Indications of suppressed high $p_T$ hadron production in nucleus-nucleus collisions at CERN-SPS

David d’Enterria

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

Abstract

Inclusive pion production at high transverse momenta ($p_T \gtrsim 2$ GeV/$c$) in nucleus-nucleus (A+A) collisions at CERN SPS ($\sqrt{s_{NN}} \approx 20$ GeV) is revisited and systematically compared to all existing proton-proton data in the same range of center-of-mass energies. The ratio of A+A to p+p pion cross-sections (nuclear modification factor) for central Pb+Pb, Pb+Au and S+Au reactions does not show a strong enhancement as a function of $p_T$ as previously found, but is consistent with scaling with the number of nucleon-nucleon ($NN$) collisions. Neutral pion yields per $NN$ collision in head-on Pb+Pb reactions are suppressed, whereas peripheral yields are enhanced. These results together indicate that some amount of “jet quenching” may already be present in central heavy-ion reactions at $\sqrt{s_{NN}} \approx 20$ GeV.

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1 Introduction

Lattice calculations of bulk Quantum Chromodynamics (QCD) in thermal equilibrium [1] predict the transition of hadronic matter to a deconfined and chirally symmetric system of quarks and gluons above energy densities of the order $\epsilon_{crit} \approx 0.7 \pm 0.3$ GeV/fm$^3$. The formation and study under laboratory conditions of this “Quark-Gluon Plasma” (QGP) phase is one of the highest priorities in high-energy nuclear physics in the present day. Several experimental results from the CERN Super Proton Synchrotron (SPS) relativistic heavy-ion programme collected during the 1990’s in fixed-target experiments with center-of-mass energies $\sqrt{s_{NN}} \approx 20$ GeV have been interpreted, not without
controversy, in terms of QGP formation [2]. Indeed, although several observations in central Pb+Pb collisions [3] are consistent with expected QGP signals, e.g. the “anomalous” suppression of charmonium states due to Debye screening of the color potential in the plasma [4] (see, however, also [5]), other expected signatures such as “jet quenching” due to parton energy loss in the dense de-confined medium [6] seem to be significatively absent from the data. In fact, high $p_T$ pion production in central A+A at CERN-SPS was found not to be suppressed but enhanced compared to production in free space [7,8,9]. Such a “Cronin enhancement”, observed earlier in p+A [10,11,12] and α+α [13] collisions, is usually interpreted in terms of multiple initial-state parton scatterings which result in a broadening of the final $p_T$ spectra [14]. In contrast, high-$p_T$ hadro-production in central Au+Au collisions at $\sqrt{s_{NN}} = 130$ GeV [15,16] and 200 GeV [17,18,19,20] at the BNL Relativistic Heavy Ion Collider (RHIC) has been found to be strongly suppressed (by up to a factor of 4–5) compared to p+p collisions measured at the same $\sqrt{s_{NN}}$ [21,18]. The observed suppression at RHIC is even more significant considering the fact that the “default” production at high $p_T$ in the “cold” nuclear environment of deuteron-nucleus reactions at collider energies is also Cronin enhanced [22,23,24,20]. These results clearly indicate that final-state effects are responsible for the high $p_T$ deficit observed in central Au+Au. The difference between the suppressed RHIC and enhanced SPS hadro-production at large $p_T$ implies that there must exist an intermediate value of collision energies at which final-state quenching starts to dominate over initial-state $p_T$ broadening. The search for the onset of high $p_T$ suppression is the main motivation behind the dedicated $\sqrt{s_{NN}} = 62.4$ GeV Au+Au run carried out at RHIC in April 2004.

Theoretical studies [25] of parton propagation in a dense medium show that the induced parton energy loss is proportional to the initial gluon density ($dN^g/dy$) in the system. In this context, the absence of suppression at CERN-SPS is surprising considering that experimental estimates of the initial energy density, based on the Bjorken prescription [26] for a boost-invariant longitudinally expanding plasma, at a canonical thermalisation time of $\tau_0 = 1$ fm/$c$, are on the order of $\epsilon^{\text{SPS}}(\tau_0) \approx 3$ GeV/fm$^3$ [27,28] and $\epsilon^{\text{RHIC}}(\tau_0) \approx 5$ GeV/fm$^3$ [29]. Such energy densities, both well above the critical value of $\sim 0.7$ GeV/fm$^3$, would correspond to a ratio of parton rapidity densities ($dN/dy \propto \rho \propto \epsilon^{3/4}$ for an ideal gas of quarks and gluons) of $\sim 0.68$ between RHIC and SPS at $\tau_0 = 1$ fm/$c$. Since $R^{\text{RHIC}}_{AA} \approx 0.2$, one would accordingly expect suppression factors of the order $R^{\text{SPS}}_{AA} \approx 0.3$ assuming the same Cronin $p_T$ broadening at RHIC and SPS (see discussion later). This is in violent contradiction with the $R^{\text{SPS}}_{AA} >> 1$ usually quoted in the literature. The usual explanations for the reported absence of suppression at SPS involve short QGP lifetime [8,9], domination of multiple soft collisions (Cronin effect) over hard scatterings [30], and modest amount of parton rescatterings [31].

