Jet and Leading Hadron Production in d+Au Collisions in the PHENIX Experiment

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Leading Hadron Production in d+Au and $^3$He+Au Collisions in the PHENIX Experiment

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Why \textit{were} we interested in $d+Au$ collisions?

- To confirm the high $p_T$ hadron suppression is due to final state effects, and not cold nuclear matter (CNM) effects
  - Needed system without additional effects from a hot medium.

- CNM effects include:
  - $k_T$-broadening
  - Shadowing of parton distributions
  - Cold nuclear matter energy loss
  - And possibly more…

- $d+Au$ was more favorable for RHIC operation because of better rigidity match
  - $p+Au$ became feasible later
Direct photons / Jets in minbias $d+Au$

- Direct photon $R_{dA}$ is consistent with unity up to 16 GeV/c
  - No modification in initial hard scattering

- Jets $R_{dA}$ is consistent with unity up to 50 GeV/c
  - As expected from PDF (EPS09), no final state effect.

- Both are as expected.

PRC87, 054907 (2013)

PRL 116, 1223011 (2016)
Centrality dependence is unexpected

- Jets $R_{dA}$ shows a sizable centrality dependence
  - Suppression in most central, enhancement in most peripheral

- Strong flow like A+A is seen in most central $d$+Au collisions
  - Similar observation by the LHC experiments
  - We didn’t anticipate “flow” in a small system like $p/d$+A

**PRL 116, 1223011 (2016)**

**PRL 114, 192301 (2015)**
$p/d$+Au is no longer a baseline or a simple system...

- Mini-QGP production?
  - Initial state effects, e.g. CGC, will affect to production cross-section of particles
  - Final state effects, e.g. hydrodynamics will produce flow-like structure
p/d+Au is no longer a baseline or a simple system...

- Mini-QGP production?
  - Initial state effects, e.g. CGC, will affect to production cross-section of particles
  - Final state effects, e.g. hydrodynamics will produce flow-like structure

- If there is QGP, detail investigation of the interaction of partons with the medium will give insight on its characteristics

- Systematic study of the leading hadron spectra in p/d/³He+A will help
PHENIX Detector and analysis

- We analyzed $^{3}$He+Au events recorded in RHIC Year-14 run.

- $\pi^0$ are reconstructed via $\pi^0 \rightarrow 2\gamma$ channel
  - Use of EM Calorimeter (EMCal, PbSc) for photon ID and energy measurement

- Events used this analysis are triggered by:
  - Beam-beam counter (BBC) as minimum bias events: $2.0 \times 10^{9}$ evts
  - EMCal and BBC coincidence trigger (ERT): $4.5 \times 10^{10}$ MinBias-equiv. evts
  - Total analyzed luminosity: 22 nb$^{-1}$
Event trigger and bias

- Min. Bias trigger has inefficiency
  - Inefficiency is already studied in \(d+Au\) collisions in detail.
  - BBC charge distribution was compared with a Glauber Monte Carlo simulation folded with a negative binomial distribution (NBD)

- Efficiencies for \(d+Au\) and \(^3He+Au\) are both determined as 88%.

- Bias factors (BF) for centrality selection are calculated
  - Bias is from auto-correlation between particles in mid- and backward rapidity
  - Same method as \(d+Au\) case is applied and calculated as in the following table

<table>
<thead>
<tr>
<th>Cent (%)</th>
<th>0-20</th>
<th>20-40</th>
<th>40-60</th>
<th>60-88</th>
<th>0-100</th>
</tr>
</thead>
<tbody>
<tr>
<td>(d+Au) BF</td>
<td>0.94</td>
<td>1.00</td>
<td>1.03</td>
<td>1.03</td>
<td>0.89</td>
</tr>
<tr>
<td>(^3He+Au) BF</td>
<td>0.95</td>
<td>1.02</td>
<td>1.02</td>
<td>1.03</td>
<td>0.89</td>
</tr>
</tbody>
</table>
\( \pi^0 \) \( p_T \) spectra in \( {}^3\text{He}+\text{Au} \) collisions

- \( p_T \) spectra have been measured up to \( p_T = 20 \) GeV for minimum bias events as well as for four centrality classes.
$\pi^0 R_{AA}$ in $^3$He+Au collisions

- $R_{AA}$ has been measured and compared with d+Au collision data.
- Both absolute magnitudes and $p_T$ dependence are consistent within quoted uncertainties.

![Graph showing $R_{AA}$ vs. $p_T$ for $\pi^0 + X, \sqrt{s_{NN}} = 200$ GeV.]
$\pi^0$ $R_{AA}$ for various centralities

$\pi^0 + X, \sqrt{s_{NN}} = 200 \text{ GeV}$

0-20%

$R_{AA}$

$PHENIX$
preliminary

$^3$He+Au $\langle N_{\text{coll}} \rangle = 22.3$

d+Au $\langle N_{\text{coll}} \rangle = 15.37$ Phys. Rev. Lett. 98, 172302

20-40%

$R_{AA}$

$PHENIX$
preliminary

$^3$He+Au $\langle N_{\text{coll}} \rangle = 14.8$

d+Au $\langle N_{\text{coll}} \rangle = 10.63$ Phys. Rev. Lett. 98, 172302

40-60%

$R_{AA}$

$PHENIX$
preliminary

$^3$He+Au $\langle N_{\text{coll}} \rangle = 8.4$

d+Au $\langle N_{\text{coll}} \rangle = 6.95$ Phys. Rev. Lett. 98, 172302

60-88%

$R_{AA}$

$PHENIX$
preliminary

$^3$He+Au $\langle N_{\text{coll}} \rangle = 3.4$

d+Au $\langle N_{\text{coll}} \rangle = 3.07$ Phys. Rev. Lett. 98, 172302

$p_T$ [GeV/c]
\( \pi^0 \) integrated \( R_{AA} \) in \(^3\text{He}+\text{Au} \) collisions

