Identified Particle Spectra and Jet Interactions with the Medium

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Through a combination of detector upgrades and advancements in analysis techniques, physicists at RHIC are extending their ability to identify particles at high $p_T$. With these new capabilities some outstanding questions are being addressed: particularly regarding baryon production. Here I present an overview of new data on identified particle elliptic flow ($v_2$), identified particle $p_T$ spectra and identified hadron-hadron correlations. The observed phenomena provide insights into hard parton interactions with the bulk matter created in heavy-ion collisions and the relevant degrees-of-freedom during its early stages.

1. Introduction

Physicists at the Relativistic Heavy Ion Collider (RHIC) have made several unexpected observations [1]. Of particular interest are measurements relating to baryon production in the intermediate transverse momentum region ($1.5 < p_T < 5$ GeV/c) [2, 3, 4]. In nucleon-nucleon collisions at $p_T = 3$ GeV/c, one baryon is produced for every three mesons (1:3). In $Au+Au$ collisions however, baryons and mesons are created in nearly equal proportion (1:1). At this same $p_T$, the elliptic anisotropy ($v_2$) of baryons is also 50% larger than meson elliptic flow: demonstrating that baryon production is also enhanced in the direction of the impact vector between the colliding nuclei (in-plane) [3, 5]. This enhancement in baryon production persists up to $p_T = 5.5$ GeV/c. Several possible explanations for the enhancement are commonly considered:

- Multi-quark or gluon processes during hadron formation—coalescence [6].
- Gluon configurations that carry baryon number—baryon junctions [7, 8].
- Collective motion amongst more massive baryons that populates the higher $p_T$ regions of baryon $p_T$ spectra—flow [9].

Coalescence models have garnered particular attention because they seem to provide a natural explanation for the constituent-quark-number scaling that has been observed in $v_2$ measurements. They also relate hadronic observables to a pre-hadronic stage of interacting quarks and gluons. As such, they touch on questions central to the heavy-ion physics program: deconfinement and chiral symmetry restoration.

Given the potential physics benefits that can be derived from these measurements, RHIC physicists have endeavored to extend their abilities to identify hadron types up to higher $p_T$ regions [10, 11]. Through these efforts, measurements of $\pi^{\pm}$, $\pi^0$, $K^0_S$, $\eta$, $p + \bar{p}$, and $\Lambda + \bar{\Lambda}$ spectra and $v_2$ which extend beyond $p_T = 8$ GeV/c have been presented at
this conference. Here I review those measurements along with correlation measurements that may help clarify some of the questions remaining about the origin and implications of the baryon enhancement in heavy-ion collisions.

1.1. Azimuthal Dependence: $v_2$

![Figure 1. Elliptic flow measurements at middle rapidity from minimum-bias Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The bands around the STAR preliminary measurements of pions and protons represent systematic uncertainties mostly from non-flow correlations. The PHENIX measurements are made by correlating hadrons at middle rapidity with an event-plane measured using hadrons at $3.1 < |\eta| < 4.0$. For this reason they are less susceptible to most spurious, non-flow correlations.](image)

Fig. 1 shows preliminary measurements of $v_2$ with a minimum bias centrality selection in $Au + Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV \cite{12, 13}. The curves show $v_2$ for pions, kaons, protons and Lambdas from a hydrodynamic calculation \cite{9}. At $p_T < 1.0$ GeV/c, the mass ordering demonstrates that $v_2$ in that region results from collective motion. The hydrodynamic calculations capture the general features of the data in this region. At much higher $p_T$ it is expected that $v_2$ will be developed via energy loss by fast partons as they traverse the medium created in the collisions. Calculations suggest that $v_2$ from this mechanism should be less than 10% \cite{14}. It is also expected that all hadrons will have similar $v_2$ values where energy loss mechanisms dominate $v_2$. The magnitude and particle-type dependence of $v_2$ seen for $p_T < 6$ GeV/c suggest that other mechanisms contribute to the development of $v_2$ up to 6–7 GeV/c. This observation is consistent with results from a parton cascade model predicting that the effects of flow may persist up to $p_T = 7$ GeV/c \cite{15}. At $p_T = 7$ GeV/c, where, within errors, the particle-type dependence of $v_2$ dissapears, the $v_2$ measurements are consistent with expectations from energy loss models \cite{14}. 
Multi-strange hadron $v_2$ measurements with unprecedented accuracy were presented at this conference [12]. These measurements are thought to be good tests for collective effects amongst quarks and gluons [16]. Measurements show that when the $p_T$ spectra of $\phi$-mesons and $\Omega$-baryons are characterized with a two component hydrodynamic inspired fit, the temperature and flow velocity parameters extracted are systematically different than those extracted for non-strange hadrons [1]. The differences are consistent with less hadronic rescattering amongst multi-strange hadrons. For this reason, it is believed that the $v_2$ of multi-strange hadrons reflect collectivity that developed before hadrons formed.

