Systematic Study of High $p_T$ Hadron Spectra in pp, pA and AA Collisions from SPS to RHIC Energies

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Abstract

High-$p_T$ particle spectra in $p+p$ ($p+\bar{p}$), $p+A$ and $A+B$ collisions are calculated within a lowest-order (LO) perturbative QCD (pQCD) parton model, including intrinsic transverse momentum, its broadening due to initial multiple parton scattering and jet quenching due to parton energy loss inside a dense medium. The intrinsic $k_T$ and its broadening in $p+A$ and $A+B$ collisions due to initial multiple parton scattering are found to be very important at low energies ($\sqrt{s} < 50$ GeV), and they decrease with energy and transverse momentum. Comparisons with $S+S$, $S+Au$ and $Pb+Pb$ data with different centrality cuts show that the differential cross sections of large transverse momentum pion production ($p_T > 1$ GeV/c) in $A+B$ collisions scale very well with the number of binary nucleon-nucleon collisions (modulo effects of multiple initial scattering). This indicates that semi-hard parton scattering is the dominant particle production mechanism underlying the hadron spectra at moderate $p_T \sim 1$ GeV/c. However, there is no evidence of jet quenching or parton energy loss. Within the parton model, one can exclude an effective parton energy loss $dE_q/dx > 0.01$ GeV/fm and a mean free path $\lambda_q < 7$ fm from the experimental data of $A+B$ collisions at the SPS energies. Predictions for high $p_T$ particle spectra in $p+A$ and $A+A$ collisions with and without jet quenching at the RHIC energy are also given. Uncertainties due to initial multiple scattering and nuclear shadowing of parton distributions are also discussed.
I. INTRODUCTION

Large-$E_T$ partons or jets are good probes of the dense matter formed in ultra-relativistic heavy-ion collisions [1,2], since they are produced in the earliest stage of heavy-ion collisions and their production rates are calculable in perturbative QCD. If a dense partonic matter is formed during the initial stage of a heavy-ion collision with a large volume and a long lifetime (relative to the confinement scale $1/\Lambda_{\text{QCD}}$), the produced large $E_T$ parton will interact with this dense medium and, according to many recent theoretical studies [3–5], will lose its energy via induced radiation. The energy loss is shown to depend on the parton density of the medium. Therefore, the study of parton energy loss can shed light on the properties of the dense matter in the early stage of heavy-ion collisions. It is also a crucial test whether there is any thermalization going on in the initial stage of heavy-ion collisions.

Even though one cannot measure directly the energy loss suffered by a high energy parton propagating through a dense medium, its effective fragmentation functions must change and leading particles must be suppressed due to the parton energy loss. This can be measured directly in deeply inelastic $e+A$ collisions (for jets going through a normal nuclear matter) [6,7] and direct-photon-tagged jets in high-energy heavy-ion collisions [7,8]. Since the large $p_T$ single-inclusive particle spectra in nuclear collisions are a direct consequence of jet fragmentation as in hadron-hadron and hadron-nucleus collisions, they are also shown [9] to be sensitive to parton energy loss or modification of jet fragmentation functions inside a dense medium.

Because of the extremely small cross sections of large $p_T$ particle production at the CERN SPS energy ($\sqrt{s} \approx 20$ GeV), measurements of particle spectra in heavy-ion collisions at moderately large $p_T$ have not become available before recent experiments [10,11]. In a recent paper [12], the author used pQCD parton model calculations to analyse the large $p_T$ spectra and found that there is no evidence of parton energy loss in high-energy heavy-ion collisions. From the analysis of the spectra, one can limit the effective energy loss to less than $dE/dx < 0.01\text{GeV/fm}$. Since experimental data have shown evidences of an interacting hadronic matter in heavy-ion collisions at the CERN SPS energy, one can also conclude that the hadronic matter dose not cause apparent jet energy loss.

In this paper, we will conduct a systematic study of high $p_T$ hadron spectra in $pp$, $pA$ and $AB$ collisions, since the reliability of the determination of a small effective parton energy loss in high-energy heavy-ion collisions crucially depends on the precision to which we understand the spectra without parton energy loss. We will include both the intrinsic $k_T$ in $p+p$ collisions and $k_T$ broadening due to multiple initial-state scattering in $p+A$ collisions, which are necessary to describe large $p_T$ particle production at energies below $\sqrt{s} < 50$ GeV. We will then compare the calculations with the experimental data for $S+S$,
$S + Au$ and $Pb + Pb$ collisions at the CERN SPS with different centrality cuts and verify the scaling behavior characteristic of hard processes. Using the same parton model we will then predict the high $p_T$ spectra in $pA$ collisions at the RHIC energy and then calculate same spectra in $AA$ collisions with and without effects of parton energy loss. Within the parton model, we will provide constraints by the experimental data on the values of parton energy loss $dE_q/dx$ and the mean free path $\lambda_q$.

II. $P + P$ Collisions: Initial $K_T$

Large $p_T$ particle production in high-energy hadron-hadron collisions has been shown to be a good test of the QCD parton model [13]. Assuming partons inside the colliding hadrons only have longitudinal momenta, the large $p_T$ particle production cross section can be calculated as a convolution of elementary parton-parton scattering cross sections, parton distributions inside the hadron and parton fragmentation functions. The factorization theorem ensures that the parton distributions and fragmentation functions are universal and can be measured in other hard processes, e.g., $e^+e^-$ annihilation, deeply inelastic $ep$ collisions. With high precision data, parton distributions and fragmentation functions have been parametrized including their QCD evolution with the momentum scale $Q$ of the hard processes [14,15] which in turn can be used to calculate particle production in many other hard processes. This procedure has been rather successful so far in describing large $p_T$ particle production in high-energy $p\bar{p}$ collisions [16] with $\sqrt{s} > 50$ GeV.

