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High p_{T} leading hadron suppression in nuclear collisions at $\sqrt{s_{NN}} \approx$ 20–200 GeV: data versus parton energy loss models

D. d'Enterria[a]

Nevis Laboratories, Columbia University, Irvington, NY 10533, and New York, NY 10027, USA

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Abstract. Experimental results on high transverse momentum (leading) hadron spectra in nucleus-nucleus collisions in the range $\sqrt{s_{NN}} \approx$ 20–200 GeV are reviewed with an emphasis on the observed suppression compared to free space production in proton-proton collisions at the corresponding center-of-mass energies. The transverse-momentum and collision-energy (but seemingly not the in-medium path length) dependence of the experimental suppression factors measured in central collisions is consistent with the expectations of final-state non-Abelian parton energy loss in a dense QCD medium.

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1 Introduction

High-energy nucleus-nucleus collisions offer the only experimental means known so far to concentrate a significant amount of energy, $\mathcal{O}$(TeV) at the RHIC collider, in a "large" volume, $\mathcal{O}(10^3\,\mathrm{fm}^3)$, under laboratory conditions. The expectations, based on first-principles lattice-QCD calculations [1], are that for energy densities above $\varepsilon \approx 0.7\,\mathrm{GeV/fm}^3$, hadronic matter will undergo a phase transition towards an extended volume of deconfined and massless quarks, and gluons: the Quark Gluon Plasma (QGP). The scrutiny of this new state of matter aspires to shed light on some of the open key questions of the strong interaction (confinement, chiral symmetry breaking, structure of the QCD vacuum, hadronization) that still evade a thorough theoretical description [2] due to their highly non-perturbative nature.

The production of an extremely hot and dense partonic system in relativistic heavy-ion reactions should manifest itself in a variety of experimental signatures. One of the first proposed "smoking guns" of QGP formation was "jet quenching" [3]. Namely, the disappearance of the collimated spray of hadrons resulting from the fragmentation of a hard scattered parton due to the "absorption" of the parent quark or gluon as it traverses the dense strongly interacting medium produced in the reaction. Extensive theoretical work on high-energy parton propagation in a QCD medium [4–7] has shown that the main mechanism of parton attenuation is of radiative nature: the traversing parton loses energy mainly by multiple gluon emission ("gluonstrahlung"). This medium-induced non-Abelian energy loss results in several observable experimental consequences:

i) depleted production of high p_{T} (leading) hadrons [4],
ii) unbalanced back-to-back di-jet azimuthal correlations [8,9],
iii) modified parton fragmentation functions (energy flow and particle multiplicity within the final jets) [10–12].

The simplest empirically testable (and most easily theoretically computable) consequence of jet quenching is the suppression of inclusive high p_{T} hadron spectra relative to their production in proton-proton collisions in free space. Since most of the energy of the fragmenting parton goes into a single *leading* hadron carrying a large fraction of the original parton energy ($\langle z\rangle = p_{\mathrm{hadron}}/p_{\mathrm{parton}} \approx$ 0.5–0.7 for $p_{\mathrm{hadron}} \gtrsim 4\,\mathrm{GeV}/c$ at RHIC energies), non-Abelian energy loss should result in a significantly suppressed production of high p_{T} hadrons [4]. The amount of suppression is proportional to two physical properties of the medium [5–7]:

i) the initial parton (gluon) density, dN^g/dy, or, equivalently, the transport coefficient $\hat{q} = \langle k_{\mathrm{T}}^2\rangle/\lambda$, which measures the average transverse momentum squared transferred to the projectile parton per unit path length,
ii) the square of the traversed path-length, L^2.

In this contribution, experimental results on inclusive single hadron production at high p_{T} in nucleus-nucleus collisions at top CERN-SPS energies ($\sqrt{s_{NN}} \approx 20\,\mathrm{GeV}$), intermediate RHIC energies ($\sqrt{s_{NN}} = 62.4\,\mathrm{GeV}$), and maximum RHIC energies ($\sqrt{s_{NN}} = 200\,\mathrm{GeV}$), are reviewed and confronted to the theoretical predictions (i) and (ii) of non-Abelian parton energy loss in a dense QCD medium.

In the absence of any initial- or final-state medium effects, the total hard interaction probability in a given A+B collision is only due to independent parton collisions which add incoherently. Based on individual point-like scattering and general QCD factorization arguments [13], the total

[a] e-mail: denterria@nevis.columbia.ed

hard cross-sections in A+B collisions can be written as the incoherent sum of all possible interactions between partons of nucleus A and partons of nucleus B,

$$E\, d\sigma^{\rm hard}_{AB\to hX}/d^3p = A \cdot B \cdot E\, d\sigma^{\rm hard}_{pp\to hX}/d^3p \quad , \qquad (1)$$

where A (B) is the mass number (i.e. the number of nucleons) of nucleus A (B). Direct experimental measurements of hard processes in nuclear collisions, such as Drell-Yan production in Pb+Pb at CERN-SPS [14], or prompt-γ [15,16] and total charm yields [17] in Au+Au at RHIC, support such a scaling. For a given centrality bin, (1) translates into the so-called "$N_{\rm coll}$ (binary) scaling" between hard pp cross-sections and A+B yields:

