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What more can be learned from high p_{T} probes at RHIC?

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Abstract. The current status of the understanding of jet quenching in nuclear collisions at RHIC is reviewed. The experimentally large level of suppression of jets in Au + Au collisions at RHIC is a success, but also introduces a challenge in terms of quantitative understanding of the properties of the collision zone. 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 recover this information, a probe to which the medium is gray needs to be found.

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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 [1–4], as are the fragments of jets on the away-side azimuthally relative to a trigger hadron [5]. More than three years ago, the lack of suppression in $d+\mathrm{Au}$ 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 [6–9]. 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 [10–13].

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 $\mathrm{GeV}^2/\mathrm{fm}$ 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.

2 Experimental methods

The methods available are rather simple. In the case of the suppression of single-particle spectra, there are two measurements and one calculation necessary to obtain the nuclear modification factor R_{AB}. One measures the differential cross-section of a final-state hadron in a simpler system, $p+p$ collisions: this forms the baseline reference. Then, in collisions between nucleus A and nucleus B, one measures the differential yield per event in some centrality class, where centrality is determined by separating events either by multiplicity in some region of rapidity or utilizing the amount of energy in spectator neutrons. Using a Glauber model, one calculates the mean number of binary collisions, $\langle N_{\mathrm{binary}}\rangle$, in that centrality class, and the corresponding overlap integral $T_{AB} = \langle N_{\mathrm{binary}}\rangle/\sigma_{NN}$, where σ_{NN} is the assumed interaction cross-section between the nucleons in the model. Then one forms the nuclear modification factor between the differential yield in $A+B$ collisions and the binary-scaled $p+p$ differential cross-section:

$$R_{AB} = (\mathrm{d}^2N/\mathrm{d}p_{\mathrm{T}}\,\mathrm{d}\eta)_{AB}/(T_{AB}(\mathrm{d}^2\sigma/\mathrm{d}p_{\mathrm{T}}\,\mathrm{d}\eta)_{pp})\,,$$

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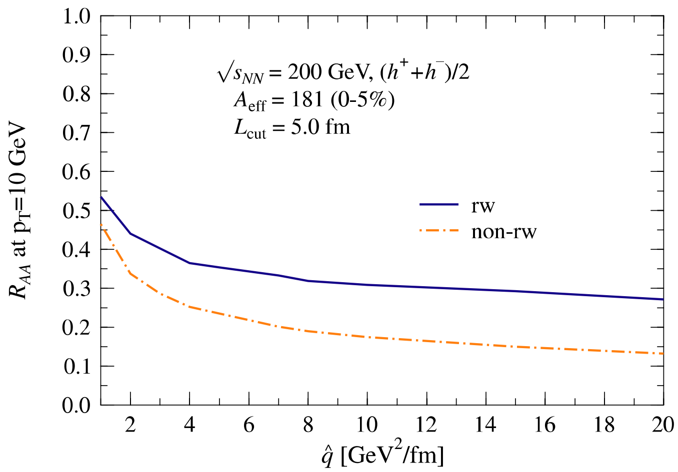

Fig. 1. Predicted suppression factor R_{AA} vs $\hat{q}$, a measure of the color charge density of the medium. "rw" and "non-rw" refer to two different methods of taking into account energy conservation. Figure is from [14]

"R_{AA}" is just R_{AB} in which nuclei A and B are the same (such as in Au + Au collisions). A related, but not identical, quantity is the binary-scaled ratio between spectra from central and peripheral collisions, R_{CP}:

$$R_{\mathrm{CP}} = \langle N_{\mathrm{binary}}^{\mathrm{peripheral}} \rangle / \langle N_{\mathrm{binary}}^{\mathrm{central}} \rangle$$
$$(\mathrm{d}^2 N/\mathrm{d}p_{\mathrm{T}}\,\mathrm{d}\eta)_{\mathrm{central}} / (\mathrm{d}^2 N/\mathrm{d}p_{\mathrm{T}}\,\mathrm{d}\eta)_{\mathrm{peripheral}} \,. \quad (1)$$

One of the major current limitations in the accuracy of R_{AB} is in the model-dependent T_{AB}, especially in peripheral collisions, where the systematic uncertainty can reach 30%–40%.

