Jet Quenching and Cronin Enhancement in $A + A$

at $\sqrt{s} = 20$ vs 200 AGeV

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Abstract

The sensitivity of semi-hard ($p_{\perp} < 10$ GeV) hadron production to parton energy loss in high energy nuclear collisions is studied via the HI-JING1.35 model. We test the model on recent WA98 data on 160 AGeV $Pb + Pb \rightarrow \pi^0$ up to 4 GeV/c and while these data are reproduced, the results depend sensitively on the model of the Cronin effect. At (RHIC) collider energies ($\sqrt{s} > 200$ AGeV), on the other hand, semi-hard hadron production becomes insensitive to the above model and is thus expected to be a cleaner probe of jet quenching signature associated with non-Abelian radiative energy loss.

Preliminary WA98 $Pb + Pb \rightarrow \pi^0$ data [1] in the $p_{\perp} \approx 2 - 4$ GeV range were analyzed recently by Wang [2] via a parton model. The Leading Log Approximation (LLA) parton model [3] was shown to reproduce the observed $\pi^0$ invariant inclusive cross sections simultaneously in $p + p$, $S + S$ [4], and central $Pb + Pb$ [1] in the CERN/SPS energy range, $\sqrt{s} < 20$ AGeV. What is remarkable about that analysis is the implied absence of quenching of high transverse momenta hadrons that should be observed if partons lose energy in dense matter [5, 6]. The $S + S$ and $Pb + Pb$ data clearly reveal the expected Cronin enhancement [7] of moderate $p_{\perp}$ pions, as seen first in $p + A$. The $pp$ data also confirm the need to supplement the LLA with non-perturbative intrinsic $k_{\perp}$ [8, 9]. However, the $Pb + Pb$ data show no sign of jet quenching expected at collider energies [6].

In central heavy ion reactions at the SPS, conservative estimates of the initial energy density suggest that $\epsilon(1 \text{ fm/c}) \approx 1 - 5$ GeV/fm$^3$, are reached. The gluon radiative energy loss of partons in such dense matter is expected to exceed $dE/dx \sim 1$ GeV/fm [5]. Recent theoretical analysis [10] predicts in fact a much larger non-linear energy loss $\Delta E \sim (\Delta x)^2$ GeV/fm$^2$ if a parton traverses a quark-gluon plasma of thickness $\Delta x$. On the other hand, the WA98 data seem to rule out $dE/dx > 0.1$ GeV/fm, as Wang showed in Ref. [2]. In this work, we consider this problem using the nuclear collision event generator, HIJING [11, 12].
Recall that in the LLA, pQCD predicts that the single inclusive hadron cross section is given by Refs. [3, 9]
\[
\frac{d\sigma}{dyd^2p_T} = K \sum_{abcd} \int d^2\vec{\kappa}_a d^2\vec{\kappa}_b g(\vec{\kappa}_a) g(\vec{\kappa}_b) 
\times \int dx_a dx_b f_{a/A}(x_a, Q^2) f_{b/B}(x_b, Q^2) 
\times \frac{d\sigma}{dt}(ab \to cd) \frac{D_{0/c}^h(z_c, Q^2)}{\pi z_c}.
\] (1)
This formula convolutes the elementary pQCD parton-parton cross sections, \(d\sigma(ab \to cd)\), with non-perturbative lowest order fits of the parton structure functions, \(f_{a/A}\), and the parton fragmentation functions, \(D_{h/c}\), to \(ep\) and \(e^+e^-\) data. Here \(\vec{\kappa}_a, \vec{\kappa}_b\) are the intrinsic transverse momenta of the colliding partons. The model includes a \(K \approx 2\) factor to simulate next-to leading order corrections [13] at a hard scale \(Q \sim p_T/z_c\). The scale dependence of the structure and fragmentation functions account for the multiple soft collinear radiative effects. However, below energies \(\sqrt{s} < 100\) GeV, it is well known [8] that LLA significantly underpredicts the \(p_T < 10\) GeV cross section, and additional non-perturbative effects must be introduced to bring LLA into agreement with data. Unfortunately, as emphasized in Ref. [3], the results are then quite model dependent below collider (RHIC) energies. As we show below, the good news is that this model dependence is reduced significantly at collider (RHIC) energies.

