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Differential probes of medium-induced energy loss

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Abstract. Results from the PHENIX experiment of measurements of high-p_{T} particle production presented at the Hard Probes 2004 Conference are summarized. This paper focuses on a sub-set of the measurements presented at the conference, namely the suppression of π^0 production at moderate to high p_{T} as a function of angle with respect to the collision reaction plane, $\Delta\phi$, for different collision centralities. The data are presented in the form of nuclear modification factor as a function of angle with respect to the reaction plane, $R_{AA}(\Delta\phi)$. The data are analyzed using empirical estimates of the medium-induced energy loss obtained from the $R_{AA}(\Delta\phi)$ values. A geometric analysis is performed with the goal of understanding the simultaneous dependence of R_{AA} on $\Delta\phi$ and centrality. We find that the centrality and $\Delta\phi$ dependence of the π^0 suppression can be made approximately consistent using an admittedly over-simplistic description of the geometry of the jet propagation in the medium but only if the energy loss is effectively reduced for short parton path lengths in the medium. We find that with a more "canonical" treatment of the quenching geometry, the π^0 suppression varies more rapidly with $\Delta\phi$ than would be expected from the centrality dependence of the suppression.

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1 Introduction

The RHIC experiments have unequivocally established the phenomenon of high transverse momentum hadron suppression in Au+Au collisions at RHIC [1–6]. Measurements in d+Au collisions that showed no suppression in the yield of high-p_{T} hadrons [7,8,6,9] indicated that the Au+Au high-p_{T} suppression was a final-state effect. Direct photon measurements by the PHENIX collaboration showing that the yield of hard direct photons in Au+Au collisions is consistent with pQCD expectations [10] have provided the final confirmation that hard scatterings occur at the expected rates in Au+Au collisions and that the suppression of high-p_{T} hadron production is necessarily a final-state effect. Predictions of high-p_{T} suppression were made before the start of RHIC operation [11] and confirmation of these predictions may be considered one of the key successes of the RHIC program so far. The suppression was predicted to result from the energy loss of hard-scattered quarks and gluons in the hot/dense medium created in ultra-relativistic heavy ion collisions (see [12, 13] and references therein). Medium-induced gluon bremsstrahlung is expected to dominate the energy loss process [14], and calculations of the high-p_{T} suppression factor incorporating this effect have been able to successfully describe the experimental measurements [15–17]. From comparisons of the energy loss calculations with the experimental data, estimates of the initial gluon rapidity density, $\mathrm{d}n_g/\mathrm{d}y$, have been obtained, yielding $\mathrm{d}n_g/\mathrm{d}y \approx 1000$, and estimates of the initial energy density have produced values in excess of 10 GeV/fm^3 [18,19].

However, in spite of this success, there are still a number of outstanding issues with the interpretation of the Au+Au high-p_{T} single-particle data. Since the properties of the medium created in heavy ion collisions are not *a priori* known, the energy-loss calculations necessarily use the observed suppression to infer initial parton densities, usually through an intermediate parameter that appears in the energy loss calculations. Thus, if we restrict ourselves to considering Au+Au central data, the only feature of Au+Au high p_{T} single-particle spectra that can be used to test the various energy loss models is the p_{T} dependence of the suppression. For π^0 spectra, the suppression in central Au+Au collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV is found to be approximately constant with p_{T} over the range, $3 < p_{\mathrm{T}} < 10$ GeV/c. While the different energy loss calculations can reproduce this p_{T}-independent suppression, the detailed explanation of the constancy is different in each model. The effects invoked to explain the p_{T} dependence of the observed Au+Au high-p_{T} suppression include: finite-energy effects, absorption of energy from the medium, evolution from incoherent (Bethe-Heitler) to coherent (LPM) radiation with increasing parton energy, the p_{T}-dependent mixture of quark and gluon contributions to the hard-scattered parton spectrum, and shadowing/EMC effect. While most calculations of the high-p_{T} suppression in Au+Au collisions account for shadowing/EMC modifications of the nuclear parton distributions and for the relative mixture of quarks and gluons in the hard-scattered parton spectra, finite-energy corrections, absorption of en-

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ergy from the medium, and the description of the energy loss process itself differs from calculation to calculation. Clearly the central Au+Au single-particle spectra are not sufficient, by themselves, to validate or exclude any of the different energy loss models, so we must use more "differential" probes of medium-induced energy loss to better understand the phenomenon.

