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HIJING 1.0: A Monte Carlo Program for Parton and Particle Production in High Energy Hadronic and Nuclear Collisions*

Miklos Gyulassy

Physics Department, Columbia University, New York, NY 10027

Xin-Nian Wang

Nuclear Science Division, Mailstop 70A-3307, Lawrence Berkeley Laboratory
University of California, Berkeley, CA 94720

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Abstract

Based on QCD-inspired models for multiple jets production, we developed a Monte Carlo program to study jet and the associated particle production in high energy pp, pA and AA collisions. The physics behind the program which includes multiple minijet production, soft excitation, nuclear shadowing of parton distribution functions and jet interaction in dense matter is briefly discussed. A detailed description of the program and instructions on how to use it are given.

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PROGRAM SUMMARY

Title of program: HIJING 1.0

Catalogue number:

Program obtainable from: xnwang@nsdssd.lbl.gov

Computer for which the program is designed: VAX, VAXstation, SPARCstation and other computers with a FORTRAN 77 compiler compiler

Computer: SPARCstation ELC; *Installation*: Nuclear Science Division, Lawrence Berkeley Laboratory, USA

Operating system: SunOS 4.1.1

Programming language used: FORTRAN 77

High speed storage required: 90k word

No. of bits in a word: 32

Peripherals used: terminal for input, terminal or printer for output

No. of lines in combined program and test deck: 6397

Keywords: relativistic heavy ion collisions, quark-gluon plasma, partons, hadrons, nuclei, jets, minijets, particle production, parton shadowing, jet quenching.

Nature of the physical problem
In high-energy hadron and nuclear interactions, multiple minijet production becomes more and more important. Especially in relativistic heavy-ion collisions, minijets are expected to dominate transverse energy production in the central rapidity region. Particle production and correlation due to minijets must be investigated in order to recognize new physics of quark-gluon plasma formation. Due to the complication of soft interactions, minijet production can only be incorporated in a pQCD inspired model. The parameters in this model have to be tested first against the wide range of data in *pp* collisions. When extrapolating

to heavy-ion collisions, nuclear effects such as parton shadowing and final state interactions have to be considered.

Method of solution

Based on a pQCD-inspired model, multiple minijet production is combined together with Lund-type model for soft interactions. Within this model, triggering on large P_T jet production automatically biases toward enhanced minijet production. Binary approximation and Glauber geometry for multiple interaction are used to simulate pA and AA collisions. A parametrized parton distribution function inside a nucleus is used to take into account parton shadowing. Jet quenching is modeled by an assumed energy loss dE/dz of partons traversing the produced dense matter. A simplest color configuration is assumed for the multiple jet system and Lund jet fragmentation model is used for the hadronization.

Restrictions on the complexity of the problem

The program is only valid for collisions with c.m. energy ($\sqrt{s}$) above 4 GeV/n. For central $Pb+Pb$ collisions, some arrays have to be extended above $\sqrt{s}=10$ TeV/n.

Typical running time

The running time largely depends on the energy and the type of collisions. For example (not including initialization):

pp	$\sqrt{s}$=200 GeV	$\sim$ 700 events/min.
pp	$\sqrt{s}$=1.8 TeV	$\sim$ 250 events/min.
$Au+Au$(central)	$\sqrt{s}$=200 GeV/n	$\sim$ 1 event/min.
$Pb+Pb$(central)	$\sqrt{s}$=6.4 TeV/n	$\sim$ 1 event/10 min.

Unusual features of the program

The random number generator used in the program is a VAX VMS system subroutine RAN(NSEED). When compiled on a SPARCstation, `-xl` flag should be used. This function is not portable. Therefore, one should supply a random number generator to replace this function whenever a problem is encountered.

LONG WRITE-UP

1 Introduction

One of the goals of ultrarelativistic heavy ion experiments is to study the quark-gluon substructure of nuclear matter and the possibility of a phase transition from hadronic matter to quark-gluon plasma (QGP)[1] at extremely high energy densities. Unlike heavy ion collisions at the existing AGS/BNL and SPS/CERN energies, most of the physical processes occurring at very early times in the violent collisions of heavy nuclei at RHIC/BNL and the proposed LHC/CERN energies involve hard or semihard parton scatterings[2] which will result in enormous amount of jet production and can be described in terms of perturbative QCD (pQCD).

The concept of jets and their association with hard parton scatterings has been well established in hadronic interactions and they have been proven to play a major role in every aspect of $p\bar{p}$ collisions at CERN Sp$\bar{\text{p}}$S and Fermilab Tevatron energies[3]. Experimentally, jets are identified as hadronic clusters whose transverse energy E_T can be reconstructed from the calorimetrical study[4, 5] of the events. However, when the transverse energy of a jet becomes smaller, $E_T < 5$ GeV, it is increasingly difficult to resolve it from the underlying background[6], though theoretically, we would expect that hard parton scatterings must continue to lower transverse momentum. We usually refer to those as minijets whose transverse energy are too low to be resolved experimentally but the associated parton scattering processes may still be calculable via pQCD. Assuming independent production, it has been shown that the multiple minijets production is important in $p\bar{p}$ interactions to account for the increase of total cross section[7] and the violation of Koba-Nielsen-Olesen (KNO) scaling of the charged multiplicity distributions[8, 9].

In high energy heavy ion collisions, minijets have been estimated[2] to produce 50% (80%) of the transverse energy in central heavy ion collisions at RHIC (LHC) energies. While not resolvable as distinct jets, they would lead to a wide variety of correlations, as in pp or $p\bar{p}$ collisions, among observables such as multiplicity, transverse momentum, strangeness, and fluctuations that compete with the expected signatures of a QGP. Therefore, it is especially important to calculate these background processes. Furthermore, the calculation could also provide the initial condition to address the issues of thermalization and equilibration of a quark gluon plasma. In this respect, the interactions of high P_T jets inside the dense medium is also interesting since the variation of jet quenching phenomenon may serve as one of the signatures of the QGP transition[10].

To provide a theoretical laboratory for studying jets in high-energy nuclear interactions and testing the proposed signatures such as jet quenching[10], we have developed a Monte Carlo model, HIJING (heavy ion jet interaction generator)[11], which combines a QCD inspired model for jet production with the Lund model[12] for jet fragmentation. The formulation of HIJING was guided by the Lund FRITIOF[13] and Dual Parton model[14] for soft $A+B$ reactions at intermediate energies ($\sqrt{s} \lesssim 20$ GeV/nucleon) and the successful implementation of pQCD processes in PYTHIA[8, 15] model for hadronic collisions. HIJING is designed mainly to explore the range of possible initial conditions that may occur in relativistic heavy ion collisions. To study the nuclear effects, we also included nuclear shadowing[16] of parton structure functions and a schematic model of final state interaction of high P_T jets in terms of an effective energy loss parameter, dE/dz[17, 18]. At pp and $p\bar{p}$ level, HIJING also made an important effort to address the interplay between low P_T nonperturbative physics and the hard pQCD processes. This Monte Carlo model has been tested extensively against data on $p+p(\bar{p})$ over a wide energy range, $\sqrt{s}$ = 50-1800 GeV and $p+A$, $A+A$ collisions at moderate energies $\sqrt{s} \leq 20$ GeV/n [11, 19]. However, in this version of HIJING program, the space-time development of final state interaction among produced partons[20] and hadrons was not considered.

In this paper, we present a detailed description of the Monte Carlo program together with a brief summary of physical motivations. Since the program uses subroutines of PYTHIA to generate the kinetic variables for each hard scattering and the associated radiations, and JETSET for string fragmentation, we refer readers to the original publications[15, 21] for the description of these programs. The physics involved in HIJING has been discussed extensively[11, 19, 17]. This paper is intended to be a documented reference for the overall structure and detailed description of the program.