The assumption of no intrinsic parton transverse momentum, however, breaks down at lower energies. One finds that inclusion of the intrinsic parton transverse momentum inside hadrons, which gives the Dell-Yan (DY) dilepton pairs large average transverse momentum [17], can also significantly increase the inclusive particle production cross section at moderately large $p_T$ and $\sqrt{s} < 50$ GeV [18,19]. Since we are interested in large $p_T$ particle production at around the CERN SPS energy, we will have to include the intrinsic $p_T$ in our calculation in $p + p$, $p + A$ and $A + B$ collisions.

In the parton model one would naturally expect that partons inside a hadron carry an average intrinsic transverse momentum of about a few hundred MeV, reflecting the hadron size via the uncertainty principle. This is consistent with the fact that hadrons produced in parton fragmentation in $e^+e^-$ annihilation also have an average transverse momentum of a few hundred MeV. However, experimental data of Dell-Yan dilepton pairs production [17] indicate an average initial parton transverse momentum (before the hard process that produces the dilepton pair) of about a few GeV much larger than expected of the intrinsic value. This is because higher order pQCD processes like initial state radiation or $2 \rightarrow$
3 subprocesses with additional radiated gluons can also give rise to an additional initial transverse momentum for the colliding partons. Such complications make it difficult to differentiate what is true intrinsic and what is QCD generated initial transverse momentum. One can re-sum all the radiative corrections into a “Sudakov” form factor up to a scale \( Q_0 \) and define (non-perturbative) contributions below this scale as “true” intrinsic [20,21], even though such an “intrinsic” average transverse momentum might still depend on colliding energy \( \sqrt{s} \) and the momentum scale \( Q \) of the hard processes. In this paper, we introduce a simple scheme of including the intrinsic transverse momentum in the lowest-order (LO) perturbative calculation of the inclusive particle spectra in high-energy \( pp \) collisions.

One can define parton distributions in both fractional longitudinal momentum \( x \) and initial transverse momentum \( k_T \) in a factorized form,

\[
dx \, dx^2 k_T g_N(k_T, Q^2) f_a/N(x, Q^2),
\]

where \( f_{a/N}(x, Q^2) \) are the normal parton distribution functions and we will use the MRS D-’ parameterization [14]. We assume the \( k_T \) distribution \( g_N(k_T) \) to have a Gaussian form,

\[
g_N(k_T, Q^2) = \frac{1}{\pi \langle k_T^2 \rangle_N} e^{-k_T^2/\langle k_T^2 \rangle_N}. \tag{2}
\]

Since the initial \( k_T \) includes both the intrinsic and QCD radiation-generated transverse momentum, the variance in the Gaussian distribution \( \langle k_T^2 \rangle_N \) should also depend on the momentum scale \( Q \) of the hard processes. We choose the following form in our scheme according to the next-to-leading order (NLO) analysis of Dell-Yan (DY) processes [22],

\[
\langle k_T^2 \rangle_N(Q^2) = 1 \text{ GeV}^2 + 0.2\alpha_s(Q^2)Q^2. \tag{3}
\]

The parameters are chosen to reproduce the experimental data in our following discussions. In DY, the \( Q^2 \)-dependent term of the average transverse momentum of the lepton-pair comes from NLO corrections. Therefore, if we were to use NLO perturbative calculation of the hard processes, the \( Q^2 \) dependence of the initial \( \langle k_T^2 \rangle \) would be much weaker. A recent NLO analysis [23] of direct photon spectra in hadron collisions still indicate an initial \( \langle k_T \rangle \approx 1.2 \text{ GeV}/c \). Since we only use LO calculation of the had processes, we will have to include the \( Q^2 \)-dependence to take into account the additional initial \( k_T \) due to the NLO corrections.

The inclusive particle production cross section in \( pp \) collisions will then be given by [13]
where $D^{0}_{h/c}(z_c,Q^2)$ is the fragmentation function of parton $c$ into hadron $h$ as parametrized in [15,24] from $e^+e^-$ data, $z_c$ is the momentum fraction of a parton jet carried by a produced hadron. We choose the momentum scale as the transverse momentum of the produced parton jet $Q = p_T/z_c$. We also use a factor $K \approx 2$ (unless otherwise specified) to account for higher order QCD corrections to the jet production cross section [25].

We define the momentum fraction $x$ in terms of the light-cone variables $x_a = (E_a + p_{\parallel a})/\sqrt{s}$ for partons in the forward beam direction and $x_b = (E_b - p_{\parallel b})/\sqrt{s}$ in the backward beam direction. The four-vector momenta for the colliding partons are then

$$p_a = (E_a, k_{Ta}, p_{\parallel a}),$$
$$p_b = (E_b, k_{Tb}, p_{\parallel b}).$$

(5)

In principle, one should also include the transverse momentum smearing from the jet fragmentation. We neglect this in our calculation of particle spectra in the central rapidity region and consider it been effectively included in the calculation by adjusting the initial $k_T$ distribution. In this case, particles are produced in the same direction of the fragmenting jet. The Mandelstam variables for the elementary parton-parton scattering processes are then

$$\hat{s} = x_a x_b \sqrt{s} + \frac{k_{T a}^2 k_{T b}^2}{x_a x_b \sqrt{s}} - 2k_{Ta}k_{Tb} \cos(\phi_a - \phi_b),$$

$$\hat{t} = -\frac{p_T}{z_c} \left( x_a \sqrt{s} e^{-y} + \frac{k_{T a}^2}{x_a \sqrt{s}} - 2 k_{Ta} \cos \phi_a \right),$$

$$\hat{u} = -\frac{p_T}{z_c} \left( x_b \sqrt{s} e^{y} + \frac{k_{T b}^2}{x_a \sqrt{s}} - 2 k_{Tb} \cos \phi_b \right),$$

(6)

where $p_T$ and $y$ are the transverse momentum and rapidity of the produced particle, $\cos \phi_a = k_{Ta} \cdot p_T/k_{Ta}p_T$, and $\cos \phi_b = k_{Tb} \cdot p_T/k_{Tb}p_T$. The momentum fraction of the produced hadron $z_c$ is then given by the identity for massless two-body scattering, $\hat{s} + \hat{t} + \hat{u} = 0$.