In principle, the centrality dependence of the high-p_T suppression [4,20,3] provides a more effective test of energy-loss calculations because the length of the path of the partons in the medium will change between peripheral and central collisions. However, the energy loss calculations also have to account for changes in the initial properties of the medium with centrality and the extra flexibility in the description of the initial conditions means that the measured centrality dependence of the high-p_T suppression also does not stringently constrain energy loss models [21]. However, the path length of the parton in the medium can also be controlled by selecting high-p_T hadrons in different bins of azimuthal angle difference from the event-by-event determined reaction plane. Indeed, shortly after experimental observations of azimuthal anisotropy were reported [22,23], arguments were made that the high-p_T anisotropy in non-central collisions was due to the spatial asymmetry of the medium and the resulting ϕ dependence of parton path lengths [24,25]. However, recent analyses have argued that the large azimuthal anisotropies at high p_T cannot be accounted for by energy loss alone — at least when realistic nuclear geometry is used to describe the spatial asymmetry of the initial state [21,26,27]. Some of these analyses were based on a picture of the energy loss process in which quarks or gluons that have emitted radiation effectively disappear from the high-p_T spectrum because they are overwhelmed by partons of lower energy that escape from the medium losing little or no energy. In this picture, the medium effectively attenuates the high-p_T quarks and gluons and the high-p_T spectrum is dominated by partons originating near the surface — i.e. partons originating in the "corona" [21,26,27]. Then, the azimuthal anisotropy could be largely determined by the shape of the surface [26]. However, it has been separately argued that fluctuations in the number of emitted gluons may be large and such fluctuations may weaken the corona effect [28].

In this paper we present preliminary results from the PHENIX experiment on detailed measurements of π^0 production as a function of centrality and azimuthal angle with respect to the event-by-event measured reaction plane. By measuring the high-p_T hadron suppression as a function of angle with respect to the reaction plane, $\Delta\phi$, for a given centrality bin, we can keep the properties of the medium fixed and vary only the geometry of the jet propagation in the medium. By comparing different centrality bins we can, in principle, test how the initial properties of the medium affect the induced energy loss. Traditionally, measurements of the $\Delta\phi$ dependence of hadron yields have been analyzed in terms of the elliptic flow parameter, v_2. While the data presented this way contain, in principle, the same information as the combination of $\Delta\phi$-averaged R_{AA} and v_2, we believe that $R_{AA}(\Delta\phi)$ provides a useful alternative way to evaluate the dependence of high-p_T suppression on geometry because it effectively combines $R_{AA}(p_T)$ and v_2 into a single set of data.

2 $R_{AA}(\Delta\phi)$ measurement

The preliminary $\sqrt{s_{NN}} = 200$ GeV Au+Au π^0 $R_{AA}(\Delta\phi)$ results presented here were obtained from Run 2 with the PHENIX central arm spectrometers used to measure the π^0's and the beam-beam counters used to measure the event-by-event reaction plane. A subset of the data was collected using the PHENIX level-2 trigger to selectively record minimum-bias level-1 triggered events containing electromagnetic clusters with energies in excess of 2.5 GeV. The $R_{AA}(\Delta\phi)$ measurements were obtained from 33 M recorded events, corresponding to a total of 104 M sampled minimum-bias events. This event sample contains approximately a factor of 3 more π^0's above 6 GeV than previously published Run 2 π^0 measurements [4].

PHENIX has previously published measurements of elliptic flow using an event-by-event measured reaction plane [29,30]. The reaction plane is measured using the two PHENIX beam-beam counters (BBC) which count charged particles in the region $3 < |\eta| < 4$ using 128 hexagonal quartz Cherenkov counters, 64 in each of two counters located 150 cm from the nominal center of the interaction diamond. The quartz crystals are close-packed and are approximately azimuthally symmetric around the beam pipe. The charge measured from each radiator is, on average, proportional to the multiplicity of particles hitting the detector. The measured charges are corrected to remove any average displacement of the centroid position and to balance the measured charge in each ring of counters. After these corrections, the reaction plane angle is obtained by calculating the charge-weighted $\langle \cos 2\phi \rangle \equiv \Phi$. A final correction is then applied to remove any non-uniformity in the obtained Φ distribution. Because the reaction plane can be measured separately in the two beam-beam counters, PHENIX can directly measure the reaction plane resolution for each of the detectors alone and, then, infer the resolution of the combined measurement using standard techniques [31].