In spite of the inherent ambiguity of the parton model analysis at SPS energies, a successful phenomenological approaches to this problem has been developed via the introduction [9] of intrinsic transverse momenta of the colliding partons as in (1). Originally, a Gaussian form for that distribution with \(\langle k_{T}^2 \rangle \sim 1\) GeV\(^2\) was proposed in Ref. [9]. However, in order to reproduce \(pp\) data more accurately and to take into account the Cronin effect, the Gaussian ansatz was generalized in Ref. [2] to include \(Q^2\) and \(A\) dependence. With \(g(\vec{k}) \to g_{a}(\vec{k}, Q^2, A)\), excellent fits [2] to the WA98 data could be obtained assuming a factorized Gaussian distribution with
\[
\langle k_T^2(b) \rangle_A = (1 + 0.2 Q^2 \alpha_s(Q^2) + \frac{0.23 \sigma_{pp} t_A(b) \ln^2 Q}{1 + \ln Q}) \text{GeV}/(c)^2 
\] (2)
where \(Q^2\) is measured here in (GeV/c\(^2\)). In (2) \(\sigma_{pp} t_A(b)\) is the average number of inelastic scatterings a nucleon suffers traversing nucleus \(A\) at impact parameter \(b\). The nuclear thickness function, \(t_A(b)\), is normalized as usual to \(\int d^2b t_A(b) = A\). Eq.(2) is the main source of the model dependence in Ref. [2].

The HIJING1.35 Monte Carlo model [11, 12] incorporates pQCD jet production together with initial and final state radiation according to the PYTHIA algorithm [14]. In addition, it incorporates a variant of the soft string phenomenology similar to the Lund/FRITIOF [15] and DPM [16] models to simulate beam jet fragmentation and jet hadronization physics. Low transverse
momenta inelastic processes are of course highly model dependent, and the parameters must be fit to \( pp \) and \( AB \) data \([11, 12]\). It is of interest to apply HIJING to the present study because it incorporates in addition to the above soft and hard dynamics, a model of soft (Cronin) multiple initial state collision effects as well as a simple jet quenching scheme. With these features, we are able to study how competing aspects of the reaction mechanism influence hadronic observables and explore the magnitude of theoretical uncertainties.

In the HIJING model, excited baryon string are assumed to pick up random transfer momentum kicks in each inelastic scattering according to the following distribution

\[
g(\vec{\kappa}) \propto \left\{ (\kappa^2 + p_1^2)(\kappa^2 + p_2^2)(1 + e^{-(\kappa^2 - p_2^2)/p_3}) \right\}^{-1},
\]

where \( p_1 = 0.1, \ p_2 = 1.4, \ p_3 = 0.4 \) GeV/c were chosen to fit low energy \( p_\perp < 1 \) GeV/c multiparticle production data in Refs. \([11, 12]\). A flag, IHPR2(5)(=1 or 0), makes it possible to compute spectra with and without this effect as shown in part (a) of Figs.1-3. The present study is the first test of this model up to 4 GeV/c in the SPS energy range.

Jet quenching is modeled via gluon splitting according to the number of mean free paths, \( \lambda = 1 \) fm, traversed by a gluon through the cylindrical nuclear reaction volume. In each partonic inelastic interaction a gluon of energy \( \Delta E = \Delta x \frac{dE}{dx} \) is assumed to be split off the parent jet and incorporated as a kink in another baryonic string \([11]\). The (constant) energy loss per unit length is an input parameter (HIPR1(14) in HIJING \([11]\)) and can switched on and off via IHPR2(4) (=1 or 0) to test the sensitivity of spectra to jet quenching as shown in Figs.1-3.

Figure 1 compares the predictions of HIJING1.35 \([11, 12]\) without jet quenching \( (dE/dx = 0) \) for the invariant \( \pi^0 \) cross section in central nuclear collisions at SPS and RHIC energies. The cross section for central \( A + A \) collisions are computed integrating over the impact parameters up to \( b_{\text{max}} \) chosen to reproduce experimental trigger cross sections. For WA98 \( Pb + Pb \) and RHIC \( Au + Au \) we took \( b_{\text{max}} = 4.5 \) fm, while for the WA80 \( S + S \) we took \( b_{\text{max}} = 3.4 \) fm. The multiple collision eikonal geometry in HIJING is based on standard Wood-Saxon nuclear densities.

