Hard Probes: Past, Present and Future

J.C. Dunlop[*]

Brookhaven National Laboratory
E-mail: `dunlop@bnl.gov`

The use of hard probes in heavy ion collisions has been a great success at RHIC, but it remains a challenge to extract quantitative properties of the matter from these probes. The medium appears to be equally black to all interacting probes utilized to date, limiting the amount of tomographic information that can be obtained from quenching phenomena. In order to make progress, probes to which the medium is grey are needed. With the higher luminosity of the RHIC II accelerator upgrade and the upgrades to the detectors, RHIC will be well positioned to make a qualitative jump in our quantitative understanding of the properties of the medium created in high energy heavy ion collisions.

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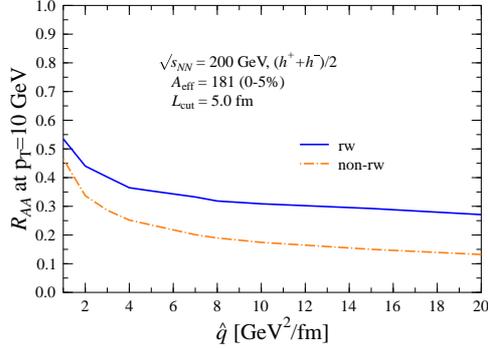*University of Jyvaskyla, Jyväskylä, Finland*

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[*]Speaker.

Figure 1: Predicted suppression factor R_{AA} vs $\hat{q}$, a measure of the color charge density of the medium. "rw" and "non-rw" refer to two different methods of taking into account energy conservation. Figure is from [14].

1. Introduction

Jet quenching in nuclear collisions at high energies is a well-established experimental fact. The effects are not small: hadron spectra at large p_T are suppressed in central Au+Au collisions by a factor of four to five relative to expectations [1, 2, 3, 4], as are the fragments of jets on the away-side azimuthally relative to a trigger hadron [5]. More than four years ago, the lack of suppression in d+Au collisions definitively proved that the quenching was due to interactions in the final-state dense medium formed in Au+Au collisions rather than from depletion of partons in the initial state [6, 7, 8, 9]. This led to statements that the initial gluon density of the matter produced in central Au+Au collisions was more than an order of magnitude greater than that of normal nuclear matter. For a more detailed description of the state of understanding a few years ago, see the RHIC "whitepapers" from the four experimental collaborations [10, 11, 12, 13].

While it is clear that the suppression seen in central Au+Au collisions requires that the matter is dense, a more quantitative statement is lacking. A fundamental problem that arises in some approaches is that the medium is too black [14, 15]: the energy loss of partons is so large that one rapidly enters into a region of diminishing returns, in which the density of the medium can increase by large factors while the measurable suppression of the final state hadrons hardly changes. Figure 1 shows one such calculation: $\hat{q}$, which is proportional to the density of the medium, can change 5 to 20 GeV^2/fm but induce only small changes in the measurable suppression factor R_{AA}. This loss of information is not generally true in all calculational frameworks, and depends on the geometry and expansion of the collision zone, along with the inherent fluctuations from the distribution of energy loss of the partons. A recent detailed study under various scenarios comes to the conclusion that the tomographic information about the collision zone obtainable from single hadron suppression is extremely limited [16]. Therefore the challenge is to come up with experimental probes that recover sensitivity to the properties of the medium.

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2. Correlations from Dijets

Correlation measurements, sensitive to dijets, introduce a different set of geometric biases than the suppression of single-particle spectra. Suppression in the internal, dense region of the collision zone biases those hadrons that escape to have come from hard interactions near the surface of the collision zone. Triggering on a hadron, and then looking at its away-side partner, biases towards those configurations in which the dijet emerges tangentially through the system [17], but has the potential to probe deeper into the collision zone [18].

Recently, STAR has measured true jet-like correlations on the away-side azimuthally to a trigger hadron [19]. Clear jet-like peaks emerge above background both the side near and opposite (180 degrees in azimuth) to the trigger hadron at large associated and trigger p_T. In previous analyses, the away-side peak was either so strongly suppressed as to be unobservable over background [5], or was so strongly widened and softened as to make it problematic to call it a collimated "jet" [20].

