion Collision**
Equation-of-state of dense matter

Matter at super nuclear density in the laboratory
Collective Effects
Flow Phenomenology

Emission relative to event plane
Interactions in medium, nuclear stopping
\[ \Rightarrow \text{buildup of non-uniform pressure gradients} \]
provides accelerating forces in different directions

Access to medium properties, e.g. viscosity, equation-of-state

Fourier-decomposition
of the triple differential invariant cross section
\[
E \frac{d^3N}{dp^3} = \frac{1}{2\pi} \frac{d^2N}{p_t \, dp_t \, dy} \left( 1 + 2 \sum_{n=1}^{\infty} v_n(p_t, y) \cos(n\phi) \right)
\]
\[ \phi = (\varphi - \Psi_{RP}) \]
Extraction of azimuthal moments \( v_n \)
\[
v_n(p_t, y) = \langle \cos(n\phi) \rangle
\]
Event Plane Reconstruction

1st-Order event plane from Q-Vector

Projectile spectators in Forward Wall

Charge-Weighting of the projectile hits, according their energy loss in scintillators

\[
\tan \psi_{EP,1} = \frac{Q_{1,y}}{Q_{1,x}}
\]

\[
Q_{n,x} = \sum_{i=0}^{N_{FW}} w_i \cos(n \phi_{FW,i})
\]

\[
Q_{n,y} = \sum_{i=0}^{N_{FW}} w_i \sin(n \phi_{FW,i}).
\]
Event Plane Determination

Correction of non-uniformities in the EP distribution (day-by-day and centrality)

Re-centering of X and Y of all FW hits

Flattening of residual Fourier components with 8 cos- and 8 sin-terms
Event Plane Resolution

EP-resolution via sub-event method with three implementations

Determination of resolution parameter $\chi$
- directly via $\langle \cos (\Delta \Phi) \rangle$
- Approximation via Fraction of Events with $\Delta \Phi > \pi/2$
- Fit-Method

Calculation of EP-Resolution of different order

$$\frac{dN}{d\Delta \Psi_{EP}}$$

$$\Delta \Psi_{EP}$$

$$\text{Centrality 20-25 \%}$$

$$\text{Au+Au 1.23 AGeV}$$

$$\chi$$

Resolution Parameter

$$\nu_n = \frac{\nu_{n}^{obs}}{\mathcal{R}_n}$$

$$\mathcal{R}_n = \langle \cos[n(\Psi_n - \Psi_{RP})]\rangle$$

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Systematic Uncertainties
Validation and Consistency Checks

Sources of uncertainties
- Track selection and PID
- Occupancy correction
- Non-uniform acceptance

Toy MC study
Influence of the incomplete acceptance and a non-uniform event-plane distribution

Consistency checks:
- Measurement symmetry with respect to mid-rapidity
- Zero-crossing of odd harmonics at $y_{cm}=0$
- Vanishing residual sine-terms
- Time-dependent systematic effects

Reversed field polarity
Comparison with flow coefficients from the full data set
Collective Effects

Energy-Dependence

Compilation of world data
Good agreement of mean transverse mass \(<m_t>-m_0\), integrated directed flow \(dv_1/dy\) and elliptic flow \(v_2\)

Out-of-Plane \(v_2\)
Long spectator passing time at HADES energy
\(\tau_{\text{passing}} \approx \tau_{\text{expansion}} \Rightarrow \text{“squeeze-out”}\)
Collective Effects

Results on $v_1$, $v_2$, $v_3$ and $v_4$ for Protons, Deuterons and Tritons

Protons

Deuterons

Tritons

$\rho_\pi$ (GeV/$c$)

- 0.35 - 0.40
- 0.55 - 0.60
- 0.75 - 0.80
- 0.95 - 1.00
- 1.15 - 1.20
- 1.35 - 1.40
- 1.55 - 1.60
- 1.75 - 1.80
- 1.95 - 2.00