- Integrated \( R_{AA} \) has been plotted with ones in \( d+\text{Au} \)
- At higher \( N_{\text{part}} \), \( d+\text{Au} \) and \(^3\text{He}+\text{Au} \) show very similar \( N_{\text{part}} \) dependence
- At lower \( N_{\text{part}} \), \( d+\text{Au} \) collisions show more enhancement
  - More Cronin effect, or less suppression (energy loss)
\( \pi^0 \) integrated \( R_{AA} \) in \(^3\text{He}+\text{Au} \) collisions

- Integrated \( R_{AA} \) has been plotted with ones in \( d+\text{Au} \) and \textbf{Au+Au}

- \( R_{AA} \) from all three systems converge for \( N_{\text{part}} \gtrsim 12 \)
  - Similar degree of suppression suggesting similar \textit{hot} matter is produced?

- System ordering of \( R_{AA} \) is seen for \( N_{\text{part}} < 12 \)
  - \( R_{d\text{Au}} > R_{\text{HeAu}} > R_{\text{AuAu}} \). Of course, better precision is desired

\[ \pi^0 + X, \sqrt{s_{NN}} = 200 \text{ GeV} \]

\begin{figure}
\centering
\includegraphics[width=\textwidth]{plot.png}
\caption{Au+Au points (hand drawing: 80-93, 70-80, 60-70\%)}
\end{figure}

\textbf{PRC87, 034911(2013)}
Fractional momentum loss in $^3\text{He}+\text{Au}$

- Let’s convert $R_{AA}$ to fractional momentum loss ($\delta p_T/p_T$).
  - One can directly measure the spectra shift ($\delta p_T$)

- 0-20% $^3\text{He}+\text{Au}$ collisions shows similar $R_{AA}$ as 60-70% Au+Au
  - At the same cms energy, the same $R_{AA}$ implies the same $\delta p_T/p_T$

- $\delta p_T/p_T = \sim 0.03$ in most central $^3\text{He}+\text{Au}$ collisions

$\delta p_T = p_T(p + p) - p_T(A + A)$

**PHENIX, PRC93, 024911 (2016)**

<table>
<thead>
<tr>
<th>Centrality</th>
<th>$p_T^{pp}$ [GeV/c]</th>
<th>$\delta p_T/p_T^{pp}$</th>
<th>Stat error</th>
<th>Syst error</th>
</tr>
</thead>
<tbody>
<tr>
<td>60–70%</td>
<td>7.0</td>
<td>0.028</td>
<td>$+0.004$</td>
<td>$-0.004$</td>
</tr>
<tr>
<td></td>
<td>10.0</td>
<td>0.011</td>
<td>$+0.021$</td>
<td>$-0.019$</td>
</tr>
<tr>
<td></td>
<td>12.0</td>
<td>0.037</td>
<td>$+0.025$</td>
<td>$-0.022$</td>
</tr>
</tbody>
</table>

**TABLE IV. Centrality dependence of $\delta p_T/p_T^{pp}$ in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV from 2007 data from the PHENIX experiment at RHIC.**
Summary

- $p/d+Au$ system is no longer a baseline or a simple system.
  - Sizable particle flow ($v_2$) has been seen in the most central $d+Au$ collisions
  - Jet $R_{AA}$ shows anomalous centrality dependence (suppression/enhancement)

- It is important to measure the spectra $R_{AA}$ systematically in small systems, i.e., $p+A$, $d+A$ and $^3He+A$

- $\pi^0$ have been measured in 200GeV $^3He+Au$ collisions for the first time.
  - $R_{AA}$ looks very similar to the ones in $d+Au$.

- Integrated $R_{AA}$ from $d+Au$, $^3He+Au$ and $Au+Au$ merge at $N_{part}>\sim12$.
  - Similar degree of suppression suggesting similar hot matter is produced?
  - System ordering of $R_{AA}$ is seen for $N_{part}<12$, i.e., $R_{dAu}>R_{HeAu}>R_{AuAu}$.

- Fractional momentum loss ($\delta p_T/p_T$) is $\sim0.03$ for 0-20% $^3He+Au$ collisions
  - From the $\delta p_T/p_T$ in 60-70% $Au+Au$ collisions at the same cms energy
Backup
Comparing with new collision systems

$V_2$

- $^3$He+Au 200GeV 0-5%, arXiv:1507.06273
- d+Au 200GeV 0-5%, PRL. 114, 192301
- p+Au 200GeV 0-5%
- SONIC $^3$He+Au
- SONIC d+Au
- SONIC p+Au

arXiv:1502.04745

Pointer to Itaru and Shengli’s talk, Seyoung’s poster.
Ridge-like structure is observed in d+Au

- $h^{+/−}$ - MPC south correlation functions in central d+Au and minbias p+p collisions
  - Au-going direction

Near-side peak clearly seen in d+Au but not in p+p

- Analyze correlation functions with Fourier fits

- 2nd order component ($c_2$) increases as $p_T$ becomes larger

- Similar correlation but the smaller strength is seen in $h^{+/−}$ - MPC north correlation
Ridge evolution in $\pi^0$--MPC south / Au-going…

- $-c_2 / c_1$ from $\pi^0$--MPC south correlations
  - Au-going direction
  - Assuming $c_1$ is a proxy of jets or global momentum conservation

- Measure shape evolution by relative magnitude of 2nd order component

- $-c_2 / c_1 > 0.25$ corresponds to near-side local maximum (if $c_3 = c_4 = 0$)