The organization of the paper is as the following. In Section 2, we give a brief review of the QCD inspired model for multiple jets production and soft interaction in nucleon-nucleon collisions. The nuclear effects on jet production and fragmentation are discussed in Section 3. Section 4 will give a detailed description of the program. Finally in Section 5 we will give instructions on how to use the program and some simple examples are provided.

2 Parton Production in pp Collisions

The QCD inspired model is based on the assumption of independent production of multiple minijets. It determines the number of minijets per nucleon-nucleon collisions. For each hard or semihard interaction the kinetic variables of the scattered partons are determined by calling PYTHIA[15] subroutines. The scheme for the accompanying soft interactions is similar to FRITIOF model[13] with some difference in the successive soft excitation of the leading quarks or diquarks and P_T transfer involved. Since minijet production is dominated by gluon scatterings, we assume that quark scatterings only involve valence quarks and restrict the subsequent hard processes to gluon-gluon scatterings. Simplification is also made for the color flow in the case of multiple jet production. Produced gluons are ordered in their rapidities and then connected with their parent valence quarks or diquarks to form string systems. Finally, fragmentation subroutine of JETSET is called for hadronization.

2.1 Cross sections

In pQCD, the cross section of hard parton scatterings can be written as[22]

$$\frac{d\sigma_{jet}}{dP_T^2 dy_1 dy_2} = K \sum_{a,b} x_1 x_2 f_a(x_1, P_T^2) f_b(x_2, P_T^2) d\sigma^{ab}(\hat{s}, \hat{t}, \hat{u})/d\hat{t}, \tag{1}$$

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 $x_1 = x_T(e^{y_1} + e^{y_2})/2$, $x_2 = x_T(e^{-y_1} + e^{-y_2})$, $x_T = 2P_T/\sqrt{s}$. A factor, $K \approx 2$ accounts roughly for the higher order corrections. The default structure functions, $f_a(x, Q^2)$, in HIJING are taken to be Duke-Owens structure function set 1[23]. In future versions some other new parametrizations might be included.

Integrating Eq. 1 with a low P_T cutoff P_0, we can calculate the total inclusive jet cross section σ_{jet}. The average number of semihard parton collisions for a nucleon-nucleon collision at impact parameter b is $\sigma_{jet} T_N(b)$, where $T_N(b)$ is partonic overlap function between the two nucleons. In terms of a semiclassical probabilistic model[7, 9, 24], the probability for multiple minijets production is then

$$g_j(b) = \frac{[\sigma_{jet} T_N(b)]^j}{j!} e^{-\sigma_{jet} T_N(b)}, \quad j \geq 1. \tag{2}$$

Similarly, we can also represent the soft interactions by an inclusive cross section σ_{soft} which, unlike σ_{jet}, can only be determined phenomenologically. The probability for only soft interactions without any hard processes is then,

$$g_0(b) = [1 - e^{-\sigma_{soft} T_N(b)}] e^{-\sigma_{jet} T_N(b)}. \tag{3}$$

We have then the total inelastic cross section for nucleon-nucleon collisions,

$$\begin{aligned}\sigma_{in} &= \int d^2b \sum_{j=0}^{\infty} g_j(b) \\ &= \int d^2b[1 - e^{-(\sigma_{soft}+\sigma_{jet})T_N(b)}]. \end{aligned} \tag{4}$$

Define a real eikonal function,

$$\chi(b,s) \equiv \frac{1}{2}\sigma_{soft}(s)T_N(b,s) + \frac{1}{2}\sigma_{jet}(s)T_N(b,s), \tag{5}$$

we have the elastic, inelastic, and total cross sections of nucleon-nucleon collisions,

$$\sigma_{el} = \pi \int_0^{\infty} db^2 \left[1 - e^{-\chi(b,s)}\right]^2, \tag{6}$$

$$\sigma_{in} = \pi \int_0^{\infty} db^2 \left[1 - e^{-2\chi(b,s)}\right], \tag{7}$$

$$\sigma_{tot} = 2\pi \int_0^{\infty} db^2 \left[1 - e^{-\chi(b,s)}\right], \tag{8}$$

We assume that the parton density in a nucleon can be approximated by the Fourier transform of a dipole form factor. The overlap function is then,

$$T_N(b,s) = 2\frac{\chi_0(\xi)}{\sigma_{soft}(s)}, \tag{9}$$

with

$$\chi_0(\xi) = \frac{\mu_0^2}{96}(\mu_0\xi)^3 K_3(\mu_0\xi), \quad \xi = b/b_0(s), \tag{10}$$

where $\mu_0 = 3.9$ and $\pi b_0^2(s) \equiv \sigma_0 = \sigma_{soft}(s)/2$ is a measure of the geometrical size of the nucleon. The eikonal function then can be written as,

$$\chi(b,s) \equiv \chi(\xi,s) = [1 + \sigma_{jet}(s)/\sigma_{soft}(s)]\chi_0(\xi). \tag{11}$$

$P_0 \simeq 2$ GeV/c and a constant value of $\sigma_{soft}(s) = 57$ mb are chosen to fit the experimental data on cross sections[9] in pp and $p\bar{p}$ collisions. We shall follow the equations listed above to simulate multiple jets production at the level of nucleon-nucleon collisions in HIJING

Monte Carlo program. Once the number of hard scatterings is determined, we then use PYTHIA to generate the kinetic variables of the scattered partons and the initial and final state radiations.

2.2 Jet triggering

Because the differential cross section of jet production decreases for several orders in magnitude from small to large P_T, we often have to trigger on jet production with specified P_T in order to increase the simulation efficiency. The triggering can then change the probability of multiple minijet production and thus the whole event structure. In particular, such rare processes of large P_T scatterings most often occur when the impact parameter of nucleon-nucleon collision is small so that the partonic overlap is large. At small impact parameters, the production of multiple jets is then enhanced.

If we want to trigger on events which have at least one jet with P_T above P_T^{trig}, the conditional probability for multiple minijet production in the triggered events is then[11],

$$g_j^{trig}(b) = \frac{[\sigma_{jet}(P_0)T_N(b)]^j}{j!}\left\{1 - \left[\frac{\sigma_{jet}(P_0) - \sigma_{jet}(P_T^{trig})}{\sigma_{jet}(P_0)}\right]^j\right\} e^{-\sigma_{jet}(P_0)T_N(b)}. \tag{12}$$

It is obvious that $g_j^{trig}(b)$ returns back to $g_j(b)$ (Eq. 2) when $P_T^{trig} = P_0$. Summing over $j \geq 1$ leads to the expected total probability for having at least one jet with $P_T > P_T^{trig}$,

$$g^{trig}(b) = 1 - e^{-\sigma_{jet}(P_T^{trig})T_N(b)}, \tag{13}$$

Since $g_j^{trig}(b)$ differs from $g_j(b)$, the triggering of a particular jet therefore has changed the production rates of the other jets in the same event. This triggering effect is especially significant when we consider large P_T^{trig}. It becomes more probable to produce multiple jets due to the triggering on a high P_T jet. In HIJING, we implement Eq. 12 by simulating two Poisson-like multiple jet distributions with inclusive cross sections $\sigma_{jet}(P_0) - \sigma_{jet}(P_T^{trig})$ and $\sigma_{jet}(P_T^{trig})$ respectively. We demand that the second one must have at least one jet and convolute the two together. The resultant distribution will be the triggered distribution.

