Understanding RHIC Collisions: Modified QCD fragmentation vs quark coalescence from a thermalized flowing medium

Tom Trainor
CENPA 354290, University of Washington, Seattle, Washington 98195, USA

DOI: will be assigned

The hydrodynamic (hydro) model applied to data from the relativistic heavy ion collider (RHIC) suggests that a dense QCD medium opaque to partons is formed in more-central Au-Au collisions. However, two-component spectrum analysis reveals a hard component, consistent with parton fragmentation described by pQCD which can masquerade as “radial flow.” Minimum-bias angular correlations reveal that most scattered partons survive as “minijets” even in central Au-Au collisions. Such alternative methods quantitatively describe spectrum and correlation structure via pQCD calculations. RHIC collisions appear to be dominated by parton scattering and fragmentation even in central Au-Au collisions.

1 Introduction

We wish to test the extent to which perturbative QCD (pQCD) can describe more-central A-A collisions at RHIC. Is a hydrodynamic (hydro) description necessary, or even allowed by data? Detailed arguments are presented in Refs. [1, 2, 3, 4] with related material on hydro interpretations in Refs. [5, 6, 7, 8]. We describe pQCD fragment distributions (FDs) obtained by folding measured fragmentation functions (FFs) with a pQCD dihadron spectrum. We adopt a parton “energy-loss” model [9] to provide FD calculations which describe fragmentation evolution with A-A collision centrality. We also introduce a method to convert jet angular correlations to fragment yields and spectra. It is then possible to calculate the minijet contribution to the A-A final state and provide a comprehensive pQCD description of RHIC collisions.

2 Spectra and parton fragmentation

The two-component model for per-participant-pair A-A spectra [1] is

\[
\frac{2}{n_{\text{part}}} \frac{1}{y_t} \frac{d n_{\text{ch}}}{d y_t} = S_{\text{NN}}(y_t) + \nu H_{\text{AA}}(y_t, \nu) = S_{\text{NN}}(y_t) + \nu r_{\text{AA}}(y_t, \nu) H_{\text{NN}}(y_t),
\]

(1)
where $S_{NN}$ is the soft component and $H_{AA}$ is the A-A hard component (with reference $H_{NN} \sim H_{pp}$). Ratio $r_{AA} = H_{AA}/H_{NN}$ is an alternative to nuclear modification factor $R_{AA}$. Centrality measure $\nu = 2n_{binary}/n_{participant}$ estimates the mean projectile-nucleon path length in A-A collisions. Soft component $S_{NN}$ by hypothesis remains unchanged with A-A centrality. For Glauber linear superposition of $p-p$ (N-N) collisions (the GLS reference) spectrum hard component $H_{AA} \rightarrow H_{NN}(y_t)$ also remains unchanged. In more-central A-A collisions $H_{AA}(y_t, b)$ deviates from reference $H_{NN}(y_t)$, reflecting “medium modification” of parton fragmentation.

We adopt the hypothesis that spectrum hard component $H_{AA}$ represents minimum-bias parton scattering and fragmentation in the form of a fragment distribution (FD). The pQCD convolution integral used to calculate fragment distributions is

$$\frac{d^2n_h}{dy_t d\eta} = 2\pi y_t H_{AA}(y_t) \approx \frac{\epsilon(\Delta \eta)/2}{\sigma_{NSD} \Delta \eta_{4\pi}} \int_0^{\infty} dy_{\max} D_{xx}(y_t, y_{\max}) \frac{d\sigma_{dijet}}{dy_{\max}}$$

where $D_{xx}(y_t, y_{\max})$ is the measured FF ensemble for collision system xx and $d\sigma_{dijet}/dy_{\max}$ is the pQCD dijet (parton) spectrum. The folding integral then predicts hadron spectrum hard component $d^2n_h/dy_t d\eta$ from parton pairs scattered into angular acceptance $\Delta \eta$. Comparisons with measured spectrum hard components in $p-p$ and Au-Au collisions are shown in Fig. 1. The two-component model appears to provide a full description of A-A spectra in terms of pQCD.