In Eq. (4), one should also restrict the initial transverse momentum $k_{Ta} < x_a \sqrt{s}$ and $k_{Tb} < x_b \sqrt{s}$ such that the partons’ longitudinal momenta in Eq. (5) have the same signs as their parent hadrons. In addition, one of the Mandelstam variables can approach to zero if the initial $k_T$ is too large and then the parton cross section could diverge. To avoid these problems, we introduce a regulator $\mu^2$ in the denominators of the parton-parton cross
sections $d\sigma/d\hat{t}(ab \to cd)$. We choose $\mu = 0.8$ GeV in our following calculations. The resultant spectra are sensitive to the choice of $\mu$ only at $p_T$ around $\mu$ where we believe that pQCD calculation becomes unreliable.

Shown in Figs. 1-4 are our calculated spectra for charged pions as compared to the experimental data [26,27] for $p + p$ collisions at $E_{\text{lab}} = 200, 300, 400, 800$ GeV. As one can see from the figures that pQCD calculations with the initial $k_T$ smearing (solid lines) fit the experimental data very well over all energy range. However, without the initial $k_T$ smearing (dot-dashed lines for $\pi^-$) the calculations significantly underestimate the experimental data, as much as a factor of 20 at $E_{\text{lab}} = 200$ GeV. This is because the QCD spectra are very steep at low energies and even a small amount of initial $k_T$ could make a big increase to the final spectra. As the energy increases, the QCD spectra become flatter and small amount of initial $k_T$ does not change the spectra much, as we can already see by comparing the spectra for $E_{\text{lab}} = 800$ GeV (Fig. 4) to that of 200 GeV (Fig. 1). This is further demonstrated in Fig. 5 where we compare the LO calculation to experimental data in high-energy $p\bar{p}$ collisions. Here we have used a $K = 1.5$ factor. One can see that at higher collider energies, the initial $k_T$ does not make much difference to the spectra at high transverse momentum. In the case of no intrinsic $k_T$, we didn’t use the regulator $\mu$ in our calculation. Instead, we used the $p_T$ of particle as a cut-off of the phase integral in Eq. (4). This is why the spectra (dot-dashed lines) increase faster at smaller $p_T$ than the ones with initial $k_T$ smearing in which a regulator of $\mu = 0.8$ GeV is used.
FIG. 1. Single-inclusive pion spectra in $p + p$ collisions at $E_{\text{lab}} = 200$ GeV. The solid lines are pQCD parton model calculations with intrinsic $k_T$ and the dot-dashed line is without. Experimental data are from Ref. [26]. The inserted figure shows the corresponding $\pi^-/\pi^+$ ratio.

FIG. 2. The same as Fig. 1, except at $E_{\text{lab}} = 300$ GeV
In the inserted boxes in Figs. 1-4, we also plot $\pi^-/\pi^+$ ratio as a function of $p_T$. At higher $p_T$, particle production is more dominated by the leading hadrons from valence quark scattering. Since there are more up-quarks than down-quarks in $p + p$ system, one should expect the ratio to become smaller than 1 and decrease with $p_T$. The pQCD calculations describe this isospin dependence of the spectra very well. For other flavors of hadrons, we show in Figs. 5-7 the calculated kaon spectra at different energies. We see that the agreement with experimental data is very good, except at large $p_T$ at low energies which
may be improved by using better fragmentation functions for kaons. One can also notice that $K^-$ spectra at large $p_T$ are about a factor of 10 smaller than $K^+$. This is because the content of strange quarks in a nucleon is much smaller than up (down) quarks which are responsible for leading $K^+ (K^0)$ hadron production. We did not calculate and compare the spectra of produced protons and anti-protons because there is no very accurate parametrization of the corresponding fragmentation functions.

![Figure 5](image_url)

**FIG. 5.** Single-inclusive spectra of charged hadrons in $p + \bar{p}$ collisions at $\sqrt{s} = 200, 900, 1800$ GeV. The solid lines are pQCD parton model calculations with intrinsic $k_T$ and the dot-dashed lines are without. Experimental data are from Refs. [28,29].
FIG. 6. Single-inclusive spectra of charged kaons in $p + p$ collisions at $E_{\text{lab}} = 200$ GeV. The lines are pQCD parton model calculations with intrinsic $k_T$ and data are from Ref. [26].

FIG. 7. The same as Fig. 6, except at $E_{\text{lab}} = 300$ GeV

FIG. 8. The same as Fig. 6, except at $E_{\text{lab}} = 400$ GeV
III. $P + A$ COLLISIONS: $K_T$ BROADENING

Since single-inclusive particle spectra at high $p_T$ in $p + A$ collisions have been shown, both experimentally [26] and theoretically [30], to be sensitive to multiple initial-state scattering, or Cronin effect, it is important that we take into account this effect here in order to have a quantitative study of the change of particle spectra at high $p_T$ in nucleus-nucleus collisions. One can study the Cronin effect in a model of multiple parton scattering [30]. In such a model, one uses Glauber multiple scattering formula to treat parton scattering between beam and target partons which is essential to incorporate the interference effect. For example, when contribution from double scattering is considered, one must also include the absorptive part of the single scattering which has a negative contribution. This absorptive part then cancels part of the contribution from double scattering. Consequently, the enhancement of particle spectra because of double scattering decreases with $p_T$ in the form of $1/p_T^2$ and in general with $\sqrt{s}$ [31]. One can also find that the dominant contribution in double scattering comes from the case where one of the scatterings is soft and large part of the final $p_T$ of the produced jet comes from just one hard scattering. At much lower $p_T$ the absorptive correction is much larger than the double scattering contribution and the spectra there is even suppressed. So the integrated cross section or average particle multiplicity at moderate $p_T$ are not affected by multiple parton scattering even though the spectra are modified, as observed in the DY case [32]. This will provide us a justification for our following phenomenological treatment of multiple parton scattering in $p + A$ and $A + A$ collisions.

