Small collision systems at RHIC

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What did we learn from A+A?

The ‘standard model’ of heavy ion collisions:
- Strongly interacting (almost) ideal fluid is created – we call it the sQGP.
  - Fluctuating initial conditions
  - Collectivity
  - Jet quenching
  - $\phi$ modification

What can small system collisions ($p/d/^{3}\text{He} + \text{Au}$) bring us in comparison?
How small can the QGP drop be?

What is the effect of initial geometry and its fluctuation?

What is the contribution from pre-equilibrium and hadronic stages?

Is there an energy loss present in small systems?

How does the \( \phi \) production behave in small systems?
Initial Geometry
Ridge (STAR)

The two particle correlations from large to small systems.

The ridge remains visible from U+U to p+Au collisions.

Long range particle correlations are usually sign of collective behavior.
Near side long-range correlation is observed by PHENIX in d/\(^3\)He+Au collisions.
Non-flow estimation in PHENIX

For $c_2$ the non-flow contribution was estimated using p+p correlation, from 5% to 33% in different systems.

In PHENIX, the non-flow contribution is not subtracted, but cited in the systematic uncertainties.
Geometrical control

Geometry control works:
- $v_2(\text{He+Au}) \sim v_2(\text{d+Au}) > v_2(\text{p+Au})$

Theoretical description:
- Hydrodynamics with small $\eta/s$ works!
- AMPT: weakly coupled partonic cascade + quark coalescence + hadronic cascade also works at lower $p_T$
$v_2$ at fixed charged multiplicity

STAR study the correlation for fixed multiplicity rather than centrality:

- $v_2$ show similar trends for all systems.
- $v_2$ is system dependent (shape).
- $v_2/\varepsilon_2$ ($p_T$) in all systems scales into single curve - initial geometry matters
$v_1^{even}$ and $v_3$

$v_1$ even and $v_3$ show similar trends and magnitudes for all systems at fixed charged multiplicity.

How about the $^3$He+Au which has slightly larger initial $e_3$?
$v_3(p_T)$ in $d+Au$ and $^3He+Au$

Eccentricity for the small systems by PHENIX:

<table>
<thead>
<tr>
<th></th>
<th>0-5% p+Au</th>
<th>0-5% d+Au</th>
<th>0-5% He+Au</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon_2$</td>
<td>0.23</td>
<td>0.54</td>
<td>0.50</td>
</tr>
<tr>
<td>$\varepsilon_3$</td>
<td>0.16</td>
<td>0.19</td>
<td>0.28</td>
</tr>
</tbody>
</table>

The results of $v_2$ and $v_3$ are in coincidence with the expectation from the initial geometry.
There is a clear mass ordering in He+Au and d+Au collisions, while in the p+Au is not working as well.

Stronger radial flow in d/³He+Au?
Identified particle $v_2$

There is a clear mass ordering in He+Au and d+Au collisions, while in the p+Au is not working as good.

Stronger radial flow in d/$^3$He+Au?

Smaller split in p+Au is predicted in hydro from smaller radial push
d+Au Energy scan
Ridge in energy scan (PHENIX)

Where is the ‘onset’ of the flow?

The ‘ridge’ is disappearing going to lower collision energies in d+Au system

$|c_1|$ component is increasing, while the $c_2$ component is decreasing

- 200 GeV
- 62.4 GeV
- 39 GeV
- 19.6 GeV
$v_2$ (EP) in d+Au energy scan

- $v_2$ is very similar in 62-200 GeV d+Au collisions at lower energies, the $v_2$ is increasing at high-$p_T$
- AMPT can reconstruct the data with including the non-flow effect
$v_2$ in $\eta$

**Forward region:**
- All collision energies in d+Au are very similar
- AMPT describe the data with the pure flow

**Backward region:**
- $v_2$ is decreasing at lower energy
- AMPT with non-flow describe the shape better, but not perfectly

soon in PRC
The cumulant method can shed light in the effect of the non-flow contributions

We observe real $v_2\{4\}$ in all d+Au collisions energies

The four particle cumulant results is between the $v_2\{2\}$ and $v_2\{2, |\Delta\eta|>2\}$. 

Submitted to PRL
Energy loss
Energy loss in A+A

The parton propagating through an opaque medium is dissipates its energy – jet quenching

\[ R_{AA}(p_T) = \frac{d^2N^{AA}}{dp_T d\eta} / \left( \frac{N_{binary}}{N_{pp}} d^2N^{pp} / dp_T d\eta \right) \]

High-\(p_T\) hadrons (\(\pi^0, \eta, \phi, \ldots\)) are suppressed, direct photons are consistent with unity
\[ \Rightarrow \text{final state energy loss} \]
\[ \Rightarrow \text{opaque to jets, but not photons - QGP} \]

\(R_{AA} > 1\) - enhancement
\(R_{AA} = \text{no modification}\)
\(R_{AA} < 1\) – suppression
Comparison of small system nuclear modifications:
- Enhancement at $p_T = 5 \text{ GeV/c}$ indicates a system size dependence

Is there a hint for suppressions at high-$p_T$?
Loss or no loss?