2.3 Soft interactions

Besides the processes with large transverse momentum transfer which are described by pQCD, there are also many small P_T exchanges or soft interactions between two colliding hadrons. We adopt a variant of the multiple string phenomenological model for such soft interactions in which multiple soft gluon exchanges between valence quarks or diquarks lead to longitudinal string-like excitations. Gluon production from hard processes and soft radiations are included as kinks in the strings. The strings then hadronize according to Lund JETSET7.2 fragmentation scheme.

In the center of mass frame of two colliding nucleons with initial light-cone momenta

$$p_1 = (p_1^+, \frac{m_1^2}{p_1^+}, \mathbf{0}_T), \quad p_2 = (\frac{m_2^2}{p_2^-}, p_2^-, \mathbf{0}_T), \tag{14}$$

and $(p_1 + p_2)^2 = s$, the excited strings will have final momenta

$$p_1' = (p_1^+ - P^+, \frac{m_1^2}{p_1^+} + P^-, \mathbf{P}_T), \quad p_2' = (\frac{m_2^2}{p_2^-} + P^+, p_2^- - P^-, -\mathbf{P}_T), \tag{15}$$

after a collective momentum exchange $P = (P^+, P^-, \mathbf{P}_T)$. The soft interactions by definition have small transverse momentum transfer, $P_T < 1$ GeV$/c$, while large effective light-come momentum[13] exchange can give rise to two excited strings with large invariant masses. Defining

$$P^+ = x_+\sqrt{s} - \frac{m_2^2}{p_2^-}, \quad P^- = x_-\sqrt{s} - \frac{m_1^2}{p_1^+}, \tag{16}$$

the excited masses of the two strings will be

$$M_1^2 = x_-(1 - x_+)s - P_T^2, \quad M_2^2 = x_+(1 - x_-)s - P_T^2, \tag{17}$$

respectively. If we require that the excited string masses must have a minimum value M_{cut}, then the kinematically allowed region of $x^\pm$ will be

$$x_\mp(1 - x_\pm) \geq M_{Tcut}^2/s, \tag{18}$$

where $M_{Tcut}^2 = M_{cut}^2 + P_T^2$. The condition for the above equations to be valid is

$$\sqrt{s} \geq 2M_{Tcut}. \tag{19}$$

This is the minimum colliding energy we will require to produce two excited strings which can be fragmented into hadrons by the Lund string fragmentation model. We have chosen M_{cut} to be 1.5 GeV/c^2 in all our calculations involving nucleon collisions. When the energy is smaller than what Eq. 19 requires, we assume that the interaction can be described by other processes like single diffractive or $N^\star$ (or ρ, $K^\star$ in cases of pions and kaons collisions) excitation. However, we usually do not expect that the model is still valid at such low energies. Eq. 19 also serves as to determine the maximum P_T that the strings can obtain from the soft interactions. If hard interactions are involved, the kinetic boundary of string formation is reduced by the hard scatterings.

In order to best fit the rapidity distributions of charged particles, we choose the following distributions for light-cone momentum transfer,

$$P(x_\pm) = \frac{(1.0 - x_\pm)^{1.5}}{(x_\pm^2 + c^2/s)^{1/4}}, \tag{20}$$

for nucleons and

$$P(x_\pm) = \frac{1}{(x_\pm^2 + c^2/s)^{1/4}[(1 - x_\pm)^2 + c^2/s]^{1/4}}, \tag{21}$$

for mesons, where $c = 0.1$ GeV is a cutoff for computational purpose with little theoretical consequences in the model. For single-diffractive events whose cross section can be obtained from an empirical parametrization[25], we fix the mass of the diffractive hadron to be its own or its vector state excitation and find the mass of the single excited string according to the well known distribution,

$$P(x_\pm) = \frac{1}{(x_\pm^2 + c^2/s)^{1/2}}, \tag{22}$$

which lead to the experimentally observed[25] mass distribution dM^2/M^2 of the disassociated hadrons.

Before fragmentation, the excited strings are also assumed to have soft gluon radiation induced by the soft interactions. Such soft gluon radiation can be approximated by color dipole model as has been successfully implemented in ARIADNE Monte Carlo program[26]. In HIJING, we adopted subroutines AR3JET and ARORIE from FRITIOF 1.7[13] to simulate the dipole radiation which appear as gluon kinks in the string. Since minijets are treated explicitly via pQCD, we limit the transverse momentum of the radiated gluons below the minijet cutoff $P_0 = 2$ GeV/c. The limitation on the transverse momentum is a characteristic feature of induced bremsstrahlung due to soft exchanges[27]. The invariant mass cutoff for strings to radiate is fixed at $M_{cut}^{rad} = 2$ GeV/c^2 by default.

2.4 P_T kick from soft interactions

As described in the above, hard or semihard scatterings in our model have at least transverse momentum of $P_T \geq P_0$. The value of P_0 we use is the result of a model dependent fit of calculated cross sections to the experimental values. One can imagine that the corresponding soft interactions, which are characterized by inclusive cross section σ_{soft}, will depend on P_0. For such processes, we include an extra low $P_T < P_0$ transfer to the valence quarks or diquarks at string end points. We assume a distribution for the P_T kick which extrapolates smoothly to the high P_T regime of hard scatterings but vary more slowly for $P_T \ll P_0$,

$$f_{kick}(P_T) \approx \frac{\theta(P_0 - P_T)}{(P_T^2 + c^2)(P_T^2 + P_0^2)}, \tag{23}$$

where $c = 0.1$ GeV$/c$. In practice, the distribution will follow a Gaussian form when $P_T > P_0$. Since diquarks are composites, we also assume that P_T transfer to a diquark is relatively suppressed by a form factor with a scale of 1 GeV$/c$.

This P_T kick to the quarks or diquarks during the soft interactions will provide an extra increase in transverse momentum to produced hadrons in order to fit the experimental data at low energies[11]. Otherwise, the transverse momentum from pair production in the default Lund string fragmentation is not enough to account for the higher P_T tail in low energy pp collisions.

3 Parton Production in pA and AA Collisions

To include the nuclear effects on jet production and fragmentation, we also consider the EMC[16] effect of the parton structure functions in nuclei and the interaction of the produced jets with the excited nuclear matter in heavy ion collisions.

3.1 Binary approximation and initial state interaction

We assume that a nucleus-nucleus collision can be decomposed into binary nucleon-nucleon collisions which generally involve the wounded nucleons. In a string picture, the wounded nucleons become strings excited along the beam direction. At high energy, the excited strings are assumed to interact again like the ordinary nucleon-nucleon collisions before they fragment. Unlike FRITIOF model, we allow an excited string to be de-excited within the kinematic limits in the subsequent collisions. The binary approximation can also be applied to rare hard scatterings which involve only independent pairs of partons. The probability for a given parton to suffer multiple high P_T scatterings is small and is not implemented in the current version of the program. We employ a three-parameter Wood-Saxon nuclear density to compute the number of binary collisions at a given impact parameter.

For each one of these binary collisions, we use the eikonal formalism as given in Section 2.1 to determine the probability of collision, elastic or inelastic and the number of jets it produces. After simulation of hard processes, the energy of the scattered partons is subtracted from the nucleon and the remaining energy is used in the soft interaction as in ordinary soft nucleon-nucleon collisions. The excited string system minus the scattered partons suffers further collisions according to the geometrical probability.

We assign one of the two scattered partons per hard scattering to each participating nucleon or they may form an independent single $(q - \bar{q})$ string system. After all binary collisions are processed, we then connect the scattered partons in the associated nucleons with the corresponding valence quarks and diquarks to form string systems. The strings are then fragmented into particles.