In this letter we explore an alternative interpretation based on a thorough re-
analysis of the p+p $\rightarrow \pi^0 + X$ baseline spectrum used to determine the A+A nuclear modification factor at $\sqrt{s} = 17.3$ GeV in [7,9]. It turns out that the absence of a concurrent proton-proton measurement at the same $\sqrt{s}$, and the use of inexact baseline references extrapolated from higher collision energies, result in apparent strong Cronin enhancements which are not actually supported by the data. The fact that the p+p reference spectra for SPS used so far are not well under control can be already realized by inspecting the original work [7] which shows two results difficult to reconcile at first sight: a suppressed $\pi^0$ production as given by the ratio of central to peripheral Pb+Pb collisions ($R_{cp} \approx 0.6$), and a strongly enhanced central Pb+Pb over p+p ratio (albeit with large systematic uncertainties), $R_{AA} \approx 8$ at the largest $p_T$. In this paper, the whole set of available high $p_T$ data from the SPS heavy-ion experiments: $\pi^0$ and $\pi^\pm$ at $\sqrt{s_{NN}} = 17.3$ GeV from Pb+Pb (WA98) [7] and Pb+Au (CERES/NA45) [32] respectively, and $\pi^0$ from S+Au at $\sqrt{s_{NN}} = 19.4$ GeV (WA80) [33], will be reexamined and carefully compared to p+p spectra constructed from a $\sqrt{s}$-dependent global fit of most of the available pion differential cross-sections in the range $\sqrt{s} \approx 7 - 63$ GeV [34]. Using this new reference, it will be shown that high-$p_T$ hadroproduction at $\sqrt{s_{NN}} \approx 20$ GeV is not enhanced in central nucleus-nucleus reactions but, within errors, is consistent instead with scaling with the number of NN collisions. Furthermore, the fact that high-$p_T$ $\pi^0$ production in the the top 1% central lead-lead collisions appears to be suppressed by a factor of $\sim 1.6 \pm 0.6$ compared to the p+p reference and that the peripheral yields are Cronin enhanced, points to some mechanism of final-state suppression at work in central Pb+Pb at CERN-SPS energies. The revised nuclear modification factors will be compared to the predictions of a pQCD-based model of parton energy loss, and the (partonic or hadronic) nature of the dissipative medium will be discussed.

2 High $p_T$ pion production in p+p collisions at $\sqrt{s} \approx 20$ GeV

Particle production at high $p_T$ ($p_T \gtrsim 2$ GeV/c) in hadronic collisions results from incoherent parton-parton scatterings with large $Q^2$. In the absence of initial and final state interactions, independent scattering and pQCD factorization\(^1\) imply that inclusive A+B cross-sections for hard processes should scale simply as $A \cdot B$ times the corresponding p+p cross-sections: $E \, d\sigma_{hard}^{AB}/d^3p = A \cdot B \cdot E \, d\sigma_{hard}^{pp}/d^3p$. Usually heavy-ion experiments measure invariant yields for a given centrality bin and, thus, the corresponding “scaling law” reads $E \, dN_{hard}^{AB}/d^3p = \langle T_{AB}(b) \rangle \cdot E \, d\sigma_{hard}^{pp}/d^3p$, where $T_{AB}(b)$

\(^1\) Incoming quarks and gluons undergoing hard scattering are considered “free” in a collinear factorized approach, i.e. the density of partons in a nucleus with atomic number $A$ is considered to be equivalent to the superposition of $A$ independent nucleons, or $f_{a/A}(x, Q^2) = A \, f_{a/p}(x, Q^2)$ in terms of parton distribution functions.
is the Glauber nuclear overlap function at impact parameter $b$ [35]. Since the number of inelastic nucleon-nucleon collisions at $b$ is proportional to $T_{AB}$ ($N_{\text{coll}}(b) = T_{AB}(b) \cdot \sigma_{pp}^{\text{inel}}$, with $\sigma_{pp}^{\text{inel}} = 32$ mb at $\sqrt{s} \approx 20$ GeV), one usually quantifies medium effects at high $p_T$ via the nuclear modification factor

$$R_{AB}(p_T) = \frac{d^2N_{AB}/dydp_T}{\langle N_{\text{coll}}(b) \rangle \times d^2N_{pp}/dydp_T},$$

which measures the deviation of A+B at impact parameter $b$ from an incoherent superposition of nucleon-nucleon collisions. Unfortunately, on the experimental side no $p+p \rightarrow \pi^0+X$ spectra measured at high $p_T$ close to mid-rapidity exists at the same collision energy$^2$ of the SPS Pb-induced nuclear collisions ($K_{\text{lab}} = 158$ AGeV corresponding to $\sqrt{s} = 17.3$ GeV). On the theoretical side, the single inclusive particle spectrum at large $p_T$ in high-energy $p+p$ collisions can be in principle calculated within the framework of collinear factorization. However, below $\sqrt{s} \approx 60$ GeV as noted already in [39], the cross-sections at $p_T < 5$ GeV/c in $p+p$ collisions are underpredicted by standard pQCD calculations, and additional non-perturbative effects (e.g. intrinsic $k_T$) must be introduced to bring parton model analysis into agreement with data. Unfortunately, those effects cannot so far be introduced in a model-independent way and different pQCD calculations [8,30,38] effectively yield different final pion spectra for $p+p$ collisions around $\sqrt{s} = 20$ GeV.

