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Directed flow of quarks from the RHIC Beam Energy Scan measured by STAR

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Abstract

Directed flow (v_1) is a good probe of the early-stage dynamics of collision systems, and the v_1 slope at midrapidity ($dv_1/dy|_{y=0}$) is sensitive to the system's equation of state. STAR has published $v_1(y)$ measurements for ten particle species ($\pi^{\pm}$, p, $\bar{p}$, Λ, $\bar{\Lambda}$, ϕ, $K^{\pm}$ and K_S^0) in Au+Au collisions at eight beam energies from $\sqrt{s_{NN}} = 7.7$ GeV to 200 GeV. In this study, we employ a simple coalescence idea to decompose v_1 of hadrons into v_1 of constituent quarks. The dv_1/dy values of $\bar{p}$, K^- and $\bar{\Lambda}$ are used to test the coalescence sum rule for produced quarks. Data involving produced quarks support the coalescence picture at $\sqrt{s_{NN}} = 11.5$ GeV to 200 GeV, and a sharp deviation from this picture is observed at 7.7 GeV. The dv_1/dy of transported quarks is studied via net particles (net p and net Λ). In these proceedings, we further extract the v_1 slopes of produced and transported quarks, assuming that the coalescence sum rule is valid.

Keywords: heavy-ion collision, directed flow, beam energy scan, coalescence, transported quark

1. Introduction

Rapidity-odd directed flow ($v_1^{\text{odd}}(y)$) is the first Fourier coefficient of the final-state azimuthal distribution relative to the collision reaction plane [1], and describes the collective sideward motion of emitted particles. The rapidity-even component ($v_1^{\text{even}}(y)$) [2] is unrelated to the reaction plane in symmetric collisions, and hereafter, $v_1(y)$ implicitly refers to the odd component. Hydrodynamic calculations [3, 4] have proposed a minimum in net-baryon directed flow versus $\sqrt{s_{NN}}$ as a signature of a first-order phase transition between hadronic matter and quark-gluon plasma. This minimum is supposedly related to the softening of the system's equation of state (EOS). STAR has published $v_1(y)$ measurements for ten particle species ($\pi^{\pm}$, p, $\bar{p}$, Λ, $\bar{\Lambda}$, ϕ, $K^{\pm}$ and K_S^0) in Au+Au collisions at eight beam energies from $\sqrt{s_{NN}} = 7.7$ GeV to 200 GeV [5, 6]. Net protons do show a minimum in dv_1/dy near $\sqrt{s_{NN}}$ of 10 to 20 GeV [5]. In more recent model calculations of $v_1(y)$ with different EOS [7, 8, 9, 10, 11, 12], the assumption of purely hadronic physics is disfavored, but there is no consensus on whether STAR measurements [5] favor a crossover or first-order phase transition. While further progress in models is needed for a definitive interpretation, the experimental data may distinguish different interpretations by advancing to the constituent quark level.

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[1] A list of members of the STAR Collaboration and acknowledgements can be found at the end of this issue.

Number-of-constituent-quark (NCQ) scaling of elliptic flow (v_2) [13] behaves as if v_2 is imposed at the level of deconfined constituent quarks, providing an example of coalescence behavior among quarks. The ten particle species available in the present analysis allow a detailed investigation of the scaling behavior of v_1 at constituent quark level versus $\sqrt{s_{NN}}$. We will test a set of assumptions, namely that v_1 is imposed at the pre-hadronic stage, that specific types of quark have the same directed flow, and that the detected hadrons are formed via coalescence [13, 14]. In a scenario where deconfined quarks have already acquired v_n, and in the limit of small v_n, coalescence leads to the v_n of the resulting mesons or baryons being the summed v_n of their constituent quarks [14, 15]. We call this assumption the coalescence sum rule. NCQ scaling in turn follows from the coalescence sum rule [14].

