System size dependence of particle production and collectivity from the STAR experiment at RHIC

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for the STAR collaboration
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RHIC has provided us with a variety of collision systems.

For different collision systems, same $N_{\text{part}}$ leads to different initial geometry.

What are the decisive factors of medium properties?

Not an exhaustive list of all collision species at RHIC!
System Size Dependence of Medium Properties

\[ \langle N_{\text{part}} \rangle \]

\begin{align*}
&10^{0.5} & 10^1 & 10^{1.5} & 10^2 & 10^{2.5} \\
&197_{79}^{\text{Au}} + 197_{79}^{\text{Au}} & & & & \\
&96_{44}^{\text{Ru}} + 96_{44}^{\text{Ru}}/\text{96}_{40}^{\text{Zr}} + 96_{40}^{\text{Zr}} & 60-80\% & & & 10-20\% & 0-5\% \\
&64_{29}^{\text{Cu}} + 64_{29}^{\text{Cu}} & 40-60\% & 20-40\% & 0-10\% & \\
&d + 197_{79}^{\text{Au}} & 0-100\% & & & 0-20\% \\
&\gamma + 197_{79}^{\text{Au}} & & & & & \\
\end{align*}

- Nuclear modification of hard partons
- Momentum distribution of identified hadrons
- Collective motion
- Long-range correlation of inclusive hadrons
The STAR Detector
System Size Dependence of Medium Properties

Nuclear modification of hard partons
Ru+Ru & Zr+Zr show similar level of suppression

Significant high-$p_T$ suppression for central events

Suppression decreases with centrality
- 40-60% looks similar to 60-80%

$$R_{AA} = \frac{1}{N_{ev}} \frac{d^2N_{AA}}{d\eta dp_T} \frac{T_{AA} d^2\sigma_{NN}^{NN}}{d\eta dp_T}, T_{AA} = \langle N_{coll} \rangle / \sigma_{inel}^{NN}$$
$R_{AA}$ as a Function of $N_{\text{part}}$

\begin{align*}
\text{Data} & \\
\text{Ru+Ru} & \\
\text{Zr+Zr} & \\
\text{pp uncertainty} & \\
\end{align*}

\begin{align*}
\text{STAR Preliminary} & \\
\text{Isobar} & \sqrt{s_{\text{NN}}}=200 \text{ GeV} \\
(\hbar^+ + \hbar^-)/2 & p_{\text{T}} > 5.1 \text{ GeV/c} \\
\end{align*}

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$R_{AA}$ as a Function of $N_{part}$

$R_{AA}$ in 0-60% central events ($\langle N_{part}\rangle > 20$) decrease with $\langle N_{part}\rangle$.

STAR Preliminary

Isobar $\sqrt{s_{NN}}=200$ GeV
$(h^+ + h^-)/2$, $p_T > 5.1$ GeV/c

Data
- Ru+Ru
- Zr+Zr
- pp uncertainty
$R_{AA}$ as a Function of $N_{\text{part}}$

- $R_{AA}$ in 0-60% central events ($\langle N_{\text{part}} \rangle > 20$) decrease with $\langle N_{\text{part}} \rangle$
- Same $R_{AA}$ at same $\langle N_{\text{part}} \rangle$ regardless of system

STAR Preliminary
Isobar $\sqrt{s_{NN}}=200$ GeV
$(h^+ + h^-)/2$ $p_\pi > 5.1$ GeV/$c$
$R_{AA}$ as a Function of $N_{part}$

- $R_{AA}$ in 0-60% central events ($\langle N_{part} \rangle > 20$) decrease with $\langle N_{part} \rangle$
- Same $R_{AA}$ at same $\langle N_{part} \rangle$ regardless of system
- Deviation from trend starting at $\langle N_{part} \rangle \lesssim 20$

STAR Preliminary
Isobar $\sqrt{s_{NN}}=200$ GeV
$(h^+ + h^-)/2 \ p_{\text{T}} > 5.1$ GeV/c

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$R_{AA}$ as a Function of $N_{part}$

- $R_{AA}$ in 0-60% central events ($\langle N_{part} \rangle > 20$) decrease with $\langle N_{part} \rangle$
- Same $R_{AA}$ at same $\langle N_{part} \rangle$ regardless of system
- Deviation from trend starting at $\langle N_{part} \rangle \approx 20$
  - Event selection bias in peripheral events causes artificial suppression?
  - HG-PYTHIA\(^1\) qualitatively gets trend but predicts steeper drop
  - Detailed studies ongoing

\[ R_{AA} = \frac{dN_{AA} - dN_{pp}}{dN_{pp}} \]

\[ \langle N_{part} \rangle \]

\[ \sqrt{s_{NN}} = 200 \text{ GeV} \]

\[ (h^+ + h^-)/2 \quad p_\perp > 5.1 \text{ GeV}/c \]

Ru+Ru/Zr+Zr Yield Ratio

- For the same centrality percentage, Ru+Ru collisions have bigger $N_{\text{coll}}$
- Ru+Ru/Zr+Zr per-event yield ratio > 1
  - strong resolution on system size difference
- $N_{\text{coll}}$-scaled ratio consistent with unity at high $p_T$
  - No significant difference on quenching
- $N_{\text{part}}$-scaled ratio beyond 1 at $p_T > 0.5$ GeV/c
  - Consistent with unity at the lowest $p_T$
  - Rising with $p_T$: flow effect?

