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Jets in Relativistic Heavy Ion Collisions

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Jets in Relativistic Heavy Ion Collisions*

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Abstract

Several aspects of hard and semihard QCD jets in relativistic heavy ion collisions are discussed, including multiproduction of minijets and the interaction of a jet with dense nuclear matter. The reduction of jet quenching effect in deconfined phase of nuclear matter is speculated to provide a signature of the formation of quark gluon plasma. HIJING Monte Carlo program which can simulate events of jets production and quenching in heavy ion collisions is briefly described.

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1 Introduction

The state of hot and dense matter which could consist of deconfined quarks and gluons has only been a theoretical topic for more than a decade until the notable experiments of relativistic heavy ion collisions[1] at CERN and BNL, which at least give us some respectable feeling, if not understanding, of what is happening in these heavy ion interactions. With the results from these experiments and the accompanying controversy on whether quark gluon plasma(QGP) is created, we are now looking forward to the experiments at Relativistic Heavy Ion Collider(RHIC). At $\sqrt{s} = 200$ GeV/n, one would expect that hard parton scattering or jet production becomes important, since it has already played a major role in every aspect of $p\overline{p}$ collisions at Sp$\overline{\text{p}}$S energies[2]. However, in heavy ion collisions nuclear effect on the jets must also come in. First, due to the large number of binary collisions in heavy ion interactions, the number of jets produced will also be large. It is estimated[3] that half of the transverse energy in a central $U + U$ collision at RHIC comes from minijets. Second, the involvement of many nucleons and the particle production in the central rapidity region over a large transverse space will give rise to the effect of initial state and final state interations on the jets production, the former resulting in the Cronin effect[4] and the later causing jet quenching in hadronic matter.

The problem of jet quenching is particularly interesting in heavy ion collisions. Unlike J/Ψ supression or strangeness enhancement, the original rate for jet production and its p_T distribution can be reliably calculated by perturbative QCD which agrees well with experiments in pp or $p\overline{p}$ collisions[5]. With some modeling[6,7], the fragmentation of these jets in free space into hadrons can also be well understood. Since the hard partons are created before the other soft interactions or the formation of QGP if possible, they must travel through the dense matter produced in the collision. Therefore, jets could serve as an external probes of the nucleus-nucleus collisions. Previous calculations[8]–[10] of the final state interactions of jets in nuclear collisions considered the enhanced acoplanarity of jets as a probe of multiple scattering in dense matter. Unfortunately, the initial state interactions also give rise to large acoplanarity and as emphasized in Ref. [9,10], increased acoplanarity is expected to occur in both confined and deconfined phases of dense matter. However, a sudden change accompanied by the phase transition, especially a reduction, in the energy loss of the jet when it interacts with the dense matter would be an outstanding effect[11]. Then jet quenching could provide us a viable signal of the formation of QGP. Futhermore, the effect of jet production and quenching on particle production is also important. To provide a conventional picture of the problem, we developed HIJING Monte Carlo program which uses perturbative QCD to simulate jet production in nucleus-nucleus collisions. The interactions of jets with the excited strings then provide the mechanism for jet quenching.

2 Jets Production in Nucleon-nucleon Collisions

We first briefly review jet production in hadronic interactions. In nucleon-nucleon collisions, one can calculate the cross section of hard parton scatterings as[12]

$$\begin{aligned}\frac{d\sigma_{jet}}{dP_T^2dy_1dy_2} &= \sum_{a,b} x_1x_2\left[f_a(x_1,P_T^2)f_b(x_2,P_T^2)d\sigma^{ab}(\hat{s},\hat{t},\hat{u})/d\hat{t}\right.\\ &\left.+ f_b(x_1,P_T^2)f_a(x_2,P_T^2)d\sigma^{ab}(\hat{s},\hat{u},\hat{t})/d\hat{t}\right](1-\frac{\delta_{a,b}}{2}), \qquad (1)\end{aligned}$$

where the summation runs over all parton species, y_1,y_2 are the rapidities of the scattered partons and x_1,x_2 are the fractions of momentum carried by the initial partons and they are related by $x_1 = x_T(e^{y_1} + e^{y_2})/2$, $x_2 = x_T(e^{-y_1} + e^{-y_2})$, $x_T = 2P_T/\sqrt{s}$. This calculation as shown in Fig. 1[13] agrees with experiments very well for different range of P_T and $\sqrt{s}$. Due to the background of soft interactions, it becomes more and more experimentally difficult to detect the jets with small P_T,whose production rates given by Eq. 1 are, however, the largest. Therefore, even

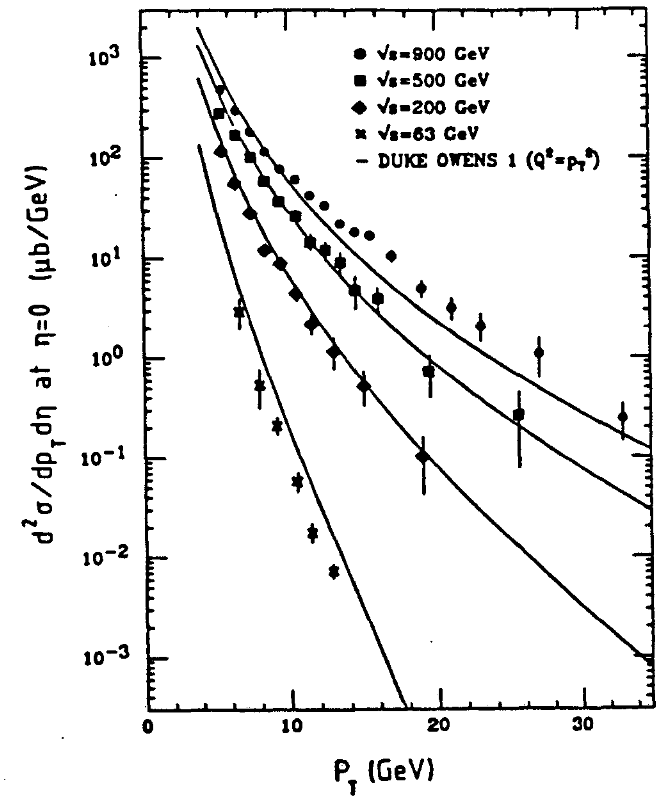

Fig. 1 Inclusive jet cross section at $\eta = 0$ for different values of $\sqrt{s}$, taken from Ref. [13].

though not directly observable, minijets whose P_T still validate the perturbative QCD have been shown to be dominant in hadronic interactions and the correponding multiparticle production[14].