For dihadron correlations, a hadron is chosen in some p_{T} bin, and the distribution between this "trigger" hadron and an "associated" hadron of difference in some kinematic quantity, usually azimuth, is plotted. Usually, the conditional yield $1/N_{\mathrm{trig}}\,\mathrm{d}N/\mathrm{d}(\Delta\phi)$ is used for raw correlation functions, which allows for a direct comparison between conditional yields in simpler collision systems and Au + Au collisions without the use of the Glauber model. However, the procedure is not completely free of modeling uncertainty, as in systems of higher multiplicity there is a combinatoric background, modulated with elliptic flow v_2, which needs to be subtracted. This uncertainty can be quite large for lower $p_{\mathrm{T}}^{\mathrm{associated}}$.

3 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. 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]. This latter low or intermediate $p_{\mathrm{T}}^{\mathrm{associated}}$ regime is interesting in its own right, since in some analyses rather odd structures are seen [21], and may be a sensitive way to probe properties of the medium other than its density [22–24]. These issues, though, become irrelevant at higher $p_{\mathrm{T}}^{\mathrm{trigger}}$ and $p_{\mathrm{T}}^{\mathrm{associated}}$, and with higher statistics.

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.

4 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 $d+\mathrm{Au}$, 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.

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 Fig. 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 [26], 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 [27]. This lack of suppression of photons stands in stark contrast to the large suppression of light hadrons such as π^0, as can be clearly seen in Fig. 3. The lack of suppression is actually somewhat surprising, as these calculations indicate that a sizeable fraction of the 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 [28]. 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.

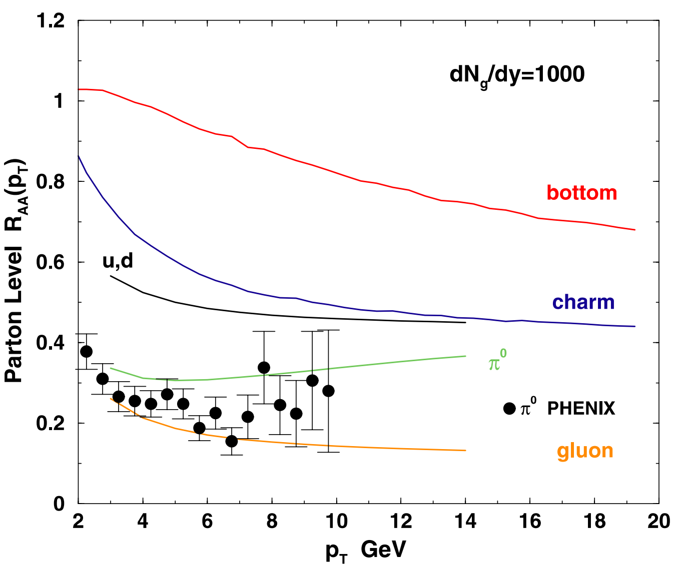

Fig. 2. Parton-level nuclear modification factor R_{AA} in central Au + Au collisions, due to gluon Bremsstrahlung in the DVGL framework, for various parton species. Figure is from [25]

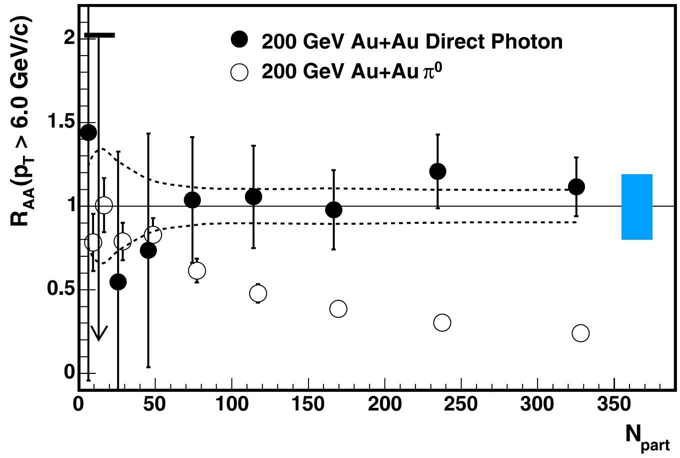

Fig. 3. Nuclear modification factor R_{AA} for photons and π^0 as a function of $N_{\rm part}$ in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV from PHENIX. Figure is from [26]

5 Gluon vs. quark probes

Simple Casimir factors in QCD indicate that gluons should interact more strongly with the medium than quarks; this is borne out by full calculations [31]. 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 [32], and in Au + Au collisions [30]. 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 [33], 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 Fig. 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.