In this paper we assume that the inclusive differential cross section for large $p_T$ particle production is still given by a single hard parton-parton scattering. However, due to multiple parton scattering prior to the hard processes, we consider the initial transverse momentum $k_T$ of the beam partons is broadened. Assuming that each scattering provide a $k_T$ kick which also has a Gaussian distribution, we can in effect just change the width of the initial $k_T$ distribution. Then the single inclusive particle cross section in minimum-biased $p + A$ collisions is,

$$
\frac{d\sigma^b_{pA}}{dy d^2p_T} = K \sum_{abcd} \int d^2bt_A(b) \int dx_a dx_b d^2k_{aT} d^2k_{bT} g_A(k_{aT}, Q^2, b) g_p(k_{bT}, Q^2) f_{a/p}(x_a, Q^2) f_{b/A}(x_b, Q^2, b) D^{b}_{\pi} / \pi z_c \frac{d\sigma}{dt} (ab \rightarrow cd),
$$

(7)

where $t_A(b)$ is the nuclear thickness function normalized to $\int d^2bt_A(b) = A$. We will use Wood-Saxon form of nuclear distribution for $t_A(b)$ throughout this paper unless specified otherwise. The parton distribution per nucleon inside the nucleus (with atomic mass number $A$ and charge number $Z$) at an impact parameter $b$,
\[ f_{a/A}(x, Q^2, b) = S_{a/A}(x, b) \left[ \frac{Z}{A} f_{a/p}(x, Q^2) + (1 - \frac{Z}{A}) f_{a/n}(x, Q^2) \right], \quad (8) \]
is assumed to be factorizable into the parton distribution in a nucleon \( f_{a/N}(x, Q^2) \) and the nuclear modification factor \( S_{a/A}(x, b) \) which we take the parameterization used in HIJING [33] for now. The initial parton transverse momentum distribution inside a projectile nucleon going through the target nucleon at an impact parameter \( b \) is then,

\[ g_A(k_T, Q^2) = \frac{1}{\pi \langle k_T^2 \rangle_A} e^{-k_T^2/\langle k_T^2 \rangle_A}, \quad (9) \]

with a broadened variance

\[ \langle k_T^2 \rangle_A(Q^2) = \langle k_T^2 \rangle_N(Q^2) + \delta^2(Q^2)(\nu_A(b) - 1). \quad (10) \]

The broadening is assumed to be proportional to the number of scattering \( \nu_A(b) \) the projectile suffers inside the nucleus. For the purpose of considering the impact-parameter dependence of the \( k_T \) broadening, we will simply assume a hard sphere nuclear distribution. Therefore,

\[ \nu_A(b) = \sigma_{NN} t_A(b) = \sigma_{NN} \frac{3A}{2\pi R_A^2} \sqrt{1 - b^2/R_A^2}, \quad (11) \]

where \( R_A = 1.12A^{1/3} \) fm and \( \sigma_{NN} \) is the inelastic nucleon-nucleon cross section.

The Gaussian distribution is certainly not a very good approximation for the soft \( k_T \) kicks that partons obtain during the multiple parton scattering, for example in the multiple parton scattering model [30,31]. One way to correct this problem is to assume that \( k_T \) broadening during each nucleon-nucleon collision \( \delta^2 \) also depends on the hard momentum scale \( Q = E_T \), the transverse momentum of the produced parton jet. We will use the following scale-dependent \( k_T \) broadening per nucleon-nucleon collision,

\[ \delta^2(Q^2) = 0.225 \left( \ln^2(Q/\text{GeV}) \over 1 + \ln(Q/\text{GeV}) \right) \text{GeV}^2/c^2. \quad (12) \]

For \( Q = 2 \sim 3 \) GeV, \( \delta^2 = 0.064 \sim 0.129 \) GeV\(^2\)/c\(^2\), which is consistent with the value obtained from the analysis of \( k_T \) broadening for \( J/\Psi \) production in \( p + A \) collisions [34,35]. We should point out that this value can be different from what one gets from the analysis of \( k_T \) broadening of Dell-Yan dilepton pairs in \( p + A \) collisions, where mainly quarks and anti-quarks are involved in the hard processes and there is no collision effect after the Dell-Yan production point.

Using the above assumptions, we calculate the large \( p_T \) particle spectra in \( p + A \) collisions and compare to the spectra in \( p + p \) collisions. As we show in the last Section, particle spectra has a strong isospin dependence in the parton model. In order to minimize this known isospin dependence of the spectra in our study of nuclear dependence of the spectra, we compare the
spectra of $p + A$ for heavy target with that for a very light nuclear target. Shown in Fig. 9 are our calculated ratios of charged pion spectra (solid lines for $\pi^+$ and dot-dashed lines for $\pi^-$) in $p + W$ over that of $p + Be$ each normalized by the atomic number of the target nucleus. The experimental data are from Ref. [26,36]. If there was no nuclear dependence due to multiple scattering, the ratios would have a flat value of 1, modulo the residual isospin dependence because of the small isospin asymmetry of the target nucleus. The difference between our calculated ratios for $\pi^+$ and $\pi^-$ gives the order of this isospin asymmetry effect. One can get rid of this effect by using the ratios of $\pi^+ + \pi^-$ spectra. As shown in the figure, our model can roughly describe the general feature of the nuclear dependence of the spectra at large $p_T$ due to multiple parton scattering. The ratios should become smaller than 1 at very small $p_T$ because of the absorptive processes as we have mentioned. But here our perturbative calculation will eventually break down because of the small momentum scale. At larger $p_T$, the spectra are enhanced because of multiple parton scattering. As $p_T$ increases further, the ratios decrease again and saturate at about 1. The decrease follows the form of $1/p_T^2$ consistent with the general features of high twist processes. Since the transverse momentum broadening due to multiple parton scattering is finite, its effect will eventually become smaller and disappear. Therefore, the $p_T$ location of the maximum enhancement can give us the scale of average transverse momentum broadening.
FIG. 9. Ratios of charged pions spectra in $p + W$ over $p + Be$ each normalized by the atomic number of the target nucleus. The lines are the parton model calculation with $k_T$ broadening due to multiple parton scattering. Experimental data are from Refs. [26,36].