We can calculate the total inclusive jet cross section by integrating Eq. 1 with a low P_T cutoff P_0,

$$\sigma_{jet} = \int_{P_0^2}^{s/4} dP_T^2 dy_1 dy_2 \frac{1}{2} \frac{d\sigma_{jet}}{dP_T^2 dy_1 dy_2}. \tag{2}$$

Since the dominant minijets have relatively small energy, we can assume that they are independently produced. Therefore, the average number of minijets production(*i.e.* pairs of minijets) for a hadron-hadron collision at impact parameter b is $\sigma_{jet}A(b)$, where $A(b)$ is partonic overlap function between the two hadrons. In terms of semiclassical probabilistic model[15], the probability for multiple minijets production is then

$$g_j(b) = \frac{[\sigma_{jet}A(b)]^j}{j!} e^{-\sigma_{jet}A(b)}. \tag{3}$$

Similarly, we can also represent the soft interactions by an inclusive cross section σ_{soft} which, unlike σ_{jet}, can only be determined phenomenologically. Then the total inelastic cross section of the hadron-hadron collision is,

$$\sigma_{in} = \int d^2b[1 - e^{-\sigma_{soft}A(b)}]e^{-\sigma_{jet}A(b)} + \int d^2b \sum_{j=1}^{\infty} \frac{[\sigma_{jet}A(b)]^j}{j!} e^{-\sigma_{jet}A(b)}, \tag{4}$$

where the first term is the cross section for only soft interactions and the second is the cross section for at least one hard with or without soft interactions. After summation, the above equation becomes

$$\sigma_{in} = \int d^2b[1 - e^{-(\sigma_{soft}+\sigma_{jet})A(b)}]. \tag{5}$$

Using eikonal approximation, we can also calculate the total cross section σ_{tot}. By assuming $P_0 = 2$ GeV, which is the lowest cutoff one can have for Duke and Owens[16] parametrization of structure function and requires a constant σ_{soft} at high energies, we found[17] as shown in Fig. 2 that the production of minijets describes well the increase of σ_{tot} and the violation of geometrical scaling.

Following the same arguement, we can calculate the particle distribution[17][19] in the case of minijets production,

$$\begin{aligned} \sigma_{in} E\frac{d^3P(n)}{d^3p} &= \int d^2b[1 - e^{-\sigma_{soft}A(b)}]e^{-\sigma_{jet}A(b)} E\frac{d^3P_s(n)}{d^3p} \\ &+ \int d^2b \sum_{j=1}^{\infty} \frac{[\sigma_{jet}A(b)]^j}{j!} e^{-\sigma_{jet}A(b)} E\frac{d^3P_j(n)}{d^3p}, \end{aligned} \tag{6}$$

where $Ed^3P_s(n)/d^3p$ is the invariant distribution for particles from soft interactions, $Ed^3P_j(n)/d^3p$ is for particles from j number of jets and the accompanying soft

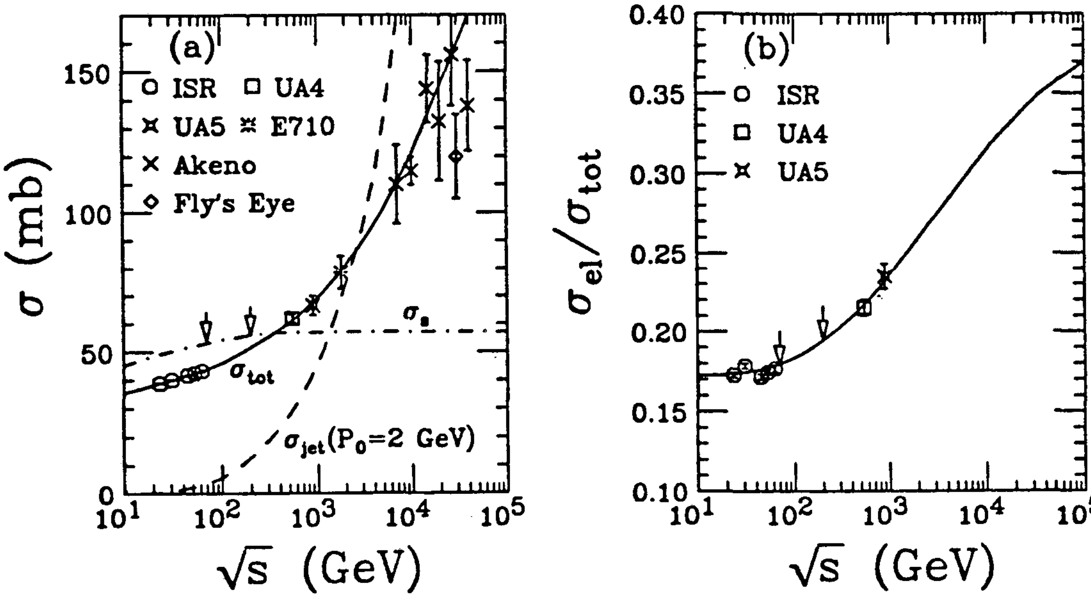

Fig. 2 (a) The calculated cross sections, σ_{tot}(solid line), σ_{jet}(dashed line) and σ_s(dot-dashed line) versus $\sqrt{s}$. (b) σ_{el}/σ_{tot} versus $\sqrt{s}$. See references of the data in Ref [17].

interaction. Using the information from e^+e^- annihilation experiments for particle production of jets and the geometrical branching model[18] for the soft particle production, we can calculate the multiplicity distributions in pp and $p\bar{p}$ collisions[17], as shown in Fig.3,4. The non-log increase of average multiplicity and broadening of the distribution with energy or KNO scaling violation are clearly attributed to jets production. Furthermore, the correlation between $<p_T>$ and multiplicity n can also be calculated[19], as shown in Fig.5, and jets production again explains why $<p_T>$ increases with n and the over all increase of $<p_T>$ with energy. One point needs special attention here. As explained in Ref. [19], the first increase of $<p_T>$ with n is due to the change of ratio between the probabilities of soft and hard interactions. However, when one increases n to some very large numbers, he might have biased the events to those of large P_T jets production, which could give a large $<p_T>$ of the total charged particles. Since experiments[20] at the Fermilab

