Abstract. Multiple parton interactions in relativistic heavy ion reactions result in transverse momentum diffusion and medium induced non-Abelian energy loss of the hard probes traversing cold and hot nuclear matter. A systematic study of the interplay of nuclear effects on the $p_T \geq 2$ GeV inclusive hadron spectra demonstrates that the competition between nuclear shadowing, multiple scattering and jet quenching leads to distinctly different enhancement/suppression of moderate and high-$p_T$ hadron production in $d + Au$ and $Au + Au$ collisions at RHIC. The associated increase of di-jet acoplanarity, measured via the broadening of the back-to-back di-hadron correlation function, provides an additional experimental tool to test the difference in the dynamical properties of the media created in such reactions.

Multiparton Tomography of Hot and Cold Nuclear Matter

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A  Nuclear modification of hadron production

Particle production from a single hard scattering with momentum exchange much larger than $1/\text{fm}$ is localized in space-time. It is multiple parton scattering before or after the hard collision that is sensitive to the properties of the nuclear matter [1,2]. By comparing the high-$p_T$ observables in $p+p$, $p+A$ and $A+A$ reactions, we are able to study the strong interaction dynamics of QCD in the vacuum, cold nuclear matter and hot dense medium of quarks and gluons, respectively. So far the first two integral moments $\int dz \, z^n \rho(z)$ of the matter density in the interaction region can be deduced from experimental measurements since they are related to the broadening [3,4] and energy loss [5,6] of a fast parton traversing nuclear matter. From [3,5] around midrapidity:

$$\left\langle \Delta k_T^2 \right\rangle \equiv 2 \xi \int dz \frac{\mu^2}{\lambda_{q,g}} = 2 \xi \int dz \frac{3 C_R \pi \alpha_s^2}{2} \rho^g(z) = \begin{cases} 2 \xi \frac{3 C_R \pi \alpha_s^2}{2} \rho^g \langle L \rangle, & \text{static} \\ 2 \xi \frac{3 C_R \pi \alpha_s^2}{2} \frac{1}{A_\perp} \frac{dN_g}{dy} \ln \left( \frac{L}{\tau_0} \right), & 1+1D \end{cases}$$

(1)
FIGURE 1. Left panel: predicted suppression for $\pi^0$ and $h^+ + h^-$ [1] in $Au + Au$ compared to PHENIX and STAR data [7]. Similar quenching is found by BRAHMS and PHOBOS [7]. Right panel: predicted small enhancement of neutral pions in $d + Au$ [8], data is from PHENIX. Left bottom panel: a test of a suggested interpretation of high $p_T$-hadron suppression as result of initial state wavefunction modification ($R_{dAu} \approx \sqrt{R_{AuAu}}$). Data is from BRAHMS, PHOBOS and STAR [8].

\[
\langle \Delta E \rangle \approx \int dz \frac{C_R \alpha_s \mu^2}{2} \frac{1}{\lambda_g} z \ln \frac{2E}{\mu^2 \langle L \rangle} = \int dz \frac{9C_R \pi \alpha_s^3}{4} \rho^g(z) \ln \frac{2E}{\mu^2 \langle L \rangle}
\]

\[
\begin{align*}
&= \begin{cases} 
\frac{9C_R \pi \alpha_s^3}{8} \rho^g \langle L \rangle^2 \ln \frac{2E}{\mu^2 \langle L \rangle}, & \text{static} \\
\frac{9C_R \pi \alpha_s^3}{4} \frac{1}{A_{\perp}} \frac{dN^g}{dy} \langle L \rangle \ln \frac{2E}{\mu^2 \langle L \rangle}, & 1+1D
\end{cases}
\end{align*}
\]

In Eq.(1) the factor 2 comes from 2D diffusion, $\xi \approx O(1)$ and $\rho^g$ is the effective gluon density. For the 1+1D Bjorken expansion scenario $A_{\perp}$ is the transverse area of the interaction region, $\tau_0$ is the initial equilibration time and $dN^g/dy$ is the effective gluon rapidity density. In Eq.(2) the dominant logarithmically enhanced contribution to mean energy loss computed in the GLV approach [5] is shown. For further discussion on medium induced radiative energy loss in QCD see [5,6].