At low energies, $E_{lab} = 200$ GeV for example, the full structure of multiple scattering cannot be revealed because of the finite phase space constrained by the kinetic limit. Furthermore, the ratio will increase at large $x_T = 2p_T/\sqrt{s}$ because of the so-called EMC effect [37] on nuclear structure function at large $x$ which is incorporated into the parametrization of the nuclear modification factor for parton distributions inside a nucleus. One word of caution should also be given here. Our calculation might not be reliable anymore near the boundary of the available phase space ($p_T \sim \sqrt{s}/2$) where overall energy and momentum conservation is very important which is not imposed in pQCD parton model.

We have also calculated the kaon spectra in $pA$ collisions. Show in Fig. 10 are the ratios of the kaon spectra in $p + W$ over $p + Be$ collisions (normalized by the atomic number). The agreement with the experimental data is quite good for $K^+$. However, for $K^-$ there is quite sizable discrepancy between the calculation and the data. This is might be due to the flavor dependence of the $k_T$ broadening suffered by the quarks. It is quite possible that $\bar{u}$ quarks have larger scattering cross sections as they propagate through the nucleus and therefore experience larger $k_T$ broadening than $\bar{s}$ quarks. Such effects will result in the observed difference in nuclear enhancement between $K^-$ and $K^+$. 
FIG. 10. Ratios of charged kaons spectra in $p + W$ over $p + Be$ each normalized by the atomic number of the target nucleus. The solid (dot-dashed) lines are the parton model calculation for $K^+$ ($K^-$) with $k_T$ broadening due to multiple parton scattering. Experimental data are from Refs. [26,36].

IV. $A + A$ COLLISIONS: JET QUENCHING?

It is straightforward to incorporate the initial $k_T$ broadening due to multiple parton scattering in $A + A$ collisions. Since partons from projectile and target beam both suffer multiple scattering before the hard process, their initial transverse momentum distributions are broadened as given by Eq. (9). In addition, the produced parton jets have to propagate through a dense medium and interact with other produced particles in the medium. Theoretical studies [3–5] show that a fast parton propagating inside a dense partonic medium will suffer considerable amount of energy loss. Since large $p_T$ particles are produced through the fragmentation of parton jets with large transverse energy, parton energy loss will definitely lead to the suppression of large $p_T$ particles. One can describe this suppression phenomenologically via effective fragmentation functions which are modified from their original forms in the vacuum [7–9]. In this approach one can then calculate the single inclusive particle spectra at large $p_T$ in $A + B$ collisions as,

$$\frac{d\sigma_{AB}^h}{dyd^2p_T} = K \sum_{abcd} \int d^2b d^2r t_A(r) t_B(|b - r|) \int dx_a dx_b d^2k_{aT} d^2k_{bT} g_A(k_{aT}, Q^2, r) g_B(k_{bT}, Q^2, |b - r|) f_{a/A}(x_a, Q^2, r) f_{b/B}(x_b, Q^2, |b - r|) \frac{D_{h/c}(z_c, Q^2, \Delta L)}{\pi z_c} \frac{d\sigma}{dt}(ab \rightarrow cd),$$

(13)

where $D_{h/c}(z_c, Q^2, \Delta L)$ is the modified effective fragmentation function for produced parton $c$ which has to travel an average distance $\Delta L$ inside a dense medium. We will not elaborate on the modelling of the modified fragmentation functions [7–9] here, except pointing out that it depends on two parameters: the energy loss per scattering $\epsilon_c$ and the mean free path $\lambda_c$ for a propagating parton $c$. The energy loss per unit length of distance is then $dE_c/dx = \epsilon_c/\lambda_c$. We also assume that a gluon’s mean free path is half of a quark and then the energy loss $dE/dx$ is twice that of a quark. In principle, the energy loss $dE/dx$ should depend on local parton density or temperature, the parton’s initial energy, the total distance and whether there is expansion [38]. These possible features will influence the final hadron spectra and their phenomenological consequences have been studied in detail in a previous publication [9]. In this paper, we will simply assume a constant energy loss and study the average effect of parton energy loss in dense matter.
After integration over the impact parameter space, Eq. (13) will give us the inclusive hadron spectra for minimum-biased events of $A + B$ collisions. If one neglects nuclear effects (parton shadowing, $k_T$ broadening and jet quenching), the resultant spectra should be exactly proportional to $AB$ which is the averaged number of binary nucleon-nucleon collisions. Very often experimentalists also measure inclusive hadron spectra for certain classes of events with different centrality cuts (total transverse energy $E_T$ or charged multiplicity in the central region). Since one cannot directly measure the impact parameters in each class of centrality, a theoretical model of correlation between impact parameter $b$ and the total transverse energy $E_T$ (or charged multiplicity) has to be introduced in order to calculate the inclusive cross section for events with different centrality cuts. In this paper, we will use the correlation function $P_{AB}(E_T,b)$ [normalized to $\int dE_T P_{AB}(E_T,b) = 1$] introduced in Ref. [39] which assumes a wounded nucleon model for transverse energy production. The differential cross section

$$\frac{d\sigma_{AB}}{dE_T} = \int d^2b [1 - e^{-\sigma_{NN} T_{AB}(b)}] P_{AB}(E_T,b)$$  \hspace{1cm} (14)$$

has been shown to reproduce the experimental data of NA35 and NA49 [40] very well, where $T_{AB}(b) = \int d^2r t_A(r) t_B(b-r)$ is the overlap function for $A+B$ collisions at impact parameter $b$. We refer readers to Ref. [39] for the details of this model.