Tevatron collider have already seen such large $<p_T>$ values which give a second

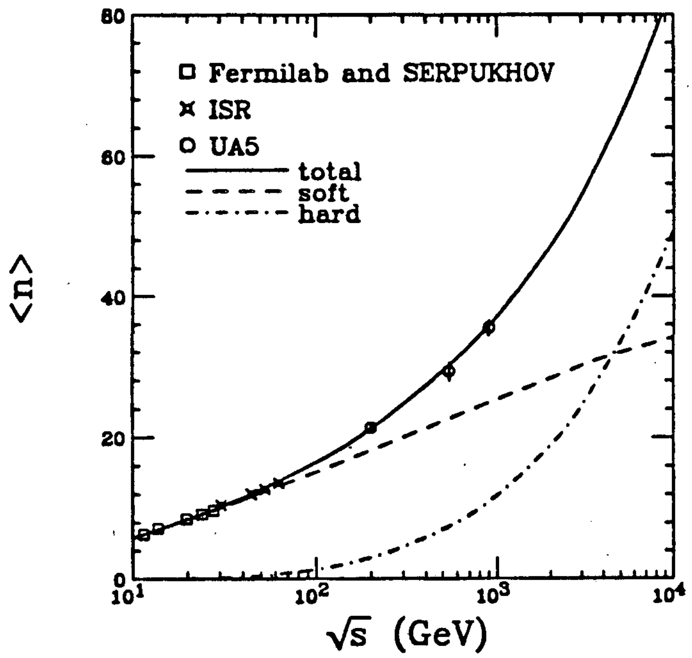

Fig. 3 The average charged multiplicities in pp or $p\overline{p}$ collisions. The solid line is for total charged particles, dashed line for particles from soft production and dotdashed line for particles from jets. See Ref. [17] for data references.

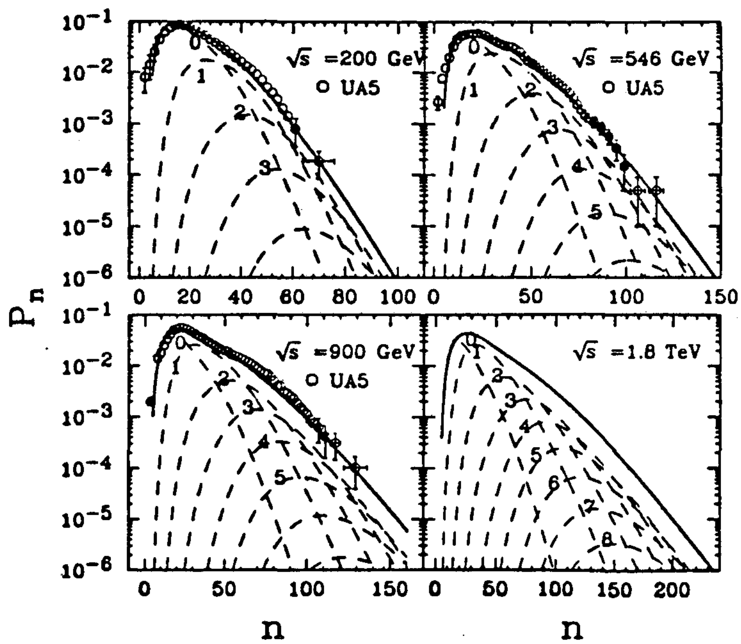

Fig. 4 The multiplicity distributions in $p\overline{p}$ collisions (solid lines). The dashed lines are contributions from events with j=0,1,2,...jets production. See Ref. [17] for data references.

rise of the correlation curve, it is necessary to look at the structure of those events with large n. If a non-neglibible fraction of these events have large P_T jets, then van Hove's scenario[21] of a rise-plateau-rise structure in $<p_T>$ and n correlation can not serve as a clean signal of QGP formation.

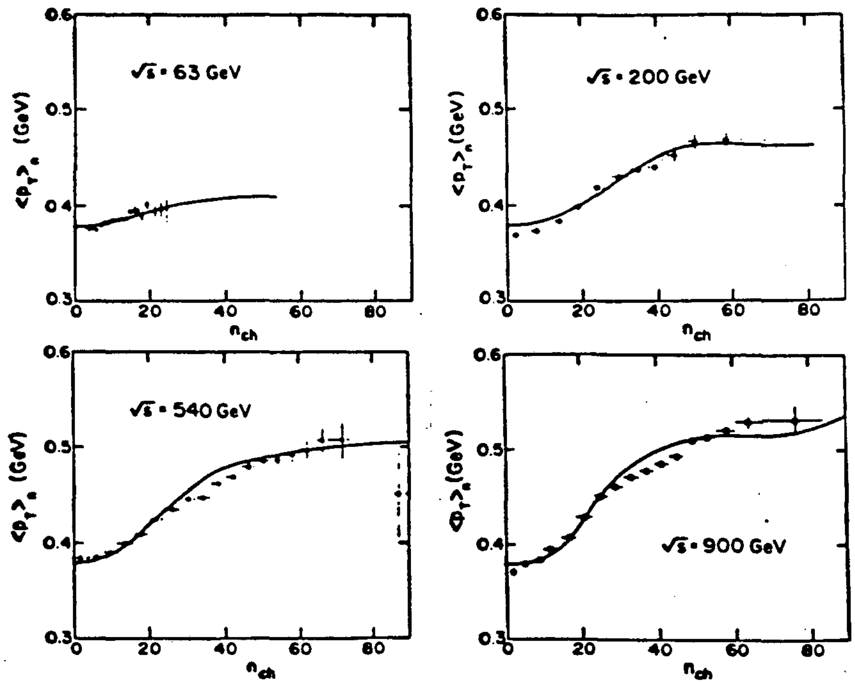

Fig. 5 Calculated $<p_T>$ versus n from Ref. [19].