$$E\, dN^{\rm hard}_{AB\to hX}/d^3p\,(b) = \langle T_{AB}(b)\rangle \cdot E\, d\sigma^{\rm hard}_{pp\to hX}/d^3p \quad , \quad (2)$$

where $T_{AB}(b)$ (Glauber nuclear overlap function) gives the number of nucleon-nucleon (NN) collisions in the A+B transverse overlap area at impact parameter b. The standard method to quantify the effects of the medium in a given hard probe produced in a A+A reaction is given by the *nuclear modification factor*:

$$R_{AA}(p_T, y; b) = \frac{\text{“hot/dense QCD medium”}}{\text{“QCD vacuum”}} = \frac{d^2N_{AA}/dydp_T}{\langle T_{AA}(b)\rangle \cdot d^2\sigma_{pp}/dydp_T} \quad , \qquad (3)$$

which measures the deviation of A+A at b from an incoherent superposition of NN collisions, at transverse momentum $p_{\rm T}$ and rapidity y.

2 A+A collisions at $\sqrt{s_{NN}} \approx$ 20 GeV

Three nucleus-nucleus experiments at the CERN-SPS measured hadron production above $p_{\rm T} = 2$ GeV/c. WA98 and CERES/NA45 measured π^0 and $\pi^\pm$ in Pb+Pb [18] and Pb+Au [19] reactions at $\sqrt{s_{NN}} = 17.3$ GeV, respectively, whereas WA80 measured π^0 in S+Au at $\sqrt{s_{NN}} = 19.4$ GeV [20]. At these relatively low center-of-mass energies, the cross-sections for hard-scattering are very low and the maximum transverse momenta measured was $p_{\rm T} \approx 4$ GeV/c in the three cases[1]. Nonetheless, the power-law tail characteristic of elementary parton-parton interactions is clearly apparent in the measured A+A spectra above $p_{\rm T} \approx 2$ GeV/c (Fig. 1). Unfortunately, no baseline high $p_{\rm T}$ pions were measured in pp collisions at SPS at the same c.m. energies as heavy-ions, and extrapolations from higher-$\sqrt{s}$ data were used to obtain the expected $d^2\sigma_{pp}/dp_{\rm T}dy$ spectrum needed to compute the nuclear modification factor, via (3).

In [25], we compared several proposed pp $\to \pi^{0,\pm} + X$ parametrizations to the existing data in the range $\sqrt{s} \approx$ 16–20 GeV, and found that the parametrization of Blattnig et al. [26] reproduced reasonably well, within ~25%, the shape and magnitude of the experimental pion differential cross-sections below $p_{\rm T} \approx 4$ GeV/c. Using this pp reference, we obtained the nuclear modification factors for

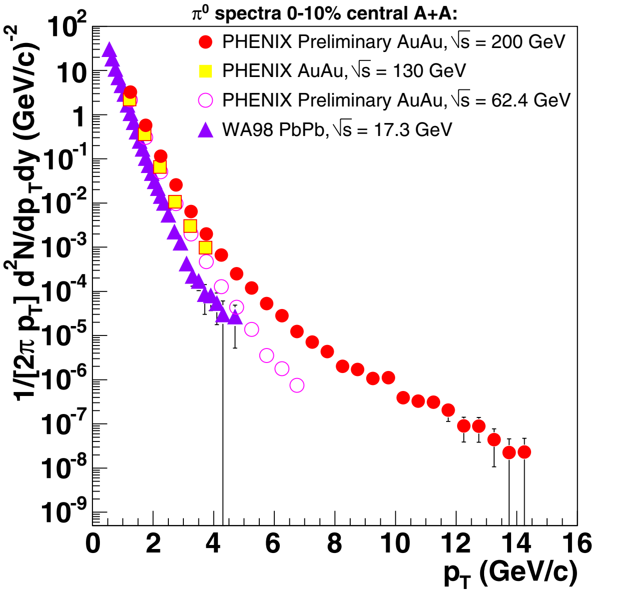

Fig. 1. High $p_{\rm T}$ neutral pion spectra measured in central A+A collisions at different center-of-mass energies: $\sqrt{s_{NN}}$ = 17.3 GeV [18], 62.4 GeV [21], 130 GeV [22], and 200 GeV [23,24].

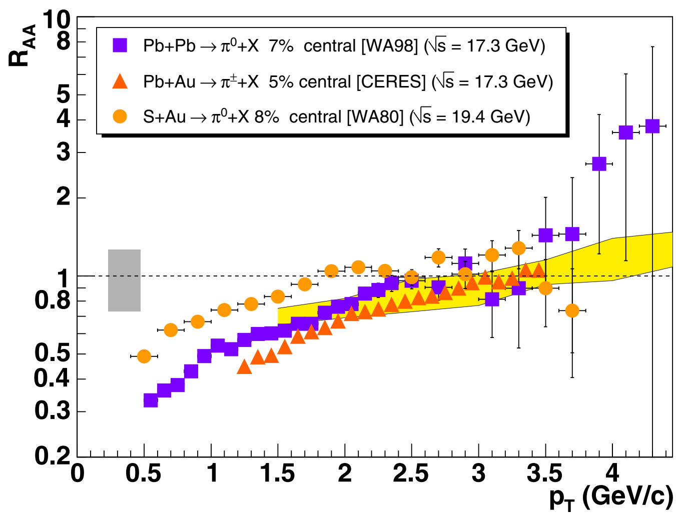

Fig. 2. Nuclear modification factors for pions produced at the CERN-SPS in central Pb+Pb [18], Pb+Au [19], and S+Au [20] at $\sqrt{s_{NN}} \approx 20$ GeV obtained using the pp parametrization proposed in [25], compared to a theoretical prediction [28] of final-state parton energy loss in a system with initial gluon densities $dN^g/dy = 400$–600. The shaded band at $R_{AA} = 1$ represents the overall fractional uncertainty of the data (the CERES data [19] have an extra uncertainty of ±15% not shown).

