Measurements of identified hadron flow in 
Au+Au, Cu+Au and U+U collisions

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Outline

- Motivation and analysis methods
- $N_q$ scaling in $Au + Au$ at 200 GeV
- Pion and proton $v_2$ in $U + U$ at 193 GeV
- Pion and proton $v_1$ and $v_2$ in $Cu + Au$ at 200 GeV
- Summary and outlook
Motivation: \( n_q \) scaling

- Baryon and meson elliptic flow follow the number of constituent quark (\( n_q \)) scaling

- \( N_q \) scaling will break at intermediate \( p_T \) and peripheral centrality, if we assume that \( \pi \) is mainly from the recombination of thermal (T) and shower (S) partons but proton is mainly from TTS or TSS.

Can we test dependence of the centrality and \( p_T \) for \( n_q \) scaling breaking?
Flow in U + U (1):
The geometry and density effect

U + U 193 GeV

Body-body

Tip-tip

1. The geometry is significantly different for body-body and tip-tip collisions

2. The medium density in U + U at 193 GeV is around 30~60% higher than that in central Au + Au at 200GeV

U. Heinz and A. Kuhlman,
PRL 94, 132301 (2005)
Strong mass ordering is observed from $v_2$ of identified particles in LHC (2.76 TeV), where the density increases by 2.5 compared to RHIC (200 GeV).

In RHIC, the proton $v_2$ almost keeps consistent while medium density almost increases a factor of 2 in Au + Au collision from 39 GeV to 200 GeV.

How about ultra-central U + U collisions at 193 GeV?
Flow in Cu + Au (I): flow in an asymmetric collision

- An asymmetric coordinate space will lead to an asymmetric density profile and pressure gradient
- Event-by-event geometry fluctuation
- The energy loss for jets from Au or Cu side will be different

$\Psi_{1,SMD}$: Combination of $\Psi_{1,SMD}^{South}$ (Au-going) with flipped $\Psi_{1,SMD}^{North}$ (Cu-going). The direction of $\Psi_1$ plane is decided by the Au spectators

- Measurements $v_1$, $v_2$ in Cu + Au will help us to understand the effect of the asymmetric density, geometry and their fluctuation.
Flow in Cu + Au (2) : anti-flow effect in Cu + Au

- Large $v_1$ is observed at forward and backward rapidity in Au + Au, which may be due to anti-flow effect.
- Shift of mass center may bring this anti-flow effect into mid-rapidity $|\eta|<0.35$ in Cu + Au collisions.
- Measure the $v_1$ of identified particle will further help us to address the dynamic mechanisms under this asymmetric distribution.
Event plane detectors:
Reaction plane detector
- $\text{RXN}_{\text{IN}}$ ($1.5<|\eta|<2.8$)
- $\text{RXN}_{\text{OUT}}$ ($1.0<|\eta|<1.5$)

Muon piston Calorimeter
$\text{MPC}$ ($3.1<|\eta|<3.9$)

Beam-beam counter
$\text{BBC}$ ($3.1<|\eta|<3.9$)

$dN/d\Delta\phi \sim 1 + 2\sum_{n=1}^{\infty} \nu_n \cos(n\Delta\phi)$

Zero Degree Calorimeters ($\text{ZDC}$)
Shower Max Detectors ($\text{SMD}$)
$\text{ZDC-SMD}$ ($|\eta|>6.5$)
$\Psi_1$ by spectator
(I) Identified particles flow in Au +Au at 200 GeV:

The centrality and $p_T$ dependence for $n_q$ scaling breaking
In 0-20% central Au + Au collisions at 200 GeV, the $v_2$ proton is higher than that of pion still $p_T$ of 6 GeV/c. While in 20-60% centrality, they approach each other.

A break of $n_q$ scaling is observed in 20-60% centrality at KE$_T$ > 0.7 GeV. But in the 0-20% centrality, this break is still roughly held.

It indicates the mechanisms for pion and proton production are different at intermediate $p_T$ for different centralities.

The centrality dependent $n_q$ scaling

- The $n_q$ scaling shows strong centrality dependence. In 0-10% centrality class, the $n_q$ scaling appears to hold to $KE_T/n_q = 1.5$ GeV, supporting parton recombination. It starts to break as $KE_T/n_q > 0.7$ GeV in 10-20% centrality.

- It is consistent with recombination model calculation qualitatively.

C. B. Chiu, R. C Hwa et al. PRC.78.044903
Comparing with $v_2$ of $K_s$ and Lambda

- The $v_2$ of pions and protons measured from PHENIX are consistent with $v_2$ of $K_s$ and Lambda from STAR in overlap $p_T$ region.

- The more accurate measurements from PHENIX indicates a clear breaking of $n_q$ scaling in $KE_T > 0.7$ GeV in 10-40% centrality.

(II) Identified particles flow in U + U 193 GeV:

The geometry and density effect
In 0-10% U + U collisions at 193 GeV, the slope of proton $v_2$ is a little bit different with that in 0-10% Au + Au collisions at 200 GeV.

But this behavior disappears in peripheral collision such as 40-60% centrality.
The $n_q$ scaling is still held in $U + U$ collision at 193 GeV with $v_2$ of pions and protons in each centrality bin.

In the future, the measurement for $v_2$ of pion at more lower $p_T < 0.5$ GeV/c will be done to further test the $n_q$ scaling.
The $\varepsilon \tau$ only increases around 20% from 0-10% Au + Au to 0-1% U + U collision.

Strong mass ordering for $\pi$ & $p$ $v_2$ in 0-2% central U + U collision at 193 GeV are observed even though the increase in $\varepsilon \tau$ is relatively small. **Radial flow or geometry?**

The geometry separation will be done in near future.
(III) Identified particles flow in Cu + Au at 200 GeV:

Flow in an asymmetric collisions
Sizeable positive $v_1$ is observed at $p_T > 1\text{GeV/c}$ with $\Psi_{1,\text{smd}}$, which direction is decided by the Au spectators. It indicates that there are more particles emitted from the Au side than from the Cu side.

- It may be due to asymmetric density profile, pressure gradient and anti-flow effect.

- The $v_1$ of protons will be measured in near future after production of full statistics. It will help us to further address the physics of this positive $v_1$. 

20% of full statistics
The $v_2$ of pions and protons are measured as a function of $p_T$ and centrality.

The $n_q$ scaling is held in Cu + Au collisions at 200 GeV.
Summary and Outlook

- In Au + Au collisions, the $n_q$ scaling is broken as $K_{ET}/n_q > 0.7$ GeV in 10-20% centrality. Alternatively, in 0-10% centrality class, the universal $n_q$ scaling appears to hold to $K_{ET}/n_q = 1.5$ GeV. It is consistent with calculation of recombination model.

- In the ultra-central U + U collision such as 0-2%, strong mass ordering is observed for the $v_2$ of pions and protons, even though the density of $\epsilon_T$ only increases by around 20% when compared to 0-10% centrality Au + Au collisions.

- A sizeable positive $v_1$ for charged pion are observed at $p_T > 1$ GeV/c in Cu + Au collision at 200 GeV with $\Psi_{1,SMD}$, which indicates that there are more particles emitting from the Au side than from the Cu side in middle rapidity $|\eta|<0.35$. The $v_1$ and $v_3$ of pions and protons will be measured in near future after production of full statistics.

- $n_q$ scaling is held in Cu + Au and U + U collisions. In U + U 0~2% centrality, more detailed testing will be done with full statistics.