After incorporating the correlation function between impact parameter and transverse energy in Eq. (13), the inclusive cross section of large $p_T$ hadron production in events with centrality cut $E_T \in (E_T^{\text{min}}, E_T^{\text{max}})$ can be shown to be roughly proportional to

$$\langle N_{\text{binary}} \rangle \equiv \int d^2b \int_{E_T^{\text{min}}}^{E_T^{\text{max}}} dE_T P_{AB}(E_T,b) T_{AB}(b)$$  \hspace{1cm} (15)$$

which is just the average number of binary nucleon-nucleon collisions. For minimum-biased events, this number is just $AB$. Since the actual $d\sigma_{AB}/dE_T$ distribution depends on each experiment’s coverage of phase space and the detector’s calibration, we will choose the values of $E_T^{\text{min}}$ and $E_T^{\text{max}}$ so that the fraction of the integrated cross section in Eq. (14) within the $E_T$ range matches the experimental value of a given centrality cut.

Shown in Fig. 11 are the calculated inclusive spectra for produced $\pi_0$ in $S+S$, $S+Au$ and $Pb+Pb$ collisions, both minimum-biased and central events. The pQCD parton model calculations with the $k_T$ broadening due to initial multiple scattering (solid lines) agree with the experimental data (WA80 and WA98) [10,11] well very at $p_T$ above 1 GeV/c. No parton energy loss has been assumed in the calculations. The dashed lines are the spectra in $pp$ collisions at the same energy multiplied by the nuclear geometrical factor as given in Eq. (15). The difference between the solid and dashed lines is simply caused by effects of $k_T$ broadening and nuclear modification of parton distributions inside nuclei. These effects are similar as in
$p + A$ collisions and are more important in collisions of heavier nuclei. Without these nuclear effects the high $p_T$ hadron spectra in $A + B$ collisions are exactly proportional to the average number of binary collisions as shown by the dashed lines. This is a common characteristic of hard processes in $p + A$ and $A + B$ collisions. Because of absorptive processes, low $p_T$ particle production, which can be considered as coherent over the dimension of nuclear size, has much weaker $A$-dependence. In the wounded-nucleon model, soft particle production cross section is proportional to the average number of wounded nucleons which is much smaller than the number of binary collisions. By studying the transition of the scaling property of the hadron spectra from low to high $p_T$ values, one can then determine at what $p_T$ value the underlying mechanism of hadron production become dominated by hard processes. This will be the subject of another study.

FIG. 11. Single-inclusive spectra of $\pi^0$ in $S + S$, $S + Au$ and $Pb + Pb$ collisions (both minimum-biased and central events) at the CERN SPS energies. The solid lines are pQCD parton model calculations with $k_T$ broadening due to initial multiple parton scattering and the dashed lines are without. Experimental data are from Refs. [10,11].

In the parton model calculations presented so far, effects of parton energy loss have not been considered yet. If there is parton energy loss and the radiated gluons become incoherent from the leading parton, the resultant leading hadron spectra at large $p_T$ from the parton fragmentation should be suppressed as compared to $p + p$ and $p + A$ collisions. As we have shown, however, the parton model calculations without parton energy loss fit the experimental data very well. To find out the consequences of an effective parton energy loss in the hadron spectra and how the experimental data constrain its value at the CERN
SPS energy, we show in Fig. 12 as the dot-dashed line the calculated $\pi_0$ spectra in central $Pb + Pb$ collisions with $dE/dx = 0.01$ GeV/fm. In the calculation (dot-dashed line) we have assumed the energy loss per scattering $\epsilon_q = 0.02$ GeV and the mean free path $\lambda_q = 2$ fm ($dE_q/dx = \epsilon_q/\lambda_q$). In our model [7,8], the modification of the fragmentation function is sensitive to both parameters. The mean free path is a measure of the strength of the interaction between the leading parton and medium while energy loss $dE/dx$ reflects the degree of attenuation induced by the interaction. Shown as the dashed line in Fig. 12 is a calculation with the same $dE_q/dx = 0.01$ GeV/fm but with a mean free path $\lambda_q = 7$ fm which is about the average total length a parton will travel through in a cylindrical system with a radius of a $Pb$ nucleus. Such a scenario of weak interaction and small energy loss is barely consistent with the systematics of the experimental data. It is clear that the large $p_T$ spectra in $Pb + Pb$ collisions at the CERN SPS energy can put very stringent limits on the interaction of energetic partons with dense medium and the induced energy loss. Within the parton model, one can exclude from the observed hadron spectra a parton energy loss larger than $dE_q/dx = 0.01$ GeV/fm and a mean free path shorter than $\lambda_q = 7$ fm. This is much smaller than the most conservative estimate of parton energy loss in a dense medium [3–5].

![Figure 12](image_url)

FIG. 12. Parton model calculations of single-inclusive spectra of $\pi^0$ with different values of parton energy loss $dE_q/dx$ and mean free path $\lambda_q$ in central $Pb + Pb$ collisions at $E_{lab} = 158$ AGeV/. The Experimental data are from Ref. [11].

There are several implications one can draw from this analysis. Most of the recent theoretical estimates of parton energy loss are based on a scenario of a static and infinitely large dense parton gas. If the system produced in a central $Pb + Pb$ collision only exists
for a period of time shorter than the interaction mean free path of the propagating parton, one then should not expect to see any significant parton energy loss. Using the measured transverse energy production $dE_T/d\eta \approx 405 \text{ GeV} \ [40]$ and a Bjorken scaling picture, one can indeed estimate $[12]$ that the life time of the dense system in central $Pb + Pb$ collisions is only about $2 - 3 \text{ fm/c}$ before the density drops below a critical value of $\epsilon_c \approx 1 \text{ GeV/fm}^3$. Even if we assume that a dense partonic system is formed in central $Pb + Pb$ collisions, this optimistic estimate of the life time of the system could still be smaller than the mean free path of the propagating parton inside the medium. Thus, one does not have to expect a significant effect of parton energy loss on the final hadron spectra at large $p_T$. Otherwise, it will be difficult to reconcile the absence of parton energy loss with the strong parton interaction which maintains a long-lived partonic system.