Something provides more information than nothing: with well-identified peaks, the properties of the peaks can be studied. The conclusion is that, if a dijet is observed, the fragmentation pattern of the away-side partner to the jet containing the trigger hadron is unchanged both longitudinally along and transverse to the jet axis. The only modification is that fewer dijets are seen per trigger hadron. Interestingly enough, the level of suppression of the away-side dihadrons is close to that of the single-particle charged-hadron spectra, about a factor of four to five, though these numbers in principle have little to do with each other. Such studies have the potential to recover additional tomographic information, and are an active area of theoretical investigation.

At lower and intermediate associated p_T, a number of interesting structures have emerged. At low p_T, there is extreme widening and softening on the away side in ϕ [20], while at intermediate p_T there are indications that the away-side jet structure splits, with a dip at π [21]. In the pseudorapidity direction, on the near side in π, the jet peak, symmetric in η and ϕ in p+p collisions, becomes, in Au+Au collisions, strongly elongated in η [22, 23]. These structures have been interpreted as the reaction of the medium to the energy deposited by the probe jets and may be a sensitive way to probe properties of the medium other than its density [24, 25, 26]. However, these measurements are difficult experimentally, and the theoretical explanations are not unique, so studies with higher-order correlations (e.g. 3-particle correlations) are underway and have potential to distinguish scenarios.

3. Gray probes

The simplest way to determine the properties of a sample is to measure the transmission of a probe through that sample. This method is used in condensed-matter physics, and in medical applications such as Positron Emission Tomography in which the probe is injected directly into the sample. In order to obtain precise results, the probe needs to be prepared with well-calibrated luminosity and have a well-calibrated interaction with the sample. In the case of jet tomography, the probe is provided by hard interactions of partons in the initial stages of the collision, and the calibration of its luminosity is provided by measurements in simpler systems, such as p+p and d+Au, along with theoretical reproduction of these measurements using perturbative QCD. Until recently, the calibration of the interaction of the probe with the medium was taken as a given.
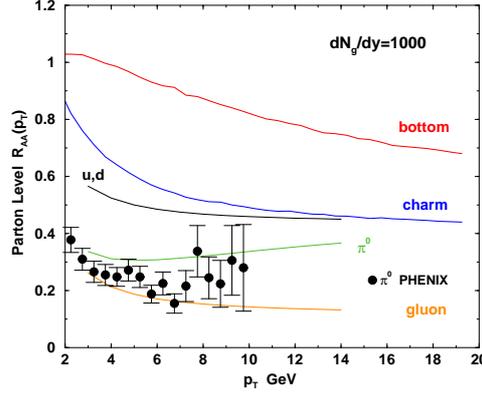
Figure 2: Parton-level nuclear modification factor R_{AA} in central Au+Au collisions, due to gluon bremsstrahlung in the DVGL framework, for various parton species. Figure is from [27].
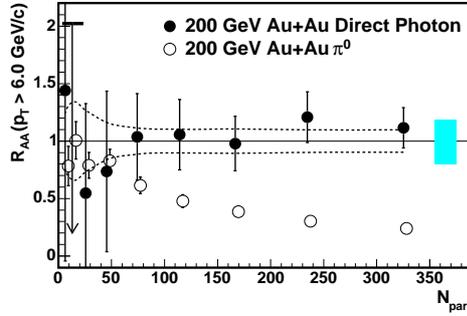

Figure 3: Nuclear modification factor R_{AA} for photons and π^0 as a function of N_{part} in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV from PHENIX. Figure is from [28].

However, if the medium is black to the probe, tomographic information is extremely limited, which may be true for partons that fragment into light hadrons such as π^0. The experimental palette is not, however, limited only to such light hadrons. By varying the hadron species measured in the final state, one can vary the parton species used as a probe, as different species of final-state hadrons fragment from different species of partons that traverse the medium. Partons of different types are expected to interact with the medium with different strengths, an example of which is shown in figure 2. Generically, heavy quarks are expected to be less suppressed than light quarks, which are in turn less suppressed than gluons. Therefore, by varying the parton species one may be able to recover some of the information lost by the blackness of the medium.