In this study, we attempt to separate "transported" quarks (u and d from the initial-state nuclei)) and "produced" quarks (u, $\bar{u}$, d, $\bar{d}$, s and $\bar{s}$ created in pair after the collision). The number of transported quarks is conserved, and transported quarks experience the whole system evolution, including the initial sideward deflection, the possible softening of equation of state, annihilation, re-scattering and so on. Conversely, the total number of produced quarks is not conserved, and produced quarks are presumably created in different stages [16], which complicates the interpretation of produced-quark v_1. Experimentally, produced quarks can be studied with purely "produced" particles, such as $\bar{p}$, $\bar{\Lambda}$ and K^-, whereas transported quarks can be probed with net particles that represent the excess yield of a particle species over its antiparticle. We define $v_{1\,\mathrm{net}\,p}$ based on expressing $v_1(y)$ for all protons as $v_{1\,p} = r(y)v_{1\,\bar{p}} + [1 - r(y)]v_{1\,\mathrm{net}\,p}$, where $r(y)$ is the ratio of observed $\bar{p}$ to p yield at each beam energy. Net-Λ v_1 is defined similarly, except $\bar{p}$ (p) becomes $\bar{\Lambda}$ (Λ).

2. Results

We first test the coalescence sum rule in a straightforward case where all quarks are known to be produced. Figure 1(a) compares the observed dv_1/dy for $\bar{\Lambda}(\bar{u}d\bar{s})$ with the calculation for $K^-(\bar{u}s) + \frac{1}{3}\bar{p}(\bar{u}\bar{u}\bar{d})$ [6]. This calculation is based on the coalescence sum rule combined with the assumption that $\bar{u}$ and $\bar{d}$ quarks have the same flow, and that s and $\bar{s}$ have the same flow. Close agreement is observed for $\sqrt{s_{NN}}$ from 11.5 to 200 GeV. The inset in Fig. 1(a) presents the same comparison, but with a larger vertical scale. The observed sharp breakdown of agreement at $\sqrt{s_{NN}} = 7.7$ GeV implies that one or more of the aforementioned assumptions no longer hold below 11.5 GeV.
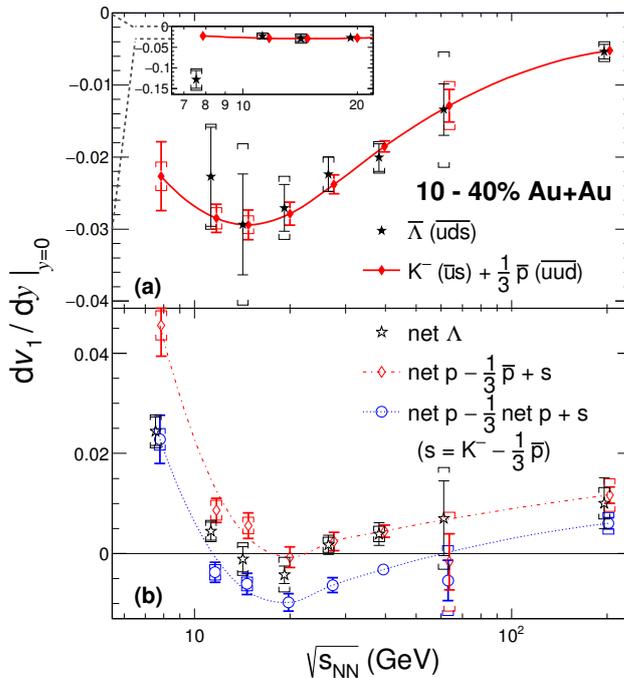
Fig. 1. (Color online) Directed flow slope (dv_1/dy) versus $\sqrt{s_{NN}}$ for intermediate centralities (10 − 40%) [6]. Panel (a) compares the observed Λ slope with the prediction of the coalescence sum rule for produced quarks. The inset shows the same comparison where the vertical scale is zoomed-out; this allows the observed flow for the lowest energy ($\sqrt{s_{NN}} = 7.7$ GeV) to be seen. Panel (b) presents two further sum-rule tests, based on comparisons with net-Λ measurements. The solid and dotted lines are smooth curves to guide the eye.

57   In the limit of low $\sqrt{s_{NN}}$, most u and d quarks are presumably transported, whereas in the limit of high

58 $\sqrt{s_{NN}}$, most of u and d are produced. In Fig. 1(b), we exploit net $\Lambda(uds)$ to test two coalescence sum rule

59 scenarios which are expected to bracket the observed dv_1/dy for a baryon containing transported quarks.