Initial state parton broadening, nuclear shadowing and jet energy loss are incorporated in the lowest order pQCD hadron production formalism as in [1]. The interplay of dynamical nuclear effects can be studied through the nuclear modification ratio

\[
R_{AB}(p_T) = \frac{dN^{AB}}{dy d^2 p_T} / \frac{T_{AB}(b) d\sigma^{pp}}{dy d^2 p_T}, \quad \text{about impact parameter } b \text{ in } A + B.
\]

(3)

Figure 1 compares the predicted [1] approximately constant suppression of $\pi^0$ and $h^+ + h^-$ in $\sqrt{s} = 200$ AGeV $Au + Au$ collisions at RHIC to PHENIX and STAR data [7]. The overall quenching magnitude and its centrality dependence are set by $(\langle L \rangle / A_{\perp}) dN^g/dy \propto N_{\text{part}}^{2/3}, dN^g/dy = 1150$. The shape of $R_{AuAu}$ is a result of the interplay of all three nuclear effects. The full numerical calculation takes into account the dynamical Bjorken expansion of the medium, finite kinematic bounds, higher order opacity corrections and approximates multiple gluon emission by a Poisson distribution [1,5]. In the right panel the Cronin enhancement, resulting from initial state parton broadening, $\langle \Delta k_T^2 \rangle - \langle \Delta k_T^2 \rangle_{\text{vac}} \sim (\mu^2 / \lambda_g)_{\text{eff}} \langle L \rangle$ [1,3] is seen to compare qualitatively to the shape of the PHENIX $\pi^0$ measurement [8] in $d + Au$. The calculations in
Fig. 1 use the value \((\mu^2/\lambda_g)^{eff} = 2 \times 0.14 \text{GeV}^2/\text{fm}\) for the cold nuclear matter transport coefficient constrained from existing Cronin data [1], although somewhat smaller scattering strength may be favored by PHENIX data. Larger enhancement of \(h^+ + h^-\) production, consistent with results from low energy \(p + A\) measurements, is also shown [8]. The lower right panel rules out the scenario for the initial wavefunction origin of moderate and high-\(p_T\) hadron suppression (see left panel of Fig. 1) since in this case \(R_{dAu} \approx \sqrt{R_{AuAu}}\). For further discussion on the Cronin effect see [1,9].

B Broadening of the away-side di-hadron correlation function

The total vacuum+nuclear induced broadening for the two partons in a plane perpendicular to the collision axis in \(p + A (A + A)\) reads [3]:

\[
\langle k_T^2 \rangle = \langle k_T^2 \rangle_{\text{vac}} + \left( \frac{1}{2} \right) \left( \frac{\mu^2}{\lambda} \right)_\text{eff} \langle L \rangle_{\text{IS}} + 2 \left( \frac{1}{2} \right) \langle L \rangle_{\text{FS}} .
\]

A typical range for the cold nuclear matter transport coefficient for gluons is given by \((\mu^2/\lambda_g)^{eff, IS=FS} = 2 \times 0.1 \text{GeV}^2/\text{fm} - 2 \times 0.15 \text{GeV}^2/\text{fm}\). For final state scattering in a 1+1D Bjorken expanding quark-gluon plasma the broadening \((\mu^2/\lambda)^{eff} \langle L \rangle_{FS}\) can be evaluated from Eq.(1) with \(dN^g/dy = 1150\), consistent with the inclusive hadron suppression pattern in Fig 1.

Figure 2 shows two measures of the predicted increase in di-jet acoplanarity for minimum bias \(d + Au\) and central \(Au + Au\) reactions [3]: \(|k_{T_y}| = \sqrt{\langle k_T^2 \rangle_{1\text{parton}}/\pi}, \langle k_T^2 \rangle_{1\text{parton}} = \langle k_T^2 \rangle/2\) and the away-side width \(\sigma_{\text{Far}}\) of the di-hadron correlation function \(C(\Delta \phi) = N^{h_1,h_2}(\Delta \phi)/N_{\text{tot}}^{h_1,h_2}\). \(C(\Delta \phi)\) is approximated by near-side and far-side Gaussians for a symmetric \(p_T\) case and the vacuum widths are taken from PHENIX [10]. In the right panel of Fig. 2 di-hadron correlations in \(d + Au\) are shown to be qualitatively similar to the \(p + p\) case and in agreement with STAR measurements [8]. In \(Au + Au\) reactions at RHIC di-jet acoplanarity is noticeably larger, but this effect alone does not lead to the reported disappearance of the back-to-back correlations [10]. To first approximation the coefficient of the away-side Gaussian (the area under \(C(\Delta \phi), \Delta \phi > \pi/2\)), is determined by jet energy loss and given by \(R_{AA} \propto N_{2/3}^{part}\). Broadening with and without away-side quenching is shown the bottom right panel of Fig. 2. Combined \(d + Au\) and \(Au + Au\) experimental data in Fig. 2 also rule out the existence of monojets at RHIC. For further discussion on di-hadron correlations see [3,11].

In summary, evidence from jet tomography [1,2], relativistic hydrodynamics [12] and parton cascade models [13] is in strong support of the creation of a deconfined phase of QCD at RHIC with initial energy density \(\sim 20 \text{GeV/ fm}^3\), more than 100 times the \(1/7 \text{GeV/ fm}^3\) density of cold nuclear matter.
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