One extreme variation of the interaction of the probe with the medium is to turn off that interaction entirely, making the medium transparent to the probe. A photon produced in hard parton-parton interactions, through the QCD Compton diagram, is one such "white" probe, as the subsequent interaction of the photon with the medium is weak. Direct photons (i.e. those photons that do not originate from the decay of hadrons) have been measured in Au+Au collisions [28], with the result that such photons show no suppression relative to expectations from next-to-leading-order perturbative QCD calculations. These calculations also describe results from p+p collisions [29]. This lack of suppression of photons stands in stark contrast to the large suppression of light hadrons
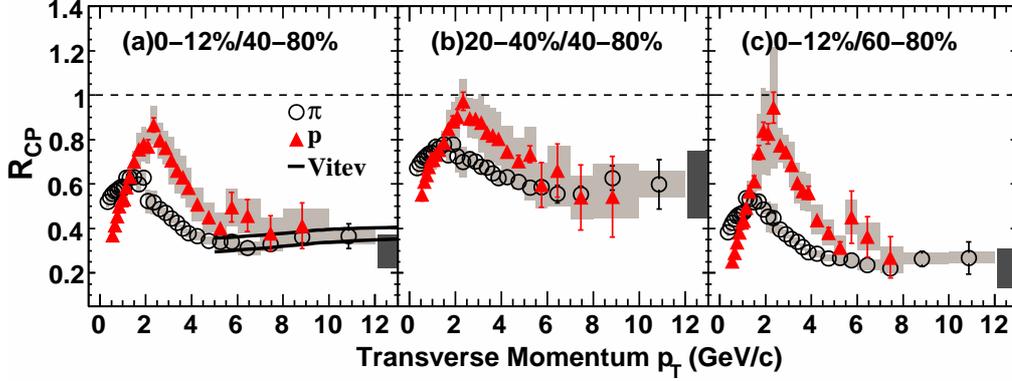
Figure 4: Binary-scaled ratio of central to peripheral spectra R_{CP} for pions and protons in $\sqrt{s_{NN}} = 200$ GeV Au+Au collisions from STAR. Point-to-point systematic uncertainties are shown as shaded boxes around the data points. Dark shaded bands show the normalization systematic uncertainty in the number of binary collisions N_{bin}. "Vitev" is a calculation for pions including energy loss from gluon bremsstrahlung [31]. Figure is from [32].

such as π^0, as can be clearly seen in figure 3. The lack of suppression is actually somewhat surprising, as these calculations indicate that a sizeable fraction of the direct photons originate from fragmentation photons, which should in principle be suppressed as the light hadrons; there are, however, calculations which indicate that jets passing through the medium can provide an additional source of photons in central nuclear collisions [30]. As a side note, the contribution from these fragmentation photons is expected to be quite a bit larger at the LHC than at RHIC. In any case, there is little additional information to be gained from spectra that are unmodified.

What is really needed is a "gray" probe, one that shows some suppression by the medium but has measurably different suppression than the π^0. By changing the final-state hadron measured, and through this the partonic species used to probe the medium, one can attempt to find such a probe.

4. Search for a Gray Probe: Light Quarks, Heavy Quarks, and Gluons

Simple Casimir factors in QCD indicate that gluons should interact more strongly with the medium than quarks; this is borne out by full calculations [33]. STAR has recently measured charged π and proton spectra out to p_T of 10 GeV/c in both the simpler d+Au and p+p systems [34], and in Au+Au collisions [32]. Both the pion and proton spectra in the simpler systems are well described by perturbative QCD calculations, though in order to describe the proton spectra the AKK fragmentation functions [35], which separate out the contribution to final-state hadrons by parton flavor, are necessary. In this context, at p_T of 10 GeV/c the contribution of quarks to the production of pions is significantly larger than that to protons, which remain produced dominantly due to the fragmentation of gluons. Therefore, by measuring the suppression of protons relative to pions in nuclear collisions, one is potentially sensitive to differences between light quark and gluon

energy loss. The surprising result of the measurement, shown in figure 4, is that protons and pions are equally strongly suppressed in central Au+Au collisions. This is true only for p_T greater than approximately 6 GeV/c, but the enhancement of baryons in the intermediate p_T region below this is not at all explainable in a fragmentation framework, and indicates interesting physics in its own right. The equal levels of suppression may indicate that the medium is equally black to both light quarks and gluons, and so in the search for gray probes one needs to find probes that interact less strongly with the medium than light quarks.