Refer to: Talk by Haojie Xu (Wed 9:00 AM T01) & Poster by Chunjian Zhang (Session 2 T14-2 #962)
System Size Dependence of Medium Properties

\[ \langle N_{\text{part}} \rangle \]

\begin{align*}
&10^{0.5} & 10^1 & 10^{1.5} & 10^2 & 10^{2.5} \\
\text{197}_7^{79}\text{Au} + \text{197}_7^{79}\text{Au} & & & & & \\
&60-80\% & 30-40\% & 10-20\% & 0-5\% \\
\text{96}_4^{44}\text{Ru} + \text{96}_4^{44}\text{Ru} / \text{96}_4^{40}\text{Zr} + \text{96}_4^{40}\text{Zr} & & & & & \\
&60-80\% & 40-60\% & 20-40\% & 0-10\% \\
\text{64}_2^{29}\text{Cu} + \text{64}_2^{29}\text{Cu} & & & & & \\
&40-60\% & 20-40\% & 10-20\% & 0-10\% \\
\text{d} + \text{197}_7^{79}\text{Au} & & & & & \\
&0-100\% & 0-20\% \\
\gamma + \text{197}_7^{79}\text{Au} & & & & & \\
& & & & & \\
\end{align*}

Momentum distribution of identified hadrons
Identified Hadron Momentum Distribution in Isobar Collisions

STAR Preliminary
Isobar $\sqrt{s_{NN}}=200$ GeV

$-0.5 < y < 0.5$
statistical uncertainty only

Ru+Ru/Zr+Zr ratio of different particle species show similar dependence on centrality

Possible difference in flow between Isobar collisions

Poster by
Yang Li
(Session 3 T16 #345)
STAR Preliminary
Isobar $\sqrt{s_{NN}}=200$ GeV
-0.5 < y < 0.5
statistical uncertainty only

Pion and proton charge ratios show extra positive particles in Ru+Ru collisions
- Kaon ratio less conclusive
- Extra protons in $^{96}_{44}\text{Ru}$ nucleus
Difference Between Baryons and Mesons

STAR Preliminary
Isobar $\sqrt{s_{NN}}=200$ GeV
$-0.5 < y < 0.5$
statistical uncertainty only

$\frac{dN}{dp_T}$ (Zr+Zr) / $\frac{dN}{dp_T}$ (Ru+Ru)

10-20%

20-40%

$-$0.5 < y < 0.5

- Ratios increase more rapidly with increasing particle mass
- Different centralities show similar trends

Poster by Yang Li
(Session 3 T16 #345)
System Size Dependence of Medium Properties

\[ \langle N_{\text{part}} \rangle \]

\[
\begin{array}{cccc}
10^{0.5} & 10^1 & 10^{1.5} & 10^2 & 10^{2.5} \\
\end{array}
\]

- \( ^{197}_{79}\text{Au} + ^{197}_{79}\text{Au} \)
- \( ^{96}_{44}\text{Ru} + ^{96}_{44}\text{Ru} \)
- \( ^{96}_{40}\text{Zr} + ^{96}_{40}\text{Zr} \)
- \( ^{64}_{29}\text{Cu} + ^{64}_{29}\text{Cu} \)
- \( d + ^{197}_{79}\text{Au} \)
- \( \gamma + ^{197}_{79}\text{Au} \)

Collective motion
Collectivity in Small & Medium Systems

- Sizable $v_2$ & $v_3$ in isobar systems
- Different $v_n$ for different methods
  - Same ratio for a fixed centrality bin
- Collectivity also seen in $p/d+Au$ systems
- What does collectivity look like in even smaller system?
System Size Dependence of Medium Properties

Long-range correlation of inclusive hadrons

- $^{197}_{79}\text{Au} + ^{197}_{79}\text{Au}$
- $^{96}_{44}\text{Ru} + ^{96}_{44}\text{Ru}$, $^{96}_{40}\text{Zr} + ^{96}_{40}\text{Zr}$
- $^{64}_{29}\text{Cu} + ^{64}_{29}\text{Cu}$
- $d + ^{197}_{79}\text{Au}$
- $\gamma + ^{197}_{79}\text{Au}$

