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

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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 ($O(\text{TeV})$ at the RHIC collider) in a “large” volume, $O(10^3 \text{ fm}^3)$, under laboratory conditions. The expectations, based on first-principles lattice-QCD calculations [1], are that for energy densities above $\epsilon \approx 0.7 \text{ GeV/fm}^3$, 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 [4,5,6,7] 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) [10,11,12].

The most simple 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 ($\langle z \rangle = p_{\text{hadron}}/p_{\text{parton}} \approx 0.5 – 0.7$ for $p_{\text{hadron}} \gtrsim 4 \text{ GeV/c}$ 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 [5,6,7]:

(i) the initial parton (gluon) density, $dN^g/dy$, or, equivalently, the transport coefficient $\hat{q} = \langle k_T^2 \rangle/\lambda$ (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 (A+A) collisions at top CERN-SPS energies ($\sqrt{s} \approx 20 \text{ GeV}$), intermediate RHIC energies ($\sqrt{s} = 62.4 \text{ GeV}$), and maximum RHIC energies ($\sqrt{s} = 200 \text{ GeV}$), 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 effect, 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 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. Namely,

\[ E \, d\sigma_{AB-hX}^{\text{hard}} / d^3p = A \cdot B \cdot E \, d\sigma_{pp-hX}^{\text{hard}} / d^3p, \quad (1) \]

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-\(\gamma\) [15] and total charm yields [17] in Au+Au at RHIC, support such a scaling. For a given centrality bin, Eq. (1) translates into the so-called “N_{coll} (binary) scaling” between hard p+p cross-sections and A+B yields:

\[ E \, dN_{AB-hX}^{\text{hard}} / d^3p (b) = (T_{AB}(b)) \cdot E \, d\sigma_{pp-hX}^{\text{hard}} / d^3p, \quad (2) \]

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:

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

which measures the deviation of A+A at \(b\) from an incoherent superposition of \(NN\) collisions, at transverse momentum \(p_T\) and rapidity \(y\).

2 A+A collisions at \(\sqrt{s_{NN}} \approx 20\,\text{GeV}\).

Three nucleus-nucleus experiments at CERN-SPS measured hadron production above \(p_T\) \(\approx 2\,\text{GeV/c}\). WA98 and CERES/NA45 measured \(\pi^0\) and \(\pi^\pm\) in Pb+Pb [18] and Pb+Au [19] reactions at \(\sqrt{s_{NN}} = 17.3\,\text{GeV}\) resp., whereas WA80 measured \(\pi^0\) in S+Au at \(\sqrt{s_{NN}} = 19.4\,\text{GeV}\) [20]. At these relatively low center-of-mass energies, the cross-sections for hard-scattering are extremely low and the maximum transverse momenta measured was \(p_T \approx 4\,\text{GeV/c}\) 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 \(p_T \approx 2\,\text{GeV/c}\) (Fig. 1). Unfortunately, no baseline high \(p_T\) pions were measured in p+p 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 \(d^2\sigma_{pp}/dp_Tdy\) spectrum needed to compute the nuclear modification factor, via Eq. (3).

[1] Which, yet, roughly corresponded to a remarkable \(\sim 1/2\) of the kinematical limit, \(p_T^{\text{max}} = \sqrt{s}/2 \approx 9\,\text{GeV/c}\).

In [25], we compared several proposed \(p+p \rightarrow \pi^{0,\pm} + X\) parametrizations, to the existing data in the range \(\sqrt{s} \approx 16 - 20\,\text{GeV}\), and found that the parametrization of Blattning et. al [26] reproduced reasonably well, within \(\sim 25\%\), the shape and magnitude of the experimental pion differential cross-sections below \(p_T \approx 4\,\text{GeV/c}\). Using this p+p reference, we obtained the nuclear modification factors for central A+A collisions at SPS shown in Fig. 2.

Hadron production below \(p_T \approx 1\,\text{GeV/c}\) falls, as expected, below \(R_{AA} = 1\) (the assumption of independent point-like scattering does not hold for soft processes), but high-\(p_T\) hadroproduction is, within errors, consistent with scaling with the number of \(N\) \(N\) collisions. Such a result is at variance with the factor of \(\sim 2\) enhancement observed in high \(p_T\) 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 \(p_T\) \(\pi^0\) production in central Pb+Pb at 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 \(dN/g/df = 400 - 600\) [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 SPS would require, however, a direct (and accurate) measurement of the high $p_T$ p+p pion spectrum at $\sqrt{s} = 17.3$ GeV. Unfortunately, the default minimum collision energy at RHIC in the proton-proton mode is $\sqrt{s} \approx 48$ GeV \cite{20}, making it difficult to directly compare at RHIC high $p_T$ hadroproduction in A+A and p+p collisions at center-of-mass energies comparable to SPS.