In the absence of a concurrent experimental measurement and lacking a fully reliable theoretical calculation, two approaches have been followed to construct a $p+p$ reference for $\pi^0$ production at SPS energies. First, the WA98 collaboration [7] has employed a semi-empirical modified power-law form $A [p_0/(p_T + p_0)]^n$ (originally proposed by Hagedorn [40]) tuned to reproduce the $p_T$ spectra measured at higher $\sqrt{s}$, plus an $x_T$ scaling prescription [41] to account for the collision energy dependence of the cross section. Second, Wang&Wang [9] have adopted a more complex power-law ansatz for the $p_T$ spectrum which describes the charged pion data at $\sqrt{s} = 19.4$ GeV [11], combined with a pQCD parton model calculation to scale the cross-section down to $\sqrt{s} = 17.3$ GeV. Both parametrizations have been tuned to reproduce a subset of the existing $p+p \rightarrow \pi^0+X$ data at $\sqrt{s} \approx 20$ GeV, but no true global analysis has been carried out to fully compare the parametrizations to all the existing results in this energy regime. Figure 1 shows a comparison of parametrizations [7] and [9] to the whole set of experimental results on high $p_T$ pion production at $\theta_{cm} \approx 90^0$ in the $\sqrt{s} = 16.9 - 19.4$ GeV range. The first thing worth to notice is the relatively large disparity among the experimental data obtained

$^2$ Ref. [36] provides a $p+p \rightarrow \pi^0+X$ measurement at $p_{\text{lab}} = 158.9$ GeV/c very close to WA98 Pb+Pb beam energy. However, these data are inconsistent with the rest of the tabulated results (the authors themselves have discarded this sample from subsequent analysis [37]) and so have not been considered in this work.
at the same energy ($\sqrt{s} = 19.4$ GeV), especially at the largest $p_T$ values. This fact highlights the importance of concurrently measuring A+A and baseline p+p differential cross-sections at the same center-of-mass energy and with the same setup in present and future heavy-ion experiments. Having said that, the WA98 reference fit [7] reproduces the available data only at $p_T \approx 2$ GeV/c whereas it systematically overpredicts the yields below this $p_T$ value and significantly underpredicts them above it. Wang&Wang parametrization [9], reproduces better the shape of the $p_T$ spectra but it systematically underpredicts most of the $\pi^0$ yields by $\sim 50\%$ in the $p_T \approx 1.5 - 4.0$ GeV/c range. Both data fits, however, seem to follow rather closely the $(\pi^+ + \pi^-)/2$ data$^3$ from Antreasyan et al. [11] which is actually used as the basic set for constraining the fit parameters at $\sqrt{s} = 19.4$ GeV in [9]. Forcing the parametrization [9] to fit the $\pi^\pm$ data of [11] above 4 GeV/c (where the scarce A+A data have large statistical errors anyway) without any other constraint from existing $\pi^0$ results in the same range of collision energies seems to be the cause of the limited agreement of this parametrization with the proton-proton data in the range $p_T \approx 1.5 - 4.0$ GeV/c where the heavy-ion measurements are available. In the case of the parametrized $\pi^0$ reference of WA98, the disagreement data-fit seems to come from the ansatz used to take into account the $\sqrt{s}$ dependence of the cross section since the original parametrization reproduces well the ISR $\pi^0$ spectra at higher energies [7].

At variance with these two works, Blattnig et. al [34] derive a parametrization of the invariant differential cross-section for inclusive $\pi^0$ production in proton-proton collisions based on a global analysis of most of the available data within $\sqrt{s} \approx 7 - 63$ GeV. This is a purely empirical 11-parameter functional form tuned to provide a reasonable description of the full $p_T$ spectral shape, angular distribution and total cross-section of the measured pions in this range of center-of-mass energies. Fig. 2 shows the level of agreement of Blattnig fit to the available pion data in p+p collisions for beam energies in the range of CERN-SPS heavy-ion experiments. The agreement between data and fit is more satisfactory, both in shape and magnitude, than the two previous parametrizations especially within $p_T \approx 1.5 - 3.5$ GeV/c. It describes rather well, in particular, the most recent (and precise) data sets from Fermilab E704 experiment [43] which were not actually considered in the fitting analysis of [34]. It is worth noticing, however, that at $p_T > 3.5$ GeV/c although the parametrization reproduces the $\pi^0$ data sets of ref. [36], it seems to be $\sim 50\%$ above the $\pi^0$ results of refs. [42,43] and the averaged $\pi^\pm$ of [11]. Nonetheless, given the relatively poor agreement between p+p experimental