Another conclusion one can also make is that the dense hadronic matter which has existed for a period of time in the final stage of heavy-ion collisions does not cause any apparent parton energy loss or jet quenching. A high $p_T$ physical pion from jet fragmentation has a very long formation time. One does not have to worry about its scattering with other soft hadrons in the system which could cause suppression of high $p_T$ pion spectra. We still do not understand the reason why a fragmenting parton does not loss much energy when it propagates through a dense hadronic matter. However, it might be related to the absence of energy loss to the quarks and anti-quarks prior to Drell-Yan hard processes in $p + A$ and $A + A$ collisions. This observation will make jet quenching a better probe of a long-lived partonic matter since one does not have to worry about the complications arising from the hadronic phase of the evolution. If one observes a dramatic suppression of high $p_T$ hadron spectra at the BNL RHIC energy as predicted $[2,7-9]$, then it will clearly indicate an initial condition very different from what has been reached at the CERN SPS energy.

V. PREDICTIONS AT RHIC: IMPORTANCE OF $P + A$ EXPERIMENTS

As we have seen in the calculation of large $p_T$ particle spectra in $p + p(\bar{p})$ collisions, the initial $k_T$ smearing is most important at low energies where the original particle spectra from jet production falls off very rapidly with $p_T$. The effect of $k_T$ broadening due to multiple parton scattering in $p + A$ collisions follows the same line. At higher energies ($\sqrt{s} > 50 \text{ GeV}$), when the original jet spectra become much flatter, the effects of both the initial or intrinsic $k_T$ and nuclear $k_T$ broadening will become smaller, as we can clearly see in both our calculation and the experimental data in Figs. 8 and 5. At the BNL RHIC collider energy, the nuclear enhancement of large $p_T$ spectra will then become smaller. Shown in Fig. 13 are the calculated ratios of charged hadron spectra in $p + Au$ over that in $p + p$ normalized to
the averaged number of binary nucleon collisions,

\[ R_{AB}(p_T) \equiv \frac{d\sigma_{AB}^b/dydp_T}{\langle N_{\text{binary}} \rangle d\sigma_{pp}^b/dydp_T} \]  \hspace{1cm} (16)

where \( \langle N_{\text{binary}} \rangle = A \) for minimum-biased events of \( p + A \) collisions. We can see that the enhancement due to multiple parton scattering will not disappear at the RHIC energy. There is still about 20–50% enhancement at moderately large \( p_T \) around 4 GeV/c. It then disappears very quickly at larger \( p_T \).

At the BNL RHIC energy, \( \sqrt{s} = 200 \) GeV, nuclear modification of the gluon distribution will become important for hadron spectra at moderately large \( p_T \). Such modifications for quark distributions have been measured in deeply inelastic lepton-nucleus collisions [41]. However, the nuclear effects on the gluon distribution have not been directly measured. In the calculation shown as the dashed line in Fig. 13 we have used a recent parametrization of the nuclear modification factors \( S_a/A(x, Q^2) \) [Eq. (8)] by Eskola, Kolhinen and Salgado [41] which is based on global fits to the most recent collection of data available and some model on nuclear modification of gluon distribution. This result is quite different from the calculation using HIJING [33] parametrization. In EKS98 parametrization, QCD evolution equation has been used to take into account the \( Q^2 \) scale dependence of the nuclear modification which is absent in HIJING parametrization. Because of QCD evolution, the nuclear shadowing effects at small \( x \) become smaller with increasing \( Q^2 \). This is why the hadron spectrum in \( p + A \) collisions using EKS parametrization is larger than that using HIJING parametrization. The EKS98 parametrization also has a gluon anti-shadowing which is larger than any parametrizations before. Hadron spectra in a moderately large \( p_T \) range at the BNL RHIC energy mainly come from fragmentation of gluon jets. This is why the EKS98 result in Fig. 13 is larger than that without nuclear modification of parton distributions (solid line) in the \( p_T \) range where anti-shadowing becomes relevant. In addition, the impact parameter dependence of the nuclear modification of parton distributions is not implemented in the calculation using EKS98 parametrization. Though EKS98 parametrization has taken into account information about nuclear shadowing of gluon distribution from the measured scale evolution of the structure functions of different nuclei, such a procedure is also model dependent. The result will depend on whether one includes the higher gluon-density terms in the QCD evolution equation. Before a direct measurement of the nuclear effect on gluon distribution inside a nucleus, one should consider it one of the uncertainties in predicting the hadron spectra in \( p + A \) collisions at the BNL RHIC energy.
FIG. 13. Predictions for the ratio of single charged hadron spectra in $p+Au$ over $p+p$ collisions normalized by the average number of binary collisions (or $A$) at $\sqrt{s} = 200$ GeV. Different lines are for different parametrizations of shadowing or nuclear modification of parton distributions.

As pointed out in Sec. II, the shape of the nuclear modification of hadron spectra at large $p_T$ is a result of multiple parton scattering inside a nucleus and their corresponding absorptive corrections. The shape is remarkably similar to the nuclear modification of parton distributions. In fact, nuclear modification of parton distributions in small $x$ region (shadowing and anti-shadowing) can be explained in a multiple scattering model [42]. Therefore, one could have double counted the same effect if he includes both the Cronin effect (or $k_T$ broadening) and nuclear modification of the parton distributions in the calculation of hadron spectra in $p + A$ collisions. Given these uncertainties, it is therefore extremely important to have a systematic study of $p + A$ collisions at the BNL RHIC energy. Such an effort is pivotal to unravel any other effects in the hadron spectra caused by the formation of dense partonic matter in $A + A$ collisions.
FIG. 14. Predictions for the ratio of single charged hadron spectra in central $Au + Au$ over $p + p$ collisions normalized by the average number of binary collisions at $\sqrt{s} = 200$ GeV. Different lines are for different parametrizations of shadowing or nuclear modification of parton distributions. The upper set of lines are without parton energy loss and lower set are with parton energy loss $dE_q/dx = 0.25$ GeV/fm and mean free path $\lambda_q = 2$ fm.