3.2 Nuclear shadowing effect

One of the most important nuclear effects in relativistic heavy ion collisions is the nuclear modification of parton structure functions. It has been observed[16] that the effective number of quarks and antiquarks in a nucleus is depleted in the low region of x. Though gluon shadowing has not been studied experimentally, we will assume that the shadowing effect for gluons and quarks is the same. We also neglect the QCD evolution of the shadowing effect in the current version. There is no experimental evidence for significant Q dependence of the nuclear effect on the quark structure functions. However, theoretical study[28] shows that gluon shadowing may evolve with Q.

At this stage, the experimental data unfortunately can not fully determine the A dependence of the shadowing. We will follow the A dependence as proposed in Ref.[29] and use the following parametrization,

$$
\begin{aligned}
R_A(x) &\equiv \frac{f_{a/A}(x)}{A f_{a/N}(x)} \\
&= 1 + 1.19 \ln^{1/6} A \, [x^3 - 1.5(x_0 + x_L)x^2 + 3x_0 x_L x] \\
&\quad - [\alpha_A - \frac{1.08(A^{1/3} - 1)}{\ln(A+1)} \sqrt{x}] e^{-x^2/x_0^2}, \qquad (24) \\
\alpha_A &= 0.1(A^{1/3} - 1), \qquad (25)
\end{aligned}
$$

where $x_0 = 0.1$ and $x_L = 0.7$. The term proportional to α_A in Eq. 24 determines the shadowing for $x < x_0$ with the most important nuclear dependence, while the rest gives the overall nuclear effect on the structure function in $x > x_0$ with some very slow A dependence. This parametrization can fit the overall nuclear effect on the quark structure function in the small and medium x region[11].

To take into account of the impact parameter dependence, we assume that the shadowing effect α_A is proportional to the longitudinal dimension of the nucleus along the straight trajectory of the interacting nucleons. We thus parametrize α_A in Eq. 24 as

$$\alpha_A(r) = 0.1(A^{1/3} - 1)\frac{4}{3}\sqrt{1 - r^2/R_A^2}, \tag{26}$$

where r is the transverse distance of the interacting nucleon from its nucleus center and R_A is the radius of the nucleus. For a sharp sphere nucleus with overlap function $T_A(r) = (3A/2\pi R_A^2)\sqrt{1 - r^2/R_A^2}$, the averaged $\alpha_A(r)$ is $\alpha_A = \pi \int_0^{R_A^2} dr^2 T_A(r)\alpha_A(r)/A$. Because the rest of Eq. 24 has a very slow A dependence, we will only consider the impact parameter dependence of α_A. After all, most of the jet productions occur in the small x region where only shadowing is important.

To simplify the calculation during the Monte Carlo simulation, we can decompose $R_A(x, r)$ into two parts,

$$R_A(x, r) \equiv R_A^0(x) - \alpha_A(r)R_A^s(x), \tag{27}$$

where $\alpha_A(r)R_A^s(x)$ is the term proportional to $\alpha_A(r)$ in Eq. 24 with $\alpha_A(r)$ given in Eq. 26 and $R_A^0(x)$ is the rest of $R_A(x, r)$. Both $R_A^0(x)$ and $R_A^s(x)$ are now independent of r. The effective jet production cross section of a binary nucleon-nucleon interaction in $A+B$ nuclear collisions is then,

$$\sigma_{jet}^{eff}(r_A, r_B) = \sigma_{jet}^0 - \alpha_A(r_A)\sigma_{jet}^A - \alpha_B(r_B)\sigma_{jet}^B + \alpha_A(r_A)\alpha_B(r_B)\sigma_{jet}^{AB}, \tag{28}$$

where σ_{jet}^0, σ_{jet}^A, σ_{jet}^B and σ_{jet}^{AB} can be calculated through Eq. 1 by multiplying $f_a(x_1, P_T^2)f_b(x_2, P_T^2)$ in the integrand with $R_A^0(x_1)R_B^0(x_2)$, $R_A^s(x_1)R_B^0(x_2)$, $R_A^0(x_1)R_B^s(x_2)$ and $R_A^s(x_1)R_B^s(x_2)$ respectively. With calculated values of σ_{jet}^0, σ_{jet}^A, σ_{jet}^B and σ_{jet}^{AB}, we will know the effective jet cross section σ_{jet}^{eff} for any binary nucleon-nucleon collision.

3.3 Final state parton interaction

Another important nuclear effect on the jet production in heavy ion collisions is the final state integration. In high energy heavy ion collisions, a dense hadronic or partonic matter must be produced in the central region. Because this matter can extend over a transverse dimension of at least R_A, jets with large P_T from hard scatterings have to traverse this hot environment. For the purpose of studying the property of the dense matter created during the nucleus-nucleus collisions, it is important to investigate the interaction of jets with the matter and the energy loss they suffer during their journey out. It is estimated[18, 30] that the gluon bremsstrahlung induced by soft interaction dominate the energy loss mechanism.

We model the induced radiation in HIJING via a simple collinear gluon splitting scheme with given energy loss dE/dz. The energy loss for gluon jets is twice that of quark jets[30]. We assume that interaction only occur with the locally comoving matter in the transverse direction. The interaction points are determined via a probability

$$dP = \frac{d\ell}{\lambda_s} e^{-\ell/\lambda_s}, \tag{29}$$

with given mean free path λ_s, where ℓ is the distance the jet has traveled after its last interaction. The induced radiation is simulated by transferring a part of the jet energy $\Delta E(\ell) = \ell dE/z$ as a gluon kink to the other string which the jet interacts with. We continue the procedure until the jet is out of the whole excited system or when the jet energy is smaller than a cutoff below which a jet can not loss energy any more. We take this cutoff as the same as the cutoff P_0 for jet production. To determine how many and which excited strings could interact with the jet, we also have to assume a cross section of jet interaction so that excited strings within a cylinder of radius r_s along the jet direction could interact with the jet. λ_s should be related to r_s via the density of the system of excited strings. We simply take them as two parameters in our model.

4 Program Description

HIJING 1.0, written in FORTRAN 77 is a Monte Carlo simulation package for parton and particle production in high energy hadron-hadron, hadron-nucleus, and nucleus-nucleus collisions. It consists of subroutines for physics simulation and common blocks for parameters and event records. Users have to provide their own main program where desired parameters and event type are specified, and simulated events can be studied. HIJING 1.0 uses PYTHIA 5.3 to generate kinetic variables for each hard scattering and JETSET 7.2 for jet fragmentation. Therefore, HIJING 1.0 uses the same particle flavor code (included in the appendix) as JETSET 7.2 and PYTHIA 5.3. Users can also obtain more flexibility by using subroutines in JETSET 7.2 and changing the values of parameters in JETSET 7.2 and PYTHIA 5.3 therein. We refer users to the original literature[15, 21] for the documentations of JETSET

7.2 and PYTHIA 5.3. For many users, however, subroutines, parameters and event information in HIJING 1.0 alone will be enough for studying most of the event types and the physics therein. To save compiling time and to meet some specific needs of HIJING 1.0, PYTHIA 5.3 has been modified and together with JETSET 7.2 is renamed as HIPYSET. Therefore, one should link the main program with HIJING and HIPYSET.

In this program, implicit integer numbers are assumed for variables beginning with letters I–M, while the implicit real numbers are assumed for variables beginning with letters A–H and O–Z.

4.1 Random numbers

Random numbers in HIJING is obtained by calling the VAX VMS system function RAN(NSEED). On SPARCstation, one has to link the program with `-xl` flag in order to compile the program. We have not checked the portability of this function on machines with other operating systems. Whenever one encounters problem with this (pseudo) random number generator on different machines other than VAX and SPARCstation, one should replace this function by another random number generator.