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$^3$ Pion production in this kinematical range of parton fractional momenta in the proton, $x > 0.2$, is dominated by valence $u$ (2 quarks) and $d$ (1 quark) fragmentation which, due to their respective quark content, results in the $\sigma(\pi^+) < \sigma(\pi^0) < \sigma(\pi^-)$ ordering of the pion cross-sections. One would, thus, indeed expect $(\pi^+ + \pi^-)/2$ to provide a good approximation of the $\pi^0$ yields in p+p collisions.
Fig. 1. Relative differences between the single inclusive pion spectra measured in p+p collisions at $\sqrt{s} = 16.9 - 19.4$ GeV \cite{11,36,42,43} and the p+p $\rightarrow \pi^0+X$ parametrizations proposed by the WA98 collaboration \cite{7} (upper figure) and Wang&Wang \cite{9} (lower figure) at the corresponding $\sqrt{s}$. The shaded band represents the 20\% overall uncertainty originally assigned to the WA98 parametrization. Wang&Wang only provides the fit parameters for 2 fixed values of $\sqrt{s} = 17.3, 19.4$ GeV.

measurements themselves above $p_T \approx 3.5$ GeV/c, and especially given that the highest $p_T$ $\pi^0$ measured in A+A reactions are at $\sim 4$ GeV/c (with statistical errors which are larger than the p+p reference uncertainty), we consider this fit to provide a much more accurate representation of the proton-proton $\pi^0$ baseline production than the two previously used parametrizations. Hereafter, we will thus use the reference of Blattning et. al \cite{34} as a reasonable estimate of the p+p $\rightarrow \pi^0+X$ spectra for $\sqrt{s} = 17 - 20$ GeV in the range $p_T = 1 -$
4 GeV/c, – with an assigned overall uncertainty of ±25% (shaded band in Fig. 2) to cover most of the existing measurements –, as a benchmark for the study of high $p_T$ pion production in heavy-ion reactions at SPS.

Fig. 2. Relative differences between the single inclusive pion spectra measured in p+p collisions at $\sqrt{s} = 16.9 – 19.4$ GeV [11,36,42,43] and the p+p → $\pi^0 + X$ parametrization proposed in ref. [34]. The shaded band represents the 25% overall uncertainty that we assign to the parametrization.

3  Nuclear modification factors at $\sqrt{s_{NN}} \approx 20$ GeV revisited

Figure 3 shows the nuclear modification factor, Eq. (1), for 0–7% most central Pb+Pb collisions at $\sqrt{s_{NN}} = 17.3$ GeV, obtained using the three p+p parametrizations discussed in the previous section. Particle production in the low $p_T$ region (below $p_T \approx 1.5$ GeV/c) naturally falls below the $N_{coll}$ scaling expectation ($R_{AA} = 1$) since the assumption of independent pointlike scattering does not hold for soft processes in nucleus-nucleus reactions (which instead scale with the number of participant nucleons in the reaction: $N_{part} \propto N_{coll}^{3/4}$ [44]). The original WA98 parametrization (open circles) results in a steeply rising Pb+Pb over p+p ratio in the whole $p_T$ range. The Cronin enhancement is apparent above $p_T \approx 2$ GeV/c going above $R_{AA} \approx 8$ at the highest $p_T$'s, which is a factor of ~4 larger than the maximum pion enhancements found in p+A collisions at fixed-target energies ($R_{pA} \approx 2$) [10,11,12]. Wang’s p+p reference (crosses) produces an overall less pronounced Cronin effect reaching a maximum $R_{AA} \approx 3$ at high $p_T$. The $R_{AA}$ obtained with the Blattng et al. fit (closed circles) shows no indication of enhancement below $p_T \approx 4$ GeV/c and actually, within uncertainties, the data seem to follow the
NN collision scaling ($R_{AA} = 1$) expected for hard scattering in the absence of medium effects.

Before addressing the interpretation of the observed high $p_T$ pattern in A+A collisions at SPS energies, it is legitimate to question the validity of the assumption of particle production via parton-parton scatterings for such moderate values of transverse momenta ($p_T \approx 2.0 - 4.5$ GeV/c). Several studies [45] have emphasized the relative importance of “soft” effects above $p_T \approx 2$ GeV/c in heavy-ion collisions at SPS. Nonetheless, there are at least four independent pieces of experimental evidence which seems to favor an interpretation for high $p_T$ production in nuclear collisions around $\sqrt{s_{NN}} = 20$ GeV based on hard scattering processes: (i) All the measured hadron $p_T$ spectra above 2 GeV/c [7,32,33] show a power-law tail characteristic of elementary parton-parton interactions, (ii) The shape and width of the near-side azimuthal correlations of pions with $p_T > 1.2$ GeV/c are jet-like [46], in agreement with parton fragmentation expectations, (iii) The measured ratio $\eta/\pi^0 \approx 0.5$ above $p_T = 1.5$ GeV/c [48] is consistent with standard parton fragmentation functions, and (iv) The observed direct photon yield at $p_T > 1.5$ GeV/c [47] is consistent with perturbative production cross-sections.

