High $p_T$ charged hadron production in $^3$He+Au collisions at $\sqrt{s_{NN}} = 200$ GeV measured with PHENIX detector

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The experiment for exploring QGP

QGP (Quark Gluon Plasma)

- Matter phase realized at **high temperature and high density**
- Quarks and Gluons are released from the confinement within hadron by strong interaction

**Heavy ion collision experiment**

- Collide heavy ions that are accelerated close to the speed of light

If collisions produce high density matter in the interaction region,
- Partons lose their energy by the interaction with matters

Momentum distribution of hadrons shifts to lower values.

RHIC (BNL, US)
LHC (CERN, CH & FR)

A state necessary for QGP formation can be created in a wide area.
Nuclear modification factor $R_{AA}$

- $R_{AA} < 1 \ldots$ suppression
- $R_{AA} = 1 \ldots$ p+p superposition
- $R_{AA} > 1 \ldots$ enhancement

$\checkmark$ High $p_T$ hadron suppression is a evidence of QGP

From the $h^\pm$ $R_{AA}$ measurement up to 5 GeV/c, there is suppression at Au+Au.
Motivation

Collision system comparison of QGP formation signal

<table>
<thead>
<tr>
<th>PHENIX 200 GeV</th>
<th>① High $p_T$ hadron suppression</th>
<th>② $v_2$</th>
<th>QGP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Au+Au (2003)</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>d+Au (2008)</td>
<td>△ ($h^\pm$, ~5GeV/c) (Central collision)</td>
<td>○</td>
<td>△</td>
</tr>
<tr>
<td>$^3$He+Au (2014)</td>
<td>○  (Central collision)</td>
<td>?</td>
<td></td>
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</tbody>
</table>

- Previous PHENIX detector couldn’t measure charged hadrons at high $p_T$ region because of background contamination.
- New detector Silicon Vertex detector (VTX) was installed in 2011, better measurement is expected at high $p_T$ charged hadron.

Topic
- Charged hadron production in $^3$He+Au collisions with VTX
- Discuss possibility of QGP formation in small system from the point of view of hadron production
Charged hadron measurement in PHENIX

**RHIC-PHENIX**

$^3$He+Au collision (2014)

1.35 $\times$ 10$^9$ events

- Event characterization
  - Centrality, Vertex point
- Track reconstruction
  - $p_T$, charge

**Track matching at PC3 and EMCal hits**

- Cut fake track (background type1)

**Event characterization**

- Centrality, Vertex point

**Track reconstruction**

- $p_T$, charge

**3He+Au collision (2014)**

1.35 $\times$ 10$^9$ events
Silicon Vertex detector (VTX)

Detect charged particle around vertex position

- **VTX** \( |\eta| < 1.2, \Delta \phi = 0.8 \pi \times 2 \)

NEW!

- 4 layer Silicon detector
  - 2.6 cm

- Determine 3D vertex position
  - Tracking quality UP ↑

- VTX track

Track matching at VTX hits
- Cut fake track (background type1)

- Distance of Closest Approach (DCA)
  - Closest distance between Primary vertex and tracking

Select tracks which have small DCA
- Cut secondary particle (background type2)

✔ VTX is used for the purpose of background reduction at high \( p_T \).
The effect of background reduction from comparison of $p_T$ spectra at various cut condition

- $dN/dp_T$ (MB 0-88%, $|\eta| < 0.35$, charged hadron)

![Graph showing $dN/dp_T$ with and without VTX hits and track matching at PC3 & EMCal, VTX 3 layer hits, and DCA cut.]

- ✔ Track matching at PC3 & EMCal
- ✔ VTX 3 layer hits
- ✔ DCA cut

- ✔ Using VTX can extend measurable $p_T$ range of charged hadron because of the effect of background reduction at high $p_T$. 
For $h^\pm$, detector acceptance and efficiency have not corrected yet. Assuming that the corrections don’t depend on centrality, the relative charge of the spectra between centralities can be compared with other corrected spectra.

