Highlights on flow measurements from the STAR experiment

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RHIC-AGS Annual Users’ Meeting
Beam energy and system scan at STAR

1) BES-II collider energies
\[ \sqrt{s_{NN}} = 7.7 - 54.4 \text{ GeV} \]

2) FXT energies
\[ \sqrt{s_{NN}} = 3.0 - 13.7 \text{ GeV} \]

- Onset of deconfinement
- Nature of the phase transition
- Critical Point
- Study of QGP properties

3) System scan at RHIC top energy
\[ \sqrt{s_{NN}} = 200 \text{ GeV} \]

K Meehan, Nuclear Physics A. 967 (2017) 10.1016
Solenoidal Tracker at RHIC (STAR)

- Enlarged rapidity acceptance
- Improved particle identification
- Enhanced event plane resolution

Anisotropic flow

Directed flow ($v_1$): Sideward collective motion of produced particles

Elliptic flow ($v_2$): Initial spatial anisotropy leading to final momentum asymmetry of produced particles

Triangular flow ($v_3$): Higher energy: Sensitive to initial state event-by-event fluctuations
Lower energy: Result of shadowing and baryon stopping; sensitive to medium potential

$$\frac{dN}{d\phi} \propto \frac{1}{2\pi} \left[ 1 + \sum_{n=1}^{\infty} 2v_n \cos(n(\phi - \Psi_R)) \right]$$

$$v_n = \langle \cos(n(\phi - \Psi_R)) \rangle$$

→ Equation of State of the medium
→ Early stage dynamics

A.M. Poskanzer & S.A. Voloshin, PRC 58 (1998), 1671
STAR, PRL 118 (2017), 212301

STAR, PRC 109 (2024), 044914

Science 337 (2012), 310

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Beam Energy Scan

Emilie Duckworth
Wednesday 3:00 PM
Limiting fragmentation of $v_1$

- Measurement of flow over nine units of pseudorapidity ($\eta$)
- Precision measurement of $v_1$ enables observation of limiting fragmentation
- The phenomenon extends for various centralities at BES-II energies

PHOBOS. PRL 91 (2003), 052303
PHOBOS. PRL 97 (2006), 012301
Excess proton $v_1$ in BES-II

- Precision measurement of $\bar{p}$ and $p$ from 7.7 to 200 GeV

- Scaling of excess proton flow with collision energy
- Indication of scale breaking at 11.5 GeV → change in medium and collision dynamics
- Mean field calculations overpredict the $v_{1,\text{excess}}$ data below 14.6 GeV

$\rho = \frac{\text{yield of } \bar{p}}{\text{yield of } p}$

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References:
- STAR, PRL 120 (2018), 62301
- Y. Nara et al., PRC 100 (2019), 054902
$v_n$ of light nuclei in BES-II

- First measurement of $v_3$ of light nuclei at collider energies
- Suggests coalescence to be the dominant mechanism of light nuclei production

PRC 72 (2005), 064901
PRC 93 (2016), 014907
PRC 88 (2013), 014902
PLB 827 (2022), 137003
Beam energy dependence of $\Delta v_1$ slope

- $\Delta v_1$ slope is more negative at lower collision energies
  - Could be due to EM-field effect, longer-lived field and shorter lifetime of fireball
  - Indication of strong $p_T$ dependence of splitting

STAR, PRX 14 (2024), 011028
U. Gürsöy et al. PRC 98 (2018), 055201; PRC 89 (2014), 054905
Beam energy dependence of flow cumulants

- Anti-correlation between \( \nu_2 \) and \( \nu_3 \)
  - Anti-correlation b/w \( \epsilon_2 \) and \( \epsilon_3 \)
- Mode coupling between \( \nu_2 \) and \( \nu_4 \)

- Weak dependence on beam energy
  - Weakly sensitive to the viscous effects (\( \eta/s \)) ; more sensitive to the initial-state effects

\[
V_4 = \nu_4 e^{i\psi_4} = \kappa_4 \epsilon_4 e^{4i\Phi_4} + \kappa_4' \epsilon_2 e^{4i\Phi_2} = V_4^{\text{Linear}} + \chi_{4.22} V_4^{\text{MC}},
\]

STAR Preliminary

Fixed–target (FXT) energies
Energy dependence of $v_1$, $v_2$ at FXT energies

- Anti-flow only of kaon at low $p_T$ at 3.83 GeV
- Anti-flow observed at $3 - 3.9$ GeV for $\pi^+ K^\pm$ and $K_s^0$, at low $p_T$
  - Shadowing effect from spectators
- Out-of-plane $\rightarrow$ In-plane expansion b/w 3 - 4.5 GeV

STAR Preliminary

E895, PRL 85 (2000), 940

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NCQ scaling of $v_2$ at 3 - 4.5 GeV

- NCQ scaling completely breaks below 3.2 GeV
- Scaling becomes gradually better above 3.2 GeV

STAR, PLB 827 (2022) 137003
\( v_1, v_3 \) at FXT energies

- Increasing collision energy \( \rightarrow \) decreasing \( v_1 \) slope; \( v_3 \) slope approach zero
- Trend consistent with HADES results at 2.4 GeV
- Non-zero \( |v_3\{\Psi_1\}| \), increase towards peripheral collisions
  - Geometry driven \( v_3 \) at lower energy
  - JAM describes the data implying importance of nuclear potential

\[ \frac{d\nu}{dy} \]

\[ \frac{d(v_3/A)}{dy} \]

\[ \text{Au+Au Collisions at RHIC, 10 - 40 \%} \]

\[ \text{STAR preliminary} \]

\[ \text{PRL 120 (2018), 062301; PLB 827 (2022), 137003} \]

\[ \text{HADES, PRL 125 (2020), 262301; STAR, PRC 109 (2024) 44914} \]
Flow of light and hyper nuclei at FXT

