Recent flow results at RHIC

Hiroshi Masui / University of Tsukuba

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Outline

• Multi-strange hadrons
  ‣ Mass ordering violation

• $v_2$ at RHIC Beam Energy Scan
  ‣ Identified hadron $v_2$
  ‣ Blast wave model fit to $v_2$

• Direct photon $v_n$ & blast wave fit

• Summary
Reminder

\[
\frac{dN}{d\phi} \propto 1 + 2 \sum_{n=1}^{\infty} v_n \cos (n[\phi - \Psi_n])
\]

\[v_n = \langle \cos (n[\phi - \Psi_n]) \rangle\]

- \(v_n \neq \) (hydrodynamical) flow
  - \(v_n\) is the azimuthal anisotropy of particles in momentum space
- Crucial to understand the non-flow background
  - momentum conservation (on \(v_1\)), resonance decay, jet, …
- Multi-particle correlation (cumulant), and/or large rapidity gap are typical methods to avoid non-flow
  - Most of non-flow is 2-particle correlation, short-range correlation in (pseudo)rapidity
Multi-strange hadrons
Multi-strange hadrons (\(\phi, \Omega\)) freeze-out early

- Ideal hydrodynamical model with hadron cascade shows mass ordering violation between \(p\) and \(\phi\)
  - \(v_2(p) < v_2(\phi)\) in low \(p_T\)
  - radial flow at late stage + less hadronic cross section for \(\phi, \Omega\)
Multi-strange hadrons

- Multi-strange hadrons (φ, Ω) freeze-out early
- Ideal hydrodynamical model with hadron cascade shows mass ordering violation between p and φ
  - \( v_2(p) < v_2(\phi) \) in low \( p_T \)
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Particle identification

- Topological reconstruction of Ξ and Ω
- Combinatorial background is estimated by rotational background from the same event
Mass ordering of $v_2(p_T)$

- Event plane with gap $|\Delta \eta| = 0.1$
- $v_2(\phi) > v_2(p)$ at low $p_T$
  - The effect is stronger in central
  - qualitatively consistent with the prediction from hydro. + hadron cascade model

STAR Preliminary
Recent update of hydro. model

- Initial geometry fluctuation (MC Glauber), Lattice EoS
- Reasonable agreement with the data


Centrality dependences of distributions for $|\eta|<0.5$, $|\eta|<1.0$, $|\eta|<0.75$, $\phi$, $\Lambda + \bar{\Lambda}$, $\Xi^- + \Xi^+$, $\Omega^- + \Omega^+$, $v_2$.
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
**$v_2(\phi)$ vs $v_2(p)$**

- **Compare $v_2$ below ~1 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**
  - ~20% effect around 0.5 GeV/c in minimum bias events
• $v_2(p) > v_2(\phi)$ in 7.7 - 62.4 GeV
  ‣ Hadronic phase become dominant ?
  ‣ Temperature dependent $\eta/s$ ?

**STAR: PRC88, 014902 (2013)**

**200 GeV is special ?**

![Graph showing $v_2$ vs. $p_T$ for various energies and particle species.](image)
$v_2$ in RHIC Beam Energy Scan
**RHIC Beam Energy Scan**

- Cross-over transition at $\mu_B=0$
  - from 1st principle Lattice QCD calculations
- If phase transition is 1st order at high baryon density, the end point is QCD critical point
- Beam energy scan $\rightarrow$ reach high baryon density
- Goals of BES at RHIC:
  - Search for turn-off QGP signals
  - Search for signals of 1st order phase transition
  - Search for signals of QCD critical point
Number of Constituent Quark scaling

**PHENIX: PRL98, 162301 (2007)**

- **Apparent scaling by** $KE_T = m_T - m_0$
  - Meson and baryon branches
- **NCQ scaling of** $v_2 \rightarrow$ hadronization by parton coalescence
  - Originally predicted in intermediate $p_T$
  - Scaling works well down to low $KE_T$ at RHIC

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**Figures 2(a) and 2(b)**

- Measurement of particle elliptic flow ($v_2$) as a function of transverse momentum ($p_T$) and invariant energy ($KE_T$) for various particle species from PHENIX and STAR collaborations.
- Scaling shown by the plots, indicating a common trend for different particle species.

**Figures 3(a) and 3(b)**

- Similar to Figures 2, showing the ratio of elliptic flow to multiplicity ($v_2/n_q$) for different particle species.
- The plots demonstrate the scaling property at different multiplicity bins.

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**Graphical Details**

- **Axes:**
  - $v_2$ vs. $p_T$ (GeV/c) and $KE_T$ (GeV)
  - $v_2/n_q$ vs. $p_T/n_q$ (GeV/c) and $KE_T/n_q$ (GeV)

**Legend:**

- Various particle species are represented with different markers and colors, including $\pi^+\pi^-$, $p\bar{p}$, $K^+K^-$, $\Lambda\bar{\Lambda}$, $K^0_s$, and $\Xi^+\Xi^-$.
- The plots show data points from PHENIX and STAR collaborations.
NCQ scaling of $v_2$

- Two branches, mesons & baryons in $v_2(m_T-m_0)$ at 62.4 GeV
- Antiparticles already scaled before dividing by $n_q$ at 11.5 GeV
  - NCQ scaling doesn’t hold for antiparticles
- $\phi$ meson could be deviated at 11.5 GeV (statistics is limited)
**Particles vs antiparticles**