In Fig. 2 $v_2$ measurements for $K_0^*$, $\phi$, $\Lambda + \bar{\Lambda}$, $\Xi + \bar{\Xi}$, and $\Omega + \bar{\Omega}$ from minimum bias $Au + Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV are shown. The $\phi$ and $\Omega$ $v_2$ values follow the same systematic trends as the non-strange hadrons: with an apparent mass ordering at low $p_T$ and a quark-number dependence at intermediate $p_T$. Combined with the spectra measurements, these measurements suggests that $v_2$ is developed during a prehadronic stage.

1.2. Quark Number Dependence

Hadronization by coalescence or recombination of constituent quarks is thought to explain many features of hadron production in the intermediate $p_T$ region ($1.5 < p_T < 5$ GeV/c) [6]. These models find that at intermediate $p_T$, $v_2$ may follow a quark-number ($n_q$) scaling with $v_2(p_T/n_q)/n_q$ for all hadrons falling on one curve. This scaling behavior has been observed in $Au + Au$ collisions at 200 GeV [5]. More sophisticated theoretical considerations have led to predictions of fine structure in quark-number scaling—with predictions for a baryon $v_2/n_q$ being smaller than meson $v_2/n_q$ [17] [18].

Fig. 3 (top panel) shows $v_2$ vs $p_T$ for identified particles, where $v_2$ and $p_T$ have been scaled by $n_q$. A polynomial function is fit to the scaled values. The deviations from the scaling are shown in the bottom panel by plotting the difference between the scaled baryon $v_2$ and the scaled meson $v_2$ divided by the sum $(B - M)/(B + M)$. Theoretical predictions for this value are also shown. The model that compares best to data is a coalescence model that includes the effect of quark momentum distributions inside the hadron (Coalescence + wavefunction) [17]. The effect of accounting for the substructure of constituent quarks (higher fock states) [18] leads to a negative $(B - M)/(B + M)$ ratio.
but with a smaller magnitude than observed in the data. It should be noted, however, that the systematic uncertainties on the measurements have not yet been estimated.

Quark-number dependences at intermediate \( p_T \) are also manifested in the centrality dependence of the \( p_T \) spectra. Fig. 4 shows the ratios \( R_{CP} \) [3, 19, 20, 21] (central \( Au + Au \) over peripheral \( Au + Au \)) in the left panel and \( R_{AA} \) [22, 23] (\( Au + Au \) over \( p + p \)) in the right panel where the spectra have been scaled by the number of binary nucleon-nucleon collisions (\( N_{bin} \)). Hard processes are expected to scale with \( N_{bin} \), so \( R_{AA,CP} \simeq 1 \) at high \( p_T \) indicates a suppression due to nuclear affects. Models incorporating energy loss of hard scattered partons in medium successfully describe the suppression of hadrons at high \( p_T \) [14]. Indeed, photons which only interact electro-magnetically are found to follow \( N_{bin} \) scaling. Here, however, we concentrate on the features of the particle-type dependence of hadrons at intermediate \( p_T \).