- Light- and Hyper-Nuclei production are enhanced at high $\mu_B$
- Understanding production mechanism of light/hyper nuclei
- Hyper-nuclei probes Y-N interactions $\rightarrow$ inner core of neutron stars

- Collision energy increases $\rightarrow$ the $v_1$ slope of light- and hyper-nuclei decreases
- $v_1$ slope scales with mass number $A$ or/and particle mass
- JAM2 mean field + coalescence calculations explains the energy dependence

STAR, PRL 130 (2023), 211301
Y. Nara et al., PRC 106 (2022), 044902
$v_1$, $v_3$ of light nuclei at 3 GeV

- A-scaling for $v_1$ and $v_3$ breaks above rapidity $\sim 0.5$ in 10-40% centrality
  - Coalescence production at mid-rapidity and indication of different production mechanism at forward rapidity
- To explore the measurement to the target rapidity
System size scan of collectivity

U+U  Au+Au  Ru+Ru  O+O  $^3\text{He}+\text{Au}$  d+Au  p+Au  $\gamma+\text{Au}$

$\text{A}+\text{A}$  $\text{p}/d/\text{He}+\text{A}$  Photonuclear $\gamma+\text{Au}$
Small system flow at STAR

- $v_2(p_T)$ values depend on the colliding systems
- $v_3(\text{p+Au}) \sim v_3(\text{d+Au}) \sim v_3(\text{3He+Au})$
  
  → IP-Glasma+MUSIC including subnucleonic fluctuations shows good agreement with $v_3(p_T)$
**Flow in O+O collisions**

- $v_2$ (O+O) $< v_2$(d+Au) $\approx v_2$(³He+Au)
- $v_3$ (O+O) $\approx v_3$(d+Au) $\approx v_3$(³He+Au)
- Gluon fluctuation around quark model:
  
  $$\varepsilon_n$(d+Au) $\approx \varepsilon_n$(³He+Au); n=2,3

Gluon field: PRC 94 (2016), 024919

- $\varepsilon_2$(O+O) $< \varepsilon_2$(³He+Au)
- $\varepsilon_3$(O+O) $\approx \varepsilon_3$(³He+Au)

$\Rightarrow$ $v_n/\varepsilon_n$ similar between O+O and ³He+Au, within a quark Glauber model

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arXiv:2312.12167 [nucl-ex]

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STAR, PRL 130 (2023) 242301

Zhengxi Yan : Tues 1 PM
Strange hadrons' flow

- $v_2$ of $K_s^0, \Lambda$, and $\bar{\Lambda}$ in isobar collisions (Ru+Ru and Zr+Zr) is smaller than in $^{197}\text{Au}+^{197}\text{Au}$ and $^{238}\text{U}+^{238}\text{U}$ collisions at $p_T > 1.5$ GeV/c

- $v_2$ in Ru+Ru and Zr+Zr collisions is larger as compared to $^{63}\text{Cu}+^{63}\text{Cu}$ collisions at higher $p_T$

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11/06/2024

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Imaging Shapes of Atomic Nuclei

- Snapshot of the spatial matter distribution imprints on the particle momentum distribution

- Enhanced $v_2$ particularly in central U+U collisions
  - Nuclear deformation influences collisions over a wide centrality range

- Mean $v_2$ ratios and $v_2$-$p_T$ correlations are used to constrain initial conditions and nuclear structure in U+U and isobar collisions

$\beta_2^U = 0.286 \pm 0.025$

$\beta_2^{Ru} = 0.16 \pm 0.02$, $\beta_3^{Zr} = 0.20 \pm 0.02$

C. Zhang and J. Jia, PRL 131 (2022), 022301

STAR, arXiv:2401.06625 [nucl-ex]
B Schenke, PRC 102 (2020), 034905
J. Jia, PRC 105 (2022), 014905
G. Giacalone et al, PRL 127 (2021), 242301
Summary

✓ More negative $\Delta v_1$ slope at lower energies: Qualitatively consistent with influence of EM-field and shorter lifetime of fireball

✓ Explored particle production in the fragmentation region and of light/hyper nuclei at wide range of rapidity
  ➔ a probe for medium dynamics

✓ Anti-flow of mesons observation showing hints of nuclear shadowing effect

✓ Hadronic interaction from 3.2 GeV towards 4.5 GeV → Partonic collectivity

✓ JAM calculations suggest potential is essential for development of geometry driven $v_3\{\Psi_1\}$ at lower energies, whereas JAM overpredicts the excess $v_1$ below 14.6 GeV → Better constraint on EoS

✓ Significance of sub-nucleonic fluctuations in small systems

✓ Exploring anisotropic flow as a new means to imaging of nuclear structure
Stay tuned for more exciting results covering the entire BES-II collider and FXT energies

γ+Au@2023, d+Au@2021 and O+O@2021 will provide more information for collectivity in small systems

Forward detectors enables the flow measurements in wider rapidity ranges, opening new windows to explore the QGP properties

This precision era takes us closer to uncover the secrets of QGP phase, its transitions and much more…

Thank you for your attention!