To start a new sequence of random numbers, one should give a new large odd integer value to variable NSEED in COMMON/RANSEED/NSEED.

4.2 Main subroutines

After supplying the desired parameters, the first subroutine a user has to call is HIJSET. Then subroutine HIJING can be called to simulate the specified events.

SUBROUTINE HIJSET (EFRM, FRAME, PROJ, TARG, IAP, IZP, IAT, IZT)

Purpose: to initialize HIJING for specified event type, collision frame and energy.

EFRM: colliding energy (GeV) per nucleon in the frame specified by FRAME.

FRAME: character variable to specify the frame of the collision.

- ='CMS': nucleon-nucleon center of mass frame, with projectile momentum in $+z$ direction and target momentum in $-z$ direction.
- ='LAB': laboratory frame of the fixed target with projectile momentum in $+z$ direction.

PROJ, TARG: character variables of projectile and target particles.

- ='P': proton.
- ='PBAR': anti-proton.
- ='N': neutron.
- ='NBAR': anti-neutron.

='PI+': π^+.
='PI−': π^-.
='A': nucleus.

IAP, IAT: mass number of the projectile and target nucleus. Set to 1 for hadrons.

IZP, IZT: charge number of the projectile and target nucleus, for hadrons it is the charge number of that hadron (=1, 0, −1).

SUBROUTINE HIJING (FRAME, BMIN, BMAX)

Purpose: to generate a complete event as specified by subroutine HIJSET and the given parameters as will be described below. This is the main routine which can be called (many times) only after HIJSET has been called once.

FRAME: character variable to specify the frame of the collision as given in the HIJSET call.

BMIN, BMAX: low and up limits (fm) between which the impact parameter squared b^2 is uniformly distributed for pA and AB collisions. For hadron-hadron collisions, both are set to zero and the events are automatically averaged over all impact parameters.

4.3 Common blocks for event information

There are mainly three common blocks which provide users with important information of the generated events. Common block HIMAIN1 contains global information of the events and common block HIMAIN2 of the produced particles. The information of produced partons are stored in common blocks HIJJET1, HIJJET2, HISTRNG.

COMMON/HIMAIN1/NATT, EATT, JATT, NT, NP, N0, N01, N10, N11

Purpose: to give the overall information of the generated event.

NATT: total number of produced stable and undecayed particles of the current event.

EATT: the total energy of the produced particles in c.m. frame of the collision to check energy conservation.

JATT: the total number of hard scatterings in the current event.

NP, NT: the number of participant projectile and target nucleons in the current event.

N0, N01, N10, N11: number of N-N, N-$N_{wounded}$, $N_{wounded}$-N, and $N_{wounded}$-$N_{wounded}$ collisions in the current event (N, $N_{wounded}$ stand for nucleon and wounded nucleon respectively).

COMMON /HIMAIN2/KATT(130000,4), PATT(130000,4)

Purpose: to give information of produced stable and undecayed particles. Parent particles which decayed are not included here.

KATT(I, 1): (I=1,$\cdots$,NATT) flavor codes (see appendix) of the produced particles.

KATT(I, 2): (I=1,$\cdots$,NATT) status codes to identify the sources from which the particles come.

=0: projectile nucleon (or hadron) which has not interacted at all.

=1: projectile nucleon (or hadron) which only suffers an elastic collision.

=2: from a diffractive projectile nucleon (or hadron) in a single diffractive interaction.

=3: from the fragmentation of a projectile string system (including gluon jets).

=10 target nucleon (or hadron) which has not interacted at all.

=11: target nucleon (or hadron) which only suffers an elastic collision.

=12: from a diffractive target nucleon (or hadron) in a single diffractive interaction.

=13: from the fragmentation of a target string system (including gluon jets).

=20: from scattered partons which form string systems themselves.

=40: from direct production in the hard processes (currently, only direct photons are included).

KATT(I,3): (I=1,$\cdots$,NATT) line number of the parent particle. For finally produced or directly produced (not from the decay of another particle) particles, it is set to 0 (The option to keep the information of all particles including the decayed ones is IHPR2(21)=1).

KATT(I,4): (I=1,$\cdots$,NATT) status number of the particle.

=1: finally or directly produced particles.

=11: particles which has already decayed.

PATT(I, 1-4): (I=1,$\cdots$,NATT) four-momentum (p_x, p_y, p_z, E) (GeV/c, GeV) of the produced particles.

COMMON/HIJJET1/NPJ(300), KFPJ(300,500), PJPX(300,500), PJPY(300,500), PJPZ(300,500), PJPE(300,500), PJPM(300,500), NTJ(300), KFTJ(300,500), PJTX(300,500), PJTY(300,500), PJTZ(300,500), PJTE(300,500), PJTM(300,500)

Purpose: contains information about produced partons which are connected with the valence quarks and diquarks of projectile or target nucleons (or hadron) to form string systems for fragmentation. The momentum and energy of all produced partons are calculated in the c.m. frame of the collision. IAP, IAT are the numbers of nucleons in projectile and target nucleus respectively (IAP, IAT=1 for hadron projectile or target).

NPJ(I): (I=1,$\cdots$,IAP) number of partons associated with projectile nucleon I.

KFPJ(I, J): (I=1,$\cdots$,IAP, J=1,$\cdots$,NPJ(I)) parton flavor code of the parton J associated with projectile nucleon I.

PJPX(I, J), PJPY(I, J), PJPZ(I, J), PJPE(I, J), PJPM(I, J): the four momentum and mass (p_x, p_y, p_z, E, M) (GeV/c, GeV, GeV/c^2) of parton J associated with the projectile nucleon I.

NTJ(I): (I=1,$\cdots$,IAT) number of partons associated with target nucleon I.

KFTJ(I, J): (I=1,$\cdots$,IAT, J=1,$\cdots$,NTJ(I)): parton flavor code of the parton J associated with target nucleon I.

PJTX(I, J), PJTY(I, J), PJTZ(I, J), PJTE(I, J), PJTM(I, J): the four momentum and mass (p_x, p_y, p_z, E, M) (GeV/c, GeV, GeV/c^2) of parton J associated with target nucleon I.

COMMON/HIJJET2/NSG, NJSG(900), IASG(900,3), K1SG(900,100), K2SG(900,100), PXSG(900,100), PYSG(900,100), PZSG(900,100), PESG(900,100), PMSG(900,100)

Purpose: contains information about the produced partons which will form string systems themselves without being connected to valence quarks and diquarks.

NSG: the total number of such string systems.

NJSG(I): (I=1,$\cdots$,NSG) number of partons in the string system I.

IASG(I, 1), IASG(I, 2): to specify which projectile and target nucleons produce string system I.

IASG(I, 3): to indicate whether the jets will be quenched (0) or will not be quenched (1).

K1SG(I, J): (J=1,$\cdots$,NJSG(I)) color flow information of parton J in string system I (see JETSET 7.2 for detailed explanation).

K2SG(I, J): (J=1,$\cdots$,NJSG(I)) flavor code of parton J in string system I.

PXSG(I, J), PYSG(I, J), PZSG(I, J), PESG(I, J), PMSG(I, J): four momentum and mass (p_x, p_y, p_z, E, M) (GeV/c, GeV, GeV/c^2) of parton J in string system I.

COMMON/HISTRNG/NFP(300,15), PP(300,15), NFT(300,15), PT(300,15)

Purpose: contains information about the projectile and target nucleons (hadron) and the corresponding constituent quarks, diquarks. IAP, IAT are the numbers of nucleons in projectile and target nucleus respectively (IAP, IAT=1 for hadron projectile or target).