$\sqrt{s_{NN}} = 2.4$ GeV

HADES, arXiv:2208.02740
Collective Effects
Results on v1, v2, v3 and v4 for Protons, Deuterons and Tritons

Protons
Centrality 20-30%

Deuterons

Tritons

$\sqrt{s_{NN}} = 2.4 \text{ GeV}$

HADES, arXiv:2208.02740

$\rho_t (\text{GeV/c})$
- 0.35 - 0.40
- 0.55 - 0.60
- 0.75 - 0.80
- 0.95 - 1.00
- 1.15 - 1.20
- 1.35 - 1.40
- 1.55 - 1.60
- 1.75 - 1.80
- 1.95 - 2.00

$\approx 2.4 \text{ GeV}$

$\text{Au+Au}$

$\text{HADES}$
Collective Effects
Results on $v_1$, $v_2$, $v_3$ and $v_4$ for Protons, Deuterons and Tritons
Collective Effects
Results on $v_1$, $v_2$, $v_3$ and $v_4$ for Protons, Deuterons and Tritons

Protons
Centrality 20-30%

Deuterons

Tritons

$\sqrt{s_{NN}} = 2.4$ GeV

HADES, arXiv:2208.02740

$\langle p_T \rangle$ (GeV/c)

$0.40 - 0.60$

$0.60 - 0.80$

$0.80 - 1.00$

$1.00 - 1.20$

$1.20 - 1.40$

$1.40 - 1.60$

$1.60 - 1.80$

$1.80 - 2.00$

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Collective Effects
Results on $v_1$, $v_2$, $v_3$ and $v_4$ for Protons, Deuterons and Tritons

Shown only a fraction of the data
In total 17k data points with individual systematic uncertainties available
Collective Effects

Results on $v_1 - v_6$ for Protons, Deuterons and Tritons

Emission Pattern

Protons

Allows to reconstruct a full 3D-picture of the emission pattern in momentum space

Shape determined by flow coefficients $v_1 - v_6$

Complex evolution of shape as function of rapidity

$$1 + 2 \sum_{n=1}^{\infty} v_n(y_{cm}) \cos n(\phi - \psi_{RP})$$

$$v_{1,3,5}(y_{cm}) = a y_{cm} + b y_{cm}^3$$

$$v_{2,4,6}(y_{cm}) = c + d y_{cm}^2$$

First Proposed in S. Voloshin and Y. Zhang

“Ideal fluid scaling”
Relation between $v_2$ and $v_4$

Scaling properties
Prediction for ideal fluid:

$$v_4(p_t)/v_2^2(p_t) = 1/2$$

Slightly higher values (~ 0.6) expected in more realistic scenario

Observed ratios for p, d and t
Independent of $p_t$ and centrality
Close to predicted value of ~ 0.6

Confirmed by transport models

Hydro-like matter at SIS energies?

Systematic Error of $v_2$ and $v_4$ are treated as correlated


P. Kolb, PRC 67 (2003) 031902
C. Gombeaud and J.-Y. Ollitrault, PRC 81 (2010) 014901

J. Wang et al., PRC 90 (2014) 054601 IQMD
Justin Mohs et al., PRC 105 (2022) 034906 SMASH
Nucleon Coalescence
Scaling Properties of $v_2$ at Mid-Rapidity

Scaling of $v_2$ and $p_t$ with nuclear mass number $A$ (including higher terms)

Works as expected in simple coalescence picture for the dominant flow coefficient

Only at mid-rapidity: odd flow coefficients vanish and $v_4$ contribution is negligible

Approximation for small $v_n$

$$v_{n,A}(A p_t) = A v_n(p_t)$$

$$v_{n,A=2}(A p_t) = 2 v_n(p_t) \frac{1}{1 + 2 v_n^2(p_t)}$$

$$v_{n,A=3}(A p_t) = 3 v_n(p_t) \frac{1 + v_n^2(p_t)}{1 + 6 v_n^2(p_t)}$$

P.F. Kolb et al., PRC 69 (2004) 051901
Nucleon Coalescence
Scaling Properties of $v_4$ at Mid-Rapidity