3 Jets Production in Nucleus-nucleus Collisions

Similar to nucleon-nucleon collisions, one can have the number of jets production in a nucleus-nucleus collision as

$$dN(b) = T_{AB}(b) d\sigma_{jet}^{NN}, \tag{7}$$

where $T_{AB}(b)$ is the overlap function of nuclei A and B at impact parameter b which is essentially the number of binary nucleon-nucleon collisions. This calculation is straight forward and one can show that jet production rate is much higher than in nucleon-nucleon collisions. What we are most interested now is the nulcear effect on the jets production. Basically, there are two aspects of the nuclear effect, one being the initial state interactions and the other being final state interactions. The effects of initial state interactions include the shadowing effect and the Cronin effect which have been thoroughly studied in many experiments. The final state interactions are then more sensitive to the property of the dense matter that a jet has to go through. It is the difference between the energy losses of a jet when it travels through a QGP and a hadronic matter that we hope to signal the QCD deconfinement transition.

Let us first look at the energy loss of a jet when it propagates through nuclear matter in e^-A scatterings. In such scatterings, the jets produced in the e^-N collision have to interact with the other target nucleons and then be attenuated on their way out. For jet energies $\nu = E_e - E_{e'} \sim 10$ GeV, data from SLAC[23] on e^-Sn indicates a substantial nuclear suppression of hadrons produced with fractional energies $x \gtrsim 0.1$. On the other hand, EMC data[24] show that jet quenching in nuclei is virtually absent for $\nu > 20$ GeV. Three mechanisms for the suppression of large x hadrons are studied[22] on the basis of a phase space extension of the Lund string model[7] and the resultant ratio of the fragmentation functions in e^-A and e^-N for two different jet energies are shown in Fig.6[22] together with the data[23,24]. The G-curves assume a zero formation length(distance from jet production point to hadron formation point) and the final hadron cascading. They best fit the data for $\nu = 10$ GeV, but can not account for the rapid onset of jet transparency beyond $\nu \gtrsim 20$ GeV. The C-curves also have hadron cascading but with a constituent formation length $\ell_c \sim x(1-x)L$, where $L = \nu/\kappa$ is the overall hadronization length scale and $\kappa \sim$1 GeV/fm is the string tension. This scheme however underestimates the large suppression of small $x \sim 0.1$ hadrons in e^-Sn for 10 GeV jets. The third mechanism represented by S-curves, which assumes color string flip when the end-point partons of a string interact with a nucleon, is most consistent with the

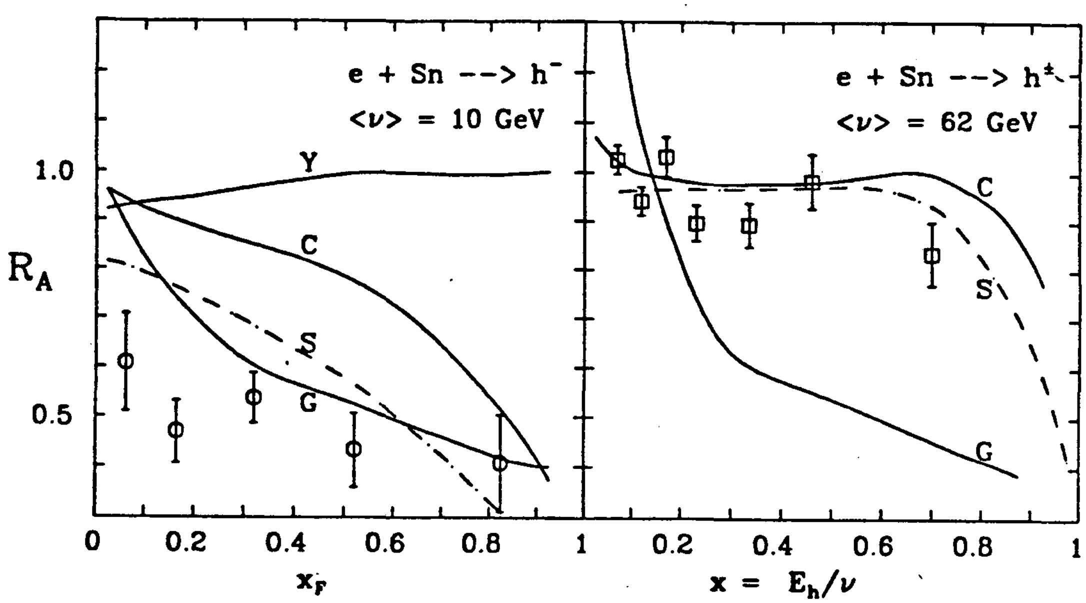

Fig. 6 The ratio $R_A(x)$ for Sn targets at $<\nu>$=10 GeV and $<\nu>$=62 GeV, taken from Ref. [22].

available data among the three schemes. In this string flip model, the hadrons from the leading string always form outside the nucleus and hence do not suffer final state cascading. When the leading string emerges from the nucleus its energy has been reduced by κR due to the kinematic rearrangement of string end points. Therefore, the jets have

$$(dE/dx)_H \equiv \kappa_H = \kappa \tag{8}$$

when they travel through nuclear matter.

In a QGP, the string flip scenario breaks down because the string between two color charges does not exist any more. The source of energy loss for jets in a QGP can only come from the collisions with the other partons in the thermalized system. It was first estimated by Bjorken[25] that such energy loss for a quark of energy E in an ideal quark gluon plasma at a temperature T is

$$(dE/dx)_Q \approx 6\alpha_s^2 T^2 \ln(4ET/M^2) e^{-M/T}(1+M/T), \tag{9}$$

where $M \sim gT$ is an infrared cutoff on the order of Debye mass. The energy loss for gluons is expected to be 9/4 larger. A full calculation[26] of dE/dx via finite temperature perturbative QCD only shows a slight correction to the above result. The magnitude of the energy loss is clearly very sensitive to the effective coupling constant α_s. Recent QCD lattice studies[27,28] of the static heavy $q\bar{q}$ potential indicate that the coupling strength of heavy quarks is quite small, $\alpha \approx 0.1$, just above $T_c \sim 200$ MeV. A possible reduction of the static string tension just below T_c is also indicated[28]. While these results all refer to static interactions in dense matter, they may suggest the possibility that both the dynamic coupling in Eq.9 in the plasma phase and the string tension in Eq.8 in the mixed phase is also small. For $E \sim 20$ GeV jets in a plasma at temperature $T \sim 250$ MeV, a value of $\alpha_s \lesssim 0.2$ would imply that $(dE/dx)_Q \lesssim 0.4$ GeV/fm. This energy loss is significantly smaller than the energy loss $(dE/dx)_H = \kappa \approx 1$ GeV in the confined phase via the string flip model[22]. Eventually at very high temperaturs the collisional energy loss will increase with T^2. But hydrodynamic studies[29,30] show that a QGP system will spend most of its expansion time in the mixed phase, where there may be a moderate reduction of dE/dx.