### 3 Correlations and parton fragmentation

We want to determine the relation between minimum-bias jets (minijets) and the spectrum hard component (fragmentation). We integrate Eq. (2) over $y_t$ to obtain the hard-component yield

$$2\pi H_{AA}(b) \approx \left\{ \frac{\sigma_{dijet} \epsilon(\Delta \eta)/2}{\sigma_{NSD} \Delta \eta_{4\pi}} \right\} \left\{ \frac{1}{\sigma_{dijet}} \int_0^{\infty} dy_{\max} n_{ch,j}(y_{\max}, b) \frac{d\sigma_{dijet}}{dy_{\max}} \right\}$$

or $2\pi H_{AA}(b) = f(b) n_{ch,j}(b)$, where the first factor is the pQCD jet frequency per NSD $p-p$ collision and the second factor is the minijet mean fragment multiplicity. Jet angular correlations (same-side jet peak integrals in Fig. 2 - first two panels) can be represented by...
mean pair ratio $j^2(b)$ averaged over angular acceptance $(\Delta \eta, 2\pi)$ [11, 12]. In terms of pQCD mean jet number $n_j(b) = n_{bin}(b) \Delta \eta f(b)$ and total multiplicity $n_{ch}(b)$ per A-A collision in $\Delta \eta$ we can write $n_{ch,j}(b) = n_{ch}(b) \sqrt{j^2(b)/n_j(b)}$, which reveals the centrality dependence of the jet fragment multiplicity in A-A collisions.

Figure 2 (third panel) shows spectrum hard component $H_{AA}(b)$ (solid curve) inferred from jet angular correlations via Eq. (3). The open point is a spectrum estimate from Ref. [10] (with $\Delta \eta = 1$). The solid points are derived from the “total hadrons” spectrum data in Fig. 15 (left panel) of Ref. [1]. Multiplying Eq. (3) through by $\nu/2\pi$ gives

$$\nu H_{AA}(b) = \frac{2}{n_{part}} n_j(b) \frac{n_{ch,j}(b)}{2\pi \Delta \eta} = \frac{2}{n_{part}} \rho_0(b) \sqrt{n_j(b) j^2(b)}.$$  

(4)

$\nu H_{AA}(b)$ is the hard component in the two-component spectrum model of Eq. (1). Figure 2 (fourth panel) shows the two-component particle yield $S_{NN} + \nu H_{AA}(b)$ predicted by measured jet angular correlations (bold solid curve). Soft component $s_{NN}$ is by hypothesis fixed at $\sim 0.4$ [2D density on $(\eta, \phi)$] for all A-A centralities. The solid points are the “total hadrons” data in Fig. 15 (left panel) of Ref. [1] divided by $2\pi$. Minimum-bias angular correlations thus demonstrate that 1/3 of the final state in central Au-Au collision is contained in resolved jets.

4 Spectrum structure and paradigm tests

Jet quenching and $R_{AA}$ Spectrum ratio $R_{AA}$ presented as in Fig. 3 (left panels) suggests strong jet suppression and possible complete absorption of the majority of large-angle scattered partons in more-central Au-Au collisions at RHIC [13]. However, $R_{AA}$ presents a misleading picture because the ratio includes spectrum soft component $S_{NN}$. In Fig. 3 (right panels) alternative hard-component ratio $r_{AA}$ reveals the true evolution of parton fragmentation with A-A centrality, demonstrating that suppression at larger $p_t$ is compensated by much larger enhancement at smaller $p_t$. The number of jet-correlated hadrons (hard-component multiplicity) in more-central A-A collisions increases dramatically compared to $p-p$ collisions.