central A+A collisions at the SPS shown in Fig. 2. Hadron production below $p_{\rm T} \approx 1$ GeV/c falls, as expected, below $R_{AA} = 1$ (the assumption of independent point-like scattering does not hold for soft processes), but high-$p_{\rm T}$ hadroproduction is, within errors, consistent with scaling with the number of NN collisions. Such a result is at variance with the factor of ~ 2 *enhancement* observed in high

[1] Which, yet, roughly corresponded to a remarkable ~1/2 of the kinematical limit, $p_{\rm T}^{\rm max} = \sqrt{s}/2 \approx 9$ GeV/c.

p_T pion production in *peripheral* Pb+Pb reactions at the same energies [18,25] attributed to initial-state p_T broadening as observed in fixed-target p+A reactions ("Cronin effect") [27]. This result points to the existence of an attenuating mechanism that reduces the underlying Cronin enhancement from $R_{AA} \gtrsim 2$ down to values consistent with $R_{AA} \approx 1$ in central A+A. Indeed, theoretical predictions of high p_T π^0 production in central Pb+Pb collisions at the SPS, including Cronin broadening, nuclear-modified parton distribution functions (PDF), and final-state partonic energy loss in an expanding system with initial effective[2] gluon densities $dN^g/dy = 400$–600 [28], reproduce well the observed nuclear modification factor (yellow band in Fig. 2).

The interesting conclusion that a moderate amount of jet quenching is already present in the most central heavy-ion reactions at the SPS would require, however, a direct (and accurate) measurement of the high p_T pp pion spectrum at $\sqrt{s} = 17.3$ GeV. Unfortunately, the default minimum collision energy at RHIC in the pp mode is $\sqrt{s} \approx 48$ GeV [29], making it difficult to directly compare at RHIC high p_T hadroproduction in A+A and pp collisions at center-of-mass energies comparable to the SPS.

3 A+A collisions at $\sqrt{s_{NN}} = 62.4$ GeV

The study of the excitation function of high p_T hadron suppression between top SPS and top RHIC energies was the main motivation behind the dedicated Au+Au run at RHIC intermediate energies ($\sqrt{s_{NN}} = 62.4$ GeV) carried out in April 2004. PHENIX measured neutral pions in the range $p_T = 1$–7 GeV/c [21]. PHOBOS [30] and STAR [31] measured inclusive charged hadrons up to $p_T \approx 4.5$ GeV/c and 12 GeV/c, respectively. However, as in the SPS case, no concurrent pp reference measurement was performed at $\sqrt{s}$ = 62.4 GeV, and the corresponding Au+Au nuclear modifications factors were determined using pp $\to h^{\pm}, \pi^0 + X$ differential cross-sections measured at the top CERN-ISR energies ($\sqrt{s} = 62$–63 GeV) in the 70's and 80's. As discussed in [29], the existing large inconsistencies (up to a factor of ∼3) among the different ISR π^0 data sets can be greatly reduced by removing the direct-γ and η contaminations not subtracted from the original "unresolved" π^0 measurements. By doing so, one can obtain an averaged $d^2\sigma_{pp\to\pi^0}/dp_T dy$ reference spectrum at $\sqrt{s} = 62.4$ GeV with uncertainties ±25% for the R_{AA} denominator.

Figure 3 shows the PHENIX and STAR preliminary nuclear modification factors for high p_T π^0 [21] and $h^{\pm}$ [31] in central Au+Au collisions at $\sqrt{s_{NN}} = 62.4$ GeV obtained using the pp references discussed in [29,31]. Above $p_T \approx 5$ GeV/c, there are ∼3 times less produced pions and inclusive hadrons than expected from point-like scaling of the pp cross-sections. The magnitude of the suppression can be reproduced by models that include parton energy loss in a system with initial gluon densities $dN^g/dy = 650$–800 [32–34] (GLV formalism [6], green band) or transport coefficients $\langle\hat{q}\rangle \approx 7\,\mathrm{GeV}^2/\mathrm{fm}$ [35,36] (Salgado-Wiedemann quenching weights [7], yellow band). The range $p_T \approx 1$–5 GeV/c shows, however, a significant rise and fall of the Au+Au spectra compared to the scaled pp reference[3]. Although part of this effect can be attributed to the expected collective radial flow and Cronin [38]-recombination [39] enhancement[3] at 62.4 GeV, there are also p_T-dependent uncertainties related to the relatively poorly known shape of the ISR pp spectra in this intermediate p_T range [29]. Clearly, a dedicated RHIC proton-proton run at this collision energy would help to reduce these uncertainties and better constrain the theoretical predictions of parton energy loss models.