Scaling of $v_4$ and $p_t$ with nuclear mass number $A$ (including higher terms)

Works as expected in simple coalescence picture if contribution of dominant flow coefficient is included

Approximation for small $v_4$ with $v_2$ contribution:

$$v_{n,A}(Ap_t) = A^2 v_n(p_t)$$

P.F. Kolb et al., PRC 69 (2004) 051901

HADES, arXiv:2208.02740

$$v_{4,A=2}(p_t) = 4v_4(p_t) \frac{1}{1 + 4v_4(p_t) + 2v_2^2(p_t)}$$

assuming: $v_4(p_t)/v_2^2(p_t) = 1/2$

P.F. Kolb et al., PRC 69 (2004) 051901
Geometry Scaling
Elliptic Flow $v_2$

Scaling with initial eccentricities
Calculated for overlap zone with Glauber MC

$v_2/\langle \varepsilon_2 \rangle$ almost independent of centrality and $p_t$

Orientation of symmetry-planes
Negative $v_2/\langle \varepsilon_2 \rangle$ values
$\implies v_2$ Flow- and $\varepsilon_2$ eccentricity-plane are perpendicular
Geometry Scaling

Quadrangular Flow $v_4$

Scaling with initial eccentricities
Calculated for overlap zone with Glauber MC

\[
\frac{v_4}{\langle \varepsilon_2 \rangle^2} \text{ almost independent of centrality and } p_t \quad (v_4/\langle \varepsilon_4 \rangle \text{ is not})
\]

\[\Rightarrow \text{ Fixed relation between } v_2 \text{ and } v_4 \text{ (different to high energies)}\]
Model Comparisons to Proton Data

Determination of EOS
New level of precision
Additional information from higher orders

Models:
- JAM 1.9 NS3 (hard EOS, mom.-indep.)
- JAM 1.9 MD1 (hard EOS, mom.-dep.)
- JAM 1.9 MD4 (soft EOS, mom.dep.)
- UrQMD 3.4 (hard EOS, mom.-indep.)
- GiBUU Skyrme 12 (soft EOS)

Conclusions
Overall trend reasonably described, but no model works everywhere

Several systematic deviations

Unified description of cluster production missing
Model Comparisons to Proton Data

**HADES**

**Slope** $v_1$

0.6 < $p_t$ < 0.9 GeV/c

**Aberrancy** $v_1$

0.6 < $p_t$ < 0.9 GeV/c

**Curvature** $v_2$

0.6 < $p_t$ < 0.9 GeV/c

**Aberrancy** $v_3$

0.6 < $p_t$ < 0.9 GeV/c

**Curvature** $v_4$

0.6 < $p_t$ < 0.9 GeV/c

*Aberrancy*: the third derivative of a curve
Conclusions and Outlook

Scaling properties of Flow Coefficients
Relation between $v_2$ and $v_4$
*Hydro-like matter at SIS energies?*

Scaling of $v_2$ and $v_4$ according simple “nucleon coalescence” via momentum addition

Scaling with Initial Eccentricities reveals fixed relation between $v_2$ and $v_4$

Model Comparison
New level of precision - multi-differential
Additional information from higher orders

Consistent modelling of cluster formation is essential

Next Steps towards EOS
Detailed comparisons and sensitivity to model parameter space $\Rightarrow$ Bayesian analysis

System-Size and Energy-dependence
Ag+Ag Beam data
at 1.23 and 1.58 AGeV (2019)

SIS Beam Energy Scan
Au+Au 0.2, 0.4, 0.6 and 0.8 AGeV is planned
HADES Collaboration

Thank you for your attention!