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 \cite{21} and PHOBOS \cite{30} and STAR \cite{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 p+p reference measurement was performed at $\sqrt{s} = 62.4$ GeV, and the corresponding Au+Au nuclear modifications factors were determined using p+p → $h^\pm, \pi^\pm + X$ differential cross-sections measured at the top CERN-ISR energies ($\sqrt{s} = 62 – 63$ GeV) in the 70s and 80s. As discussed in \cite{20}, the existing large inconsistencies (up to a factor of $\sim 3$) among the different ISR $\pi^0$ data sets can be greatly reduced by removing the direct-$\gamma$ and $\eta$ contaminations not subtracted from the original “unresolved” $\pi^0$ measurements. By doing so, one can obtain an averaged $d^2\sigma_{pp \rightarrow \pi^0}/dp_Tdy$ reference spectrum at $\sqrt{s} = 62.4$ GeV with uncertainties $\pm 25\%$ for the $R_{AA}$ denominator.

Figure 2 shows the PHENIX and STAR preliminary nuclear modification factors for high $p_T$ $\pi^0$ \cite{21} and $h^\pm$ \cite{31} in central Au+Au collisions at $\sqrt{s_{NN}} = 62.4$ GeV obtained using the p+p references discussed in \cite{20,31}. Above $p_T \approx 5$ GeV/c, there are $\sim 3$-times less produced pions and inclusive hadrons than expected from point-like scaling of the p+p cross-sections. The magnitude of the suppression can be reproduced by models that include parton energy loss in a system with initial gluon densities $dN^g/dy = 650 – 800$ \cite{20,32,33,34} (GLV formalism \cite{6}, green band) or transport coefficients $\langle \hat{q} \rangle \approx 7$ GeV$^2$/fm \cite{35,36} (Salgado-Wiedemann quenching weights \cite{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 p+p reference\cite{3}. Although part of this effect can be certainly attributed to the expected collective radial flow and Cronin enhancement\cite{39} at 62.4 GeV, there are also $p_T$-dependent uncertainties related to the relatively poorly known shape of the ISR p+p spectra in this intermediate $p_T$ range \cite{20}. Clearly, a dedicated RHIC proton-proton run at this collision energy would help to reduce these uncertainties and better constraint the theoretical predictions of parton energy loss models.

![Figure 2](image_url) **Fig. 2.** Nuclear modification factors for pions produced at CERN-SPS in central Pb+Pb \cite{18}, Pb+Au \cite{19}, and S+Au \cite{20} at $\sqrt{s_{NN}} \approx 20$ GeV obtained using the p+p parametrization proposed in \cite{25} compared to a theoretical prediction \cite{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 (CERES data \cite{19} have an extra uncertainty of $\pm 15\%$ not shown).

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

Figure 3 shows the PHENIX and STAR preliminary nuclear modification factors for high $p_T$ $\pi^0$ \cite{21} and $h^\pm$ \cite{31} in central Au+Au collisions at $\sqrt{s_{NN}} = 62.4$ GeV obtained using the p+p references discussed in \cite{20,31}. The data are compared to two theoretical predictions for parton energy loss in a dense medium with initial gluon density $dN^g/dy = 650 – 800$ \cite{32} or, equivalently, transport coefficient $\langle \hat{q} \rangle = 7$ GeV$^2$/fm \cite{35,36}. The error “bands” around each data point indicate the $\sim 25\%$ systematic uncertainty of the ISR p+p 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).

![Figure 3](image_url) **Fig. 3.** Preliminary PHENIX and STAR nuclear modification factors, $R_{AA}(p_T)$, for $\pi^0$ \cite{21} and $h^\pm$ \cite{31} obtained in central Au+Au at $\sqrt{s_{NN}} = 62.4$ GeV using the p+p → $\pi^0, h^\pm + X$ references discussed in \cite{20,31}. The data are compared to two theoretical predictions for parton energy loss in a dense medium with initial gluon density $dN^g/dy = 650 – 800$ \cite{32} or, equivalently, transport coefficient $\langle \hat{q} \rangle = 7$ GeV$^2$/fm \cite{35,36}. The error “bands” around each data point indicate the $\sim 25\%$ systematic uncertainty of the ISR p+p 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).