Due to their mass, heavy quarks were predicted to interact less strongly with the medium than light quarks due to the so-called "Dead Cone Effect" [36]. Extended calculations were performed on this effect for both charm and bottom quarks, for the case of energy loss due to gluon radiation [27, 37], with the conclusion that the decay products of heavy quarks should be significantly less suppressed than the fragmentation products of light quarks. For charm, the effect could be rather subtle, as seen by the approach between the u,d and c curves at higher p_T in figure 2, though it still remains useful as a clear tag for quarks rather than gluons. The suppression of bottom quarks is predicted to be significantly smaller than that of light quarks in all frameworks. Therefore heavy quarks are a perfect candidate for a gray probe.

Experimentally, direct reconstruction of charm (D) or bottom (B) mesons has not been possible in the high p_T regime, though STAR has directly reconstructed D mesons in both d+Au [38] and Au+Au [39] up to p_T of 3 GeV/c. However, "non-photonic" electrons (i.e. those electrons that do not arise from decays of lighter mesons such as π^0 that involve photons or photon conversions) arise predominantly from decays of B and D mesons, and so can be used as a proxy. PHENIX originated this type of measurement at RHIC with an early measurement at $\sqrt{s_{NN}} = 130$ GeV [40]. The conclusion of the original study was that charm was not suppressed in Au+Au collisions, a conclusion that has been falsified at higher p_T and with the realization that the calculation used for the p+p reference did not reproduce actual data. Subsequent analyses at $\sqrt{s_{NN}} = 200$ GeV for p+p collisions by STAR [38, 41] and PHENIX [42], along with measurements in Au+Au collisions [41, 43, 44, 45] have shown that, instead, non-photonic electrons are highly suppressed in Au+Au collisions.

These measurements of non-photonic electrons in Au+Au collisions have induced a crisis. The medium is not gray to non-photonic electrons: in fact is it just as black as to light hadrons. Figure 5 shows the nuclear suppression factor R_{AA} for non-photonic electrons as measured by STAR and PHENIX: out to p_T of 8 GeV/c the electrons are suppressed as strongly as charged hadrons. This was a major surprise, and has led to significant questioning of the mechanism of energy loss itself. The calibration of the interaction of the probe with the medium, previously taken as a theoretical given, is currently undergoing major scrutiny.

In short, while theoretically there was predicted to be a hierarchy of interaction between the probe and the medium, where gluons would interact more strongly than light quarks, which would in turn interact more strongly than charm quarks, which would in turn interact more strongly than bottom quarks, there is no sign of this hierarchy in experimental measurements.

5. Conclusion and Outlook for the Future: b, c, and γ+hadron

Where does this leave us in the search for gray probes? So far the search has failed, as the
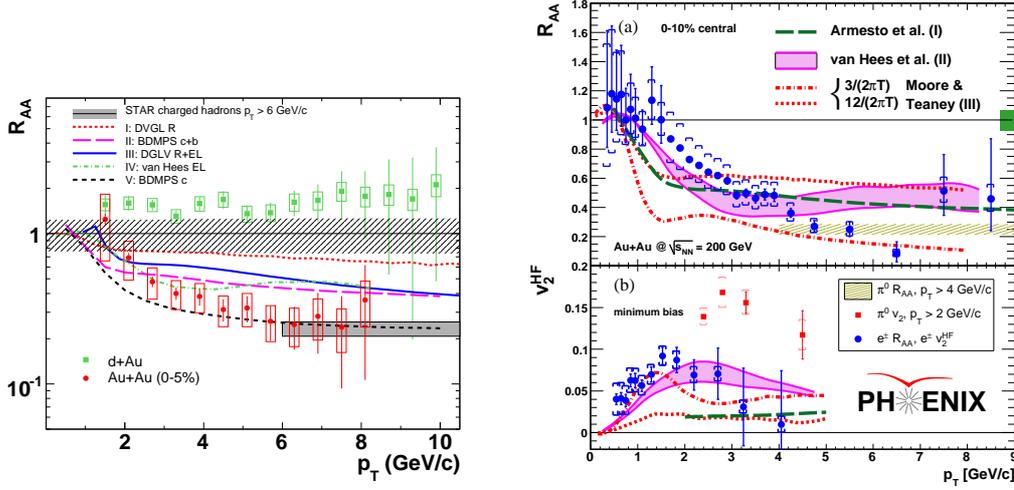
Figure 5: Nuclear modification factor R_{AA} for non-photonic electrons. Figures from [41, 43].

nuclear modification factor for all probes accessible to date is independent of the probe. Either there is no gray probe, and there is therefore little additional tomographic information available using hadronic probes, or we have not searched hard enough. If there is no gray probe, it is not at all clear that a medium so black can be accommodated within a picture based on perturbative QCD, and so the calibration of the interaction of the probe with the medium would be lost.