Taking into account of the expansion of a QGP, the total energy loss of a jet when it is out of the system is then,

$$\Delta E_a(r,\phi) \approx C_a \int_0^{\tau_f(r,\phi)} d\tau dE(\tau)/dx, \tag{10}$$

where C_a is the color factor such that $C_q = 1$ and $C_q = 9/4$, r is the initial

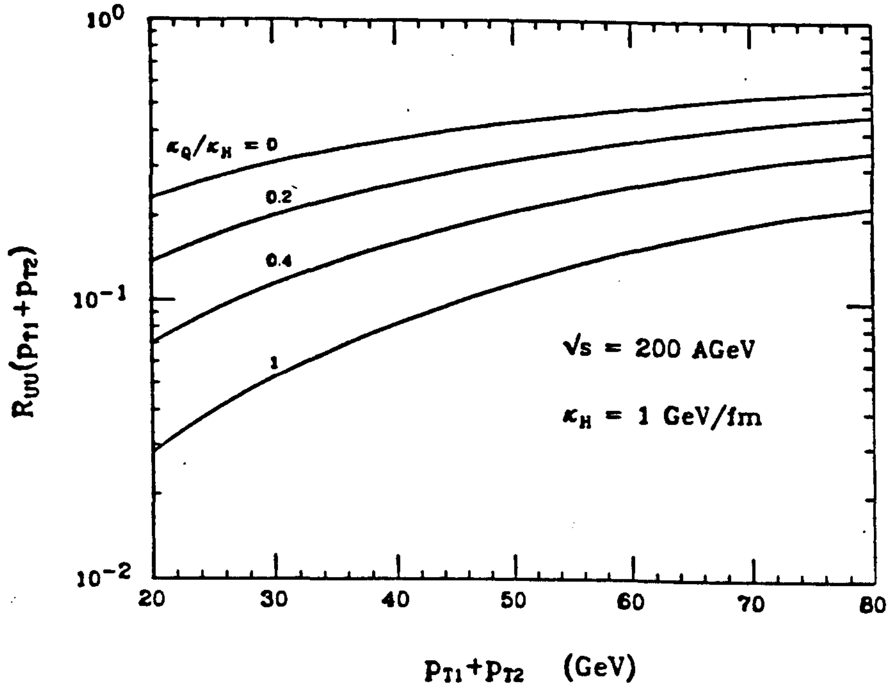

Fig. 7 Dijet reduction factor for central $U+U$ collisions at $\sqrt{s}$ =200 GeV/n as a function of the dijet energy $E = P_{T1} + P_{T2}$, for different values of κ_Q/κ_H assuming κ_H =1 GeV/fm.

transverse coordinate, ϕ the azimuthal angle of the jet and $\tau_f(r,\phi)$ the escape time. Assuming only Bjorken[31] scaling longitudinal expansion and a Bag model equation of state[31], one can find the time dependence of $dE(\tau)/dx$ and get the reduction rate of jet production at fixed P_T by averaging over the initial coordinates (r,ϕ)[22],

$$R_{AA}(E) = \frac{\sigma^{jet}(E)_{quenching}}{\sigma^{jet}(E)_{no-quenching}}. \tag{11}$$

In the plasma phase, the temperature decreases as $T(\tau)/T_c = (\tau_Q/\tau)^{1/3}$. According to Eq. 9, $dE/dx \approx \kappa_Q(\tau_Q/\tau)^{2/3}$, denoting the energy loss in the plasma phase by κ_Q. Fig.7 shows the calculated reduction factors for central $U+U$ collisions as a fucntion of the dijet energy at $\sqrt{s}$ = 200 GeV/n. The Bag model parameters were chosen such that T_c = 190 MeV, B = 0.5 GeV/fm^3, ϵ_Q = 2.5 GeV/fm^3, and ϵ_H = 0.5 GeV/fm^3. The initial conditions for these calculations were assumed to be $\tau_0 = 1$ fm/c and

$$\epsilon_0 = \epsilon_s A^{1/3} + \epsilon_h A^{2/3}, \tag{12}$$

where the energy density due to soft processes is $\epsilon_s \approx 0.5$ GeV/fm^3 and the energy density due to semi-hard minijets is $\epsilon_h(\sqrt{s} = 200) \approx 0.08$ GeV/fm^3[3]. Note that the overall magnitude of jet quenching in heavy nuclei is quite large, reducing the expected number of jets by around an order of magnitude. The quenching is also very sensitive to the ratio of dE/dx in the two phases.

Because jet quenching depends on the size of the dense matter and the energy of the jet, one should consider the reduction factor for fixed A and dijiet energy E, but varing the c.m. energy $\sqrt{s}$ or the initial energy density ϵ_0. If the reduction factor is plotted as a function of ϵ_0, we would see an increases in R_{AA} as illustrated in Fig. 8, where $U + U$ is considered. In obtaining Fig. 8, the low bound of the correlation of thermalization time with initial temperature $\tau_0 \gtrsim 1/T_0$ is taken, with $T_0^4 \approx (\epsilon_0 - B)/12$. We note that for reduced energy loss in plasma phase transition