60 The first compared data operation (red diamond markers) consists of net proton (uud) minus $\bar{u}$ plus s, where

61 $\bar{u}$ is estimated from $\frac{1}{3}\bar{p}$, and the s quark flow is obtained from $K^-(\bar{u}s) - \frac{1}{3}\bar{p}(\bar{u}\bar{u}\bar{d})$. Here we assume that a

62 produced u quark in net p is replaced with an s quark. This sum-rule calculation agrees closely with the

63 net-Λ measurement at $\sqrt{s_{NN}} = 19.6$ GeV and above, remains moderately close at 14.5 and 11.5 GeV, and

64 deviates significantly only at 7.7 GeV. With decreasing beam energy, the number of transported quarks per

65 net proton increases (as shown in Fig. 4), and there is an increasing departure from the assumption that a

66 produced u quark is removed by keeping the term (net $p - \frac{1}{3}\bar{p}$). The second coalescence operation in Fig. 1(b)

67 corresponds to $\frac{2}{3}$ net proton plus s (blue circle markers). In this case, we assume that the constituent quarks

68 of net protons are dominated by transported quarks in the limit of low beam energy, and that one of the

69 transported quarks is replaced by s. This approximation only seems to hold at $\sqrt{s_{NN}} = 7.7$ GeV, and breaks

70 down as the beam energy increases.
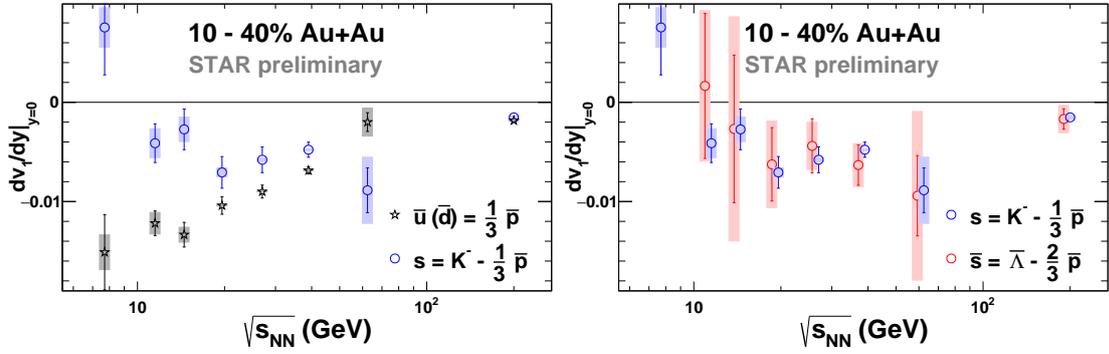
Fig. 2. (Color online) Directed flow slope (dv_1/dy) of $\bar{u}(\bar{d})$ and s Fig. 3. (Color online) Directed flow slope (dv_1/dy) of s and $\bar{s}$ quarks versus $\sqrt{s_{NN}}$ for intermediate centralities (10 − 40%).   quarks versus $\sqrt{s_{NN}}$ for intermediate centralities (10 − 40%).

71   With the assumption of the coalescence sum rule, we can further extract dv_1/dy of constituent quarks.

72 Figures 2 and 3 present directed flow slope (dv_1/dy) of produced quarks as function of $\sqrt{s_{NN}}$ for inter-

73 mediate centralities (10 − 40%). dv_1/dy of the produced $u(d, \bar{u}, \bar{d})$ quarks is approximated with $\frac{1}{3}\bar{p}(\bar{u}\bar{u}\bar{d})$,

74 whereas the s quark flow is obtained from $K^-(\bar{u}s) - \frac{1}{3}\bar{p}$, and $\bar{s}$ from $\bar{\Lambda}(\bar{u}\bar{d}\bar{s}) - \frac{2}{3}\bar{p}$. At $\sqrt{s_{NN}} = 200$ GeV, the

75 produced $u(d, \bar{u}, \bar{d})$ and s quarks have very similar v_1 slopes, and they deviate towards lower beam energies.

76 The consistency between s and $\bar{s}$ holds within uncertainties for almost all studied beam energies, except at

77 $\sqrt{s_{NN}} = 7.7$ GeV, where dv_1/dy of $\bar{s}$ is -0.097 ± 0.023(stat.) ± 0.026(syst.), far off the scale.

78   Next, we estimate the number of transported quarks per net proton. Assuming that the chemical potential

79 of $u(d)$ quarks is one third of that of baryons, $\mu_{u(d)} = \mu_B/3$, we derive from thermal equilibrium that the

80 number of transport quarks per net proton is $N_{\text{trans. u+d}} = 3 \times (1 - e^{-2\mu_{u(d)}/T_{ch}})/(1 - r)$ [17]. Here T_{ch} is the

81 chemical freeze-out temperature, and $r \propto e^{-6\mu_{u(d)}/T_{ch}}$ is the aforementioned ratio of observed $\bar{p}$ to p yield.