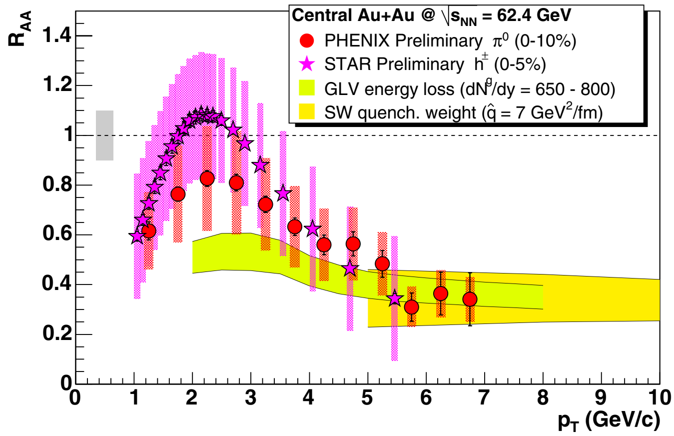

Fig. 3. Preliminary PHENIX and STAR nuclear modification factors, $R_{AA}(p_T)$, for π^0 [21] and $h^{\pm}$ [31] obtained in central Au+Au at $\sqrt{s_{NN}} = 62.4$ GeV using the pp $\to \pi^0, h^{\pm} + X$ references discussed in [29,31]. The data are compared to two theoretical predictions for parton energy loss in a dense medium with initial gluon density $dN^g/dy = 650$–800 [32] or, equivalently, transport coefficient $\langle\hat{q}\rangle = 7\,\mathrm{GeV}^2/\mathrm{fm}$ [35,36]. The error "bands" around each data point indicate the ∼25% systematic uncertainty of the ISR pp baseline spectra at $\sqrt{s}$ = 62.4 GeV. The shaded band at $R_{AA} = 1$ represents the overall fractional uncertainty of the data (absolute normalization of Au+Au spectra and $\langle T_{AA}\rangle$ uncertainties).

4 A+A collisions at $\sqrt{s_{NN}} = 200$ GeV

Undoubtedly, one of the most significant results from the first 4 years of operation at RHIC is the large high p_T hadron suppression observed in central Au+Au reactions at $\sqrt{s_{NN}} = 200$ GeV. Above $p_T \approx 5$ GeV/c, pions [23], eta mesons [24], and inclusive hadrons ($h^{\pm}$) [40,41] show a "universal" factor of ∼5 suppression compared to the corresponding T_{AA}-scaled proton-proton yields. Such a deficit is *not* observed for direct photons [15,16] (Fig. 4). The observed hadron suppression remains constant as a function of p_T up to the highest transverse momenta measured so far ($p_T \approx 14$ GeV/c for π^0 [24], see Fig. 4) in agreement with the parton energy loss model predictions. In the first theoretical predictions [5], approximations of the underlying

[2] Note that at SPS energies, the initial medium is probably more "quarkonic" than "gluonic".

[3] An effect which is larger for the charged hadrons than for π^0 due to the observed enhanced (anti)proton production [37].

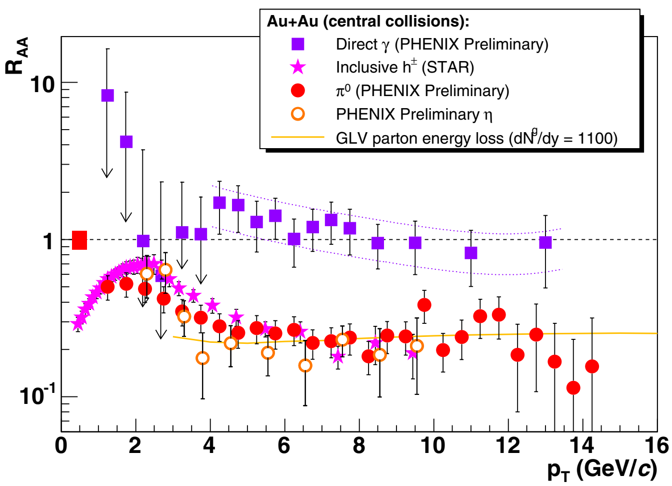

Fig. 4. $R_{AA}(p_T)$ measured in central Au+Au at 200 GeV for: direct photons [15,16], inclusive charged hadrons [40], π^0 [24], and η [24] compared to theoretical predictions for parton energy loss in a dense medium with $dN^g/dy = 1100$ [28]. The shaded band at $R_{AA} = 1$ represents the overall fractional uncertainty of the data (absolute normalization of spectra and $\langle T_{AA}\rangle$ uncertainties). The baseline pp reference of the direct γ Au+Au data is a NLO calculation whose uncertainties are indicated by the dotted lines around the points [16].