(size) $\langle N_{\text{part}} \rangle$

$10^{0.5}$ $10^1$ $10^{1.5}$ $10^2$ $10^{2.5}$

- 0-10%
- 10-20%
- 20-40%
- 30-40%
- 60-80%

- 0-20%
- 0-5%
- 0-10%
- 10-20%
- 20-40%
- 30-40%
- 60-80%

Tong Liu
Tagging Photonuclear Events in Heavy-Ion Collisions

- Photo-nuclear collision: proxy for low-$Q^2$ DIS
- Experimental access: tagged heavy-ion events
- Take advantage of asymmetric nature in tagging
  - Forward particle production on nucleus-going side & absence on photon-going side
  - See backup slide for more details on tagging $\gamma$+Au events

Inclusive UPC at RHIC

$E_{Au} = 27$ GeV

$E_{\gamma} \sim 0.8$ GeV

STAR Detector State & coverage ($\eta$)

- ZDCE (1n)
- VPDE, BBCE, EPDE (Gap)
- TPC, iTPC (Activity)
- FTS, FCS, VPDW, BBCW, EPDW (Activity)
- ZDCW ($X_n$)
Collectivity in Photonicuclear Events?

- Di-hadron correlation: probe collectivity of system

\[ Y(\Delta\phi, |\Delta\eta| > 1) = \frac{2\pi}{N_{\text{trig}} N_{\text{assoc}}} \frac{dN_{\text{pair}}}{d\Delta\phi} \]

= 1 + \sum_n 2\nu_n \cos(n\Delta\phi)

- No near-side ridge within uncertainty: **No clear sign of collectivity**

- Higher activity $\gamma$+Au events under exploration

- Improved measurements with forward upgrade in 2023-25 with 200 GeV Au+Au collisions

STAR Preliminary

Au+Au $\sqrt{s_{NN}}$ = 54 GeV, 1nXn ($\gamma$+Au-rich)

h$^\pm$ ($|\eta|<1$, $|\Delta\eta|>1$, $0.2 < p_T^{\text{trig,asco}} < 2$ GeV/c

Activity: $1 \leq N_{\text{trk}}^{\text{TOF-match}} < 8$

- Data

- Fit
Conclusions

- Medium suppression of high-$p_T$ hadrons mainly determined by $\langle N_{part} \rangle$
- Selection bias observed in peripheral events
- Ru+Ru/Zr+Zr particle yield ratios show species dependence
- Charge ratio shows hint on isospin effect
- No significant collectivity in photonuclear collisions observed

Outlook

- Detailed study of selection bias in high-$p_T$ particle yield
- More differential study on dependence of quenching: volume, path-length, etc.
- Detailed study of identified particle spectrum & ratio as a function of rapidity & centrality
- STAR forward upgrade: opportunities for $\gamma + A$ system
Thank you!
Dziękuję Ci!
Backup
STAR Isobar Collisions

- **Zr+Zr/Ru+Ru collision system**
  - System size between large (Au+Au) and small (p/d+Au) system

- **Run 18 Zr+Zr/Ru+Ru Collisions**
  - Fine change in nuclear structure & system size: impact of difference in overlapping geometry
  - Large statistics: 2B Zr+Zr & 1.8B Ru+Ru Minimum-biased Events
  - Highly controlled for detector uniformity across runs & luminosity condition
  - Minimized systematics

Photo Credit: [https://en.wikipedia.org/wiki/Nucleon](https://en.wikipedia.org/wiki/Nucleon)  
Hadron Yield at High Momentum & Medium Modification

- Hard partons lose energy to QGP: Jet Quenching
- High $p_T$ hadrons: proxy to hard partons
- Glauber model:
  - $\langle N_{\text{part}} \rangle$ scaling for lower- $p_T$
  - $\langle N_{\text{coll}} \rangle$ scaling for high- $p_T$
- Nuclear Modification factor $R_{AA}$: comparison to p+p collisions
- Combine with existing U+U, Au+Au, Cu+Cu & d+Au data
  - Continuous evolution with system size

STAR, Phys. Rev. Lett. 91, 172302
ALICE show different selection biases on different centrality definitions

CMS observed suppression in peripheral events for $Z$-boson yield

$R_{AA}$ with PHENIX results

Different nuclear density function lead to different multiplicity in same centrality

Difference in proton numbers also create net charge difference

Refer to: Talk by Haojie Xu (Wed 9:00 AM T01) & Poster by Chunjian Zhang (Session 2 T14-2 #962)
Selection of Photonuclear Events

- $\gamma+$ Au rich event selection:
  - Multiplicity: $1 < N_{trk}^{TOF-Match} \leq 8$
  - VPD: $|\nu_z^{VPD} - \nu_z^{TPC}| > 10$ cm, mismatch with TPC
  - ZDC: ln ($\gamma$-going) & Xn (nucleus-going)
  - BBC($\gamma$-going)$<200$ & BBC(nucleus-going)$>400$

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