At high-$p_T$ they are consistent with 0.85

<table>
<thead>
<tr>
<th></th>
<th>p+Au</th>
<th>d+Au</th>
<th>$^3$He+Au</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{\text{Coll}}$</td>
<td>4.67</td>
<td>7.59</td>
<td>10.4</td>
</tr>
<tr>
<td>Bias Factor</td>
<td>0.86</td>
<td>0.89</td>
<td>0.89</td>
</tr>
</tbody>
</table>

Corrected picture:
$R_{AA}^h \equiv R_{AA}^\gamma \Rightarrow$ no FS suppression
$R_{p/d}^{3}\text{He+Au} - \text{centralities}$

Nuclear modification in centralities:

- Centrality determined similarly as for large systems (PRC90,034902)

- $p+Au$ results show large centrality dependence
Nuclear modification in centralities:

- Centrality determined similarly as for large systems (PRC90,034902)
- \( p+Au \) results show large centrality dependence
- \( d+Au \) results agree with \( p+Au \) at high-\( p_T \)
$R_{p/d}/^{3}\text{He}+\text{Au}$ – centralities

Nuclear modification in centralities:

- Centrality determined similarly as for large systems (PRC90, 034902)
  - $p+\text{Au}$ results show large centrality dependence
  - $d+\text{Au}$ results agree with $p+\text{Au}$ at high-$p_T$
  - $^{3}\text{He}+\text{Au}$ results agree with $p+\text{Au}$ and $d+\text{Au}$ at high-$p_T$
  - At moderate $p_T$ an ordering is seen in most central collisions

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\( \phi \) production
The $\phi$ production is suppressed at 200 GeV in more central collisions – between $\pi$ and $p$

The suppression disappears reaching more peripheral events or reaching to lower $\sqrt{s_{NN}}$. 
Forward and backward rapidity

Wide $p_T$ range of $\phi$ measurement in forward rapidity:
- Suppression in forward (p-going) rapidity
- Enhancement in backward (Au-backward) rapidity
**φ production in small systems**

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**PHENIX**

$d+Au \ \sqrt{s_{NN}} = 200$ GeV  
Centrality: 0-100%

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**φ production in forward and backward rapidities in p/d/3He +Au and p+Al collisions at 200 GeV**

- Enhancement in the **backward region**
- Suppression in the **forward region**
Summary

• **Geometry:**
  - The initial geometry and multiplicity play important roles for the ridge and $v_n$ in small systems. And these results can be well described by the viscous hydro.
  - The mass ordering, NCQ scaling and four particles cumulant results indicate a collective behavior in small system.

• **Energy scan:**
  - The $v_2$ has been measure in small system from 200 GeV to 19.6 GeV by event plane method, but non-flow effect need to be further studied.

• **Energy loss:**
  - $\pi^0$ production at mid-rapidity in p+Au, d+Au and $^3$He+Au at 200 GeV.
  - Energy loss is not yet conclusive.

• **$\phi$ production:**
  - New measurement in forward and backward regions in p+Al, p+Au, d+Au and $^3$He+Au.
  - Observed suppression in forward region, enhancement (or unity) in the backward region.
Outlook

• Many more results to come from both PHENIX and STAR
  • Direct photon measurement:
    • low-\( p_T \) for the thermal signal (or need high precision di-electron results)
    • high-\( p_T \) to disentangle the IS and FS effects
  • Strangeness measurement:
    • Particle yields, ratios
    • Is the scaling observed in ALICE relevant in lower \( \sqrt{s_{NN}} \)?
    • Does the \( \phi \) still scales with the number of quarks, where it breaks down?
  • Identified particle spectra, \( v_n \):
    • Study the enhancement in \( p_T \sim 5 \) GeV/c, how the proton/pion looks like?
    • flow of identified particles, where it breaks down?
  • Heavy flavor:
    • Both STAR (HFT) and PHENIX (VTX,FVTX) invested in upgrades in order to study the \( c, b \) production in \( p+p \) and \( p(d)+Au \) data

... and many more!
Backups
Looking forward and backward

Strong centrality and rapidity dependence of charged hadrons
Comparison of $R_{CP}$ in same centralities in p+Au and p+Al collisions:

- **Forward** hadrons show **same suppression**
- **Backward** hadron production show smaller **enhancement** in p+Al than in p+Au collisions

What is the physics behind the **backward enhancement**? Is it connected with the mid-rapidity enhancement?
The enhancement is more visible when integrating the full away side jet.

Harder jets seems to have no visible modifications.
Non-Abelian Gauge Theory

- Factorization breaking predicted in a transverse-momentum-dependent (TMD) framework in dihadron production [Rogers, Mulders, Phys. Rev. D 81,094006 (2010)]

- Back-to-back two particle angular correlations give sensitivity to initial- and final-state transverse momentum $k_T$ and $j_T$

- $\geq 2$ gluon exchanged with the proton remnants predicts the breakdown
The Gaussian widths of the $p_{out}$ distribution are decreasing with $p_T$
- Opposite of the prediction from TMD factorization

Surprising centrality dependency of the gaussian widths in p+Au

Are there some centrality dependence of nuclear effects: $k_T$ broadening, multiple scattering, flow, etc.

Interpretations are still ongoing
$s^{1/2}=200$ GeV $\pi^0 A_N$ for pp vs. pAu

Error bars represent statistical errors only.

Luminosity:
pAu=204.6 nb$^{-1}$
pp=34.8 pb$^{-1}$

Average Polarization:
pp $55.6 \pm 2 \%$
pAu $60.4 \pm 2 \%$

Shaded bands represent systematic uncertainty, dominated by dependence of $A_N$ on observed East BBC energy (gold or proton breakup charge multiplicity)

Capability to measure the $R_{pAu}$ with the new upgrade!