Using Blattnig’s parametrization [34] as proton-proton reference, and the associated mean number of collisions $\langle N_{\text{coll}} \rangle$ for each centrality, we present in Fig. 4 the nuclear modification factors for high $p_T$ pion produced near midra-
Fig. 4. Nuclear modification factors for pion production at CERN-SPS in central Pb+Pb [7], Pb+Au [32], and S+Au [33] reactions, obtained using the p+p parametrization of ref. [34]. The shaded band around $R_{AA} = 1$ represents the overall fractional uncertainty (including in quadrature the 25% uncertainty of the p+p reference and the 10% error of the Glauber calculation of $N_{coll}$: $\langle N_{coll} \rangle = 726 \pm 72, 774 \pm 77$, and $174 \pm 20$ for Pb+Pb, Pb+Au and S+Au resp.). CERES data have an additional overall uncertainty of $\pm 15\%$ not shown in the plot [32]. The “curved” band is a theoretical calculation from Vitev and Gyulassy [50] including standard nuclear effects (Cronin and shadowing) and final-state parton energy loss in a system with initial gluon densities $dN_g/dy = 400 – 600$.

Pion production in the three A+A reactions studied at SPS (Table 4) at comparable centrality bins. For the three systems, pion production in the range $p_T \approx 2 – 4$ GeV/c is consistent with $R_{AA} = 1$. Although with large experimental uncertainties, there is an indication of enhancement ($R_{AA} > 1$) at the highest $p_T$ values for the Pb+Pb reaction. The magnitude and $p_T$ dependence of the nuclear modification factors are compared in the same plot to a theoretical calculation by Vitev and Gyulassy [50] (yellow band) which includes “standard” nuclear effects like Cronin broadening and (anti)shadowing, plus final-state partonic energy loss in an expanding system with initial gluon rapidity densities $dN_g/dy = 400 – 600$. The influence of nuclear modifications (“shadowing”) of the parton distributions functions (PDFs) in this kinematical range is small. For $\sqrt{s_{NN}} \approx 20$ and $p_T \approx 2 – 5$ GeV/c at mid-rapidity, the colliding partons have fractional momenta of the order $x_{Bj} = 2 P/\sqrt{s_{NN}} = 2 z p_T/\sqrt{s_{NN}} \approx 0.2 – 0.4$, using $\langle z \rangle = p_T/P \sim 0.8$ for the average fraction of the parton momentum $P$ carried by the outgoing (leading) $\pi^0$. Such an intermediate $x$ region is mainly dominated by valence $u, d$ quarks which are barely modified in the nucleus.
The EKS98 parametrization [51] of nuclear PDFs used by Vitev\&Gyulassy predicts a very modest $\sim$5\% antishadowing effect in this $p_T$ range. On the other hand, the Cronin effect does play a relevant role in $\pi^0$ production. The $p_T$ broadening is modeled in [50] via multiple scattering in the cold nucleus so as to reproduce the magnitude, $p_T$ and $\sqrt{s}$ dependence of the enhancements in pion observed in p+A collisions between $\sqrt{s} \approx 20 - 40$ GeV [10,11,12]. For SPS energies the expected effect is $R_{pA} \approx 1.4$ at $p_T = 2$ GeV/c, steadily increasing up to $R_{pA} \approx 3$ at $p_T = 4$ GeV/c (see yellow band in Fig. 5 and discussion below). In contrast to this expectation, the central A+A reactions at SPS show $R_{AA} \approx 1$ within $p_T = 2 - 4$ GeV/c (Fig. 4), a factor of $\sim$2 below the expected Cronin enhancement. Introducing non-Abelian energy loss [25] of the hard scattered partons in a dense expanding system with initial gluon densities $dN_g/dy = 400 - 600$, provides the suppression needed to reproduce the nuclear modification factor observed in the A+A data in this centrality bin. Qualitatively similar conclusions have been also reached by closely-related pQCD-based calculations of Levai and collaborators [38].

Aside from model predictions, the presence of a final-state quenching medium in central A+A is confirmed by comparing high-$p_T$ $\pi^0$ production in different centrality bins. Fig. 5 shows the nuclear modification factor $R_{AA}$ versus $p_T$ for peripheral (48\%–66\% of $\sigma_{p\bar{p}p\bar{p}}$, open triangles), central (0–7\% of $\sigma_{p\bar{p}p\bar{p}}$, circles), and 0–1\% most central (closed triangles) Pb+Pb collisions measured by WA98. Pions produced in peripheral collisions above $p_T \approx 1.5$ GeV/c are indeed enhanced compared to “collision scaling”, in agreement with the phenomenological parametrization of the Cronin effect (yellow band) implemented in [50]. However, as aforementioned, 0–7\% most central reactions are consistent with $R_{AA}$ being unity up to $p_T \approx 3.5$ GeV/c, and the top 1\% most central Pb+Pb reactions are actually found to be suppressed, $R_{AA} \approx 0.6 \pm 0.15$ (stat) $\pm 0.15$ (syst), in this $p_T$ range\(^4\). These results clearly indicate, regardless of the p+p $\rightarrow \pi^0+X$ reference used in the denominator of $R_{AA}$, that hard hadron production in head-on Pb+Pb collisions at CERN-SPS is actually quenched by a factor of $\sim$2 compared to peripheral collisions. It is worth to note that this was actually an observation already reported in the original WA98 work [7] which, however, remained somehow eclipsed by the (conflicting) enhanced values of $R_{AA}$ for all centralities quoted in the same papers.

