Elliptic flow for multi-strange hadrons as penetrating probes at RHIC

Hiroshi Masui / University of Tsukuba

High Energy Strong Interactions: A school for Young Asian Scientists, Wuhan, Sep. 22-26, 2014
Outline

- Introductions
  - Elliptic flow
  - Why multi-strange hadrons?
- Latest STAR results in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV
  - Number of constituent quark (NCQ) scaling
  - Violation of mass ordering between $\phi$ meson and proton
- Hybrid hydrodynamical model calculations
- Summary

I would like to thank Shiori Takeuchi and Tetsufumi Hirano for allowing me to present their recent hydrodynamical model calculations
Azimuthal anisotropy

\[
\frac{dN}{d\phi} \sim 1 + 2v_1 \cos (\phi - \Psi_1) + 2v_2 \cos (2[\phi - \Psi_2]) + 2v_3 \cos (3[\phi - \Psi_3]) + \cdots,
\]

\[
v_2 = \langle \cos (2[\phi - \Psi_2]) \rangle
\]

- **Azimuthal anisotropy**
  - Fourier expansion of azimuthal distribution with respect to the reaction plane
  - Fluctuation of constituents (nucleons or partons) → participant plane
    - Reaction plane ≠ participant plane
- **Elliptic flow - \(v_2\)**
  - Final state momentum anisotropy, 2nd harmonic coefficient
  - not necessary to describe collective hydrodynamic flow
  - 2 particle correlation is the most popular method

\[
v_{2}^{\text{obs}} = \langle \cos (2\phi - 2\phi_r) \rangle = v_2 \cdot \langle \cos (2\phi_r - 2\Psi_2) \rangle
\]

\[
v_{2}^{\text{obs}} = \langle \cos (2\phi - 2\Phi_2) \rangle = v_2 \cdot \langle \cos (2\Phi_2 - 2\Psi_2) \rangle
\]

\(v_{2}^{\text{obs}}\) is the observed elliptic flow, \(v_2\) is the second harmonic coefficient, and \(\Phi_2\) is the event plane resolution.
Mass ordering of $v_2$ - radial flow

$T_{\text{eff}} = T_{\text{fo}} + m_0 \langle \beta_T \rangle^2$

- Radial flow pushes heavier hadrons to higher $p_T$
  - Inverse slope ($T_{\text{eff}}$) of $p_T$ spectra depends on mass linearly
  - Due to the geometry deformation, hadrons around participant plane are pushed more than those around out-of-plane
  - $v_2$ decreases at low $p_T$, and the effect is stronger for heavier hadrons
    - Mass ordering of $v_2$
Why multi-strange hadrons?

- Blast-wave model fit for $p_T$ spectra support early freeze-out of multi-strange hadrons: $T_{fo} \sim T_{ch}$
  - probe to collectivity in early partonic stage of heavy ion collisions
- Statistics is limited in previous data to study the number of constituent quark (NCQ) scaling
Motivations

• $v_2$ for multi-strange hadrons is a good probe to partonic collectivity
  ‣ Multi-strange hadrons freeze-out earlier than others
    ➡ less hadronic rescattering (less radial flow effect)
    ➡ penetrating probe to study partonic stage
  ‣ Powerful tool to study NCQ scaling of $v_2$
  ‣ We can also study the effect of hadronic rescattering on $v_2$ by comparing $\phi$ meson with proton

• Statistics is limited in previous data set
  ‣ We have huge amount of data in year 2010 & 2011
  ‣ In addition, particle identification will be improved with fully installed MRPC-TOF detector
STAR experiment

- Large acceptance at midrapidity
  - Full azimuth, $|\eta| < 1$
- Excellent particle identification
  - TPC + TOF
Particle identifications

- Topological reconstruction of $\Xi$ and $\Omega$ weak decay
  - reduce combinatorial backgrounds
- Calculate invariant mass
  - Combinatorial background is estimated by rotational background from the same event
● Clear centrality dependence - initial geometry
● Similar $p_T$ dependence with light hadrons

- Event plane method with $\Delta \eta = 0.1$ gap
- Improve statistical error $\phi$ for meson
  - compare with left figure
- 2 centrality bins for $\Omega$ baryon
Transverse kinetic energy scaling

- Mass ordering is almost vanished in terms of transverse kinetic energy $m_T - m_0$
- Clear baryon and meson splitting above 1-2 GeV/$c^2$
- Multi-strange hadrons seem to be smaller than other hadrons in 30-80%
NCQ scaling for multi-strange hadrons

- Measure deviation relative to $K^0_s$
  - deviation at 30-80% is larger than 0-30%?
Mass ordering violation, prediction

MASS ORDERING OF DIFFERENTIAL ELLIPTIC FLOW . . .

at chemical freeze-out

hydro. + JAM

hydro. only

FIG. 9. (Color online) Transverse-momentum dependence of the elliptic flow parameters for pions (dotted blue), protons (dashed green), and \( \phi \) mesons (solid red), for Au+Au collisions at \( b = 7.2 \) fm. (a) Before hadronic rescattering. (b) After hadronic rescattering. (c) Ideal hydrodynamics with \( T_{\text{th}} = 100 \) MeV. The results for pions and protons are the same as shown in Fig. 5.

- **Prediction:** \( v_2(\phi) > v_2(p) \) at low \( p_T \)
  - Due to less hadronic rescattering on \( \phi \) meson
  - based on ideal hydrodynamical model + JAM hadronic cascade, single shot hydro (**no initial fluctuations**), ideal gas equation of state
$v_2$ at low $p_T$

- $v_2(\phi) > v_2(p)$ in data at low $p_T$
  - The effect is stronger in central collisions
- Consistent with the scenario predicted in hydro. + hadron cascade model
- Systematic & quantitative comparison is necessary
Recent update of hydro. model

S. Takeuchi,
ATHIC 2014

- Integrated dynamical model - hydro. + hadron cascade
  - Initial geometry fluctuation by MC Glauber model
  - Lattice equation of state
- Spectra are reproduced well at low $p_T$
\( v_2(p_T) \)

- Compared with previous published STAR data
- Reasonable agreement with the data
- Some deviations at peripheral collisions
  - due to the difference between event plane method (data) and reaction plane method (model)
Effect of hadronic rescattering

- Less rescattering effect on multi-strange hadrons
  - Mean $p_T$ for multi-strange hadrons deviate from $m_T$ scaling
  - $v_2$ almost unchanged between fluid and final stages
\[ v_2(\phi) \text{ vs } v_2(p) \]

- **Compare** \( v_2 \) below \( \sim 1 \text{ GeV/c} \) in \( p_T \):
  - \( v_2(\pi) > v_2(p) \geq v_2(\phi) \) without rescattering
  - \( v_2(\pi) > v_2(\phi) > v_2(p) \) with rescattering

- **Confirmed violation of mass ordering**
  - \( \sim 20\% \) effect around 0.5 GeV/c in minimum bias events
Summary

- Multi-strange hadrons can be used as penetrating probes to understand medium properties in heavy ion collisions
- We have confirmed NCQ scaling for multi-strange hadrons with high precision data set
  - partonic collectivity for light quark sectors ($u$, $d$, $s$)
- Violation of mass ordering has been predicted, and observed by the comparison of $\phi$ meson and proton $v_2$
  - The effect is stronger in central collisions
- Recent hybrid hydrodynamical model provides realistic (initial state fluctuations + lattice EoS) calculation
  - which will allow us to make quantitative and systematic comparison with the data