NFP(I, 1): (I=1,$\cdots$,IAP) flavor code of the valence quark in projectile nucleon (hadron) I.

NFP(I, 2): flavor code of diquark in projectile nucleon (anti-quark in projectile meson) I.

NFP(I, 3): present flavor code of the projectile nucleon (hadron) I (a nucleon or meson can be excited to its vector resonance).

NFP(I, 4): original flavor code of projectile nucleon (hadron) I.

NFP(I, 5): collision status of projectile nucleon (hadron) I.

=0: suffered no collision.

=1: suffered an elastic collision.

=2: being the diffractive one in a single-diffractive collision.

=3: became an excited string after an inelastic collision.

NFP(I, 6): the total number of hard scatterings associated with projectile nucleon (hadron) I. If NFP(I,6)<0, it can not produce jets any more due to energy conservation.

NFP(I, 10): to indicate whether the valence quarks or diquarks (anti-quarks) in projectile nucleon (hadron) I suffered a hard scattering,

=0: has not suffered a hard scattering.

=1: suffered one or more hard scatterings in current binary nucleon-nucleon collision.

=-1: suffered one or more hard scatterings in previous binary nucleon-nucleon collisions.

NFP(I, 11): total number of interactions projectile nucleon (hadron) I has suffered so far.

PP(I, 1), PP(I, 2), PP(I, 3), PP(I, 4), PP(I, 5): four momentum and the invariant mass (p_x, p_y, p_z, E, M) (GeV/c, GeV, GeV/c^2) of projectile nucleon (hadron) I.

PP(I, 6), PP(I, 7): transverse momentum (p_x, p_y) (GeV/c) of the valence quark in projectile nucleon (hadron) I.

PP(I, 8), PP(I, 9): transverse momentum (p_x, p_y) (GeV/c) of the diquark (anti-quark) in projectile nucleon (hadron) I.

PP(I, 10), PP(I, 11), PP(I, 12): three momentum (p_x, p_y, p_z) (GeV/c) transferred to the quark or diquark (anti-quark) in projectile nucleon (hadron) I from the last hard scattering.

PP(I, 14): mass (GeV/c^2) of the quark in projectile nucleon (hadron) I.

PP(I, 15): mass of the diquark (anti-quark) in projectile nucleon (hadron) I.

NFT(I, 1–15), PT(I,1–15): give the same information for the target nucleons (hadron) and the corresponding quarks and diquarks (anti-quarks) as for the projectile nucleons.

4.4 Options and parameters

The following common block is for input parameters for HIJING which are used mainly for specifying event options and changing the default parameters. It also contains some extra event information. The default values of the parameters are given by D. Some parameters are simply used to redefine the parameters in JETSET 7.2 and PYTHIA 5.3. Users have to find the detailed explanations in JETSET and PYTHIA documentations.

COMMON/HIPARNT/HIPR1(100), IHPR2(50), HINT1(100), IHNT2(50)

Purpose: contains input parameters (HIPR1, IHPR2) for event options and some extra information (HINT1, IHNT2) of current event.

HIPR1(1): (D=1.5 GeV/c^2) minimum value for the invariant mass of the excited string system in a hadron-hadron interaction.

HIPR1(2): (D=0.35 GeV) width of the Gaussian P_T distribution of produced hadron in Lund string fragmentation (PARJ(21) in JETSET 7.2).

HIPR1(3), HIPR1(4): (D=0.5, 0.9 GeV^{-2}) give the a and b parameters of the symmetric Lund fragmentation function (PARJ(41), PARJ(42) in JETSET 7.2).

HIPR1(5): (D=2.0 GeV/c^2) invariant mass cut-off for the dipole radiation of a string system below which soft gluon radiations are terminated.

HIPR1(6): (D=0.1) the depth of shadowing of structure functions at $x = 0$ as defined in Eq. 25: $\alpha_A = \text{HIPR1(6)} \times (A^{1/3} - 1)$.

HIPR1(7): not used

HIPR1(8): (D=2.0 GeV/c) minimum P_T transfer in hard or semihard scatterings.

HIPR1(9): (D=$-$1.0 GeV/c) maximum P_T transfer in hard or semihard scatterings. If negative, the limit is set by the colliding energy.

HIPR1(10): (D=$-$2.25 GeV/c) specifies the value of P_T for each triggered hard scattering generated per event (see Section 2.2). If HIPR1(10) is negative, its absolute value gives the low limit of the P_T of the triggered jets.

HIPR1(11): (D=2.0 GeV/c) minimum P_T of a jet which will interact with excited nuclear matter. When the P_T of a jet is smaller than HIPR1(11) it will stop interacting further.

HIPR1(12): (D=1.0 fm) transverse distance between a traversing jet and an excited nucleon (string system) below which they will interact and the jet will lose energy and momentum to that string system.

HIPR1(13): (D=1.0 fm) the mean free path of a jet when it goes through the excited nuclear matter.

HIPR1(14): (D=2.0 GeV/fm) the energy loss dE/dz of a gluon jet inside the excited nuclear matter. The energy loss for a quark jet is half of the energy loss of a gluon.

HIPR1(15): (D=0.2 GeV/c) the scale Λ in the calculation of α_s.

HIPR1(16): (D=2.0 GeV/c) the initial scale Q_0 for the evolution of the structure functions.

HIPR1(17): (D=2.0) K factor for the differential jet cross sections in the lowest order pQCD calculation.

HIPR1(18): not used

HIPR1(19), HIPR1(20): (D=0.1, 1.4 GeV/c) parameters in the distribution for the P_T kick from soft interactions (see Eq. 23), $1/[(\text{HIPR1(19)}^2 + P_T^2)(\text{HIPR1(20)}^2 + P_T^2)]$.

HIPR1(21): (D=1.6 GeV/c) the maximum P_T for soft interactions, beyond which a Gaussian distribution as specified by HIPR1(2) will be used.

HIPR1(22): (D=2.0 GeV/c) the scale in the form factor to suppress the P_T transfer to diquarks in hard scatterings,

HIPR1(23)–HIPR1(28): not used.

HIPR1(29): (D=0.4 fm) the minimum distance between two nucleons inside a nucleus when the coordinates of the nucleons inside a nucleus are initialized.

HIPR1(30): (D=2×HIPR1(31)=57.0 mb) the inclusive cross section σ_{soft} for soft interactions. The default value $\sigma_{soft} = 2\sigma_0$ is used to ensure the geometrical scaling of pp interaction cross sections at low energies.

HIPR1(31): (D=28.5 mb) the cross section σ_0 which characterizes the geometrical size of a nucleon ($\pi b_0^2 = \sigma_0$, see Eq. 10). The default value is only for high-energy limit ($\sqrt{s} > 200$ GeV). At lower energies, a slight decrease which depends on energy is parametrized in the program. The default values of the two parameters HIPR1(30), HIPR1(31) are only for NN type interactions. For other kinds of projectile or target hadrons, users should change these values so that correct inelastic and total cross sections (HINT1(12), HINT1(13)) are obtained by the program.

HIPR1(32): (D=3.90) parameter μ_0 in Eq. 10 for the scaled eikonal function.

HIPR1(33): fractional cross section of single-diffractive interaction as parametrized in Ref. [25].

HIPR1(34): maximum radial coordinate for projectile nucleons to be given by the initialization program HIJSET.

HIPR1(35): maximum radial coordinate for target nucleons to be given by the initialization program HIJSET.

HIPR1(36)-HIPR1(39): not used.

HIPR1(40): (D=3.141592654) value of π.

HIPR1(41)–HIPR1(42): not used.

