Collective flow measurements with HADES in Au+Au collisions at 1.23 A GeV

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Outline

- HADES and Au+Au data at 1.23 AGeV
- Radial flow
- Directed and elliptic flow of protons
- Higher harmonics $v_3(\Psi_{PR})$
- Effect of Coulomb potential on pion spectra
Motivation

- Bulk properties of extreme nuclear matter
- Equation of State
- Effect of mean-field potentials

\[ F = \langle \frac{p_x}{A} \rangle \]
Motivation

![Graph showing the ratio of entropy to entropy density (η/s) as a function of temperature (T) for different models and data points. The graph includes lines for QCD, HRG, perturbative HRG, and KSS, and data points from experiments such as ALICE and HADES.]

Legend:
- QCD result
- HRG /pert
- KSS
- Bass et al.
  - Phys. Rev. Lett. 102, 172302
- Danielewicz et al.
  - arXiv:1612.04874
- Bernhard et al.
  - Phys. Rev. C 91, 054910
- ALICE Data (Glauber)
- KLN
- Ivanov et al.
- Khvorostukhin et al.

Behavior of η/s at different incident energies (100 MeV/n, 400 MeV/n, 1000 GeV/n).
Collective Flow

radial flow

\[ v_1 = \langle \cos(\phi) \rangle = \langle \frac{p_x}{p_t} \rangle \]

directed flow

\[ v_1 = \langle \cos(\phi) \rangle \]

elliptic flow

\[ v_2 = \langle \cos(2\phi) \rangle = \langle \frac{p_x^2 - p_y^2}{p_t^2} \rangle \]

triangular flow

\[ v_3 = \langle \cos(3\phi) \rangle = \langle \frac{p_x^3 - 3p_xp_y^2}{p_t^3} \rangle \]

\[ \phi = (\varphi - \Psi_{RP}) \]

STAR: Phys. Rev. C 86, 054908
High Acceptance Di-Electron Spectrometer
High Acceptance Di-Electron Spectrometer

- Fixed-target experiment located at GSI, Darmstadt

- **Large acceptance**
  - symmetric azimuthal coverage
  - 18°-85° in polar angle

- **Tracking system and magnetic spectrometer**
  - 4 planes of low-mass mini-drift chambers (MDC)
  - superconducting toroidal magnet

- **Forward Wall**
  - reaction plane reconstruction
Au+Au at 1.23 AGeV

- HADES Au+Au beam time
  - Beam: $1.5 \times 10^6$ Au ions/s
  - Trigger rate of up to 8 kHz
- High statistics
  - total number of event recorded: $7 \times 10^9$
  - $2.1 \times 10^9$ most central analysed (~40% of total cross section)
Event Plane Reconstruction

- Event plane based on projectile spectators
- Resolution determined with two sub-event method and corrected with method described in J.-Y. Ollitrault, arXiv:nucl-ex/9711003

\[
\psi_{EP} = v_{n}^{obs} / \mathcal{R}_n
\]

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

\[
= \sqrt{2} \langle \cos[n(\Psi_n^A - \Psi_n^B)] \rangle
\]
Proton Spectra

**Measured Protons in Acceptance**

- **TOF**
- **RPC**
- **FW**

**Proton Spectra**

- **P_{1} [MeV/c]**

**d^{2}N/dm_{t}dy** [(MeV/c^2)^{-1}]

- 0.09 < y ≤ 0.19 (x10^6)
- 0.99 < y ≤ 1.09 (x10^6)

**p**

- 0-40%

**preliminary**
Pion Spectra

Measured Pion in Acceptance

- TOF
- RPC
- FW

\( P_\pi \) [MeV/c]

\( y_{cm} \)

\( m_t - m_0 \) [MeV/c^2]

\[ \frac{1}{m_t} \frac{d^2N}{dm_t dy} \]

- 0.09 \( \leq y \leq 0.19 \times 10^0 \)
- 1.19 \( \leq y \leq 1.29 \times 10^{11} \)

Preliminary
Simultaneous Blast-Wave Fit

Phys. Rev. C 48, 2462

**blast wave model:**

\[
\frac{dN}{p_T dp_T} \propto \int_0^R r \, dr \, m_T I_0 \left( \frac{p_T \sinh \rho(r)}{T_{kin}} \right) \times K_1 \left( \frac{m_T \cosh \rho(r)}{T_{kin}} \right)
\]

linear radial flow velocity profile:

\[
\beta = \beta_S (r/R)^n \\
\beta_r = 0.36 \pm 0.04
\]

- Good description of Protons, Kaons and Pions (higher \( m_t \))

\[
T_{kin} = 62 \pm 10 \text{ MeV}
\]

- \( \Lambda \) and \( \Phi \) spectra steeper than expected from Blast-Wave

\[
\frac{1}{m_t} \frac{d^2N}{m_t \, dm_t \, dy} \cdot [(\text{MeV}/c^2)^3]
\]