- **Quantify the difference of** \( v_2 \) **between particles and antiparticles**
  - NCQ scaling does not hold between particles and antiparticles
  - Scaling seems to work separately

- **Difference of** \( v_2 \) **increase with decreasing beam energy, in particular for baryons**

- **Difference of** \( v_2 \) **is linear as a function of** \( \mu_B \)
  - Related to baryon stopping?
Blast wave model

\[ v_2(p_T) = \frac{\int_0^{2\pi} d\phi_s \cos(2\phi_s) I_2[\alpha_t(\phi_s)] K_1[\beta_t(\phi_s)][1 + 2s_2 \cos(2\phi_s)]}{\int_0^{2\pi} d\phi_s I_0[\alpha_t(\phi_s)] K_1[\beta_t(\phi_s)][1 + 2s_2 \cos(2\phi_s)]} \]

\[ \alpha_t(\phi_s) = \frac{p_T}{T} \sinh \rho(\phi_s), \quad \beta_t(\phi_s) = \frac{m_T}{T} \cosh \rho(\phi_s), \]

\[ \rho(\phi_s) = \rho_0 + \rho_a \cos 2\phi_s, \quad \beta = \tanh(\rho_0) \]

- **Assumptions**
  - boost invariant longitudinal expansion
  - system expands with common transverse velocity \( \beta \)
  - freeze-out at constant temperature \( T \)
- **Mass dependence only appears in \( \beta_t \) via \( m_T \)**
- **Fit particles and antiparticles separately in \( p_T < 1.2 \text{ GeV/c} \)**
  - Simultaneous fit for measured particles (or antiparticles) with 3 parameters \( (s_2, \rho_0, \rho_a) \)
  - \( T \) is fixed to 120 MeV since published \( p_T \) spectra is not available
**Blast wave fit to $v_2(p_T)$**

- Excluded pions from the fit for RHIC data (huge feed down)
- Clear mass ordering in blast wave fit
Why does blast wave work?

\[ \beta_t(\phi_s) = \frac{m_T}{T} \cosh \rho(\phi_s) \]

- For the same \( \beta \)
  - heavier particles have larger \( p_T \)
    - \( K_1(\beta_1) \sim \exp(-\beta_1) \)
  - For a given \( p_T \), \( v_2 \) is more out-of-plane extended for heavier particles
    - because particles around in-plane pushes to higher \( p_T \)
  - lighter particles have larger \( v_2 \)
Feed down on pions?

- pions
  - data > blast wave in 7.7-200 GeV

- feed down?
  - Use MC simulation to evaluate feed down
    - due to lack of spectra, resonance measurements
Large radial flow for antiparticles

- Large spread of $v_2$ for antiparticles at lower energies
- Fit is better for antiparticles in terms of $\chi^2$
Transverse velocity

- Different $\beta$ for particles and antiparticles at lower energies
- Possible scenarios
  - Antiparticles produced early $\rightarrow$ large $\beta$ since radial flow is cumulative
- Fraction of net-protons (stopped protons) increase, already significant at 62.4 GeV $\rightarrow$ baryon stopping?
Transverse velocity

- Baryon stopping?
  - $v_2$ could be different for produced and transported quarks $\rightarrow$ particles are contaminated by transported $u$ & $d$ quarks
  - Surface emission of antiprotons due to the absorption $\rightarrow$ effect is larger for lower energies (larger $\mu_B$), smaller at higher energies
Direct photon $v_n$
Direct photon puzzle

- Enhancement of direct photon $p_T$ spectra relative to $p+p$
  - Inverse slope $T \sim 240$ MeV (0-20%) for the excess of $p_T$ spectra
- Large $v_2$ for direct photon at low $p_T$
  - Comparable to the $v_2$ for $\pi^0$
- Is direct photon emitted early ($p_T$ spectra) or late ($v_2$)?

$PHENIX: \text{PRL}109$, 122302 (2012)
Several scenarios

- Strong magnetic field $\rightarrow v_2 > 0$, $v_3 \sim 0$
- Radial flow effect $\rightarrow v_2 > 0$, $v_3 > 0$
- Measurements of $v_3$ provide additional constraints on direct photon production mechanism
**Direct photon $v_3$**

- Non-zero, positive $v_3$
- No strong centrality dependence, similar with hadron $v_3$
- Strong magnetic field scenario cannot explain the data
Blast-wave fit to direct photon $p_T$ spectra & $v_n$

- $p_T$ spectra can be fitted with the same $T$ for hadrons
- Reasonable description for $v_2$ & $v_3$
Summary

• Multi-strange hadron $v_2$ at 200 GeV shows mass ordering violation
  ‣ need quantitative comparison with the latest hydrodynamical models

• $v_2$ at RHIC BES (particles vs antiparticles)
  ‣ NCQ scaling break down between particles and antiparticles
  ‣ can be understood as different radial flow velocity (if mass ordering of $v_2$ is only due to radial flow)
  ‣ Need more statistics, better model calculations

• Finite direct photon $v_n$ at RHIC
  ‣ Naive strong magnetic field scenario cannot explain the data
  ‣ Large $v_n$, blast wave fit (if applicable) could support that direct photons are emitted from late stage