PHENIX has published the results of a number of π^0 measurements [1,4,32,9,33] and the technique for obtaining π^0 yields as a function of p_T is now well established. Because the beam-beam counters have 2π acceptance, PHENIX can measure the π^0 yields with uniform acceptance over $0 < \Delta\phi < 2\pi$, even though the electromagnetic calorimeters have only 1π nominal azimuthal acceptance. For the $R_{AA}(\Delta\phi)$ analysis, the same procedures as used in previous analyses were applied except that the π^0 yields were measured in two-dimensional bins of p_T and $\Delta\phi \equiv \phi - \Phi$ where ϕ is the azimuthal angle of the detected π^0. Since the measurement of Φ is ambiguous with respect to a 180° rotation of the reaction plane, and since we expect the π^0 yields to be symmetric with respect to reflection around $\Delta\phi = 0$, we measure the π^0 yields in 6 bins of $|\Delta\phi|$ over the range $0 < |\Delta\phi| < \pi/2$. For each p_T

bin we evaluate the ratio,

$$R(\Delta\phi_i, p_{\mathrm{T}}) = \frac{\Delta N(\Delta\phi_i, p_{\mathrm{T}})}{\sum_{i=1}^{6} \Delta N(\Delta\phi_i, p_{\mathrm{T}})} \quad , \tag{1}$$

where $\Delta N(\Delta\phi_i, p_{\mathrm{T}})$ is the measured number of π^0's in a given $\Delta\phi$ and p_{T} bin. Because the PHENIX central arm acceptance is effectively constant as a function of $\Delta\phi$, $R(\Delta\phi_i, p_{\mathrm{T}})$ is the same as the $\Delta\phi$-dependent nuclear modification factor, $R_{AA}(\Delta\phi)$, divided by the $\Delta\phi$-averaged nuclear modification factor,

$$R(\Delta\phi_i, p_{\mathrm{T}}) = R_{AA}(\Delta\phi, p_{\mathrm{T}})/R_{AA}(p_{\mathrm{T}}) \quad . \tag{2}$$

Using previously published measurements of $R_{AA}(p_{\mathrm{T}})$ [4], we can then, in principle, obtain $R_{AA}(\Delta\phi, p_{\mathrm{T}})$ simply by inverting (2). We perform this analysis in several bins of centrality, with each bin accounting for 10% of the Au+Au inelastic cross-section.

Before applying this procedure to obtain $R_{AA}(\Delta\phi, p_{\mathrm{T}})$ we must first correct the $R(\Delta\phi, p_{\mathrm{T}})$ values for the finite resolution of the reaction plane measurement. One goal of our measurement is to determine $R_{AA}(\Delta\phi, p_{\mathrm{T}})$ without assuming any particular functional dependence on $\Delta\phi$. However, for purposes of correcting for reaction plane resolution, we take advantage of the fact that the observed π^0 yields vary with $\Delta\phi$ approximately as

$$R(\Delta\phi_i, p_{\mathrm{T}}) \approx R_0\,(1 + 2v_2 \cos 2\Delta\phi) \quad . \tag{3}$$

The resolution of the reaction plane approximately reduces v_2 by the factor $\sqrt{2\langle\cos 2\,(\Psi_1 - \Psi_2)\rangle}$ [31]. For each p_{T} bin, in a given centrality class, we fit the $R(\Delta\phi, p_{\mathrm{T}})$ values to the functional form in (3) and then correct each measured $R(\Delta\phi, p_{\mathrm{T}})$ value according to

$$R^{\mathrm{corr}}(\Delta\phi_i, p_{\mathrm{T}}) = R^{\mathrm{raw}}(\Delta\phi_i, p_{\mathrm{T}}) \left(\frac{1 + {v_2}^{\mathrm{corr}} \cos(2\Delta\phi)}{1 + {v_2}^{\mathrm{raw}} \cos(2\Delta\phi)} \right) \tag{4}$$

with ${v_2}^{\mathrm{corr}} = {v_2}^{\mathrm{raw}}/\sqrt{2\langle\cos 2\,(\Psi_1 - \Psi_2)\rangle}$. We estimate the systematic error in the reaction plane resolution correction by propagating the centrality-dependent uncertainties in $\langle\cos 2\,(\Psi_1 - \Psi_2)\rangle$. Of course, the above-described correction only strictly applies if $R_{AA}(\Delta\phi)$ is well-described by the functional form in (3). While we do observe some departure from this form in the data, the differences are typically $< 5\%$ so our correction will not introduce a large error.

We are interested in evaluating the $\Delta\phi$ dependence and centrality dependence of the π^0 suppression, so we take advantage of previous observations that the π^0 $R_{AA}(p_{\mathrm{T}})$ is nearly constant for $p_{\mathrm{T}} > 3$–4 GeV/c [4], and apply (1) and (2) after summing the yields over p_{T} to obtain $R_{AA}(\Delta\phi)$. We show the preliminary results of this analysis in Fig. 1 for different centrality bins and for two different minimum p_{T} values, 3 and 4 GeV/c. The systematic errors in the $R_{AA}(\Delta\phi)$ measurement resulting from uncertainties in the reaction plane resolution correction are indicated by the bands surrounding the data points. We note that potential errors in the reaction plane resolution correction produce