\(^4\) Note that impact parameter fluctuations for this very narrow 0–1\% centrality bin could result in uncertainties in $R_{AA}$ larger than the quoted $\pm$25\% systematic error coming from the p+p reference and from the Glauber MC determination of the average $N_{coll}$. 

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Table 1
Measurements of single inclusive pion production at high $p_T$ in heavy-ion reactions at CERN-SPS. For each reaction we quote the center-of-mass energy and rapidity, the experimental rapidity coverage, and the estimated Bjorken energy density attained in the most central (0–2%) collisions.

| System [ref] | $\sqrt{s_{NN}}$ (GeV) | $y_{cm}$ | $y_{exp}^{\pi}$ | $\epsilon_{Bj}$ (GeV/fm$^3$) |
|--------------|-----------------------|---------|----------------|------------------|
| Pb+Pb $\rightarrow$ $\pi^0$+X [7] | 17.3 | 2.9 | 2.3 < $y$ < 3.0 | 3.0 [27] |
| Pb+Au $\rightarrow$ $\pi^0$+X [32] | 17.3 | 2.9 | 2.1 < $y$ < 2.6 | 3.0 [28] |
| S+Au $\rightarrow$ $\pi^0$+X [33] | 19.4 | 3.0 | 2.1 $\leq y$ $\leq$ 2.9 | 2.0 [49] |

Fig. 5. Nuclear modification factor for $\pi^0$ production in peripheral (48–66%, $\langle N_{coll} \rangle = 78 \pm 12$, open triangles), central (0–7%, $\langle N_{coll} \rangle = 726 \pm 72$, circles) and most central (0–1%, $\langle N_{coll} \rangle = 807 \pm 81$, closed triangles) Pb+Pb reactions at $\sqrt{s_{NN}} = 17.3$ GeV [7] obtained using the p+p baseline spectrum of ref. [34]. The shaded band centered on $R_{AA} = 1$ represents the overall fractional uncertainty from the p+p reference and Glauber calculation of $N_{coll}$. The curved band is a pQCD-based theoretical calculation from Vitev and Gyulassy [50] of pion production in central Pb+Pb at 17.3 GeV including standard nuclear effects (Cronin enhancement and shadowing) but no final-state parton energy loss.

4 Discussion

Figure 6 shows the nuclear modification factors for $\pi^0$ production in nucleus-nucleus reactions at four different center-of-mass energies and different centralities. Single inclusive pion spectra above $p_T \approx 2$ GeV/c produced at midra-
pidity in heavy-ion reactions at SPS and RHIC are suppressed by as much as a factor of \( \sim 1.6 \pm 0.6 \) (in top 0–1% central Pb+Pb at SPS) and of \( \sim 5 \pm 1 \) (in 0–10% most central Au+Au at RHIC) respectively, compared to proton-proton reactions scaled by the corresponding number of \( NN \) collisions. In contrast, high \( p_T \) \( \pi^0 \) production in minimum-bias light-ion \((\alpha + \alpha)\) reactions at ISR energies is enhanced \( (R_{AA} \approx 1.5) \) with respect to this scaling. Such observations are consistent with the expectations of final-state energy loss of the hard scattered partons in dense strongly interacting matter produced at midrapidity in central reactions with heavy nuclei. Determining whether the quenching medium is of partonic or hadronic nature (or both) is the ultimate goal behind the study of high \( p_T \) hadroproduction in high-energy heavy-ion collisions. The SPS and RHIC measurements of the total transverse energy at central rapidities yield values of the Bjorken energy density at \( \tau_0 = 1 \text{ fm}/c \), \( \epsilon_{Bj}^{SPS}(\tau_0) \approx 3 \text{ GeV/fm}^3 \) and \( \epsilon_{Bj}^{RHIC}(\tau_0) \approx 5 \text{ GeV/fm}^3 \), in the top 2% central Pb+Pb,Au [27,28] and top 5% central Au+Au [29] reactions resp., which are well above any possible scenario involving hadronic degrees of freedom. The equivalent parton densities are \( \rho_{Bj}^{SPS}(\tau_0) \approx 4.7 \text{ fm}^{-3} \) and \( \rho_{Bj}^{RHIC}(\tau_0) \approx 6.9 \text{ fm}^{-3} \) using the thermodynamical relation \( \rho \approx 2.1 \epsilon_{Bj}^{3/4} \) \((\epsilon \text{ in GeV/fm}^3) \) for a gas of partons as given from lattice QCD thermodynamics \(^5\) [1]. The corresponding parton densities per unit rapidity, \( dN/dy = \rho \cdot \tau_0 \cdot A_\perp \), where \( A_\perp \approx 150 \text{ fm}^2 \) is the transverse area in a head-on A+A collision with \( A \approx 200 \), are \( (dN/dy)^{SPS}(\tau_0) \approx 700 \) and \( (dN/dy)^{RHIC}(\tau_0) \approx 1100 \) respectively. Both values are consistent with the initial \( dN^g/dy \) gluon densities obtained from the respective “tomographic” parton energy loss studies [50] described before \(^6\).