0-10% most central

\[ \Lambda \times 10^5 \]

\[ \phi \times 10^6 \]

\[ p \]

\[ K_S^0 \times 4 \times 10^2 \]

\[ K^+ \times 10^2 \]

\[ \pi^- \times 2 \times 10^{-2} \]

\[ \pi^+ \times 10^{-1} \]
Radial Flow Parameter

\[ T \text{ (MeV)} \]

\[ \sqrt{s_{NN}} \text{ (GeV)} \]

World data
HADES Preliminary
STAR BES

\[ T_{\text{ch}} \quad T_{\text{kin}} \]

Andronic et al.
Cleymans et al.

\[ \beta \]

\[ \beta < 0 \text{ (GeV)} \]

\[ \beta > 0 \text{ (GeV)} \]
Directed Proton Flow $v_1$

\begin{figure}
\centering
\includegraphics[width=\textwidth]{diagram.png}
\end{figure}

HADES
Au+Au 1.23 AGeV
Preliminary
centrality 20-30%
Elliptic Proton Flow $v_2$

HADES
Au+Au 1.23 AGeV
Preliminary

$\Delta y > 300 \text{MeV/c}$

$y - y_{cm}$

$0.1$

$v_2$

$0$

$-0.1$

$-0.2$

$-0.3$

$0$

$0.2$

$0.4$

$0.6$

$0.8$

$1$

$1.2$

$1.4$

$p_t$ [GeV/c]
Elliptic Proton Flow $v_2$

**Graphs:**
- Left graph: V$_2$ vs. $y$-$y_{cm}$ for different $p_t$ ranges:
  - $300.00 < p_t < 350.00$
  - $400.00 < p_t < 450.00$
  - $500.00 < p_t < 550.00$
  - $600.00 < p_t < 650.00$
  - $700.00 < p_t < 750.00$
  - $800.00 < p_t < 850.00$
  - $900.00 < p_t < 950.00$
  - $1000.00 < p_t < 1050.00$
  - $1100.00 < p_t < 1150.00$

- Right graph: V$_2$ vs. $p_t$ for different $y$ ranges:
  - $0.05 < y < 0.05$
  - $-0.45 < y < -0.35$

**Legend:**
- Common Systematic Error
- Preliminary
- Centrality 20-30%
v2 - Elliptic Flow


**STAR:** Phys. Rev. C 86, 054908


**CERES:** Nucl. Phys. A 698 (2002) 253

**NA49:** Phys. Rev. C 68 (2003) 034903


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Proton $v_3\{\Psi_{RP}\}$

$$v_3\{\Psi_{RP}\} = \langle \cos 3(\varphi - \Psi_{RP}) \rangle$$
$$= \langle \cos 3(\varphi - \Psi_3) \cos 3(\Psi_3 - \Psi_{RP}) \rangle$$
$$= \langle v_3\{\Psi_3\} \langle \cos 3(\Psi_3 - \Psi_{RP}) \rangle \rangle$$

- Note: $v_3\{\Psi_{RP}\}$ w.r.t reaction plane
- Convolution of fluctuation of initial state ($\Psi_3$) and spectator plane

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Coulomb Potential Analysis

\[ E_f = E_i \pm V_C \]

\[ R_f(E_f) = \frac{E_f - V_C \sqrt{(E_f - V_C)^2 - m^2}}{E_f + V_C \sqrt{(E_f + V_C)^2 - m^2}} \]

\[ A^+(e^{(E_f+V_C)/T_\pi} - 1) \]

\[ A^-(e^{(E_f-V_C)/T_\pi} - 1) \]

\[ V_{\text{eff}} = V_C(1 - e^{-E_{\text{max}}/T_p}) \]

\[ E_{\text{max}} = \sqrt{(m_p\rho_\pi/m_\pi)^2 + m_p^2} - m_p \]

Recipe followed from: arXiv:1408.1369

Bose-Einstein Formula

Jacobian

Coulomb Potential

Recipe followed from: arXiv:1408.1369
Coulomb Potential Analysis
Conclusion

- Radial flow (Blast-Wave Fits)
  \[ T_{\text{kin}} = 62 \pm 10 \text{ MeV} \]
  \[ \langle \beta_r \rangle = 0.36 \pm 0.04 \]
- Fits to systematic of world data
- Directed and elliptic flow of protons \( v_1 \) and \( v_2 \)
  - Large phase-space coverage and high statistics
  - Multi-differential analysis (\( p_t \), rapidity, centrality)
- Higher order harmonics
  - First look of \( v_3 \{ \Psi_{RP} \} \) at SIS energies
- Pion Coulomb potential analysis
HADES Collaboration

Thank you for your attention!
Backup
Energy-dependence $v_3^2\{2\}$

- $v_3^2$ w.r.t $\Psi_3$ symmetry plane
- origin: initial state fluctuation (at higher energies)
- other explanation for lower energies

STAR: arXiv:1601.01999
ALICE: Phys. Rev. Lett. 107, 032301
arXiv:1602.01119