82 In the limit of low $\sqrt{s_{NN}}$ or high μ_B, $N_{\text{trans. u+d}}$ is close to three, whereas in the limit of high $\sqrt{s_{NN}}$ or low

83 μ_B, $N_{\text{trans. u+d}}$ approaches unity. These features are confirmed by Fig. 4 that shows the number of transported

84 quarks per net proton versus $\sqrt{s_{NN}}$ for intermediate centralities (10 − 40%). The values of μ_B and T_{ch} are

85 based on previous STAR measurements [18]. Quoted errors are statistical uncertainties only.

86   Finally, the v_1 slope of transported quarks is obtained by removing produced quarks from net protons:

87 $v_{1\,\text{trans.}\,u(d)} = [v_{1\,\text{net}\,p} - (3 - N_{\text{trans. u+d}}) \times v_{1\,\bar{u}(\bar{d})}]/N_{\text{trans. u+d}}$. Figure 5 illustrates dv_1/dy of transported $u(d)$ quarks

88 versus $\sqrt{s_{NN}}$ for intermediate centralities (10−40%), which is positive for all the beam energies under study,

89 and demonstrates a minimum at $\sqrt{s_{NN}} \approx 14.5$ GeV. Compared with previous STAR results on net-proton

90 v_1, these data on the constituent quark level provide a stronger evidence of the softening of equation of state,

91 though a definite interpretation still requires further theoretical inputs.
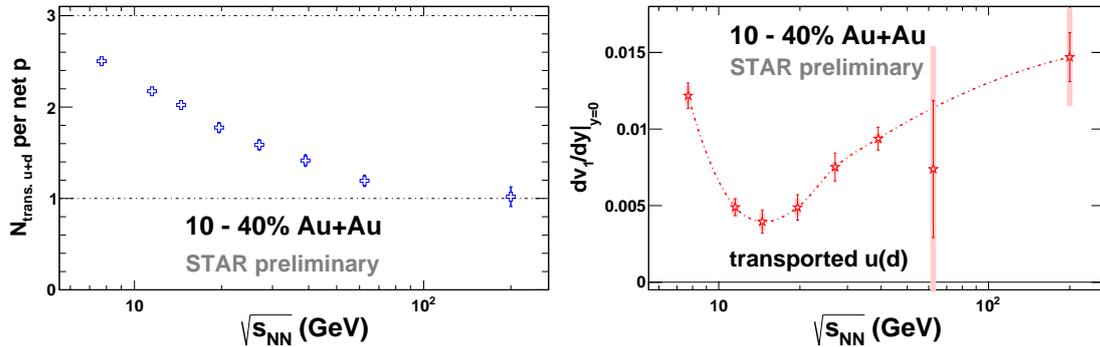
Fig. 4. (Color online) Number of transported u and d quarks per net proton versus $\sqrt{s_{NN}}$ for intermediate centralities ($10-40\%$).

Fig. 5. (Color online) Directed flow slope (dv_1/dy) of transported $u(d)$ quarks versus $\sqrt{s_{NN}}$ for intermediate centralities ($10-40\%$).

3. Summary

STAR has published directed flow results for ten particle species in Au+Au collisions at eight beam energies. These data enable us to test the coalescence sum rule on the constituent quark level, for both produced and transported quarks. The observed pattern of scaling behavior for produced quarks at and above $\sqrt{s_{NN}}$ = 11.5 GeV, with a breakdown at 7.7 GeV, warrants further study. Two coalescence sum rule scenarios have been explored to bracket the observed dv_1/dy of net Λ that contains transported quarks. Assuming the validity of the coalescence picture, we have extracted the v_1 slopes of produced $u(d, \bar{u}$ and $\bar{d})$, s and $\bar{s}$ quarks, as well as transported $u(d)$ quarks as function of $\sqrt{s_{NN}}$ for intermediate centralities. Among produced quarks, u and s have similar dv_1/dy at 200 GeV, and deviate towards lower beam energies. The v_1 slopes of s and $\bar{s}$ are consistent with each other, except at 7.7 GeV. dv_1/dy of transported quarks is positive for all the beam energies under study, and supports the softening of equation of state with a minimum at $\sqrt{s_{NN}} \approx 14.5$ GeV. These energy-dependent measurements will be enhanced after STAR acquires greatly increased statistics using upgraded detectors in Phase II of the RHIC Beam Energy Scan [19].

Acknowledgments

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