Since jet quenching models predict that the induced parton energy loss is proportional to the initial parton densities, one could use the measured suppression at RHIC together with the relative values of \( \epsilon_{Bj} \), or \( dN/dy(\tau_0) \), between RHIC and SPS to determine the expected value of quenching factor \( R_{AA} \) at SPS. Indeed, the fact that high-\( p_T \) hadron spectra in proton-proton collisions are well reproduced by a simple power-law \( 1/p_T^n \) \((\text{with } n \approx 10 \text{ above } p_T \approx 2 \text{ GeV}/c \text{ at SPS, and } n \approx 8 \text{ above } p_T \approx 4 \text{ GeV}/c \text{ at RHIC})\), and that \( R_{AA} \) in central A+A reactions is approximately constant at high-\( p_T \) both at SPS and RHIC, indicates that the basic \( p_T \) dependence of the yields is not changed by the quenching medium (i.e. the power law \( n \) exponent remains the

\(^5\) Mind that the use of the ideal gas EOS from lattice calculations with zero baryochemical potential may be justified at central rapidities for RHIC highest energies \((\text{where } \mu_B < < T_c)\) but is less evident for SPS where \( \mu_B \gtrsim T_c \), and should be taken \textit{cum grano salis} in this latter case.

\(^6\) The values \( (dN^g/dy)^{SPS}(\tau'_0) \approx 600 \) and \( (dN^g/dy)^{RHIC}(\tau'_0) \approx 1100 \) \cite{52} are actually obtained for \( \tau'_0^{SPS} = 0.8 \text{ fm}/c \) and \( \tau'_0^{RHIC} = 0.6 \text{ fm}/c \) respectively, for a system with transverse area \( A_\perp \approx 115 \text{ fm}^2 \). However, when scaled to the same area and initial proper time \( (\text{taking into account the decrease in energy density } \epsilon \propto \tau'^{-4/3} \text{ in a } 1+1\text{D Bjorken expansion}) \) one gets coincident results between \( dN^g/dy(\tau_0) \) \((\text{from tomographic studies})\) and \( dN/dy(\tau_0 = 1 \text{ fm}/c) \) \((\text{from Bjorken energy densities})\).
Fig. 6. Nuclear modification factor, $R_{AA}(p_T)$, for $\pi^0$ production in ion-ion reactions at CERN-SPS [7] (triangles), CERN-ISR [13] (stars), and BNL-RHIC [15,17] (squares and circles). The boxes around the CERN-SPS data points represent the normalization uncertainty from the p+p reference and Glauber calculation of $N_{coll}$. We can thus relate the suppression in A+A compared to p+p as due to a corresponding (energy loss) shift $\Delta p_T$ in the single inclusive spectrum $dN/dp_T$. The ratio of A+A over p+p invariant $dN/p_T dp_T$ spectra, the nuclear modification factor, is then $R_{AA} = (1 + \Delta p_T/p_T)^{-(n-1)}$, from which the corresponding fractional energy loss can be derived: $\Delta p_T/p_T = R_{AA}^{-1/(n-1)} - 1$. Thus, from the measured $R_{AA}^{RHIC} \approx 0.2$ one gets $(\Delta p_T/p_T)_{RHIC} \approx 0.25$, and since $(dN/dy)_{SPS}^{RHIC} \approx 0.68 (dN/dy)_{RHIC}$ implies $(\Delta p_T)_{SPS} \approx 0.68 (\Delta p_T)_{RHIC}$, one would expect $R_{AA}^{SPS} \approx 0.4$. The minimum value of $R_{AA}^{SPS}$ measured is, however, $R_{AA}^{SPS} \approx 0.6$ for the 1% most central Pb+Pb reactions (Fig. 5) which is $\sim$70% larger than this simple estimate. The reason for this apparent inconsistency is the implicit assumption made above that the counteracting effect of the (Cronin) $p_T$ broadening is the same at SPS and RHIC energies. Since the high-$p_T$ spectra at SPS (with power law exponent $n \approx 10$) are much steeper than at RHIC ($n \approx 8$) the effect of the initial-state multiple parton scatterings leads to a much larger $p_T$ enhancement at $\sqrt{s_{NN}} \approx 20$ GeV than at $\sqrt{s_{NN}} = 200$ GeV. This fact, as pointed out by Gyulassy and Levai in [30], explains partially why the observed suppression at SPS is apparently much lower than at RHIC even though the estimated energy densities are only a factor of $\sim$2 larger at RHIC.