For \( p_T > 1.5 \) GeV/c, \( R_{CP} \) values are grouped by particle type (mesons vs. baryons). The larger baryon \( R_{CP} \) values indicate that baryon production increases more quickly with centrality than meson production. This observation is confirmed with good precision for protons and hyperons. The \( \phi \) is a particularly interesting test particle since it is a meson but is more massive than the proton. With good precision, the \( \phi \) is now confirmed to follow the systematics of the other mesons. Additionally \( R_{AA} \) has been measured for the \( \eta \)-meson and its values are similar to those of the pions.

Particular progress has been made in the measurement of charged pion and proton \( R_{CP} \). These measurements now extend into the region where fragmentation in vacuum is thought to be the dominate hadronization mechanism. In this region, if the relative fraction of quark and gluon jets (fragmenting to a hadron with a given \( p_T \)) changes from peripheral to central \( Au + Au \) collisions, the \( R_{CP} \) of different particle types may take on different values. This is a result of the difference in the shapes of the fragmentation functions of quark and gluon jets. Within errors however, the \( \pi^{\pm}, K_S^0, p + \bar{p}, \) and \( \Lambda + \bar{\Lambda} \)
Identified Particle Measurements

Figure 4. Preliminary identified particle $R_{CP}$ (left panel) and $R_{AA}$ (right panel). Grey bands represent the error on the $N_{bin}$ and $N_{part}$ calculations. For the $R_{AA}$ data, error bars represent both systematic and statistical uncertainties. For pion $R_{CP}$, the yellow band includes both systematic and statistical uncertainties. For proton $R_{CP}$, the systematic uncertainties are shown as brackets on the final five points (systematic uncertainties are similar for lower $p_T$ points).

$R_{CP}$ values at $p_T = 6.5$ GeV/c appear to be consistent with each other. The systematic errors on the proton $R_{CP}$ still, however, allow for significant deviations between proton and pion $R_{CP}$.

Measurement of $K^0_S$ and $\Lambda + \bar{\Lambda}$ $R_{CP}$ at $\sqrt{s_{NN}} = 17.2$ GeV indicate that baryon production is also enhanced at lower center-of-mass energies [22]: with $\Lambda + \bar{\Lambda}$ $R_{CP}$ values well above $N_{bin}$ scaling. It has been proposed that the large baryon $R_{CP}$ values at RHIC may be a result of the suppression of meson production coupled with novel baryon production mechanisms scaling with $N_{bin}$ or $N_{part}$ [8]. The lower energy measurements call this interpretation into question since baryon production is still enhanced even while the suppression of mesons is much weaker.

Figure 5. A sketch of what $R_{CP}$ may look like for the $f_0(980)$ meson if it is a non-$q\bar{q}$ state. At $p_T = 3$ GeV, $f_0(980)$ $R_{CP} > 1$ would favor the $f_0(980)$ as a four-quark or $K\bar{K}$-molecular state. If $f_0(980)$ $R_{CP}$ values are similar to those for other mesons, either the $f_0(980)$ is a two-quark state or coalescence/recombination is not the dominant formation mechanism.
Since the grouping of $R_{CP}$ with quark number appears to extend across many hadron species, the centrality dependence of intermediate $p_T$ particle yields may provide information about the quark content of non-$q\overline{q}$ candidates. The $f_0(600)$, $f_0(980)$, $a_0(980)$, and $\kappa(800)$ are all candidates for four-quark or $K\overline{K}$-molecular states [25, 26, 27]. The branching ratio for $\phi \rightarrow \pi^0\pi^0\gamma$ decays, which is sensitive to the structure of the $f_0$, favors the $f_0$ as a four-quark state [28]. In Fig. 5 a sketch is shown of what $R_{CP}$ may look like for the $f_0$ if it is a four-quark or $K\overline{K}$-molecular state. $f_0(980)$ $R_{CP}$ can be measured from the $\pi^+\pi^-$ invariant mass spectrum [29]. If at $p_T = 3$ GeV/c its value is similar to other mesons, the $f_0$ is either a two quark-state or the baryon enhancement is not a function of the number of quarks: strongly favoring baryon junctions as the source of the baryon enhancement. The result that $f_0$ $R_{CP}$ is greater than the baryon $R_{CP}$, will strongly favor $f_0$ as a four-quark or $K\overline{K}$-molecular state and coalescence as the dominant hadronization process for intermediate $p_T$ hadrons. Measurements of the $\pi^+\pi^-$ invariant mass spectrum should be sensitive to the large difference between these scenarios.