A more discriminating set of measurements will be available in the future with the use of photon-tagged correlations. Such correlations have long been seen to have the advantage that the kinematics of the underlying QCD Compton process are strongly constrained [34], and the recoiling parton is tagged to be predominantly a quark. There is the additional advantage that the tagging photon shines through the collision zone, reducing the geometrical surface biases that induce the saturation of R_{AA} with

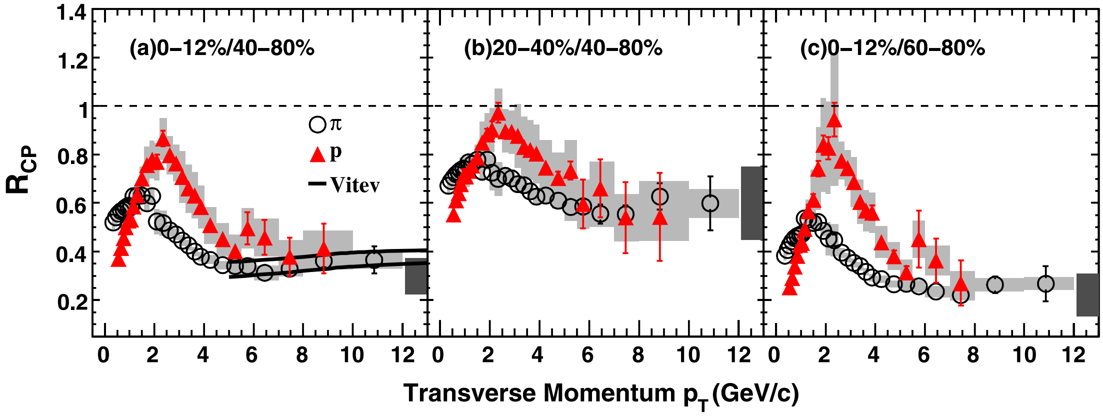

Fig. 4. Binary-scaled ratio of central to peripheral spectra R_{CP} for pions and protons in $\sqrt{s_{NN}} = 200$ GeV Au + Au collisions from STAR. Point-to-point systematic uncertainties are shown as *shaded boxes* around the data points. *Dark shaded bands* show the normalization systematic uncertainty in the number of binary collisions N_{bin}. "Vitev" is a calculation for pions including energy loss from gluon Bremsstrahlung [29]. Figure is from [30]

increasing density, perhaps recovering the tomographic information lost by the blackness of the collision zone [16]. While first steps have been made towards these measurements [35], it is clear that the higher luminosities available in the future with the RHIC II accelerator upgrade, along with additional experimental work to subtract backgrounds from fragmentation and decay photons, are critically needed in order to make definitive measurements in this channel.

6 Heavy 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 [25, 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 Fig. 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] have shown that, instead, non-photonic electrons are highly suppressed in Au + Au collisions.

Before discussing electron measurements in Au + Au collisions, it is critical to calibrate the probe using measurements in simpler systems. Figure 5 shows a comparison between all measurements to date and the most sophisticated perturbative QCD calculation on the market, the fixed-order next to leading log (FONNL) calculation [45]. The first conclusion to take from this is that, in contrast to π^0 [46, 47], direct photons [27], and protons [32], the calculations underpredict the measurements by approximately a factor of 5. The calibration of the luminosity of the probe is therefore suspect. This can be ameliorated somewhat by accurate measurements in $p + p$ collisions, along with the observation that the total integrated yields of charm, measured in the D channel, scale well with N_{bin}[39]. In addition, within these calculations the source of the electrons is highly uncertain. The relative yield of charm and bottom to the electrons is shown as the wide bands at the bottom of the figure: within theoretical uncertainties, bottom production could dominate electron production for electron p_T anywhere between 3 and 10 GeV/c. This greatly complicates the interpretation of single-electron suppression, since as can be seen in Fig. 2 the suppression levels of charm and bottom are expected to be significantly different.

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 6 shows the nuclear suppression factor R_{AA} for non-photonic electrons as measured by STAR: 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