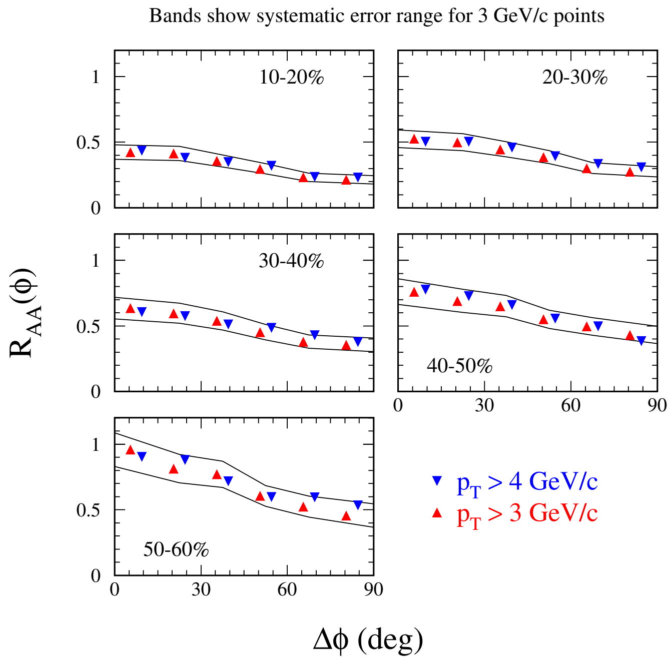

Fig. 1. $R_{AA}(\Delta\phi)$ for π^0 production in $\sqrt{s_{\mathrm{NN}}} = 200$ GeV Au+Au collisions integrated over $p_{\mathrm{T}} > 3, 4$ GeV/c for different bins of collision centrality. The statistical errors are everywhere smaller than the size of the points. The bands show the systematic errors on the $p_{\mathrm{T}} > 3$ GeV/c values resulting from the uncertainty in the reaction plane resolution correction and from systematic uncertainties in the published π^0 R_{AA} values

correlated errors on the data points; the points at small $\Delta\phi$ move in opposite direction to the points are large $\Delta\phi$. Figure 1 shows that the high-p_{T} π^0 yields vary strongly with angle with respect to the reaction plane, consistent with previous observations of substantial π^0 v_2 at high p_{T}. The variation in π^0 yield versus $\Delta\phi$ in the 50–60% centrality bin is particularly striking. There is apparently no suppression for π^0's produced aligned with the reaction plane (in the direction of maximal elliptic flow) while production of π^0's at 90° to the reaction plane is suppressed by a factor of 2. This observation demonstrates the importance of using $R_{AA}(\Delta\phi)$ to characterize the reaction plane dependence of the high-p_{T} suppression.

3 Empirical energy loss analysis

An appropriate question to ask, then, is how can we learn more from the data shown in Fig. 1? PHENIX has recently pursued an analysis that attempts to extract empirical information about the energy loss responsible for the high-p_{T} suppression from the measured R_{AA} values. This procedure is based on the observation that the π^0 p_{T} spectrum in pp collisions is well-described by a pure power-law function,

$$E\frac{d^3N}{dp^3} \propto \frac{1}{{p_{\mathrm{T}}}^n} \tag{5}$$

with $n = 8.1 \pm 0.1$ [34] and the observation that $R_{AA}(p_{\mathrm{T}})$ is approximately flat above 3–4 GeV/c. A constant $R_{AA}(p_{\mathrm{T}})$ might result if the fractional medium-induced energy loss of the parent partons were approximately p_{T}-independent [27,34]. Such a dependence naturally results in the Bethe-Heitler regime [35–37] which may be relevant for this analysis [37], which extends down to p_{T} values below 5 GeV/c. We note that an alternative explanation of the flat $R_{AA}(p_{\mathrm{T}})$, assuming LPM-dominated energy loss [17], may be appropriate at high-p_{T}, but that explanation requires the underlying parton spectrum to decrease exponentially with p_{T} and such a dependence is inconsistent with the power-law π^0 spectrum observed in pp collisions in the experimentally accessible p_{T} range [32]. We also note that an explicit numerical calculation of the dependence of the energy loss on jet energy in the GLV formulation shows a weak dependence of the average energy loss on jet energy at moderate p_{T} [12]. Using the constant fractional energy loss assumption and some straight-forward manipulations not repeated here [34], the estimate of the fractional parent parton energy loss, S_{loss}, can be obtained from the measured π^0 R_{AA},

$$S_{\mathrm{loss}} = 1 - {R_{AA}}^{1/(n-2)} \quad . \tag{6}$$

It has been noted previously that estimates of the average parton energy loss using such a procedure will underestimate the true energy loss by a substantial factor (~ 2) because the observed π^0 spectrum (e.g.) will be dominated by fragments of partons that have suffered less energy loss than the average [36,28]. Thus, the values that we obtain for S_{loss} will differ from the true average energy loss by some unknown multiplicative factor. Whether we should expect this factor to be constant as a function of $\Delta\phi$ and centrality is a point that we will address below.