2. Baryon to Meson Ratios

![Figure 6](image.png)

Figure 6. Left panel: the $\bar{p}/\pi^-$ ratio at middle rapidity for central $Au + Au$ and $p + p$ collisions at $\sqrt{s_{NN}} = 200$ GeV. ARGUS measurements of the proton to pion ratio in $e^+ + e^-$ collisions at $\sqrt{s} = 10$ GeV are shown for two classes of events: $e^+e^- \rightarrow \Upsilon \rightarrow ggg$ and continuum events dominated by $e^+e^- \rightarrow q\overline{q}$. Measurements of the proton to pion ratio made for particles associated with a trigger hadron ($p_T > 2.5$) are also shown. Left panel: $\Lambda/K_S^0$ in central $Au + Au$, mid-peripheral $Au + Au$ and minimum-bias $p + p$ collisions. Values are scaled by 0.5.

The quark-number scaling of $v_2$ favors the number of constituent-quarks as the relevant
quantity in the baryon enhancement. Before this scaling was observed, however, the baryon enhancement was seen in the proton-to-pion ratio [2]. Fig. 6 (left panel) shows the $p/\pi^-$ ratio measured in $e^+e^-$ [30], $p+p$ [20], and $Au+Au$ [2, 20] collisions. The right panel shows the $\Lambda/K^0_S$ ratio for $p+p$, mid-peripheral $Au+Au$, and central $Au+Au$ collisions scaled by 0.5 to fit on the same axis. The baryon enhancement at intermediate $p_T$ is pronounced in central $Au+Au$ collisions with $p/\pi^-$ reaching a maximum value of nearly 1 at $p_T \approx 3 \text{ GeV/c}$. The baryon junction calculations in Ref. [8] predict that the $p_T$ value where the $B/M$ ratio is at its maximum will increase with collision centrality. This prediction can be compared to the $\Lambda/K^0_S$ data. Measurements are still not precise enough, however, to confirm nor disprove this prediction.

Fig. 6 also demonstrates that the baryon enhancement in $Au+Au$ collisions may be part of a systematic trend. Baryon production is also enhanced in $\sqrt{s} = 10 \text{ GeV} e^+e^- \rightarrow \Upsilon \rightarrow ggg$ events when $e^+e^- \rightarrow \Upsilon \rightarrow ggg$ events are compared to continuum $e^+e^- \rightarrow q\bar{q}$ events [30]. From those measurements the question arises: is the enhancement related to multiparton topological effects or a difference between quark and gluon fragmentation? Since $e^+e^- \rightarrow \Upsilon \rightarrow ggg$ is a purely gluonic process, the observation that the $p/\pi^-$ ratio is even larger in $Au+Au$ collisions indicates that multi-parton topological effects drive the enhancement (baryon junctions or coalescence).

3. Jet Interactions with the Medium

Also included in the left panel of Fig. 6 are measurements of the $(p+\bar{p})/(\pi^+ + \pi^-)$ ratio in jets observed in $Au+Au$ collisions [31]. The analysis triggers on “high $p_T$” hadrons ($2.5 < p_T < 4.0 \text{ GeV/c}$) and measures the proton and pion yields in the peak around the trigger hadron (near-side) and the peak opposite the trigger hadron (away-side). Because of energy-loss, triggering on high $p_T$ hadrons will select events where a hard scattering occurred near the surface of the $Au+Au$ collision overlap region. In this case, one of the fast partons can escape relatively unperturbed while the other fast parton must traverse the bulk matter created in the $Au+Au$ collision. The near-side baryon-to-meson ratio then should reflect hadron production outside the matter, while the away-side ratio should reflect hadron production within the matter. The result $(p+\bar{p})/(\pi^+ + \pi^-)_{\text{away-side}} > (p+\bar{p})/(\pi^+ + \pi^-)_{\text{near-side}}$ is then consistent with the baryon enhancement arising from multi-gluon or multi-quark processes in hadron production.