The parton model fit to the WA98 data are labeled by ‘Wang’ from Ref. \([2]\). (The normalization of both the WA98 data and Wang’s latest calculations (not shown) have increased \( \sim 20-40\% \) relative to \([2]\).) We note that the HIJING1.35 calculation for this interaction given by the solid jagged line also reproduces remarkably well the \( \pi^0 \) invariant cross sections without jet quenching. However, for the lighter \( S + S \) reaction, HIJING, underestimates the \( p_\perp > 1 \) GeV/c tail significantly. This error is traced to the failure of the model to reproduce the \( pp \) high \( p_\perp \) data at these energies, in contrast to its successful account of higher energy data \([11]\). This can be seen by comparing the filled squares to the dotted curves as explained below. Therefore, we find that the agreement with
the WA98 data is accidental and the observed $A$ scaling of the high $p_{\perp}$ region at SPS energies is not reproduced.

Fig. 1a shows that the soft transverse momentum kick model is the source for the agreement of HIJING with the $Pb + Pb$ data. The dot-dashed curves show what happens if the soft $p_{\perp}$ kicks modeled with eq.(3) is turned off. The very strong decrease of the pion yield in the $Pb + Pb$ case and the somewhat smaller but still large decrease in the $S + S$ case shows clearly the important role multiple transverse kicks at these energies. In fact both $S + S$ and $Pb + Pb$ dot-dashed curves are found to coincide with the calculated $pp \rightarrow \pi$ differential cross section scaled by the wounded nucleon factor $W_A \sigma_{AA}/\sigma_{NN}$, where $W_A = 21,172$ is the average number of wounded projectile nucleons and $\sigma_{AA} = 32,363,636$ mb for $A = 1, 32, 207$.

On the other hand, the data follow closely the shape of the measured $pp \rightarrow \pi^+$ data taken from [2] and scaled to $AA$ by multiplying by the Glauber binary collision number factor, $T_{AA} \sigma_{AA}$. From HIJING the average number of binary collisions in these systems is 45, 751 resp. The fact that the WA98 data scale with the above Glauber factor within a factor of three, suggests that the additional $p_{\perp}$ broadening due to initial state collisions is relatively small. The very large $A$ dependence of the HIJING $p_{\perp}$ tail at SPS energies is due to the $A^{1/3}$ times convolution of the distribution (3). This problem is avoided in the parton model calculation [2] using (2) through the separation of larger intrinsic momentum effects and smaller $A^{1/3}$ dependent contributions.

We conclude that the missing intrinsic transverse momentum component of HIJING precludes an accurate simultaneous reproduction of of $pp, SS, PbPb$ data at SPS energies. However, unlike the parton model where no global conservation laws have to be enforced, it is not clear how to incorporate intrinsic momenta in a global event generator like HIJING without destroying the satisfactory reproduction of low $p_{\perp} < 1$ GeV/c data. We do not attempt to solve this problem here.

Our main point is that this problem goes away fortunately at higher (RHIC) collider energies ($\sqrt{s} = 200$ AGeV). As seen in Fig.1a) the effect of multiple soft interactions is very much reduced at that energy. This is due to the well known effect that as the beam energy increases, the $p_{\perp}$ spectra become harder and additional $p_{\perp}$ smearing from initial state effects becomes relatively less important. It is the extreme steepness of the cross sections at SPS energies that amplifies so greatly the sensitivity of the moderate $p_{\perp}$ yields to this aspect of multiple collision dynamics.

In Fig. 1b, we consider next the sensitivity of the pion yields to the sought after parton energy loss dynamics. The striking difference between Figs. 1a and 1b is that in 1b the SPS yield is not sensitive to the energy loss model in HIJING, while at RHIC energies the suppression of semi-hard hadrons is seen to be sensitive to jet quenching as predicted in Ref. [6]. This seems counter intuitive at first because the increasing steepness with decreasing beam energy is naively expected to result in greater quenching for a fixed jet energy loss.
However, in this model the observed $p_\perp$ range is dominated by multiple soft collisions. The moderate $p_\perp < 5$ GeV quarks, which fragment into the observed pions, are not produced in rare pQCD semi-hard interactions but are gently nudged several times into that $p_\perp$ range. Since in HIJING jet-quenching is restricted to only those partons that suffer a semi-hard pQCD interaction with $p_\perp$ at least $p_0 = 2$ GeV/c (the mini-jet scale), no quenching arises at this energy.