A related important issue that must be addressed is that the above-described empirical energy loss analysis is appropriate when the energy loss is effectively continuous — i.e. where all partons lose energy and the energy loss varies smoothly with length of path in the medium. This picture could be valid if the energy loss mechanism resulted from the emission of many soft gluons. However, analyses of the radiated gluon spectrum have shown that in a dense medium hard gluon radiation plays an important role. Then, the observed π^0 spectrum may be dominated by fragments of partons that suffer little or no energy loss while fragments of partons that have suffered energy loss effectively disappear from the spectrum. If this picture applies, then the high-p_{T} suppression is more appropriately interpreted as resulting from attenuation [21], and the constancy of the suppression as a function of p_{T} naturally follows. If the high-p_{T} suppression is viewed as an attenuation, then we can estimate an *effective* absorption length, $\bar{\nu}$, by writing $R_{AA} = e^{-\bar{\nu}}$. Just as with S_{loss}, it is clear that by extracting a single parameter from the high-p_{T} suppression we are averaging out many details of the energy loss process. Nonetheless, if the attenuation picture is correct, the variation of $\bar{\nu}$ with centrality and $\Delta\phi$ will reflect the geometric variation of the average number of absorption lengths of material encountered by the jets in leaving the medium. Using, $\bar{\nu} = -\ln(R_{AA})$, we compare in Fig. 2 the dependence of $\bar{\nu}$ and S_{loss} on R_{AA} with $\bar{\nu}(R_{AA})$ rescaled by a multiplicative factor to match $S_{\mathrm{loss}}(R_{AA})$ at $R_{AA} = 0.2$. Surprisingly, the dependence of these two different quantities on R_{AA} is essentially the same for $R_{AA} > 0.2$, i.e. for all R_{AA} values currently measured at RHIC. Although we have used two completely different physical pictures for describing the high-p_{T} suppression, the resulting parameters will have precisely the same dependence on centrality and $\Delta\phi$. The technical explanation for this surprising result is straight-forward if we consider the Taylor expansion of the function $x^{1/N}$. For large N that expansion differs from the expansion of $\ln x$ by approximately only a multiplicative constant. The physics implication of the similarity of the dependences of S_{loss} and $\bar{\nu}$ on R_{AA} is that measurements of high-p_{T} single hadron suppression as a function of centrality and/or reaction plane angle cannot, by themselves, uniquely constrain the mechanism responsible for the high-p_{T} suppression. On the other hand, the results in Fig. 1 show that the suppression clearly changes with centrality and azimuthal angle of parton with respect to the reaction plane. Then, if we extract S_{loss} from the data, while we cannot be certain about its physical interpretation, we can treat it as a robust effective quantity characterizing the high-p_{T} suppression and evaluate how it depends on both centrality and $\Delta\phi$. We also note that the results of the empirical energy loss analysis are not very sensitive to n (for n sufficiently large) as shown by the curve for $n = 4$ in Fig. 2 scaled to match the $n = 6$ curve at $R_{AA} = 0.2$.

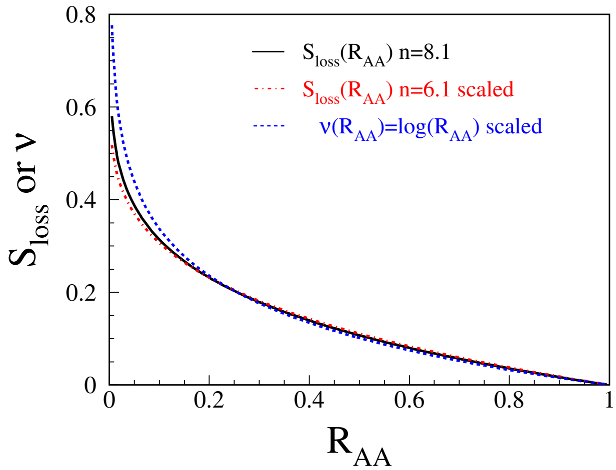

Fig. 2. A comparison of different quantities extracted from R_{AA} (see text for details)