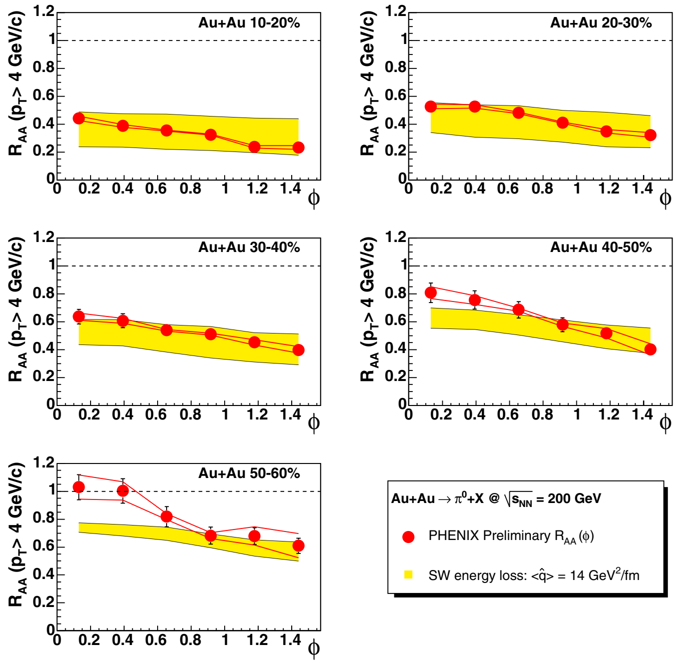

Fig. 5. Preliminary PHENIX nuclear modification factor, $R_{AA}(\phi)$, for π^0 production above $p_T = 4$ GeV/c as a function of the azimuthal angle ϕ with respect to the reaction plane in 5 centrality classes of Au+Au at $\sqrt{s_{NN}} = 200$ GeV [43]; compared to parton energy loss calculations [35] for an azimuthally asymmetric system with average transport coefficient $\langle \hat{q}\rangle \approx 14\,\mathrm{GeV}^2/\mathrm{fm}$ (yellow band, encompassing the limits of two different prescriptions for the sampling of the energy loss). The lines around the experimental data show the uncertainties in the reaction plane and R_{AA} determinations.

Landau-Pomeranchuk-Migdal (LPM) interference effect in gluon bremsstrahlung resulted in a logarithmic dependence of the quenching factor on the parton energy and, therefore, in a $R_{AA}(p_T)$ that (slowly) increased for increasing hadron p_T's in apparent contradiction with the data. However, (i) the use of a realistic energy distribution of the emitted gluons (rather than the mean value) [42], (ii) finite kinematic constraints (in the energy loss and in-medium path length), and/or depleted nuclear PDFs (in the EMC region for Bjorken $x \approx \frac{2p_T/\langle z\rangle}{\sqrt{s_{NN}}} \gtrsim 0.2$ values corresponding to $p_T \gtrsim 12$ GeV/c) [28], and (iii) the increasing power-law (local) exponent of the parton spectra with p_T [36], all explain the effectively constant R_{AA} evolution as a function of transverse momentum.

A robust prediction of non-Abelian parton energy loss calculations is the expected $\propto L^2$ dependence of the average energy loss as a function of the in-medium path length [5]. Such a behaviour, predicted for a *static* QCD medium, turns into an effective $\propto L$-dependence in an expanding QGP [6]. An interesting way to experimentally test the L dependence of the energy loss is by exploiting the spatial azimuthal asymmetry of the system produced in non-central nuclear collisions. Indeed, due to the characteristic almond-like shape of the overlapping matter produced in A+A reactions with finite impact parameter, partons traversing the produced medium along the direction perpendicular to the reaction plane ("out-of-plane") will comparatively go through more matter than those going parallel to it ("in-plane"), and therefore are expected to lose more energy. In general, the total path length along a given azimuthal angle ϕ with respect to the reaction plane is $L(\phi) \approx 1 - (\varepsilon/2)\cos(2\phi)$ [43], where ε is the eccentricity of the system. By looking at the suppression pattern along different ϕ trajectories one can test the L dependence of the energy loss. PHENIX [43] has recently presented nuclear modification factors for high p_T π^0 in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV binned in ϕ angle with respect to the reaction plane (determined with the Beam-Beam-Counters at high rapidities). The resulting $R_{AA}(\phi)$ curves (Fig. 5) show clearly a factor of $\sim$2 more suppression out-of-plane ($\phi = \pi/2$) than in-plane ($\phi = 0$) for all the centralities (eccentricities) considered. Theoretical calculations of parton energy loss (based in the quenching weights formalism [7]) in an azimuthally asymmetric medium [35] predict a significantly smaller difference between the suppression patterns for partons emitted at $\phi = 0$ and $\phi = \pi/2$ (bands in Fig. 5). The discrepancy model–data is stronger for more peripheral centralities (with correspondingly larger eccentricities) and challenges the underlying in-medium path-length dependence of non-Abelian parton energy loss (a detailed discussion of this observation can be found in [43]) and/or points out the necessity of an additional source of azimuthal anisotropy in pion production at high p_T. Likely, collective elliptic flow is responsible for the extra boost of in-plane pions (even at p_T values above 4 GeV/c), though this should be confirmed quantitatively.