At both center-of-mass energies, however, it is conceivable that not all of the high-$p_T$ hadron suppression in central heavy-ion reactions is due to the attenuating effects of a partonic medium alone. Indeed, since the produced medium undergoes a longitudinal expansion, its initial energy density will decrease with time as $\epsilon \propto (\tau_0/\tau)^\alpha$ where $\alpha = 1$, 4/3 for free streaming and
1-D Bjorken expansion\(^7\) respectively \([8]\) in the schematic time-scale evolution outlined here. Therefore, even starting at \(\tau_0 = 1 \text{ fm/c}\) with energy densities well above \(\epsilon_{\text{crit}} \approx 0.7 \text{ GeV/fm}^3\), the bulk partonic system will drop below \(\epsilon_{\text{crit}}\) and hadronize into a hadron gas phase at \(\tau_{\text{crit}}^{\text{SPS}} \approx 4 \text{ fm/c}\) and \(\tau_{\text{crit}}^{\text{RHIC}} \approx 7 \text{ fm/c}\) respectively. The subsequent hadron system remains strongly self-interacting until its density is too low for further rescatterings to take place. At both center-of-mass energies, the total lifetime of the strongly interacting system (\(\tau_{\text{fo}} \approx 15 \text{ fm/c}\) \([53,54]\)) is comparable to the time it takes a hard scattered parton with typical momentum \(P = 4 \text{ (8) GeV/c}\) to hadronize into a fully formed meson \([55]\): \(\tau_h \approx P \cdot R^2_h \approx 12 \text{ (25) fm/c}\) for a pion of radius \(R_h \sim 0.8 \text{ fm}\) \([56]\). In this context, the produced high-energy parton travels (and loses energy) first through a dense partonic system during \(\tau < \tau_{\text{crit}}\) and then, for a time \(\tau_{\text{crit}} < \tau < \tau_{\text{fo}}\), through a hadronic environment. In this second hadronic stage, inelastic scattering of the “pre-hadron” object with comover soft hadrons of the type described in \([5,57]\) can also partially account for the suppression of the final high-\(p_T\) inclusive spectra. In any case, it is reasonable to admit that the energy loss will be larger in the denser (partonic) phase than in the more rarefied hadronic one.

5 Conclusions

We have reexamined high-\(p_T\) (\(p_T \gtrsim 2 \text{ GeV/c}\)) inclusive pion production in nucleus-nucleus reactions from CERN-SPS fixed-target experiments at center of mass energies around \(\sqrt{s_{NN}} = 20 \text{ GeV}\), and systematically compared them to the available proton-proton data in the same range of collision energies per nucleon-nucleon pair. In contrast to what has been usually considered so far, we conclude that there is no indication of a strong \(p_T\) broadening (Cronin enhancement) in the high-\(p_T\) yields measured in central Pb+Pb, Pb+Au and S+Au reactions. Instead, the data appear to be consistent within errors with the perturbative expectations of scaling with the number of nucleon-nucleon collisions. The peripheral yields, however, are still found to be Cronin enhanced. These facts, together with the complementary observation that high-\(p_T\) pion yields in head-on (0–1% most central) Pb+Pb reactions are suppressed by a factor of \(\sim 1.6 \pm 0.6\) compared to \(p+p\) collisions, is consistent with a moderate amount of final-state quenching of the hard scattered partons traversing the dense system produced in the course of the most central heavy-ion reactions at SPS. Theoretical calculations of parton energy loss in an expanding deconfined medium require initial gluon rapidity densities of the order \(dN^g/dy \approx 600\) to reproduce the observed yields, consistent with

\(^7\) The assumption of pure Bjorken (longitudinal boost invariant) expansion is an idealistic approximation that can be only applied in heavy-ion collisions at best in a narrow rapidity window around \(y = 0\).
estimations of the Bjorken energy densities attained in the reactions. Additionally, we have provided arguments based on hadronization time estimates that support the idea that the hard scattered partons must lose their energy in the dense partonic and hadronic phases of the reaction. The 2004 $\sqrt{s_{NN}} = 62.4$ GeV Au+Au run at RHIC will undoubtedly help to clarify the “excitation function” evolution of the high-$p_T$ hadron suppression observed in high energy nucleus-nucleus reactions. The discussion presented here highlights the importance of a concurrent and precise measurement of the high-$p_T$ production yields in baseline p+p collisions at the same center-of-mass energies as the nucleus-nucleus data.

Note added: Preliminary RHIC results from Au+Au reactions at $\sqrt{s_{NN}} = 62.4$ GeV, obtained after submission of this letter, indicate that high $p_T$ hadron production per NN collision is also significantly reduced (by up to a factor of $\sim 3$) in central Au+Au compared to p+p collisions at these energies. These results are consistent with the indications of moderate high $p_T$ suppression in heavy-ion reactions at lower SPS energies, discussed here.

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