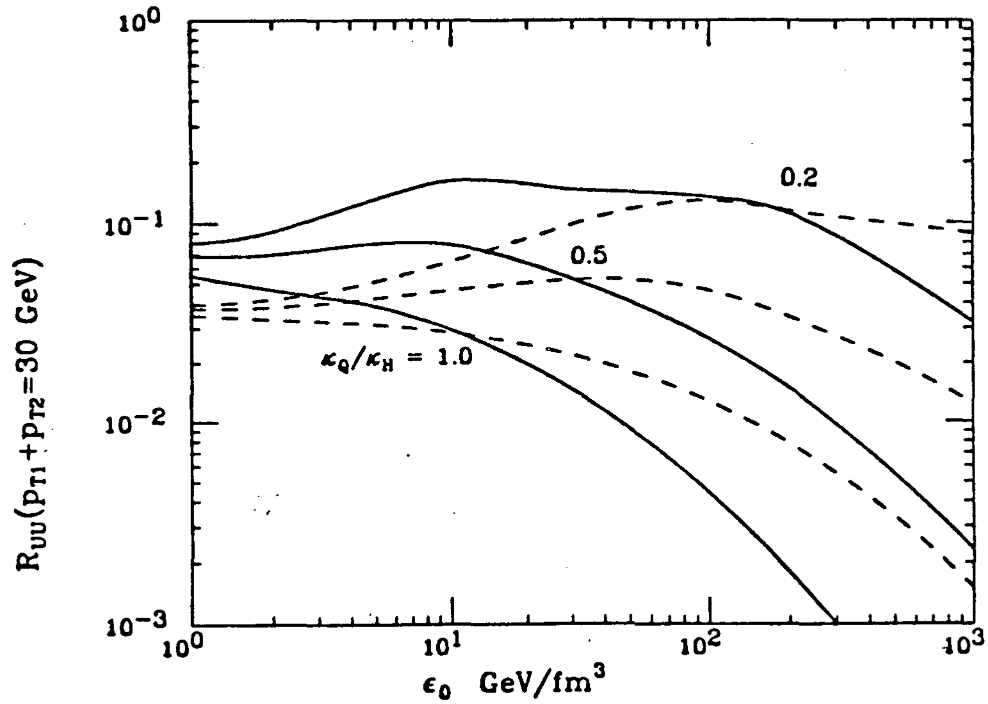

Fig. 8 Dijet reduction factor for central $U + U$ collisions at $\sqrt{s}$ =200 GeV/n for dijet energy $E = 30$ GeV as a function of the initial energy density ϵ_0 assumin a thermalization time $\tau_0 = 1/T_0$(solid lines) and $\tau_0 = 1/3T_0$(dashed lines).

there should be a period of increase in R_{AA} with ϵ_0 just above ϵ_Q. If we assume the estimation of the initial energy density ϵ_0 by Eq. 12 and a linear increase of ϵ_h with $\sqrt{s}$, we could see such an increase in the energy range of $\sqrt{s} = 20 \sim 200$ GeV but only for $A = 45 \sim 90$. For smaller nuclei, ϵ_Q can never be achieved and for larger nuclei we would miss the phase transition point where dE/dx might be small.

4 HIJING Monte Carlo Program

In nucleus-nucleus collisions, there are larger number of jets production than in nucleon-nucleon interactions. One would expect that it is easier to study the jets. However, as we have mentioned before, among the numerous jets most of them have relatively small P_T of a few GeV, characterizing that of minijets. These minijets then will have large background in the E_T distribution of the events. The continuation from minijets to high P_T jets will make the detection of dijets very difficult. To estimate the background of the minijets and to study the overall effect of jets production is our main purpose to develope HIJING Monte Carlo program for nucleus-nucleus collisions at high energy. The program also tries to study jet quenching in hadronic matter and its effect on the particle production.

The genealogy of the Monte Carlo programs related to HIJING stems from Lund/JETSET[7] which was developed for jet fragmentation in e^+e^- annihilation. From there emerged two programs for hadronic interactions. FRITIOF[32] considered that the hadronic interactions in hadron-hadron,hadron-nucleus and nucleus-nucleus collisions can be described by the excitation of the strings formed between the leading quarks and diquarks(or anti-quarks). Later on, it also took into account of the Glauber geometry for nuclear collisions which was introduced first in the ATTILA[33] version and the soft radiation was also considered[34]. The philosophy of PYTHIA[35] however is to employ perturbative QCD as much as possible in hadron-hadron interactions. It uses Eq. 1 to simulate multiple hard or semi-hard parton interactions and conducts initial and final state radiation. The final partons are connected as strings and fragmented via Lund/JETSET. What we have done in HIJING is basically to combine FRITIOF and PYTHIA together to simulate multiple jets production in nucleus-nucleus collisions and consider the effect of initial and final state interaction of the scattered partons. Therefore HIJING contains:

1. The Glauber geometry of nuclear interactions. The probability of inelastic nucleon-nucleon collisions is described by eikonal formalism in Eq. 5.

2. FRITIOF soft excitation and soft radiation. We also have a low p_T cutoff for the radiation to aviod producing jet-like gluons.

3. Multiple jets production which could also include the production of two hard jets of fixed P_T with initial and final state radiation.

4. Jet quenching mecahnism.

5. JETSET hadronization.

6. Shadowing effect and multiple initial state interactions are also going to be included.

Our scheme of multiple jets production is based on Eq. 3, which determines the number of jets produced per nucleon-nucleon collision. Then PYTHIA is call to determine the four-momentum and flavors of the scattered partons. After each call of PYTHIA the initial momenta of scatterd partons are subtracted from the incident nucleons. Each nucleon-nucleon collision is also accompanied by FRITIOF soft excitations. Finally the accumulated partons which have been scattered are linked with the valence partons and soft radiations are performed. The fragmentation of the strings is via JETSET.

In principle, the interaction of jets with the excited hadronic matter must be considered in a space-time evolution picture. A large P_T gluon jet must begin to fragment on its way to interact with an excited string which also have to break up. The jet will lose its energy and therefore be quenched by stretching the string which links it with other partons. The interaction or string flip only happens between the reduced jet and a section of the excited string. This scheme of jet quenching, however, can not be realized now in HIJING due to the limited computer power. We have adopted an approximate scheme in which we do not consider the space-time evolution. We determine the interaction point via

$$dP = \frac{dr}{\lambda_s} e^{-r/\lambda_s}, \tag{13}$$

where λ_s is the mean free path of the jet interaction, r is the distance the jet has travelled after the last interaction. Then we subtract κr from the jet's energy and add a gluon kink with the same amount of energy to the excited string that the jet interacts with. We continue the procedure until the jet is out of the whole excited system or the jet's energy is below the cutoff for the jet production.