$^3$ An effect which is larger for the charged hadrons than for $\pi^0$ due to the observed enhanced (anti)proton production \cite{37}.
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 \( \text{Au+Au} \) reactions at \( \sqrt{s_{_{NN}}} = 200 \text{ GeV} \). Above \( p_T \approx 5 \text{ GeV}/c \), pions [23], eta mesons [24], and inclusive hadrons \( (h^\pm) \) [40,41] show all a “universal” factor of \( \sim 5 \) 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 \( (p_T \approx 14 \text{ GeV}/c \text{ for } \pi^0) \) see Fig. 4 in agreement with the parton energy loss model predictions. In the first theoretical predictions [5], approximations of the underlying 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 \( x \approx 2p_T/\sqrt{s_{_{NN}}} \gtrsim 0.2 \) values corresponding to \( p_T \gtrsim 12 \text{ GeV}/c \) [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.

**Fig. 4.** \( R_{AA}(p_T) \) measured in central \( \text{Au+Au} \) at 200 GeV for: direct photons [15,16], inclusive charged hadrons [40], \( \pi^0 \) [24], and \( \eta \) [24] compared to theoretical predictions for parton energy loss in a dense medium with \( dN^\gamma/dy = 1100 \) [23]. The shaded band at \( R_{AA} = 1 \) represents the overall fractional uncertainty of the data (absolute normalization of spectra and \( T_{AA} \) uncertainties). The baseline \( p+p \) reference of the direct \( \gamma \) \( \text{Au+Au} \) data is a NLO calculation whose uncertainties are indicated by the dotted lines around the points [16].

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 [24]. Such a behaviour predicted for a static QCD medium, turns into an effective \( \propto L \)-dependence in an expanding QGP [4]. 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 \( \phi \) with respect to the reaction plane is \( L(\phi) = 1 - (\varepsilon/2) \cos(2\phi) \) [43], where \( \varepsilon \) is the eccentricity of the system. By looking at the suppression pattern along different \( \phi \) trajectories one can test the \( L \) dependence of the energy loss. PHENIX [43] has recently presented nuclear modification factors for high \( p_T \) \( \pi^0 \) in \( \text{Au+Au} \) collisions at \( \sqrt{s_{_{NN}}} = 200 \text{ GeV} \) binned in \( \phi \) 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

**Fig. 5.** Preliminary PHENIX nuclear modification factor, \( R_{AA}(\phi) \), for \( \pi^0 \) production above \( p_T = 4 \text{ GeV}/c \) as a function of the azimuthal angle \( \phi \) with respect to the reaction plane in 5 centrality classes of \( \text{Au+Au} \) at \( \sqrt{s_{_{NN}}} = 200 \text{ GeV} \) [43]; compared to parton energy loss calculations [36] for an azimuthally asymmetric system with average transport coefficient \( \langle \hat{q} \rangle \approx 14 \text{ GeV}^2/\text{fm} \) (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 \( R_{AA} \) determination.

4 \( \text{A+A} \) collisions at \( \sqrt{s_{_{NN}}} = 200 \text{ GeV}. \)
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 \(\phi = \pi/2\) (yellow bands in Fig. 4). 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 \[13\]) 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.

5 QCD medium properties via “jet tomography”

Fig. 6 compiles all the available \(R_{AA}(p_T)\) 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/fm \[33\] (see Table 1).

| \(\sqrt{s_{NN}}\) (GeV) | \(dN^g/dy\) | \(\langle \hat{q} \rangle\) (GeV/\(\text{fm}^3\)) | \(dN_{ch}^{exp}/d\eta\) |
|-----------------------|-------------|-----------------|------------------|
| SPS 17.3              | 400         | 3.5             | 312 ± 21         |
| RHIC 62.4             | 650         | 7.              | 475 ± 33         |
| RHIC 130              | \(\sim 900\) | \(\sim 11\)     | 602 ± 28         |
| RHIC 200              | 1100        | 14 - 15         | 687 ± 37         |

Table 1. Effective initial gluon densities, \(dN^g/dy\), and time-averaged transport coefficients \(\langle \hat{q} \rangle\), for the strongly interacting media produced in central A+A collisions at different impact energies \(\sqrt{s_{NN}}\). The measured charged particle multiplicity densities at mid-rapidity \[35\], \(dN_{ch}^{exp}/d\eta\), are also quoted for each \(\sqrt{s_{NN}}\).