We show in Fig. 3 extracted values for S_{loss} as a function of centrality and $\Delta\phi$. We observe that the most peripheral bin included in this analysis, 50–60%, shows the largest variation of S_{loss} with $\Delta\phi$ though the magnitude of the absolute variation of $S_{\mathrm{loss}}(\Delta\phi)$ does not dramatically change with centrality. This result may be, at first, surprising since the eccentricity of the collision zone is expected to change significantly over the studied centrality range. However, the variation of S_{loss} with $\Delta\phi$ will also depend on the average energy loss, which increases with

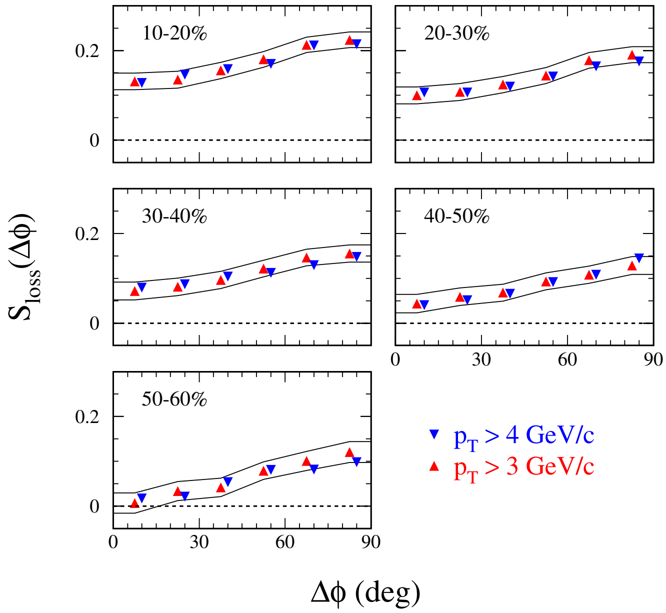

Fig. 3. The extracted parameter S_{loss} (see text for details), as a function of $\Delta\phi$, for $p_{\mathrm{T}} > 3$ GeV/c and $p_{\mathrm{T}} > 4$ GeV/c, for different bins of collision centrality. The bands show the systematic errors on the $p_{\mathrm{T}} > 3$ GeV/c values resulting from the uncertainty in the reaction plane resolution correction and from systematic uncertainties in the published π^0 R_{AA} values

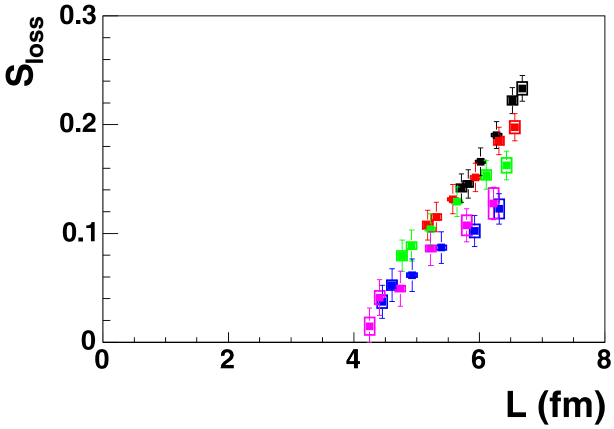

Fig. 4. Variation of π^0 S_{loss} with L, using a simplistic analysis of parton path length in the medium (see text for details)

centrality, so there may be a partial cancellation of these two contributions. A simplistic, but illustrative geometric analysis shows that such a cancellation is expected. If we assume that S_{loss} varies with path length of the parent partons in the medium as $S_{\mathrm{loss}} \propto l^m$ and that the path length of the partons in the medium varies with $\Delta\phi$ as $l(\Delta\phi) = l_0 + l_2 \cos(2\Delta\phi)$, then we would expect $S_{\mathrm{loss}}(\Delta\phi)$ to take the form

$$S_{\mathrm{loss}}(\Delta\phi) \propto l_0^m \left(1 + \frac{l_2}{l_0}\cos\left(2\Delta\phi\right)\right)^m . \tag{7}$$

For $m = 1$ or l_2/l_0 small, we can use the binomial approximation to (7) and the resulting $\Delta\phi$-averaged S_{loss}, $\langle S_{\mathrm{loss}}\rangle$, will simply be proportional to l_0^m. The quantity l_2/l_0 is the spatial analog of v_2 and it should be proportional to the spatial eccentricity $\varepsilon \equiv \langle y^2 - x^2\rangle / \langle y^2 + x^2\rangle$ [38]. Then, again using the binomial approximation to (7), the amplitude of the variation of S_{loss} with $\Delta\phi$ will be proportional to $\langle S_{\mathrm{loss}}\rangle\varepsilon$. The increase in $\langle S_{\mathrm{loss}}\rangle$ in more central collisions will partially offset the reduction in the collision eccentricity. Indeed, using PHENIX estimates of the centrality dependence of the eccentricity of the collision zone, we find that $\langle S_{\mathrm{loss}}\rangle\varepsilon$ changes by only $\sim 30\%$ over the centrality range covered by the data while ε changes by a factor of > 2.