There is one possibility remaining: it is still possible that we have not measured any beauty in these collisions. The relative fraction of charm and beauty that contribute to non-photonic electrons is highly uncertain, and the possibility remains open that in the accessible p_T regime non-photonic electrons are predominantly from charm. If this were the case, as shown in curve V in figure 5, it would be much easier to accommodate the measured suppression, and the crisis would be resolved.

This leads to the future. Experimentally, it is critical to measure charm and bottom separately, both in Au+Au collisions and in simpler systems. Both STAR [46] and PHENIX have vertexing upgrades proposed which will allow a separation of charm and bottom directly, utilizing techniques much like those used in high-energy experiments like CDF and D0. If the bottom quark is indeed less suppressed than the other partons, tomographic information will be recovered.

The increased luminosity at RHIC II, combined with the detector upgrades, will allow for an extremely precise measurement of photon-hadron correlations. These have the advantage that the photons, if they are prompt, tag the kinematics of the underlying parton-parton process precisely, allowing for precision tomographic measurements. Combined with beauty measurements, and measurement of the full spectrum of quarkonium states (including the separated states of the Upsilon), RHIC II will provide a major quantitative step in the understanding of the medium created in heavy ion collisions.

References

[1] **PHENIX** Collaboration, K. Adcox *et. al.*, *Suppression of hadrons with large transverse momentum in central au + au collisions at s**(1/2)(n n) = 130-gev*, *Phys. Rev. Lett.* **88** (2002) 022301 [nucl-ex/0109003].

[2] **STAR** Collaboration, C. Adler *et. al.*, *Centrality dependence of high p(t) hadron suppression in au + au collisions at s(nn)**(1/2) = 130-gev*, *Phys. Rev. Lett.* **89** (2002) 202301 [nucl-ex/0206011].

[3] **PHENIX** Collaboration, S. S. Adler *et. al.*, *Suppressed pi0 production at large transverse momentum in central au + au collisions at s(nn)**(1/2) = 200-gev*, *Phys. Rev. Lett.* **91** (2003) 072301 [nucl-ex/0304022].

[4] **STAR** Collaboration, J. Adams *et. al.*, *Transverse momentum and collision energy dependence of high p(t) hadron suppression in au + au collisions at ultrarelativistic energies*, *Phys. Rev. Lett.* **91** (2003) 172302 [nucl-ex/0305015].

[5] **STAR** Collaboration, C. Adler *et. al.*, *Disappearance of back-to-back high p(t) hadron correlations in central au + au collisions at s(nn)**(1/2) = 200-gev*, *Phys. Rev. Lett.* **90** (2003) 082302 [nucl-ex/0210033].

[6] **PHOBOS** Collaboration, B. B. Back *et. al.*, *Centrality dependence of charged hadron transverse momentum spectra in d + au collisions at s(nn)**(1/2) = 200-gev*, *Phys. Rev. Lett.* **91** (2003) 072302 [nucl-ex/0306025].

[7] **PHENIX** Collaboration, S. S. Adler *et. al.*, *Absence of suppression in particle production at large transverse momentum in s(nn)**(1/2) = 200-gev d + au collisions*, *Phys. Rev. Lett.* **91** (2003) 072303 [nucl-ex/0306021].

[8] **STAR** Collaboration, J. Adams *et. al.*, *Evidence from d + au measurements for final-state suppression of high p(t) hadrons in au + au collisions at rhic*, *Phys. Rev. Lett.* **91** (2003) 072304 [nucl-ex/0306024].

[9] **BRAHMS** Collaboration, I. Arsene *et. al.*, *Transverse momentum spectra in au + au and d + au collisions at s(nn)**(1/2) = 200-gev and the pseudorapidity dependence of high p(t) suppression*, *Phys. Rev. Lett.* **91** (2003) 072305 [nucl-ex/0307003].