HIPR1(43): (D=0.01) fractional energy error relative to the colliding energy permitted per nucleon-nucleon collision.

HIPR1(44), HIPR1(45), HIPR1(46): (D=1.5, 0.1 GeV, 0.25) parameters α, c and β in the valence quark distributions for soft string excitation, $(1-x)^\alpha/(x^2+c^2/s)^\beta$ for baryons, $1/(x^2+c^2/s)[(1-x)^2+c^2/s)]^\beta$ for mesons.

HIPR1(47), HIPR1(48): (D=0.0, 0.5) parameters α and β in valence quark distribution, $(1-x)^\alpha/(x^2+c^2/s)^\beta$, for the disassociated excitation in a single diffractive collision.

HIPR1(49)–HIPR1(100): not used.

IHPR2(1): (D=1) switch for dipole-approximated QCD radiation of the string system in soft interactions.

IHPR2(2): (D=3) option for initial and final state radiation in the hard scattering.

=0: both initial and final radiation are off.
=1: initial radiation on and final radiation off.
=2: initial radiation off and final radiation on.
=3: both initial and final radiation are on.

IHPR2(3): (D=0) switch for triggered hard scattering with specified $P_T \geq$HIPR1(10).
=0: no triggered jet production.
=1: ordinary hard processes.
=2: only direct photon production.

IHPR2(4): (D=1) switch for jet quenching in the excited nuclear matter.

IHPR2(5): (D=1) switch for the P_T kick due to soft interactions.

IHPR2(6): (D=1) switch for the nuclear effect on the parton distribution function such as shadowing.

IHPR2(7): (D=1) selection of Duke-Owens set (1 or 2) of parametrization of nucleon structure functions.

IHPR2(8): (D=10) maximum number of hard scatterings per nucleon-nucleon interaction. When IHPR2(8)=0, jet production will be turned off. When IHPR2(8)< 0, the number of jet production will be fixed at its absolute value for each NN collision.

IHPR2(9): (D=0) switch to guarantee at least one pair of minijets production per event (pp, pA or AB).

IHPR2(10): (D=0) option to print warning messages about errors that might happen. When a fatal error happens the current event will be abandoned and a new one is generated.

IHPR2(11): (D=1) choice of baryon production model.
=0: no baryon-antibaryon pair production, initial diquark treated as a unit.
=1: diquark-antidiquark pair production allowed, initial diquark treated as a unit.
=2: diquark-antidiquark pair production allowed, with the possibility for diquark to split according to the “popcorn” scheme (see the documentation of JETSET 7.2).

IHPR2(12): (D=1) option to turn off the automatic decay of the following particles: π^0, K_S^0, $D^\pm$, Λ, $\Sigma^\pm$.

IHPR2(13): (D=1) option to turn on single diffractive reactions.

IHPR2(14): (D=1) option to turn on elastic scattering.

IHPR2(15) – IHPR2(17): not used.

IHPR2(18):(D=0)option to switch on B-quark production. Charm production is the default. When B-quark production is on, charm quark production is automatically off.

IHPR2(19): (D=1) option to turn on initial state soft interaction.

IHPR2(20): (D=1) switch for the final fragmentation.

IHPR2(21): (D=0) option to keep the information of all particles including those which have decayed and the decay history in the common block HIMAIN2. The line number of the parent particle is KATT(I,3). The status of a partcile, whether it is a finally produced particle (KATT(I,4)=1) or a decayed particle (KATT(I,4)=11) is also kept.

IHPR2(22)-IHPR2(50): not used.

HINT1(1): (GeV) colliding energy in the c.m. frame of nucleon-nucleon collisions.

HINT1(2): Lorentz transformation variable β from laboratory to c.m. frame of nucleon nucleon collisions.

HINT1(3): rapidity y_{cm} of the c.m. frame $\beta = \tanh y_{cm}$.

HINT1(4): rapidity of projectile nucleons (hadron) y_{proj}.

HINT1(5): rapidity of target nucleons (hadron) y_{targ}.

HINT1(6): (GeV) energy of the projectile nucleons (hadron) in the given frame.

HINT1(7): (GeV) energy of the target nucleons (hadron) in the given frame.

HINT1(8): (GeV) the rest mass of projectile particles.

HINT1(9): (GeV) the rest mass of target particles.

HINT1(10): (mb) the averaged cross section for jet production per nucleon-nucleon collisions, $\int d^2b\{1 - \exp[-\sigma_{jet}T_N(b)]\}$.

HINT1(11): (mb) the averaged inclusive cross section σ_{jet} for jet production per nucleon-nucleon collisions.

HINT1(12): (mb) the averaged inelastic cross section of nucleon-nucleon collisions.

HINT1(13): (mb) the averaged total cross section of nucleon-nucleon collisions.

HINT1(14): (mb) the jet production cross section without nuclear shadowing effect σ_{jet}^0 (see Eq. 28).

HINT1(15): (mb) the cross section σ_{jet}^A to account for the projectile shadowing correction term in the jet cross section (see Eq. 28).

HINT1(16): (mb) the cross section σ_{jet}^B to account for the target shadowing correction term in the jet cross section (see Eq. 28).

HINT1(17): (mb) the cross section σ_{jet}^{AB} to account for the cross term of shadowing correction in the jet cross section (see Eq. 28).

HINT1(18): (mb) the effective cross section $\sigma_{jet}^{eff}(r_A, r_B)$ for jet production of the latest nucleon-nucleon collision which depends on the transverse coordinates of the colliding nucleons (see Eq. 28).

HINT1(19): (fm) the (absolute value of) impact parameter of the latest event.

HINT1(20): (radians) the azimuthal angle ϕ of the impact parameter vector in the transverse plane of the latest event.

HINT1(21)–HINT1(25): the four momentum and mass (p_x, p_y, p_z, E, M) (GeV/c, GeV, GeV/c^2) of the first scattered parton in the triggered hard scattering. This is before the final state radiation but after the initial state radiation.

HINT1(26)–HINT1(30): not used.

HINT1(31)–HINT1(35): the four momentum and mass (p_x, p_y, p_z, E, M) (GeV/c, GeV, GeV/c^2) of the second scattered parton in the triggered hard scattering. This is before the final state radiation but after the initial state radiation.

HINT1(46)–HINT1(40): not used.

HINT1(41)–HINT1(45): the four momentum and mass (p_x, p_y, p_z, E, M) (GeV/c, GeV, GeV/c^2) of the first scattered parton in the latest hard scattering of the latest event.

HINT1(46): P_T (GeV/c) of the first scattered parton in the latest hard scattering of the latest event.

HINT1(47)–HINT1(50): not used.

HINT1(51)–HINT1(55): the four momentum and mass (p_x, p_y, p_z, E, M) (GeV/c, GeV, GeV/c^2) of the second scattered parton in the latest hard scattering of the latest event.

HINT1(56): P_T (GeV/c) of the second scattered parton in the latest hard scattering of the latest event.

HINT1(57)–HINT1(58): not used.

HINT1(59): (mb) the averaged cross section of the triggered jet production (with P_T specified by HIPR1(10) and with switch by IHPR2(3)) per nucleon-nucleon collision, $\int d^2b\{1 - \exp[-\sigma_{jet}^{trig} T_N(b)]\}$

HINT1(60): (mb) the averaged inclusive cross section of the triggered jet production σ_{jet}^{trig} (with P_T specified by HIPR1(10) and with switch by IHPR2(3)) per nucleon-nucleon collision.

HINT1(61): (mb) the triggered jet production cross section without nuclear shadowing effect (similar to HINT1(14)).

HINT1(62): (mb) the cross section to account for the projectile shadowing correction term in the triggered jet cross section (similar to HINT1(15)).