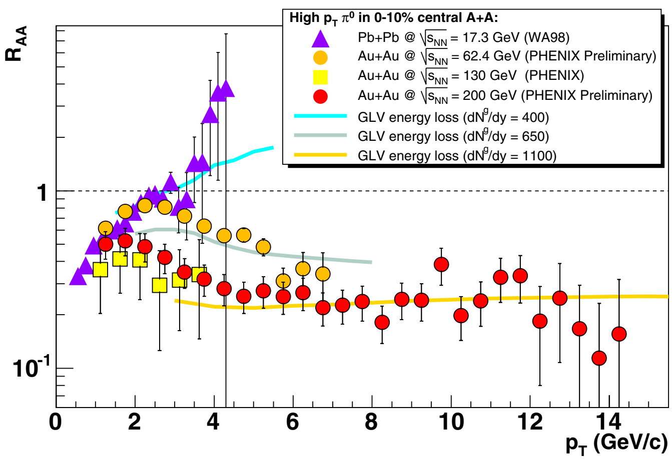

Fig. 6. Nuclear modification factor, $R_{AA}(p_\mathrm{T})$, for high p_T pion production in central nucleus-nucleus reactions in Pb+Pb [18] at $\sqrt{s_{NN}}$ = 17.3 GeV, Au+Au at $\sqrt{s_{NN}}$ = 62.4 [21], 130 [22], and 200 GeV [23], compared to GLV parton energy loss calculations [28, 32] for different initial gluon densities (dN^g/dy = 400, 650 and 1100). Absolute normalization errors of the data, $\mathcal{O}$(10–25%), are not shown.

Table 1. Effective initial gluon densities, dN^g/dy, [28,32] and time-averaged transport coefficients $\langle\hat{q}\rangle$ [35], for the strongly interacting media produced in central A+A collisions at four different center-of-mass energies obtained from parton energy loss calculations reproducing the observed high p_T leading π^0 suppression at each collision energy ("jet tomography"). The measured charged particle multiplicity densities at mid-rapidity [45], $dN_\mathrm{ch}^\mathrm{exp}/d\eta$, are also quoted for each $\sqrt{s_{NN}}$.

	$\sqrt{s_{NN}}$ (GeV)	dN^g/dy	$\langle\hat{q}\rangle$ (GeV^2/fm)	$dN_\mathrm{ch}^\mathrm{exp}/d\eta$
SPS	17.3	400	3.5	312 ± 21
RHIC	62.4	650	7.	475 ± 33
RHIC	130.	∼900	∼11	602 ± 28
RHIC	200.	1100	14.–15.	687 ± 37

5 QCD medium properties via "jet tomography"

Figure 6 compiles all the available $R_{AA}(p_\mathrm{T})$ for high p_T (leading) neutral pions measured in central A+A collisions in the range $\sqrt{s_{NN}} \approx$ 20–200 GeV. The experimental suppression factors can be well reproduced by parton energy loss calculations that assume the formation of strongly interacting systems with initial gluon densities per unit rapidity in the range $dN^g/dy \approx$ 400–1200 [28,32] or, equivalently [7], with time-averaged transport coefficients $\langle\hat{q}\rangle \approx$ 3.5–15 GeV^2/fm [35] (see Table 1).

For each collision energy, the derived values for the initial rapidity density, dN^g/dy, and transport coefficient, $\langle\hat{q}\rangle$, are consistent with each other and with the final particle density measured in the reactions. Indeed, assuming an isentropic expansion process, all the hadrons produced at mid-rapidity in a heavy-ion collision come directly from the original gluons released in the initial phase of the reaction[4]:

$$\frac{dN^g}{dy} \approx \frac{N_\mathrm{tot}}{N_\mathrm{ch}}\left|\frac{d\eta}{dy}\right|\frac{dN_\mathrm{ch}}{d\eta} \approx 1.2 \cdot \frac{dN_\mathrm{ch}}{d\eta} \quad . \tag{4}$$

This relation is relatively well fulfilled by the data as can be seen by comparing columns third and fifth of Table 1. The time-dependent transport coefficient scales with the energy density of the medium[5] (ε in GeV/fm^3) like [36]:

$$\hat{q}(\tau) \approx 8 \cdot \varepsilon^{3/4}(\tau) \quad . \tag{5}$$

Since, for an ideal QGP (with 2+1 flavors, i.e. degeneracy $g \approx 42$), the particle ($\rho \approx 4.7\cdot(T/\hbar c)^3$) and energy ($\varepsilon \approx 14\cdot T^4/(\hbar c)^3$) densities [44] are related via $\rho \approx 0.66\cdot(\varepsilon/\hbar c)^{3/4} \approx 2.3\cdot\varepsilon^{3/4}$, one can express (5) as

$$\hat{q}(\tau) \approx 3.5 \cdot \rho(\tau) = 3.5 \cdot \rho_0\left(\frac{\tau_0}{\tau}\right) = 3.5 \cdot \frac{dN^g}{dV}\left(\frac{\tau_0}{\tau}\right) , \tag{6}$$

where for the second equality we have assumed a 1-D Bjorken expansion. In this scenario, since the medium expands boost-invariantly in the longitudinal direction, we can further write $dV = A_T\,\tau_0\,dy$ where A_T is the transverse area of the system, and therefore

$$\hat{q}(\tau) \approx \frac{3.5}{A_T}\cdot\frac{dN^g}{dy}\cdot\frac{1}{\tau} \quad . \tag{7}$$