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 A+A collision come directly from the original gluons released in the initial phase of the reaction:\(^4\)

\[
\frac{dN^g}{dy} \approx N_{int} \frac{dn}{dy} \frac{dN_{ch}}{d\eta} \approx 1.8 \cdot \frac{dN_{ch}}{d\eta} \tag{4}
\]

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\(^5\) \(\varepsilon \approx \langle \hat{q} \rangle \approx 3.5 \cdot \varepsilon^{3/4}(\tau)\). 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 \(\varepsilon \approx 14 \cdot T^3/((hc)^3\) densities \[44\] are related via \(\rho \approx 0.66 \cdot \varepsilon^{3/4}\), one can express Eq. \(4\) as

\[
\hat{q}(\tau) \approx 3.5 \cdot \rho(\tau) = 3.5 \cdot \rho_0 \left(\frac{\tau_0}{\tau}\right) = 3.5 \cdot \frac{dN^g}{dV} \left(\frac{\tau_0}{\tau}\right), \tag{5}
\]

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

\[
\hat{q}(\tau) \approx \frac{3.5}{A_T} \cdot \frac{dN^g}{d\tau} \cdot \frac{1}{\tau}. \tag{7}
\]

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

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

where \(L_{eff}\) is the effective length traversed by the parton in the medium. Despite the simplifying assumptions used,

\(^4\) We use here: \(N_{int}/N_{ch} \approx 3/2\), and \(dn/dy \approx 1.2\).

\(^5\) 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 \[7\].
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 $L_{\text{eff}} \approx 4 \text{ fm}$ and $\langle \Delta T \rangle \approx 125 \text{ fm}^2$ for 0-10% central Au+Au we get

$$\langle \hat{q}(\tau) \rangle \approx 0.014 \cdot \frac{dN_g}{dy}. \quad (9)$$

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

Indeed, on the one hand, since $\Delta E_{\text{loss}} \propto dN^g/dy \propto dN_{\text{ch}}/dy$, and since the total particle multiplicity produced at mid-rapidity in A+A collisions is observed to follow the approximate scaling [12]:

$$dN_{\text{ch}}/dy \approx 0.75 \cdot (N_{\text{part}}/2) \cdot \ln(\sqrt{s_{NN}/1.5}), \quad (10)$$

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 Eq. 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 probability for a quark, 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 [17] gives the results shown in Fig. 7 (bottom).

In reference [15], Wang&Wang presented a pQCD calculation of the expected $\sqrt{s_{NN}}$-dependence of the nuclear modification factor for high-$p_T$ $\pi^0$ 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 $\sim 3$ 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, $p_T \approx 6 \text{ GeV/c}$, the total suppression factors from non-Abelian and non-QCD energy losses are relatively similar below $\sqrt{s_{NN}} \approx 100 \text{ GeV}$, since quarks are the dominant parton fragmenting into a high $p_T$ hadron (Fig. 7 bottom). Above $\sqrt{s_{NN}} \approx 100 \text{ GeV}$, gluons take over as the dominant parent parton of hadrons with $p_T \approx 6 \text{ GeV/c}$ and, consequently, the $R_{AA}$ values drop faster in the canonical non-Abelian scenario. The experimental excitation function of high $p_T$ $\pi^0$ suppression in central A+A collisions supports the expected QCD radiative energy loss behaviour as demonstrated in Fig. 8.
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Fig. 8. Excitation function of the nuclear modification factor, \( R_{AA}(\sqrt{s_{NN}}) \), for \( \pi^0 \) production in central A+A reactions at a fixed \( p_T \approx 4 \text{ GeV}/c \) value, compared to predictions of a jet-quenching model with canonical non-Abelian (solid line) and “non-QCD” (dashed line) energy losses [53]. The shaded band around each data point represents the absolute systematic errors (absolute normalization of A+A and p+p spectra and nuclear overlap, \( T_{AA} \), uncertainties)

Summary

Experimental results on high \( p_T \) leading hadron production in nucleus-nucleus reactions at center-of-mass energies \( \sqrt{s_{NN}} \approx 20 - 200 \text{ GeV} \) have been discussed with an emphasis on the observed suppression of the per-nucleon yields relative to p+p collisions at the same \( \sqrt{s} \). The amount of suppression steadily increases from CERN-SPS energies (\( \text{Pb+Pb at } \sqrt{s_{NN}} \approx 20 \text{ GeV} \)) reaching a maximum quenching factor of \( \sim 5 \) at the highest RHIC energies (\( \text{Au+Au at } \sqrt{s_{NN}} = 200 \text{ GeV} \)) 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 \( \alpha L \) 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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