- $h^\pm$ raw spectra are compared with $\pi^0$ invariant yield. ($h^\pm$ are scaled by an arbitrary value)

Fit function: “$a \times p_T^b$“ for each centralities ($a$ and $b$ are free parameters)

Have good match at 5~9 GeV/c

$\pi^0$ and $h^\pm$ seem to have similar shape of $p_T$ spectra in this $p_T$ range
In $^3\text{He}+\text{Au}$ $\pi^0 R_{AA}$ suppression at high $p_T$ is observed in central collision. → will expect that charged hadron results have same $p_T$ dependence. QGP signal in small system?
Summary and Outlook

- Charged hadron production is measured in $^3$He+Au collisions
  - New track selection method with VTX
    - VTX is expected to improve background contamination at higher $p_T$

- Spectra comparison between $h^\pm$ and $\pi^0$ in $^3$He+Au collisions
  - They have similar shape with small centrality dependence

- $\pi^0$ $R_{AA}$ in $^3$He+Au collisions
  - High $p_T$ suppression is observed at 0-20 % centrality
    - Will expect that charged hadron results are similar
    - A hint of QGP formation at small systems at RHIC energy

Outlook

- Calculate invariant yields and $R_{AA}$ by applying acceptance and efficiency correction for $h^\pm$ results
Back up
QGP probe ①high $p_T$ hadron suppression

高横運動量粒子の生成過程：ジェット

\[ p_T = \sqrt{p_{x}^2 + p_{y}^2} \]

パートン同士の衝突・散乱によって生成

クォークやグルーオン

もし、反応領域に高密度物質ができていれば、

高密度物質

物質中での相互作用によりエネルギー損失。

高横運動量粒子の生成抑制

原子核効果比 $R_{AA}$

- $R_{AA} < 1 \cdots$ 抑制
- $R_{AA} = 1 \cdots$ 核子+核子衝突の重ね合わせ
- $R_{AA} > 1 \cdots$ 増加

核子間衝突数でスケール

核子+核子衝突の不変生成量

A+A 衝突の不変生成量

$p+p$ 衝突の不変生成量
$v_2$ in small system

\[ A. \text{Adare et al. (PHENIX Collaboration) PRL 114,192301(2015)} \]

\[ d+Au \text{ 衝突} \]

\[ 3\text{He}+Au \text{ 衝突} \]

Au+Au 中心衝突と似た $v_2$ の横運動量依存性が d+Au 中心衝突でも確かめられた。

d+Au より大きな衝突系として $3\text{He}+Au$ 中心衝突でも $v_2$ が測定される。

→ 流体計算モデルの予想とよく合っている。

\[ p_T \text{ 依存性が類似} \]

\[ A. \text{Adare et al. (PHENIX Collaboration) PRL 115,142301(2015)} \]
Vertex selection

- **3 types of vertex**

  **PRECISE**  
  ⋯ 3D reconstruction by VTX Standalone tracks

  **SEED**  
  ⋯ Z direction by VTX & BeamCenter (mean vertex X-Y)

  **BBCZ**  
  ⋯ Z direction by BBC & BeamCenter (mean vertex X-Y)

- **PRECISE**
  - 3~4 clusters are needed for 3D vertex reconstruction.

- **SEED**
  - If not
  - Use only B0 & B1 clusters.
  - Decide only vertex z-position.
  - X-Y is defined by BeamCenter.

- **BBCZ**
  - If not
  - Use forward-backward timing difference. (resolution |Δz| ~3cm at pp)
  - X-Y is defined by BeamCenter.
$R_{AA}$ reference


$\sqrt{s_{NN}} = 200 \text{ GeV}$

charged hadrons
- $R_{AA}$ d-Au min. bias
- $R_{AA}$ Au-Au 0-10% central

neutral pions
- charged hadrons
- neutral pions


$\text{Au+Au at } \sqrt{s_{NN}} = 200 \text{ GeV}$

- $\pi^+ + \pi^-$
- $K^- + K^+$
- $K^0$
- $\phi$
- $\bar{p} + p$
- $\pi^0$


$\text{d+Au at } \sqrt{s_{NN}} = 200 \text{ GeV}$

- $\pi^+ + \pi^-$
- $K^- + K^+$
- $K^0$
- $\phi$
- $\bar{p} + p$
- $\pi^0$
$^3$He+Au $\pi^0$ production

$^3$He+Au, $\pi^0 + X$
$\sqrt{s_{NN}} = 200$ GeV

$\frac{d^2N}{2\pi p_T dp_T dy}$

$^3$He+Au, $<N_{\text{Coll}}>$ = 10.4

$^{10}$ Au, $<N_{\text{Coll}}>$ = 7.6

PHENIX preliminary

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