One must be reminded that the calculations we present here are very preliminary. In order to investigate the background of minijets and how it will affect the detection of high P_T jets, we show in Fig. 9 the lego plot of the transverse energy E_T of two central $Au+Au$ events, one with minijets production and one without. In addition, two jets with $P_T = 40$ GeV are also added in each event. Each cell of the plots has $\delta\eta = 0.2$ and $\delta\phi = 13°$. In the event without minijets, the two high P_T jets stand out very well. When minijets are included, the background and the fluctuation are quite large even though the two jets with $P_T = 40$ GeV can still be detectable. However, for P_T=20 GeV or less the fluctuation of the background will be comparable to the signal of the jets. It can be estimated that for a central $Au + Au$ collision at RHIC, there could be about 6 jets with $P_T \approx 5$ GeV. Even though one could manage to detect a single jets with such P_T, it is not trivial to find so many dijets at the same time. For the bulk effects of multiple minijets we show the rapidity

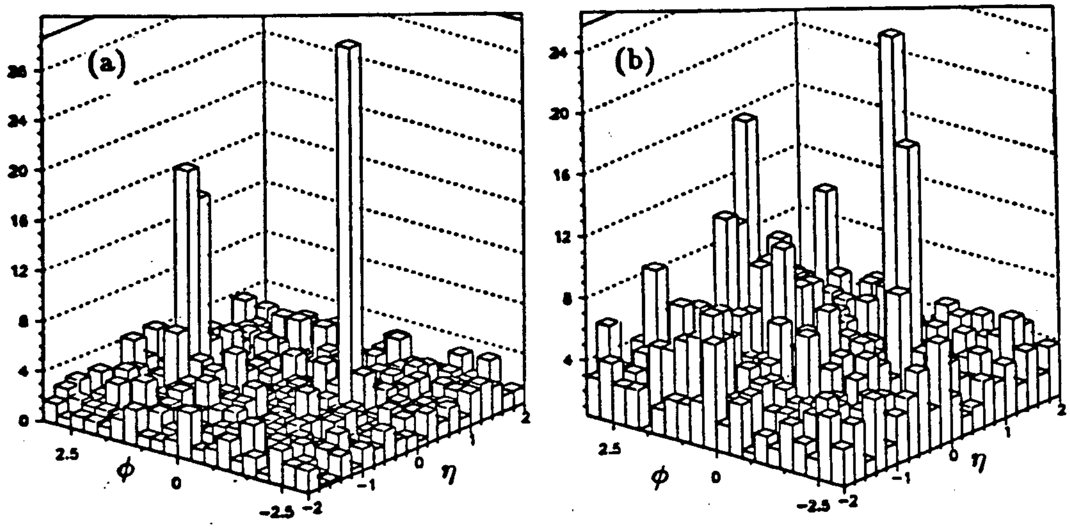

Fig. 9 Lego plot of the transverse energy distribution in central $Au + Au$ collisions at $\sqrt{s}$ =200 GeV/n (a)without and (b)with minijets production.

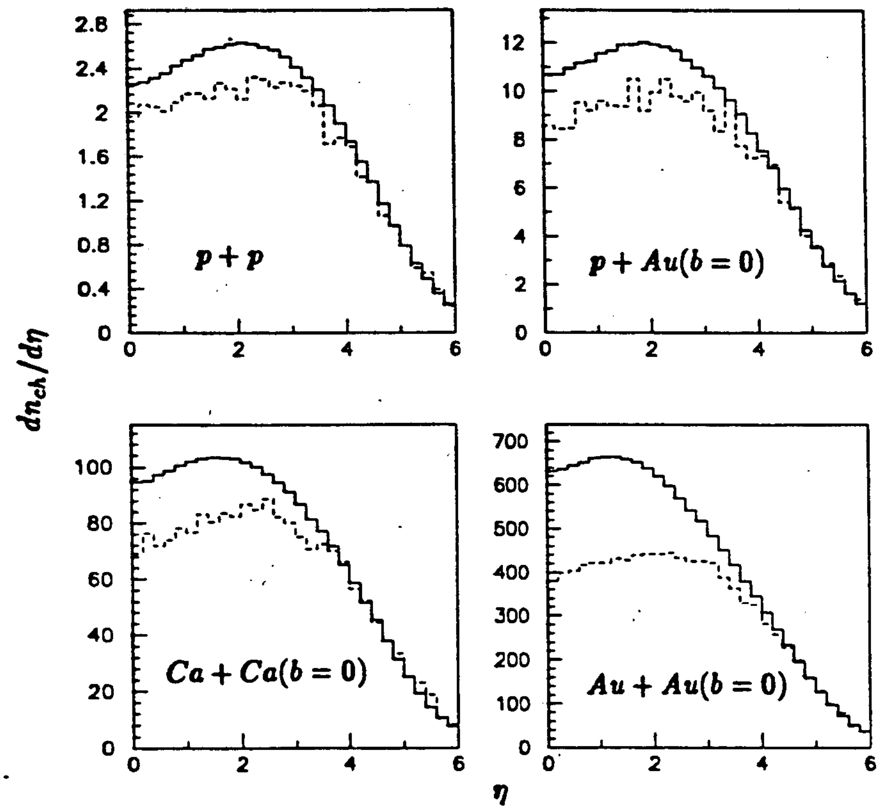

Fig. 10 Rapidity distributions of charged particles in p+p, central p+Au, Ca+Ca, and $Au + Au$ collisions at $\sqrt{s}$ =200 GeV/n.

distributions of charged particles in Fig. 10 for $p+p$, central $p+Au$,$Ca+Ca$ and $Au+Au$ collisions at $\sqrt{s}=200$ GeV/n. The dashed lines are the same plots without jets production. We note that the contributions to particle production from jets becomes more important for heavier nuclei. For $Au+Au$ collisions, almost half of the charged particles come from the fragmentation of jets which are about 400 in number. These results are in agreement with the estimates of Ref. [3]. When one goes to even higher energy, at $\sqrt{s}=2$ TeV of the proposed LHC for example, the contribution from minijets production will become the dominant effect as shown in Fig. 11. Of cause, the effect of shadowing will reduced the number of minijets and the initial multiple parton interaction will increase the P_T of the scattered partons.

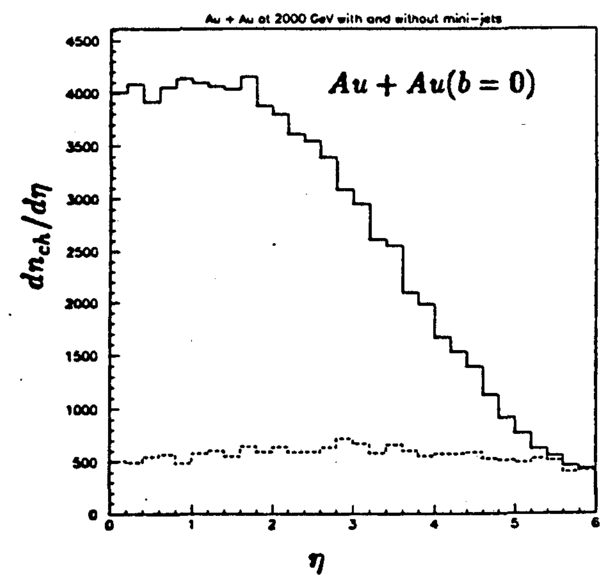

Fig. 11 Rapidity distributions of charged particles in central $Au+Au$ collisions at $\sqrt{s}$ =2000 GeV/n.