[10] **BRAHMS** Collaboration, I. Arsene *et. al.*, *Quark gluon plasma and color glass condensate at rhic? the perspective from the brahms experiment*, *Nucl. Phys.* **A757** (2005) 1–27 [nucl-ex/0410020].

[11] B. B. Back *et. al.*, *The phobos perspective on discoveries at rhic*, *Nucl. Phys.* **A757** (2005) 28–101 [nucl-ex/0410022].

[12] **STAR** Collaboration, J. Adams *et. al.*, *Experimental and theoretical challenges in the search for the quark gluon plasma: The star collaboration's critical assessment of the evidence from rhic collisions*, *Nucl. Phys.* **A757** (2005) 102–183 [nucl-ex/0501009].

[13] **PHENIX** Collaboration, K. Adcox *et. al.*, *Formation of dense partonic matter in relativistic nucleus nucleus collisions at rhic: Experimental evaluation by the phenix collaboration*, *Nucl. Phys.* **A757** (2005) 184–283 [nucl-ex/0410003].

[14] K. J. Eskola, H. Honkanen, C. A. Salgado and U. A. Wiedemann, *The fragility of high-p(t) hadron spectra as a hard probe*, *Nucl. Phys.* **A747** (2005) 511–529 [hep-ph/0406319].

[15] A. Dainese, C. Loizides and G. Paic, *Leading-particle suppression in high energy nucleus nucleus collisions*, *Eur. Phys. J.* **C38** (2005) 461–474 [hep-ph/0406201].

[16] T. Renk, *Towards jet tomography: gamma hadron correlations*, hep-ph/0607166.

[17] A. Dainese, C. Loizides and G. Paic, *Leading-particle suppression and surface emission in nucleus nucleus collisions*, hep-ph/0511045.

[18] T. Renk, *Through the blackness: High p(t) hadrons probing the central region of 200-agev au - au collisions*, hep-ph/0602045.

[19] **STAR** Collaboration, J. Adams *et. al.*, *Direct observation of dijets in central au + au collisions at s(nn)**(1/2) = 200-gev*, *Phys. Rev. Lett.* **97** (2006) 162301 [nucl-ex/0604018].

[20] **STAR** Collaboration, J. Adams *et. al.*, *Distributions of charged hadrons associated with high transverse momentum particles in p p and au + au collisions at s(nn)**(1/2) = 200-gev*, *Phys. Rev. Lett.* **95** (2005) 152301 [nucl-ex/0501016].

[21] **PHENIX** Collaboration, S. S. Adler *et. al.*, *Modifications to di-jet hadron pair correlations in au + au collisions at s(nn)**(1/2) = 200-gev*, *Phys. Rev. Lett.* **97** (2006) 052301 [nucl-ex/0507004].

[22] **Star** Collaboration, J. Adams *et. al.*, *Delta(phi) delta(eta) correlations in central au + au collisions at s(nn)**(1/2) = 200-gev*, *Phys. Rev.* **C75** (2007) 034901 [nucl-ex/0607003].

[23] **STAR** Collaboration, J. Adams *et. al.*, *Minijet deformation and charge-independent angular correlations on momentum subspace (eta, phi) in au-au collisions at s(nn)**(1/2) = 130-gev*, *Phys. Rev.* **C73** (2006) 064907 [nucl-ex/0411003].

[24] J. Casalderrey-Solana, E. V. Shuryak and D. Teaney, *Conical flow induced by quenched qcd jets*, *J. Phys. Conf. Ser.* **27** (2005) 22–31 [hep-ph/0411315].

[25] H. Stoecker, *Collective flow signals the quark gluon plasma*, *Nucl. Phys.* **A750** (2005) 121–147 [nucl-th/0406018].

[26] J. Ruppert and B. Muller, *Waking the colored plasma*, *Phys. Lett.* **B618** (2005) 123–130 [hep-ph/0503158].

[27] M. Djordjevic, M. Gyulassy, R. Vogt and S. Wicks, *Influence of bottom quark jet quenching on single electron tomography of au + au*, *Phys. Lett.* **B632** (2006) 81–86 [nucl-th/0507019].

[28] **PHENIX** Collaboration, S. S. Adler *et. al.*, *Centrality dependence of direct photon production in s(nn)**(1/2) = 200-gev au + au collisions*, *Phys. Rev. Lett.* **94** (2005) 232301 [nucl-ex/0503003].