Shown in Fig. 14 are predictions for the ratio of hadron spectra in central $Au + Au$ collisions over that in $p + p$ [as defined in Eq. (16)], with and without parton energy loss. In both cases, uncertainties in the nuclear modification of parton distributions are still important. If there is significant parton energy loss in the dense medium at the BNL RHIC energy, leading hadrons from jets which are produced in the center of a overlapped region will be suppressed. As we can see this is where the Cronin effect and the effect of nuclear modification of parton distributions are the strongest. This is why the relative uncertainty caused by nuclear parton distributions is reduced compared to the case when there is no parton energy loss. In the calculations, we also included possible contribution to hadron production from soft processes at low $p_T$ as implemented in Ref. [9]. When hadrons from hard parton scattering are suppressed, these soft contributions might become dominant at intermediate $p_T$. This is why the spectra ratio increases again when $p_T < 2$ GeV/$c$ in Fig. 14. The spectra at lower $p_T$ could also be broadened due to the rescattering effect which also drives the system into local equilibrium. We should emphasize that the soft particle spectra we use here are extremely schematic and qualitative. This is another uncertainty one should keep in mind which could affect the shape of spectra at intermediate $p_T$. Nevertheless, the spectra at moderately large $p_T$ is most sensitive to parton energy loss in dense medium. Therefore, one should study hadron spectra in $p + A$ very carefully and
pin down the uncertainty due to multiple scattering and parton (anti)shadowing as much as possible. Only then one can draw more accurate conclusions about parton energy loss from the single inclusive hadron spectra in heavy-ion collisions at the BNL RHIC energy.

VI. CONCLUSIONS AND DISCUSSIONS

In this paper, we have analysed systematically large $p_T$ hadron spectra in $p + p$, $p + A$ and $A + A$ collisions from CERN SPS to BNL RHIC energies within a pQCD parton model. We found that both the initial $k_T$ in $p + p$ collisions and the $k_T$ broadening due to multiple parton scattering in $p + A$ collisions are important to describe the experimental data within the parton model calculations. The value of initial $k_T$ in order to fit the data is found to be larger than the conventional wisdom of 300 – 500 MeV for intrinsic $k_T$ according to the uncertainty principle. This finding is also consistent with analysis of Drell-Yan data [22] and recent study [23] of direct photon and pion production at around CERN SPS energy range. In both studies, one found that an intrinsic $k_T$ of the order of 1 GeV/$c$ is needed to describe the data within NLO parton model calculations. Since we only used LO pQCD calculation, we have to introduce some $Q^2$ dependence of the initial $k_T$ induced by initial-state radiation processes. The parton model describes very well the energy and isospin dependence of the hadron spectra.

The parton model calculation can also describe the large $p_T$ pion spectra in heavy-ion collisions at the CERN SPS energies very well, both the $A$ or centrality and energy dependence. There is no evidence of proposed parton energy loss caused by dense partonic matter. Based on recent theoretical estimates [3–5] of parton energy loss in dense partonic matter, one should expect a parton energy loss in the order of $dE/dx \sim 2 – 4$ GeV/fm. The absence of such energy loss in large $p_T$ hadron spectra implies that either there is no such dense partonic matter formed or the life time of such medium is smaller then the mean free path of the parton interaction inside such a medium. It also tells us that the hadronic matter which must have existed for a period of time in heavy-ion collisions at the CERN SPS will not cause apparent energy loss or jet quenching effect. Therefore, if one observes suppression of high $p_T$ hadrons at the BNL RHIC energy, it will unambiguously reflect an initial condition very different from what has been achieved at the CERN SPS.

As pointed out in a recent paper by Gyulassy and Levai [43], even though HIJING [33] Monte Carlo model fails to reproduce the hadron spectra in $p + p$, $p + A$ and $S + S$ (and $S + Au$) data at the CERN SPS energy, it accidentally reproduces the central $Pb + Pb$ data very well because some unique form of transverse momentum kick introduced in HIJING to the end-points of strings each time they suffer an interaction. A hydrodynamic model
calculation [44] with significant transverse expansion can also be used to fit the high $p_T$ hadron spectra. So one should wonder how one can make sure that the high $p_T$ hadron production in $A + B$ collisions is indeed dominated by hard parton scattering. As we have proposed earlier [12,45], measurement of two-particle correlation in azimuthal angle in the transverse plane should be able to distinguish these models from parton model. In the parton model, jets are always produced in pairs and back-to-back in the transverse plane. High $p_T$ particles from jet fragmentation should then have strong back-to-back correlation. Neither hydro-dynamical model nor multiple scattering of string end-points can give such correlation. If such correlation is seen, one can then study the $p_T$ dependence of the correlation to find out at what $p_T$ value the correlation disappears. One can then at least quantify above what $p_T$ value thermal-hydro model can be ruled out as the underlying particle production mechanism. Such a study is underway and will be reported elsewhere.

At the BNL RHIC energy, things will become a little cleaner. As pointed out by Gyulassy and Levai [43], most of hadron production at moderate $p_T$ will be dominated by gluon production and are not influenced by the fate of strings or valence quarks (except net baryons). The spectra should be more sensitive to parton energy loss. Moreover, the hadron spectra in $p + A$ and $A + A$ collisions without parton energy loss will have a unique shape similar to those shown in Fig. 13 at high energies which can not be fully revealed at the CERN SPS energies. This unique shape will be hard to explain by any thermal-hydrodynamic models. However, as we have demonstrated in the previous section, there are still some uncertainties related to nuclear modification of parton distributions. It is therefore very important to have a systematic study of $p + p$, $p + A$ and $A + A$ collisions at the BNL RHIC energy in order to make more quantitative conclusions about parton energy loss in dense medium from the single hadron spectra at moderately high $p_T$.

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