Baryon production may be further favored as a result the recoil that the matter undergoes in response to an impinging hard parton. Fig. 7 shows measurements of $p_T$ autocorrelations in 20%-30% central, 200 GeV, $Au+Au$ collisions [32, 33]. The left panel shows the autocorrelations after subtracting sinusoidal modulations associated with $v_2$. The remaining features are a positive near-side peak (associated with an escaping hard parton), a negative near-side valley, and a broad, positive, away-side peak. The right panel shows the same data plotted on a cylinder after the positive near-side peak is subtracted. The data show that the $p_T$ distribution of hadrons—close in $\eta$ and $\phi$ to an escaping hard parton—is red-shifted. This apparent recoil can lead to collective motion amongst the matters constituents in the direction of the impinging partons momentum. This jet-induced flow will lead to an increase in the number of co-moving constituents on the away-side of an escaping hard parton. The data, in Figs. 1, 4, and 6 show that...
Figure 7. Left panel: $p_T$ autocorrelations derived from the $\langle p_T \rangle$ fluctuation scale dependence in $Au + Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV [32]. Sinusoidal modulations associated with $v_2$ have been subtracted. Right panel: $p_T$ autocorrelations plotted in cylindrical coordinates. The positive near-side mini-jet peak is subtracted. The figure demonstrates that the medium in $Au + Au$ collisions recoils in response to an impinging parton [33].

wherever the density of co-moving constituents is larger, baryon production is enhanced. Now, the near-side and away-side data in 6 shows that baryon production is also enhanced in the recoil region of quenched jets.

4. Anti-baryon to Baryon Ratios

Further information about baryon production can be gleaned from anti-baryon to baryon ratios ($\overline{B}/B$). Fig. 8 shows $\overline{B}/B$ for protons (left panel) and lambda hyperons (right panel). The curves show model expectations from Ref. [8]. Disagreement between the pQCD calculation and the data are evident and indicate the importance of non-perturbative effects in baryon production at $p_T < 6$ GeV/c. The Soft+Quench calculation uses a phenomenological treatment of baryon junctions to successfully describe the observed trends. For this calculation, the apparent baryon enhancement is revealed through the suppression of high-$p_T$ meson production. It is not clear, however, that this model can successfully describe the $\sqrt{s_{NN}}$, and system-size dependence of the $\overline{p}/\pi^-$ ratio: particularly given that baryon production appears to be enhanced in $d + Au$ collisions [34] collisions and $Pb + Pb$ collisions at $\sqrt{s_{NN}} = 17.2$ GeV [24], where little or no high-$p_T$ suppression is seen.

5. Conclusions

Pion, kaon, proton, and hyperon momentum-space distributions have been measured up to $p_T \approx 10$ GeV/c. Several observations indicate that at $p_T > 6$ GeV/c, hard processes may dominate particle production. Below this, measurements of the $B/M$ ratios, the $\overline{B}/B$ ratios, $R_{CP}$, and $v_2$ indicate that processes beyond the reach of perturbative QCD are prevalent. Measurements favor pictures involving either a large contribution from coalescence processes during hadronization or the presence baryon junctions. The systematics of the baryon enhancement—including the $\sqrt{s_{NN}}$ dependence, the collision system dependence (particularly $d + Au$), and the $B/M$ ratios on the near- and away-side
Figure 8. Left panel: $\bar{p}/p$ at middle rapidity from central $Au + Au$ collisions for $\sqrt{s_{NN}} = 200$ GeV. The yellow band represents the systematic uncertainties on the preliminary STAR measurements. Right panel: Preliminary STAR measurements of $\Lambda/\Lambda$ at middle rapidity in central $Au + Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV.

of trigger hadrons—may be a challenge to the baryon junction picture. If the coalescence models are correct, identified particle $v_2$ measurements imply that a highly interacting quark and gluon phase exists in heavy ion collisions prior to hadron formation. The existence of such a phase is also favored by the large $v_2$ values observed for multiply strange hadrons.

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