[29] **PHENIX** Collaboration, S. S. Adler *et. al.*, *Mid-rapidity direct-photon production in p + p collisions at s**(1/2) = 200-gev*, *Phys. Rev.* **D71** (2005) 071102 [hep-ex/0502006].

[30] R. J. Fries, B. Muller and D. K. Srivastava, *High energy photons from passage of jets through quark gluon plasma*, *Phys. Rev. Lett.* **90** (2003) 132301 [nucl-th/0208001].

[31] I. Vitev, *Testing the theory of qgp-induced energy loss at rhic and the lhc*, hep-ph/0603010.

[32] **STAR** Collaboration, B. I. Abelev *et. al.*, *Identified baryon and meson distributions at large transverse momenta from au + au collisions at s(nn)**(1/2) = 200-gev*, *Phys. Rev. Lett.* **97** (2006) 152301 [nucl-ex/0606003].

[33] S. Wicks, W. Horowitz, M. Djordjevic and M. Gyulassy, *Heavy quark tomography of a + a including elastic and inelastic energy loss*, nucl-th/0512076.

[34] **STAR** Collaboration, J. Adams *et. al.*, *Identified hadron spectra at large transverse momentum in p + p and d + au collisions at s(nn)**(1/2) = 200-gev*, *Phys. Lett.* **B637** (2006) 161–169 [nucl-ex/0601033].

[35] S. Albino, B. A. Kniehl and G. Kramer, *Fragmentation functions for light charged hadrons with complete quark flavour separation*, *Nucl. Phys.* **B725** (2005) 181–206 [hep-ph/0502188].

[36] Y. L. Dokshitzer and D. E. Kharzeev, *Heavy quark colorimetry of qcd matter*, *Phys. Lett.* **B519** (2001) 199–206 [hep-ph/0106202].

[37] N. Armesto, M. Cacciari, A. Dainese, C. A. Salgado and U. A. Wiedemann, *How sensitive are high-p(t) electron spectra at rhic to heavy quark energy loss?*, *Phys. Lett.* **B637** (2006) 362–366 [hep-ph/0511257].

[38] **STAR** Collaboration, J. Adams *et. al.*, *Open charm yields in d + au collisions at s(nn)**(1/2) = 200-gev*, *Phys. Rev. Lett.* **94** (2005) 062301 [nucl-ex/0407006].

[39] H. Zhang, *Open charm production in s(nn)**(1/2) = 200-gev au + au collisions at star*, nucl-ex/0510063.

[40] **PHENIX** Collaboration, K. Adcox *et. al.*, *Measurement of single electrons and implications for charm production in au + au collisions at s(nn)**(1/2) = 130- gev*, *Phys. Rev. Lett.* **88** (2002) 192303 [nucl-ex/0202002].

[41] **STAR** Collaboration, B. I. Abelev *et. al.*, *Transverse momentum and centrality dependence of high-pt non-photonic electron suppression in au+au collisions at $\sqrt{s_{NN}}$ = 200 gev*, *Phys. Rev. Lett.* **98** (2007) 192301 [nucl-ex/0607012].

[42] **PHENIX** Collaboration, S. S. Adler *et. al.*, *Single electrons from heavy flavor decays in p + p collisions at s**(1/2) = 200-gev*, *Phys. Rev. Lett.* **96** (2006) 032001 [hep-ex/0508034].

[43] **PHENIX** Collaboration, A. Adare *et. al.*, *Energy loss and flow of heavy quarks in au + au collisions at s(nn)**(1/2) = 200-gev*, *Phys. Rev. Lett.* **98** (2007) 172301 [nucl-ex/0611018].

[44] **PHENIX** Collaboration, S. S. Adler *et. al.*, *Centrality dependence of charm production from single electrons measurement in au + au collisions at s(nn)**(1/2) = 200-gev*, *Phys. Rev. Lett.* **94** (2005) 082301 [nucl-ex/0409028].

[45] **PHENIX** Collaboration, S. S. Adler *et. al.*, *Nuclear modification of electron spectra and implications for heavy quark energy loss in au + au collisions at s(nn)**(1/2) = 200-gev*, *Phys. Rev. Lett.* **96** (2006) 032301 [nucl-ex/0510047].

[46] **STAR** Collaboration, K. Schweda, *A heavy-flavor tracker for star*, nucl-ex/0510003.