Identified particle measurements at RHIC: elucidating hadronization mechanisms for bulk partonic matter

Paul Sorensen
Lawrence Berkeley National Laboratory, 94720 Berkeley, USA

Abstract. Measurements of identified particle momentum spectra at $\sqrt{s_{NN}} = 200$ GeV are reviewed. Emphasis is placed on the azimuthal dependence and the centrality dependence of hadron yields at intermediate transverse momentum ($1.5 < p_T < 5$ GeV/c). The first measurements of the fourth harmonic term ($v_4$) in the azimuthal variation of identified particle yields are shown. The recombination mechanism of hadron formation provides a consistent description of the dependence of these measurements on particle-type.

Keywords: Nuclear Modification, Elliptic Flow
PACS: 25.75.-q, 25.75.Ld

1. Introduction

Experimenters at the Relativistic Heavy Ion Collider (RHIC) have made several unexpected observations. Perhaps most surprising are measurements relating to baryon production in the intermediate transverse momentum region ($1.5 < p_T < 5$ GeV/c) [1, 2]. At this $p_T$, while in nucleon-nucleon collisions, one baryon is produced for every three mesons (1:3), in Au+Au collisions baryons and mesons are created in nearly equal proportion (1:1). Although these initial observations were considered a puzzle, they can easily be reconciled when multi-parton mechanisms for hadron production such as recombination or coalescence are considered [3]. The azimuthal dependence of production provides compelling support for this picture with baryon and meson anisotropies scaling in a manner predicted by coalescence models [2, 4]. Since these measurements were made, no other picture has been presented that can account for this apparent meson/baryon dependence. We note, however, that several of the defining measurements — particularly those for the more massive mesons — are either preliminary or statistically limited [5]. Data recently taken at RHIC will allow experimentalists to measure identified particle distributions to higher $p_T$ and test multi-parton hadronization predictions with
greater precision.

We use the ratio of yields from central and peripheral collisions, $R_{CP}$, scaled by the number binary collisions $N_{\text{bin}}$:

$$R_{CP}(p_T) = \frac{[dN/(N_{\text{bin}}dp_T)]^{\text{central}}}{[dN/(N_{\text{bin}}dp_T)]^{\text{peripheral}}},$$

(1)

to study the evolution of a particle’s $p_T$ spectra with collision centrality. In Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV, $R_{CP}(p_T > 6 \text{ GeV/c}) \approx 0.2$ [6], indicating that hadron yields in central collisions at this $p_T$ are a factor of five smaller than expected from scaling of peripheral collisions. To study production with respect to the collision orientation (i.e. the reaction-plane direction), the azimuthal component of a particle’s distribution is expanded as a Fourier series, $dN/d\phi \propto 1 + \sum_n 2v_n \cos n\phi$, where $\phi$ is the azimuth angle of the particle momentum with respect to the reaction-plane direction [7]. Owing to the elliptic shape of the reaction volume in off-axis collisions, the second term $v_2$ is the largest and most studied of the coefficients.

2. Intermediate-$p_T$ defined

Based on the yields and azimuthal anisotropies of identified particles in relativistic nuclear collisions, three $p_T$ regions with distinct characteristics have been delineated. The low-$p_T$ region is compellingly characterized by a mass dependence of $v_2$ that signifies the development of a collective velocity [4, 8]. At intermediate-$p_T$ a strong number-of-constituent-quark (NCQ) dependence dominates both $v_2$ and $R_{CP}$. At $p_T > 5 \text{ GeV/c}$ the lack of a species dependence in $R_{CP}$ indicates that baryon and meson production increases with centrality at similar rates [2].

![Fig. 1. Left: Hydrodynamic predictions for identified particle $v_2$ with data from the STAR and PHENIX experiments [10]. Center: STAR measurements of identified particle $R_{CP}$ [2, 5]. Grey bands indicate model uncertainties in the number of collision participants and $N_{\text{bin}}$. These uncertainties are correlated between species and therefore, cannot change the species dependence. Right: Comparison of pedestal subtracted azimuthal distributions (relative to high-$p_T$ trigger particles) for p+p, central d+Au, and central Au+Au collisions [12].](image-url)
Consideration of the characteristic length scales associated with each of these regions provides a simple framework for understanding the observed dependencies in each region [9]. In the low-$p_T$–long-wavelength limit, observables are dominated by bulk properties such as pressure and temperature. As demonstrated in Fig. 1 (left), hydrodynamic descriptions of the systems evolution — relying on a zero mean-free-path approximation — successfully describe the conversion of spatial anisotropy to momentum anisotropy ($v_2$) [10]. In addition, thermodynamic models successfully predict the relative abundances of various particles [11].

In the high-$p_T$–short-wavelength limit, hard scattered partons first lose energy in the high density medium then hadronize in vacuum [6]. As demonstrated in Fig. 1 (right), parton energy loss in central collisions tends to suppress away-side jet-like correlations [12]. High-$p_T$ trigger particles are predominantly generated from a fast parton escaping from the surface of the reaction volume while the other fast parton created in the hard scattering is directed into the reaction volume and absorbed by the medium. Since the surviving fast partons tend to hadronize in vacuum, the particle composition is determined by the probability of producing a given arrangement of colorless quarks from the breaking of strings and becomes similar to that seen in p+p collisions.