Radial flow Radial flow is inferred by so-called blast-wave fits to $p_t$ spectra [14]. Such fits generally span a limited $p_t$ interval below 2 GeV/c attributed to “soft physics” described by
hydro models. But most of the parton fragments from jets fall below 2 GeV/c. It can be
demonstrated that the spectrum evolution attributed to radial flow is quantitatively predicted
by pQCD \cite{1, 2}. Inferred blast-wave parameters actually follow minijet systematics \cite{4}.

The baryon/meson ratio The baryon/meson (B/M) ratio in more-central A-A collisions
is said to be anomalous in a pQCD context, suggesting that constituent-quark coalescence
from a thermalized partonic medium may provide the dominant particle-production mechanism
at intermediate $p_t$ \cite{15}. However, examination of corresponding spectrum hard components
suggests that parton fragmentation remains the fundamental hadronization process.

Figure 3: Left: Conventional spectrum ratios $R_{AA}$ for (resp.) pions and protons from 200 GeV
Au-Au collisions. Right: Equivalent hard-component ratios $r_{AA}$ for (resp.) pions and protons.

Figure 4: Left: Spectrum hard components for five centralities of 200 GeV Au-Au collisions
for (resp.) pions and protons. Third: Soft and hard components for pions and protons from
peripheral ($\nu = 1$) and central ($\nu = 6$) Au-Au collisions. Fourth: Proton/pion spectrum ratios.

Figure 4 (left panels) shows spectrum hard components for identified pions and protons.
The modes for both species in peripheral collisions are located at $p_t = 1$ GeV/c reflecting a
common underlying parton spectrum. For more-central collisions the pion mode moves down
to $\sim 0.5$ GeV/c but the proton mode remains fixed on $p_t$ \cite{11}. Both changes can be seen as
FF modification as proposed in Ref. \cite{9}, but differently controlled in each case by the hadron
fragment mass. Figure 4 (third panel) shows two-component parametrizations of pion and
proton spectra accurate to about 10%. The parameterizations lead to proton/pion spectrum
ratios (solid and dashed curves, fourth panel) which accurately describe the B/M “anomaly”
data, details of which then correspond exactly to parton fragment distributions in the left
panels. The structure in the fourth panel correspond exactly to that in Fig. 3 (right panels).
5 Correlation structure and paradigm tests

Dihadron azimuth correlations  Dihadron azimuth correlations are intended to probe in-medium jet modifications in A-A collisions. A critical issue is subtraction of the combinatoric background modulated by an azimuth quadrupole measured by $v_2$ and conventionally interpreted as “elliptic flow.” The absolute background offset is estimated by the ZYAM method, and $v_2$ is obtained from published data derived from nongraphical numerical methods. ZYAM subtraction leads to two principal conclusions: (i) most partons are thermalized in an opaque medium and (ii) the development of Mach cones by parton passage through the medium leads to distortion of the away-side azimuth peak (double humps) [16]. Close examination of the ZYAM subtraction method reveals that the “zero-yield-at-minimum” background estimate is not valid for the overlapping same-side and away-side jet peaks encountered in more-central A-A collisions. And published $v_2$ data are typically overestimated due to strong jet (nonflow) contributions [3, 4]. In effect, jet components are subtracted from other jet structure, and jet peak amplitudes are underestimated by an artificially high background offset estimate.

Azimuth quadrupole  The azimuth quadrupole conventionally interpreted as elliptic flow is measured by quantity $v_2$ which can be defined in terms of nongraphical numerical methods [17]. Alternatively, $v_2\{2D\}$ can be obtained by fitting 2D angular correlations, and novel systematic trends then emerge [6]. Substantial differences between the two methods can be attributed to strong jet contributions to the former [7, 8]. The differences have implications for ZYAM subtraction and Mach-cone inferences [4]. The resulting energy and centrality trends of $v_2\{2D\}$ suggest that interpretation of the azimuth quadrupole as a hydro phenomenon is questionable.