According to [7], the relation between the time-averaged $\hat{q}(\tau)$ in an expanding medium and that of a fixed static medium is (taking $\tau_0 \ll \tau_f$):

$$\langle\hat{q}(\tau)\rangle = \frac{2}{L_\mathrm{eff}^2}\int_{\tau_0}^{\tau_0+L_\mathrm{eff}}(\tau-\tau_0)\,\hat{q}(\tau)\,d\tau \approx \frac{2}{L_\mathrm{eff}}\,\frac{3.5}{A_T}\,\frac{dN^g}{dy} \tag{8}$$

where L_eff is the effective length traversed by the parton in the medium. Despite the simplifying assumptions used, this approximate relation between the medium transport coefficient and the original gluon rapidity density is relatively well fulfilled by the data too (Table 1). E.g. by taking $L_\mathrm{eff} \approx 4$ fm and $\langle A_T\rangle \approx 125$ fm^2 for 0–10% central Au+Au we get

$$\langle\hat{q}(\tau)\rangle \approx 0.014 \cdot \frac{dN^g}{dy} \quad . \tag{9}$$

6 Excitation function of high p_T leading hadron suppression

Based on rather general grounds, the total amount of leading hadron suppression at a fixed (large) p_T in central A+A collisions should depend on the collision energy only via two $\sqrt{s}$-dependent factors:

i) the initial parton density of the produced system, and

[4] We use here: $N_\mathrm{tot}/N_\mathrm{ch} = 3/2$, and $|d\eta/dy| \approx 0.8$.

[5] Rather than a thermodynamical variable, $\hat{q}$ is actually a *dynamical* quantity resulting from the product of the time-dependent density of scattering centers times the strength of each single elastic scattering [7].

ii) the relative fraction of quarks and gluons fragmenting into the hadron at the p_T value in question.

Indeed, on one hand, since $\Delta E_{\rm loss} \propto dN^g/dy \propto dN_{\rm ch}/d\eta$, and since the total particle multiplicity produced at midrapidity in A+A collisions is observed to follow the approximate scaling [45]

$$dN_{\rm ch}/d\eta \approx 0.75 \cdot (N_{\rm part}/2) \cdot \ln(\sqrt{s_{NN}}/1.5) \quad , \qquad (10)$$

one expects the amount of suppression to increase accordingly with $\sqrt{s_{NN}}$ (note, however, that the true evolution of the suppression will be faster than that given by (10) since, for increasing energies, *both* dN^g/dy and the corresponding lifetime of the quenching medium are larger). On the other hand, the probability for a gluon to lose energy is a factor $C_A/C_F = 9/4$ larger than the corresponding probability for a quark[6], and the relative fraction of hard scattered quarks and gluons (going through the medium and) fragmenting into a hadron at a fixed p_T varies with $\sqrt{s_{NN}}$ in a proportion given by a tradeoff between (i) the relative density of quarks and gluons at the corresponding Bjorken $x = 2p_T/\sqrt{s}$, and (ii) the relative fragmentation "hardness" of quarks and gluons at the corresponding z value. A full NLO calculation [47] gives the results shown in Fig. 7 (bottom).

In [48], Wang&Wang presented a pQCD calculation of the expected $\sqrt{s_{NN}}$-dependence of the nuclear modification factor for high-p_T π^0 production in central Au+Au collisions due to parton energy loss in the produced (2-D expanding) QGP. The resulting curve is shown in Fig. 7 (top). The amount of suppression (for a 6 GeV/c leading hadron) increases monotonically with $\sqrt{s_{NN}}$ due to the growing initial parton density, QGP lifetime, and gluonic nature of the quenched parton, and seems to saturate at $R_{AA} \approx 0.02$ for c.m. energies above ~3 TeV. The existence of a maximum amount of suppression is due to "irreducible" particle production from the outer corona of the medium, which remains unsuppressed even for extreme energy densities [36].

In order to test the effect of the radiative QCD energy loss, they compared the expected non-Abelian prescription (in which gluons lose $\Delta E_q/\Delta E_g = 9/4$ times more energy than quarks) to an arbitrary "non-QCD" recipe in which quarks and gluons lose the same amount of energy ($\Delta E_q = \Delta E_g$). For a fixed hadron p_T value, say $p_T \approx$ 6 GeV/c, the total suppression factors from non-Abelian and non-QCD energy losses are relatively similar below

[6] In QCD, the relative strengths of the three distinct quark and gluon vertices, $\alpha_s C_F$ for $q \to qg$, $\alpha_s C_A$ for $g \to gg$, and $\alpha_s T_F$ for $g \to q\bar{q}$, are completely determined by the structure of the gauge group (Casimir factors) describing the strong force. For $SU(N_c)$ where N_c is the number of colors, $C_A = N_c$, $C_F = (N^2-1)/2N_C$ and $T_F = 1/2$. The probability for a gluon (quark) to radiate a gluon is proportional to the color factor $C_A = 3$ ($C_F = 4/3$). In the asymptotic limit, and neglecting the splitting of gluons to quark-antiquark pairs (proportional to the smaller color factor $T_R = 1/2$), the average number of gluons radiated by a gluon is, therefore, a factor $C_A/C_F = 9/4$ higher than the number of gluons radiated by a quark [46].