In both of the above regions the spatial distribution of the partonic matter generated in the collision is ignored during the hadronization process. At low-$p_T$, a locally homogenous cell of energy and momentum radiates particles and the chemical potentials and masses of the particles along with the matter’s temperature determine the relative particle abundances. At very high-$p_T$, after the partons initially lose some fraction of their energy in the medium, the medium’s influence on the process of hadronization is ignored.

At intermediate-$p_T$, however, the composite nature of the partonic matter cannot be neglected and the low- and high-$p_T$ treatments of hadronization fail — low-$p_T$ because it is blind to the individuality of the matter’s constituents and high-$p_T$ because the matter is ignored entirely. The lower bound of the intermediate-$p_T$ region can be defined by the break-down of the hydrodynamic description of $v_2$ (an observable that is less polluted by the post hydrodynamic/hadronic phase). The upper bound is determined by the onset of independent fragmentation, where the relative particle abundances return to those values measured in p+p collisions. The lower and upper bounds were measured experimentally [2] and found to be $\sim 1.5$ and $\sim 5$ GeV/$c$ respectively. As will be discussed below, the manner in which the composite nature of the matter manifests itself in $v_2$ and $R_{CP}$ provides strong evidence for the existence of matter with partonic degrees-of-freedom.

Given the above considerations it becomes apparent that by varying the phase-space density (with A+A, N+N, or N+A collisions) the microscopic processes by which hadron formation occur can be studied. The manner in which the quark-number dependencies manifest themselves at intermediate-$p_T$ gives insight into the nature of these microscopic processes. Particularly the larger rate-of-increase for baryon production, i.e. $R_{CP}^{\text{Baryon}} > R_{CP}^{\text{Meson}}$, along with the quark-number-scaling for $v_2$ shown in Fig. 3 (left), i.e. $v_2^{\text{Baryon}}(p_T) = \frac{3}{2}v_2^{\text{Meson}}(p_T)$, suggests hadrons at
intermediate-$p_T$ are formed by coalescence of co-moving constituent quarks [3]. The quark-number dependence demonstrates that the relevant degrees-of-freedom are partonic, while the high degree of collectivity, developed by even the heavier strange-quarks, suggests that the partonic degrees of freedom are locally equilibrated. We note that the baryon–meson dependence of $v_2$ and $R_{CP}$ contradicts expectations from simple energy loss considerations. Specifically, while $v_2^{\text{Baryon}} > v_2^{\text{Meson}}$ would suggest partons that fragment into baryons suffer more energy loss, $R_{CP}^{\text{Baryon}} > R_{CP}^{\text{Meson}}$ (Fig. 1) contradicts this interpretation.

3. Testing coalescence scaling

![Anisotropy Parameter](image)

**Fig. 2.** Left: Identified particle $v_2$, hydrodynamic predictions and quark $v_2$ derived from NCQ-scaling. Right: Preliminary $K_S^0$ and $\Lambda$ $v_4$.

In Fig. 2 (left) we show $v_2$ for kaons, protons, $\Lambda$s, $\Xi$s and $\Omega$s [2 5 8]. At lower $p_T$, hydrodynamic calculations describe $v_2(p_T, \text{mass})$ well, with heavier particles at a given $p_T$ having smaller $v_2$ values. At $p_T > 1.5$ GeV/c, the mass ordering breaks down with the heavier baryon $v_2$ becoming larger than the lighter meson $v_2$. We also show the quark $v_2$ derived by scaling the $K_S^0$ and $\Lambda$ $v_2$ by their number of constituent quarks. In coalescence models, the NCQ-scaled $v_2$ values reflect the anisotropy of the parton distributions at the moment just prior to hadronization [3]. In Fig. 2 (right) we show the first measurements of the higher harmonic Fourier coefficient $v_4$ for identified particles. An NCQ-dependence is expected to be present in higher harmonic terms — although in a slightly more complicated form [13]. The ratio $v_4/(v_2)^2$ is preferred for model comparisons and in a coalescence model simplifies the relationship between partonic and hadronic anisotropies.

Fig. 3 (left) shows the ratio of $v_4/(v_2)^2$ for kaons, $\Lambda$s, and charged hadrons [14]. Although the statistical uncertainty in $v_4/(v_2)^2$ for kaons is large, if we assume that the $\Lambda$s are representative of all baryons we can infer that the meson ratio must be above the inclusive charged hadron ratio. Using this consideration, we attempt to find values for parton $v_2$ and $v_4$ that when scaled by the number of constituent
Identified particles at RHIC

2

\( \frac{v_4}{v_2^2} \) (GeV/c)

0 1 2 3 4 5

0 2

0 2

0

2

0

2

2

0

2

0

2

NCQ-scaling

meson baryon +h +Λ −h +K

Fig. 3. Left: Identified particle \( \frac{v_4}{v_2^2} \). Hatched regions indicate \( \langle \frac{v_4}{v_2^2} \rangle \).