In Fig. 5 the same published minimum-bias $v_2(p_t)$ data for three hadron species are plotted in several formats. Plotted as $v_2(p_t)/p_t$ on transverse rapidity $y_t = \ln[(p_t + m)/m_h]$ with hadron mass $m_h$ (middle panels) the $v_2$ data reveal an apparent common source boost $\Delta y_{T0} \sim 0.6$ and large deviations from a viscous-hydro theory based on Hubble expansion (R) [9]. When further multiplied by the single-particle spectrum $\rho_0(y_t)$ the $v_2(p_t)$ data (fourth panel) reveal a common quadrupole spectrum in the form of a Lévy distribution on $m_t$, much “colder” than the single-particle spectrum for most hadrons [7, 8]. Those results strongly suggest that “elliptic flow” in the form of the azimuth quadrupole is associated with a small fraction of the hadronic final state and results from QCD field-field interactions of low-\(x\) gluon condensates [18].
6 Summary

Hydro analysis of RHIC data interprets particle production below 2 GeV/c in terms of flow phenomena. The role of parton scattering and fragmentation is minimized. But model-independent analysis of spectrum and correlation structure reveals new fragmentation features quantitatively described by pQCD. \( p_t \) spectrum hard components are manifestations of minimum-bias parton fragmentation quantitatively matched to minimum-bias jet angular correlations (minijets). Calculated pQCD fragment distributions accurately describe measured hard components.

The reference for all fragmentation in nuclear collisions is the FD derived from measured in-vacuum \( e^+e^- \) FFs and the parton (dijet) spectrum for \( p-p \) collisions. Relative to the reference the spectrum hard component for \( p-p \) and peripheral Au-Au collisions is found to be strongly suppressed for smaller momenta. At a specific point on Au-Au centrality the hard component transitions to strong enhancement at smaller fragment momentum and suppression at larger momentum.

Minimum-bias jet (minijet) correlations have been converted to absolute fragment yields which are found to comprise approximately one third of the final state in central 200 GeV Au-Au collisions, implying that almost all large-angle scattered partons down to 3 GeV parton energy survive as jet manifestations in the final state, albeit with some modification. pQCD calculations should be applied to all aspects of spectrum and correlation data to discover what is truly novel in RHIC collisions. pQCD describes almost all RHIC collision evolution—hydro interpretations are questionable.

I greatly appreciate the hospitality of the ISMD organizing committee. This work was supported in part by the Office of Science of the U.S. DOE under grant DE-FG03-97ER41020.

References

[1] T. A. Trainor, Int. J. Mod. Phys. E 17 (2008) 1499.
[2] T. A. Trainor, Phys. Rev. C 80 (2009) 044901.
[3] T. A. Trainor, Phys. Rev. C 81 (2010) 014905.
[4] T. A. Trainor, J. Phys. G 37 (2010) 085004.
[5] T. A. Trainor, Phys. Rev. C 78 (2008) 064908.
[6] D. T. Kettler (STAR collaboration), Eur. Phys. J. C 62 (2009) 175.
[7] D. Kettler (STAR Collaboration), arXiv:1008.4793
[8] D. Kettler (STAR Collaboration), arXiv:1011.5254
[9] N. Borghini and U. A. Wiedemann, hep-ph/0506218
[10] J. Adams et al. (STAR Collaboration), Phys. Rev. D 74 (2006) 032006.
[11] T. A. Trainor and D. T. Kettler, arXiv:1008.4759
[12] M. Daugherity (STAR Collaboration), J. Phys. G 35 (2008) 104090.
[13] C. Adler et al. (STAR Collaboration), Phys. Rev. Lett. 89 (2002) 202301.
[14] F. Retiere and M. A. Lisa, Phys. Rev. C 70 (2004) 044907.
[15] B. I. Abelev et al. (STAR Collaboration), Phys. Rev. C 77 (2008) 054901.
[16] J. Adams et al. (STAR Collaboration), Phys. Rev. Lett. 95 (2005) 152301.
[17] T. A. Trainor and D. T. Kettler, Int. J. Mod. Phys. E 17 (2008) 1219.
[18] T. A. Trainor, Mod. Phys. Lett. A 23 (2008) 569.