Prior analyses of v_2 at high p_{T} [26,21,27] have argued that the variation of yields as a function of $\Delta\phi$ cannot be explained by energy loss alone. However, it has been recently suggested that the larger energy loss for partons crossing a (radial) flow field could lead to a larger $\Delta\phi$ dependence in the high-p_{T} suppression [39]. Experimentally we can approach the problem differently — namely we can ask whether there is some way to make the dependence on $\Delta\phi$ in different centrality bins consistent. We show in Fig. 4 an example of such analysis that, at first sight, is too simplistic to be expected to work. In this analysis, we use PHENIX estimates of ε and an estimate of the average radius of the collision zone to determine the parameters of an ellipse for each centrality bin. We then use the angular dependence of the distance from the center to the edge of the ellipse, L, as a function of $\Delta\phi$ and centrality, as a gauge of how path lengths of partons would vary in the medium. This overly simplistic geometry clearly ignores important effects such as fluctuations in the production points of the jets and the fact that the parton density should not be uniform in the transverse plane, but because the geometry is so simple it provides a useful starting point for an attempt to make sense of the data. Figure 4, then, is a plot of S_{loss} versus L combining all of the data points from Fig. 3. The different centrality bins are represented by different symbols. Surprisingly, this overly simplistic geometry makes the different centrality and $\Delta\phi$ bins approximately consistent in that for a given value of L, approximately the same S_{loss} (and thus R_{AA}) is observed. The most striking aspect of the figure is that an extrapolation of the trend in the data would suggest that the high-p_{T} suppression will go to zero for L significantly larger than zero. We note that a re-analysis of the L estimates indicate that the values used in Fig. 4 are too large — particularly for the more peripheral bins. The updated analysis will be included in an upcoming PHENIX publication. However, even after the re-analysis we find that extrapolating the trend of the data in Fig. 4 would imply no suppression for finite path length of the parton in the medium. We note that this result is not simply due to the calculation of S_{loss} since, as Fig. 2 shows, for small S_{loss} (R_{AA} close to 1), S_{loss} and R_{AA} are linearly related.

A more realistic attempt to describe the geometry has been made by assuming that the density of partons in the medium causing the induced energy loss varies across the transverse plane proportionally to the participant nucleon density and that the parton density decreases as $1/\tau$, where τ is the proper time, as would be expected from pure 1-d expansion. This density is then integrated along paths from the center of the nucleus, at a given angle $\Delta\phi$, to give an effective "thickness" seen by the propagating partons

$$T_{\text{eff}} \propto \int_0^\infty dr\ r^{(n-1)} \rho_{\text{part}}(r, \Delta\phi) \quad . \tag{8}$$

This formula includes an extra path-length dependent weighting, r^n, to account for a possible faster than linear dependence of the induced energy loss on path length. When radiation is predominantly in the LPM regime, then we might naively expect $n = 1$. However, the time evolution of the medium will also affect the dependence of energy loss on r. For the assumed $1/\tau$ decrease of the parton densities, one power of r is effectively cancelled by the time evolution. We note that proper handling of the formation time of the medium must be accounted for. Although not explicit in (8), we have tested two different formation assumptions: that the medium appears at fixed formation time, τ_0; and, separately, a prescription [40] motivated by explicit calculation of induced radiation. We observed only minimal differences between these two prescriptions. Figure 5a shows a plot of extracted S_{loss} values from the data in Fig. 1 as a function of the extracted T_{eff} values for the different centrality and $\Delta\phi$ bins. The result is that this still simplistic, but more realistic treatment of the geometry of the medium destroys the consistency of the measured $\Delta\phi$ variation of S_{loss} or the corresponding R_{AA} values. This occurs because of the growth of the participant density in more central collisions — an effect that did not appear in Fig. 3 which only evaluated the $\Delta\phi$ dependence of the path lengths. The lack of agreement between different centrality bins can be interpreted as indicating that if T_{eff} is (roughly) the correct variable for characterizing energy loss, then the high-p_{T} suppression in Au+Au collisions varies much faster with $T_{\text{eff}}(\Delta\phi)$ within a given centrality bin than it does between centrality bins. This suggests that an additional mechanism is required to produce the observed $\Delta\phi$ variation of the high-p_{T} suppression, consistent with prior observations that energy loss alone cannot explain the magnitude of the high-p_{T} v_2. However, if we effectively remove the contribution of the growth in the participant density with centrality in (8) by dividing by $\rho_{\text{part}}(0,0)$, then we obtain the results shown in Fig. 5b. Here the centrality and $\Delta\phi$ dependences of the π^0 suppression — as exhibited by S_{loss} — are consistent. We state, without showing the results due to lack of space, that an analysis that takes into account fluctuations in jet production point (i.e. not necessarily at the center of the nucleus), and the resulting fluctuations in the path length for partons propagating at angle $\Delta\phi$, yields the same qualitative result as shown in Fig. 5 even when T_{eff} is calculated with the effective thickness weighted by the survival probability. The fluctuations effectively average out to give a result that is similar to Fig. 5a when the centrality dependence of the participant density is included, whereas T_{eff} obtained by dividing out the maximum participant density yields a result similar to Fig. 5b. We do not claim to understand this result. Taken at face value, it would suggest that the energy loss mechanism is not sensitive to the expected increase in parton density in more central collisions. This result would contradict the understanding that the medium-induced energy loss is sensitive to the local color-charge density. However, if the sQGP paradigm is correct then it may be that current descriptions of the energy loss process may not apply. If we accept the implications of the simultaneous agreement of the centrality and $\Delta\phi$ dependence in Figs. 4 and 5b, then we would also have to infer that the effective energy loss for π^0's in the measured p_{T} range may reach zero for finite parton path length in the medium. This result, coupled with the lack of apparent sensitivity of the π^0 suppression to the centrality dependence of the (maximum) participant density might explain why attempts to explain high-p_{T} v_2 measurements using canonical descriptions of the energy loss process may fail.