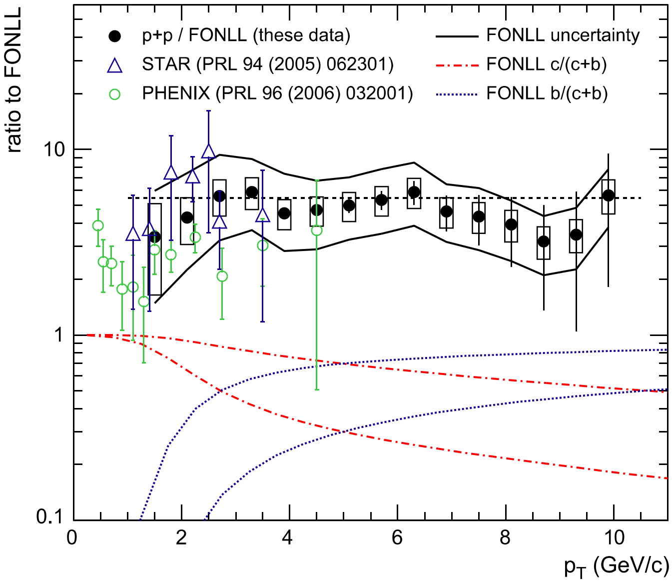

Fig. 5. Comparison between non-photonic electrons in $p+p$ collisions at $\sqrt{s} = 200$ GeV and FONLL calculations. *Bands* at the *bottom* indicate allowed regions of relative contributions to the electrons from charm and bottom. Figure is from [41]

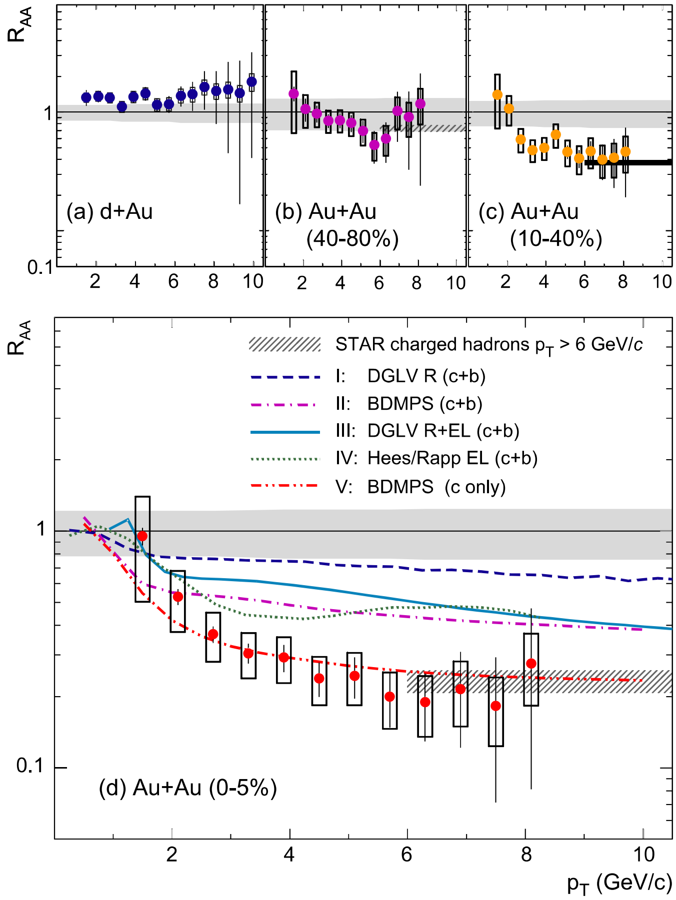

Fig. 6. Nuclear modification factor R_{AA} for non-photonic electrons. Figure is from [41]

itself. The calibration of the interaction of the probe with the medium, previously taken as a theoretical given, is currently undergoing major scrutiny.

The curves in Fig. 6 show various theoretical attempts to explain the data. Curve I [31] shows a calculation including both charm and bottom contributions, in which the gluon density is fixed at $\mathrm{d}N_g/\mathrm{d}y = 1000$ to match the final-state multiplicity of hadrons. Curve III [31] shows a calculation in the same framework, in which an additional, collisional, component of energy loss, first pointed out to be significant in [48], is added. Curve II [49] shows a calculation in a different framework, in which the gluon density is increased to a rather extreme level, but in which the dominant source of energy loss remains radiative. Curve V shows the same calculation, but with the additional assumption that the bottom contribution to the electron spectra is negligible. Curve IV [50] shows a calculation in which the energy loss is due to elastic scattering mediated by resonance excitations (D and B) and LO t-channel gluon exchange. Only curve V can reproduce the measurement. Clearly this measurement provides an extreme challenge to theory.

7 Conclusion and outlook

Where does this leave us in the search for gray probes? So far the search has failed, as the 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. That the FONNL calculation does not reproduce the measurement in $p+p$ collisions leaves open the possibility 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 Fig. 6, 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. Ideas have been floated as to the use of electron-hadron correlations [51] for this purpose, at least in simpler systems. Both STAR [52] 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, and this, combined with photon-jet correlations, will allow the technique of jet tomography to enter into a new, more quantitative stage.

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