The above conclusions are further clarified in Figs. 2 and 3, where the effects of $p_\perp$ kicks and jet quenching are shown for valence quarks and diquarks and gluons prior to hadronization. In Figure 2a, the valence quark plus diquark distribution, $dN_{\text{val}}/dp_\perp$, is seen to be enhanced by two orders of magnitude due to the assumed Cronin mechanism at SPS energies whereas they are enhanced only by $\sim 50\%$ at RHIC energies. In Fig.2b, on the other hand, quark jets are seen to be suppressed by an order of magnitude at RHIC energies, while at SPS energies no quenching arises because only about $< 1\%$ of the 5 GeV/c quarks are produced directly by hard pQCD processes.

Figure 3a shows that the (negligible) gluon component of partons undergoing hard processes at SPS energies are in fact quenched by an order of magnitude just as at RHIC energies, but because they represent such a small fraction of the produced partons, their effect on the final hadron observables is negligible. Note the three order of magnitude rise of the mini-jet gluon component going from SPS to RHIC energies in Fig. 3b. In that Figure, the minimum momentum $p_0 = 2$ GeV/c assumed for jet quenching is seen by the rapid drop of the gluon spectra beyond $p_0$. We see that the ratio of valence quarks to gluons after quenching at RHIC energies remains $\sim 2/1$ for mini-jets up to $p_\perp \sim 10$ GeV/c.

In conclusion, we found that HIJING1.35 fits the WA98 data with or without jet quenching. However, this model fails to account for the weak $A$ dependence of the data that scale approximately with the Glauber $T_{AA}$ factor, and therefore the fit must be viewed as accidental. We note that the current WA98 data can also be reproduced by entirely soft physics models utilizing hydrodynamic equations, which unfortunately make no prediction for the $A$ dependence. On the other hand, another Monte Carlo parton cascade model overpredicted the $\pi^0$ cross section at 4 GeV/c by a factor of 100! Those results do not prove the validity of hydrodynamics nor the absence of parton cascading, but emphasize the strong model dependence of the SPS spectra due to non-perturbative aspects of the problem. Those aspects, while phenomenologically interesting, make it difficult to identify perturbative QCD phenomena and search for jet quenching.

The main point of this work, is not to improve the HIJING soft $p_\perp$ phenomenology, but to emphasize the good news that at collider energies there is much less sensitivity to the above uncertain element of the reaction mechanism. At $\sqrt{s} > 100$ AGeV the expected jet quenching signature should be readily observable in the $p_\perp \sim 10$ GeV range. Such experiments will commence in 1999 at RHIC and should provide important tests of the theory of non-Abelian multiple collisions and energy loss.
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Figure 1: Invariant $A + A \rightarrow \pi^0$ cross section for central collision at SPS and RHIC energies are compared. a) The WA80 $S + S$ data (triangles) and the preliminary WA98 $Pb + Pb$ data (dots) are compared to HIJING1.35 with soft $p_L$ kicks (full lines) and without $p_T$ kicks (dot-dashed curves). The later scale with the wounded projectile number times $\sigma_{AA}$ times the invariant distribution calculated for $pp$. The parton model curve from Ref. [2] is labeled by 'Wang'. The filled squares show $pp \rightarrow \pi^+$ data scaled by the (Glauber) number of binary collisions times $\sigma_{AA}$ for both $SS$ and $PbPb$. b) Jet quenching, predicted at RHIC energies [6], is not significant at SPS energies in the HIJING model.
Figure 2:  a) Effect of soft $p_T$ kicks in HIJING on the valence quark and diquark $dN/dp_T$ is shown for central Pb+Pb collision at SPS versus Au+Au at RHIC. The dashed lines correspond to neglecting the $p_T$ kicks. b) The effect of jet quenching at the valence quark-diquark level with (dashed) $dE/dx = 1$ GeV/fm is compared for the same systems.
Figure 3: a) Effect of jet quenching on $dN_{q}/dp_{T}$ of mini-jet gluons (dot-dashed) is shown for central Pb+Pb at $\sqrt{s} = 17$ AGeV. The solid and dotted curves show the dominant valence quark and diquark distribution from Fig. 2b. b) The effect of jet quenching in Au+Au at $\sqrt{s} = 200$ AGeV is shown.