As we have noticed that numerous minijets will complicate the detection of high P_T jets especially those with $P_T \lesssim 20$ GeV. However, we are most interested in these jets because they are most affected by jet quenching from the study of e^-A interaction. Since jets are finally represented by large p_T secondary hadrons, we can study the inclusive p_T distribution of hadrons as a supplement to the study of jet properties. In Fig. 12, we show the p_T distribution of charged particles from central $Au+Au$ collisions at $\sqrt{s}=200$ GeV. The solid histogram is for the case when jets are quenched via interactions while the dashed histogram is for the case

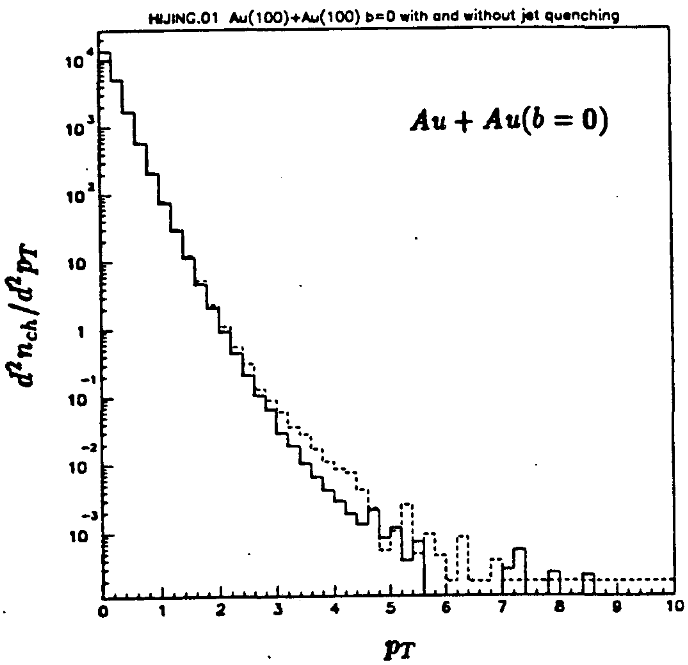

Fig. 12 Transverse momentum distributions of charged particles in central $Au+Au$ collisions at $\sqrt{s}$ =200 GeV/n with(solid line) and without(dashed line) jet quenching.

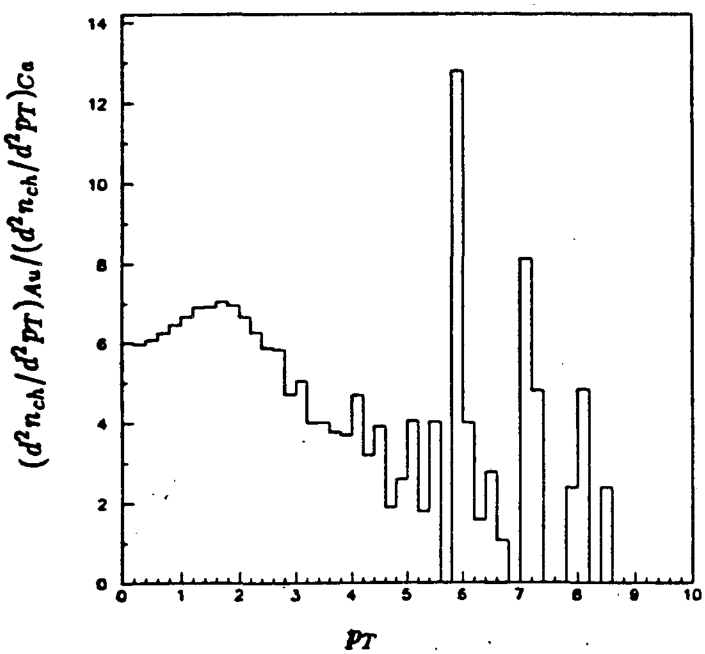

Fig. 13 The ratio of p_T distribution of charged particles in central $Au + Au$ over that in $Ca + Ca$ collisions at $\sqrt{s}$ =200 GeV/n.

that has no final state interactions between jets and the excited strings. We note that jet quenching indeed suppresses the production of high p_T hadrons and should also enhance hadrons at small p_T. To look at the effects of jet quenching more closely, one should compare the p_T distribution of heavy nucleus interaction with that of lighter nucleus or nucleon-nucleon collision for the best result, because in the later case jet quenching should be smaller than the formal one. Fig. 13 shows our calculation of the ratio between the p_T distribution of charged particles from central $Au + Au$ collisions and that of central $Ca + Ca$. It indeed shows some enhancement of particle production at $p_T \sim 2$ GeV and a substantial suppression at large p_T. If initial state interaction are taken into account, Cronin effect will compensate the suppression via jet quenching at high p_T and one would see an increase of the ratio again. Similarly to the discussion at the end of last section, one should also investigate the variation of the ratio with energy at fixed p_T where jet quenching is most prominent. HIJING will give a constant ratio at all energies because the only energy dependence in HIJING is cancelled out. If any form of variation of the ratio with energy, especially like the one in Fig. 8, are to be observed, something beyond the conventional understanding of HIJING must have happend.

5 Conclusions and Remarks

We have discussed the effect of hard or semi-hard parton scatterings in heavy ion collisions at RHIC energy and beyond. Due to their calculable production rate, hard jets can serve as external probes of the excited nuclear matter in relativistic heavy ion collisions. HIJING Monte Carlo program which is near completion can provide us with the conventional production of QCD jets and their quenching. We motivated that a noval reduction of energy loss dE/dx for a jet in a dense matter near QCD phase transition T_c would result in an abnormal behavior of the jets production rate. By studying the suppression factor of jets in heavy nucleus-nucleus collisions and its energy variation we could get some information about the state of the excited nuclear matter and hopefully to indentify the formation of quark gluon plasma.

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