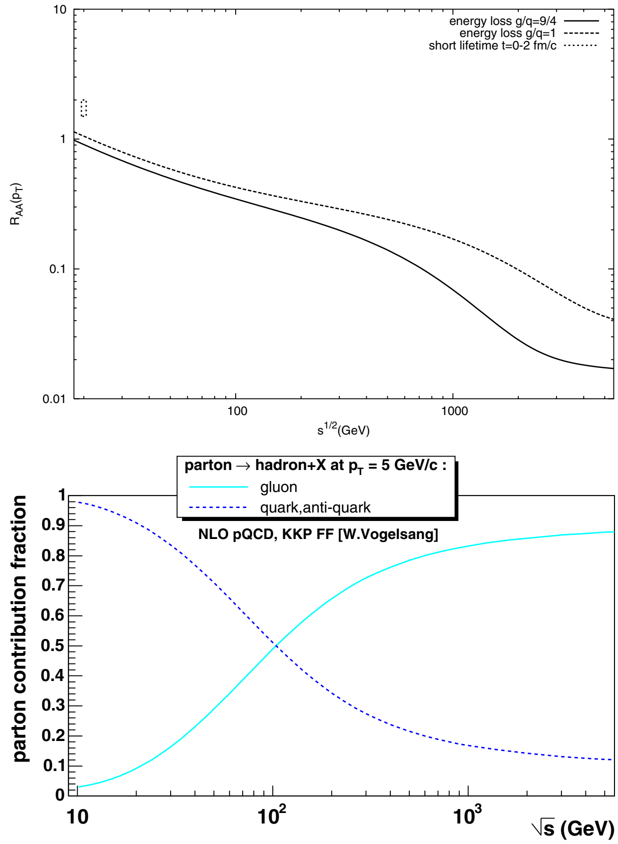

Fig. 7. Top (Fig. taken from [48]): R_{AA} for neutral pions as a function of collision energy at fixed $p_T = 6$ GeV/c in the 10% most central Au+Au collisions for non-Abelian (lower curve) and "non-QCD" (upper curve) energy loss patterns. Bottom: Relative proportion of quarks and gluons fragmenting into a hadron at fixed $p_T = 5$ GeV/c in pp collisions in the range $\sqrt{s}$ = 10–5500 GeV as given by NLO pQCD [47].

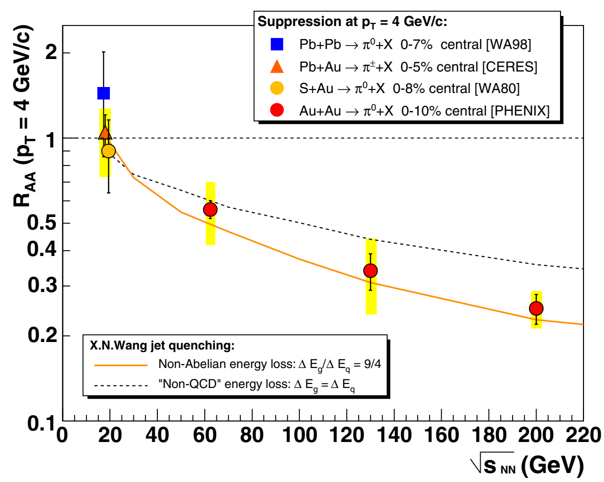

Fig. 8. Excitation function of the nuclear modification factor, $R_{AA}(\sqrt{s_{NN}})$, for π^0 production in central A+A reactions at a fixed p_T = 4 GeV/c value, compared to predictions of a jet-quenching model with canonical non-Abelian (solid line) and "non-QCD" (dashed line) energy losses [48]. The shaded band around each data point represents the absolute systematic errors (absolute normalization of A+A and pp spectra and nuclear overlap, $\langle T_{AA} \rangle$, uncertainties).

$\sqrt{s_{NN}} \approx 100$ GeV, since quarks are the dominant parton fragmenting into a high p_T hadron (Fig. 7, bottom). Above $\sqrt{s_{NN}} \approx 100$ GeV, gluons take over as the dominant parent parton of hadrons with $p_T \approx 6$ GeV/c and, consequently, the R_{AA} values drop faster in the canonical non-Abelian scenario. The experimental excitation function of high p_T π^0 suppression in central A+A collisions supports the expected QCD radiative energy loss behaviour, as demonstrated in Fig. 8.

Summary

Experimental results on high p_T leading hadron production in nucleus-nucleus reactions at center-of-mass energies $\sqrt{s_{NN}} \approx$ 20–200 GeV have been discussed with an emphasis on the observed suppression of the per-nucleon yields relative to pp collisions at the same $\sqrt{s}$. The amount of suppression steadily increases from CERN-SPS energies (Pb+Pb at $\sqrt{s_{NN}} \approx 20$ GeV) reaching a maximum quenching factor of $\sim$5 at the highest RHIC energies (Au+Au at $\sqrt{s_{NN}} = 200$ GeV) due to the increased initial parton density, lifetime of the dissipative medium, and gluonic nature of the parent fragmenting parton. The p_T and $\sqrt{s_{NN}}$ dependences of the measured nuclear modification factors are in agreement with theoretical calculations of final-state non-Abelian energy loss in a dense QCD medium. The observed dependence of the suppression factors on the reaction plane orientation is, however, significantly stronger than the one expected from the $\propto L$ in-medium path-length dependence predicted by jet quenching models, and points to an additional source of azimuthal anisotropy (likely collective elliptic flow) in hadron production at p_T values above 4 GeV/c.

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