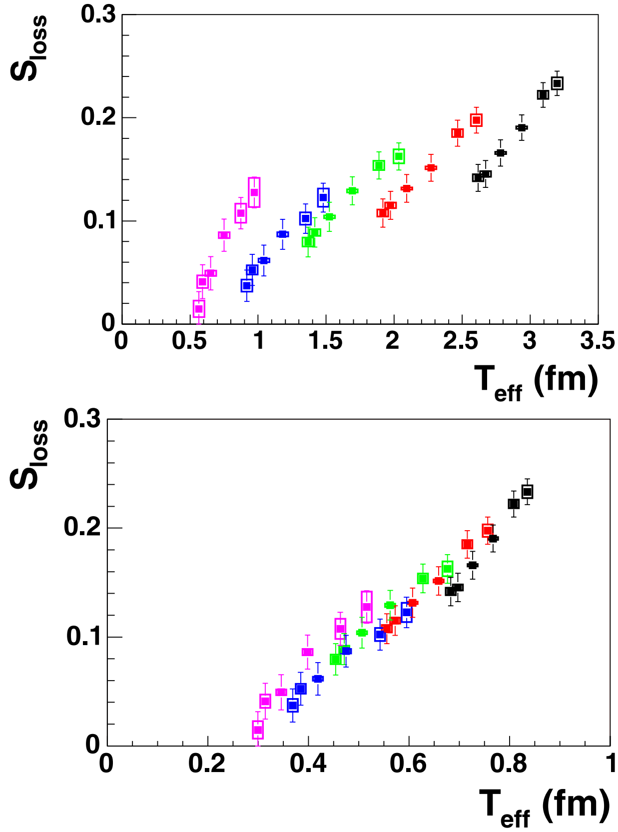

Fig. 5. Variation of S_{loss} with the calculated T_{eff} for different centrality and $\Delta\phi$ bins, using T_{eff} as calculated according to (8) (top) and after dividing out the central participant density, $\rho_{\text{part}}(0,0)$ (bottom)

4 Conclusions

This paper has described a subset of the PHENIX measurements presented at the Hard Probes 2004 conference focusing on the measurement of π^0 suppression relative to the reaction plane in $\sqrt{s_{\rm NN}} = 200$ GeV Au+Au collisions. The results show substantial variation of the suppression as a function of $\Delta\phi$, consistent with observations of large v_2 at high $p_{\rm T}$. The data also show that the production of π^0's is not significantly suppressed in the 50–60% centrality bin for π^0 mesons produced aligned with the reaction plane, while there is substantial suppression for larger $\Delta\phi$. An attempt to evaluate the consistency of the measured centrality and $\Delta\phi$ dependence of the π^0 suppression, using different geometric measures of the path length of the parton in the medium, shows that the data can be made consistent, but only if the growth of parton density with collision centrality is neglected. However, we don't claim to rule out other explanations for the combined centrality and $\Delta\phi$ dependence of the π^0 suppression. Clearly, the attempts to explain the data here are simplistic and no substitute for a detailed analysis in the context of a real energy-loss calculation. However, the analyses may suggest an alternative direction to explore in trying to understand the $\Delta\phi$ dependence of jet quenching.

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