Right: The relationship of hadron and parton \( \frac{v_4}{v_2^2} \) for coalescence scaling. Values of \( \frac{v_4}{v_2^2} \) consistent with measurements are indicated in both plots.

quarks are consistent with the data. Fig. 3 (right) shows the relationship between the partonic and hadronic anisotropies in a coalescence model \[13\]. The specific values of parton anisotropy — \( v_2 \approx 6.5\% \) and \( v_4 \approx 0.9\% \) — that are consistent with preliminary measurements are indicated in the figures.

4. Conclusions

Identified particle \( R_{CP} \) and \( v_2 \) measurements made in Au+Au collisions at RHIC have revealed an apparent constituent-quark-number dependence in the region \( 1.5 < p_T < 5 \) GeV/c. The \( v_2 \) measurements follow a quark-number scaling predicted by models of hadron formation by coalescence of co-moving partons. The \( R_{CP} \) measurements show that baryon production increases more sharply with centrality than meson production — an observation that also supports a picture of hadron formation by coalescence or recombination. Preliminary measurements of identified particle \( v_4 \) have been presented and are shown to be consistent (within the large statistical uncertainties) with quark-number scaling predictions. Recombination or coalescence of partons provides the most economical and compelling explanation for these measurements. RHIC data that is currently being analyzed will allow experimentalists to test these models more stringently. If the initial observations of a quark-number dependence are verified, the conclusion that a highly interacting matter with parton degrees-of-freedom has been created at RHIC will be unavoidable. Furthermore, a greater understanding of the hadron formation process will have been achieved — perhaps revealing how quarks and gluons from the very early universe formed into the colorless hadronic matter that dominates the visible universe today.
Acknowledgements

The author thanks the conference organizers D. Kharzeev, R. Lacey, M. Lisa, and S. Panitkin along with V. Greco, A. Tang, and S. Gulerce for stimulating discussions.

References

1. S. S. Adler et al. [PHENIX Collaboration], Phys. Rev. Lett. 91, 172301 (2003).
2. J. Adams et al. [STAR Collaboration], Phys. Rev. Lett. 92, 052302 (2004).
3. D. Molnar and S. A. Voloshin, Phys. Rev. C 67, 064902 (2003); R. C. Hwa and C. B. Yang, Phys. Rev. C 67, 064902 (2003); R. J. Fries, B. Muller, C. Nonaka and S. A. Bass, Phys. Rev. C 68, 044902 (2003); V. Greco, C. M. Ko and P. Levai, Phys. Rev. C 68, 034904 (2003); V. Greco, C. M. Ko and P. Levai, Phys. Rev. Lett. 90, 202302 (2003); R. J. Fries, B. Muller, C. Nonaka and S. A. Bass, Phys. Rev. Lett. 90, 202303 (2003).
4. P. Sorensen [STAR Collaboration], J. Phys. G 30, S217 (2004); P. R. Sorensen, Ph.D. thesis, UCLA, 2003, arXiv:nucl-ex/0309003; X. Dong, S. Esumi, P. Sorensen, N. Xu and Z. Xu, arXiv:nucl-th/0403030.
5. H. Long [STAR Collaboration], J. Phys. G 30, S193 (2004); K. Schweda [STAR collaboration], arXiv:nucl-ex/0403032; J. Castillo [STAR Collaboration], arXiv:nucl-ex/0403027.
6. S. S. Adler et al. [PHENIX Collaboration], Phys. Rev. Lett. 91, 072301 (2003); J. Adams et al. [STAR Collaboration], Phys. Rev. Lett. 91, 172302 (2003).
7. S. Voloshin and Y. Zhang, Z. Phys. C 70, 665 (1996); A. M. Poskanzer and S. A. Voloshin, Phys. Rev. C 58, 1671 (1998).
8. C. Adler et al. [STAR Collaboration], Phys. Rev. Lett. 87, 182301 (2001); C. Adler et al. [STAR Collaboration], Phys. Rev. Lett. 89, 132301 (2002); S. S. Adler et al. [PHENIX Collaboration], Phys. Rev. Lett. 91, 182301 (2003).
9. U. A. Wiedemann, arXiv:hep-ph/0402251; M. Gyulassy, arXiv:nucl-th/0403032.
10. P. Huovinen, P. F. Kolb, U. W. Heinz, P. V. Ruuskanen and S. A. Voloshin, Phys. Lett. B 503, 58 (2001); P. F. Kolb, AIP Conf. Proc. 698, 694 (2004).
11. P. Braun-Munzinger, D. Magestro, K. Redlich and J. Stachel, Phys. Lett. B 518, 41 (2001); J. Rafelski and J. Letessier, Acta Phys. Polon. B 34, 5791 (2003).
12. J. Adams et al. [STAR Collaboration], Phys. Rev. Lett. 91, 072304 (2003).
13. L. W. Chen, C. M. Ko and Z. W. Lin, Phys. Rev. C 69, 031901 (2004); P. F. Kolb, L. W. Chen, V. Greco and C. M. Ko, arXiv:nucl-th/0402049.
14. J. Adams et al. [STAR Collaboration], Phys. Rev. Lett. 92, 062301 (2004).