HINT1(63): (mb) the cross section to account for the target shadowing correction term in the triggered jet cross section (similar to HINT1(16)).

HINT1(64): (mb) the cross section to account for the cross term of shadowing correction in the triggered jet cross section (similar to HINT1(17).

HINT1(65): (mb) the inclusive cross section for latest triggered jet production which depends on the transverse coordinates of the colliding nucleons (similar to HINT1(18)).

HINT1(67)–HINT1(71): not used.

HINT1(72)–HINT1(75): three parameters for the Wood-Saxon projectile nuclear distribution and the normalization read from a table inside the program, $\rho(r) = C[1 + W(r/R_A)^2]/\{1+\exp[(r-R_A)/D]\}$, R_A=HINT1(72), D=HINT1(73), W=HINT1(74), C=HINT1(75).

HINT1(76)–HINT1(79): three parameters for the Wood-Saxon projectile nuclear distribution and the normalization read from a table inside the program, $\rho(r) = C[1 + W(r/R_A)^2]/\{1+\exp[(r-R_A)/D]\}$, R_A=HINT1(76), D=HINT1(77), W=HINT1(78), C=HINT1(79).

HINT1(80)–HINT1(100): the probability of $j = 0 - 20$ number of hard scatterings per nucleon-nucleon collisions.

IHNT2(1): the mass number of the projectile nucleus (1 for a hadron).

IHNT2(2): the charge number of the projectile nucleus. If the projectile is a hadron, it gives the charge of the hadron.

IHNT2(3): the mass number of the target nucleus (1 for a hadron).

IHNT2(4): the charge number of the target nucleus. If the target is a hadron, it gives the charge of the hadron.

IHNT2(5): the flavor code of the projectile hadron (0 for nucleus).

IHNT2(6): the flavor code of the target hadron (0 for nucleus).

IHNT2(7)–IHNT2(8): not used.

IHNT2(9): the flavor code of the first scattered parton in the triggered hard scattering.

IHNT2(10): the flavor code of the second scattered parton in the triggered hard scattering.

IHNT2(11): the sequence number of the projectile nucleon in the latest nucleon-nucleon interaction of the latest event.

IHNT2(12): the sequence number of the target nucleon in the latest nucleon-nucleon interaction of the latest event.

IHNT2(13): status of the latest soft string excitation.
=1: double diffractive.
=2: single diffractive.
=3: non-single diffractive.

IHNT2(14): the flavor code of the first scattered parton in the latest hard scattering of the latest event.

IHNT2(15): the flavor code of the second scattered parton in the latest hard scattering of the latest event.

IHNT2(16)–IHNT2(50): not used.

4.5 Other physics routines

Inside HIJING main routines, calls have to be made to many other routines to carry out the specified simulations. We give here a brief description of some of those routines.

SUBROUTINE HIJINI

Purpose: to reset all relevant common blocks and variables and initialize the program for each event.

SUBROUTINE HIJCRS

Purpose: to calculate cross sections of minijet production, cross section of the triggered processes, elastic, inelastic and total cross section of nucleon-nucleon (or hadron) collisions within the eikonal formalism.

SUBROUTINE JETINI (I_TYPE)

Purpose: to initialize the program for generating hard scatterings as specified by the parameters and options.

SUBROUTINE HIJHRD (JP, JT, JOUT, JFLG, IOPJET0)

Purpose: to simulate one hard scattering among the multiple jet production per nucleon-nucleon (hadron) collision and the associated radiations by calling PYTHIA subroutines.

SUBROUTINE HARDJET (JP, JT, JFLG)

Purpose: to simulate the triggered hard processes.

SUBROUTINE HIJSFT (JP, JT, JOUT, IERROR)

Purpose: to generate the soft interaction for each binary nucleon-nucleon collision.

SUBROUTINE HIJSRT (JPJT, NPT)

Purpose: to rearrange the gluon jets in a string system according to their rapidities.

SUBROUTINE QUENCH (JPJT, NTP)

Purpose: to perform jet quenching by allowing final state interaction of produced jet inside the excited strings. The energy lost by the jets will be transferred to other string systems.

SUBROUTINE HIJFRG (JTP, NTP, IERROR)

Purpose: to arrange the produced partons together with the valence quarks and diquarks (anti-quarks) and LUEXEC subroutine in JETSET is called to perform the fragmentation for each string system.

SUBROUTINE ATTRAD (IERROR)

Purpose: to perform soft radiations according to Lund dipole approximation.

SUBROUTINE ATTFLV (ID, IDQ, IDQQ)

Purpose: to generate the flavor codes of the valence quark and diquark (anti-quark) inside a given nucleon (hadron).

SUBROUTINE HIJCSC (JP, JT)

Purpose: to perform elastic scatterings and possible elastic nucleon-nucleon cascading.

SUBROUTINE HIJWDS (IA, IDH, XHIGH)

Purpose: to set up a distribution function according to the three-parameter Wood-Saxon distribution to generate the coordinates of the nucleons inside the projectile or target nucleus.

FUNCTION PROFILE (XB)

Purpose: gives the overlap profile function of two colliding nuclei at given impact parameter XB. This can be used to weight the simulated events of uniformly distributed impact parameter and obtain the results of the minimum biased events.

SUBROUTINE HIBOOST

Purpose: to transform the produced particles from c.m. frame to the laboratory frame.

BLOCK DATA HIDATA

Purpose: to give the default values of the parameters and options and initialize the event record common blocks.

4.6 Other common blocks

There also other two common blocks which contain information users may find useful.

COMMON/HIJJET4/NDR,IADR(900,2),KFDR(900),PDR(900,5)

Purpose: contains information about directly produced particles (currently only direct photons).

NDR: total number of directly produced particles.

IADR(I, 1), IADR(I, 2): the sequence numbers of projectile and target nucleons which produce particle I during their interaction.

KFDR(I): the flavor code of directly produced particle I.

PDR(I, 1,$\cdots$,5): four momentum and mass (p_x, p_y, p_z, E, M) (GeV/c, GeV, GeV/c^2) of particle I.

COMMON/HIJCRDN/YP(3,300),YT(3,300)

Purpose: to specify the space coordinates of projectile and target nucleons inside their parent nuclei.

YP(1,$\cdots$,3, I): x, y, z (fm) coordinates of the number I projectile nucleon relative to the center of its parent nucleus.

YT(1,$\cdots$,3, I): x, y, z (fm) coordinates of the number I target nucleon relative to the center of its parent nucleus.

5 Instruction on How to Use the Program

HIJING program was designed for high energy pp, pA and AB collisions. It is relatively easy to use with only two main subroutines and a few adjustable parameters. In this section we will give three example programs for generating events of fixed impact parameter, minimum bias, and triggered hard processes. In all the cases, users should write their own main program with all the relevant common blocks included. To study the event, users may have to call some routines in JETSET. Therefore, knowledge of JETSET will be helpful. Two special routines of JETSET which users may frequently use are function LUCHGE(KF) to give three times the charge, and function ULMASS(KF) to give the mass for a particle/parton with flavor code KF.

5.1 Fixed impact parameter

For relativistic hadron-nucleus and heavy ion collisions, events at fixed impact parameter especially central collisions with $b = 0$ are most commonly studied. It is also the simplest simulation for HIJING. For pp collisions, one should always use zero impact parameter and HIJING will give the results averaged over the impact parameter. In the following example program, we generate 1000 central events of $Au + Au$ at $\sqrt{s} = 200$ GeV/n and calculate the rapidity and transverse momentum distributions of produced charged particles. The projectile and target nucleons in the beam directions which have not suffered any interaction are not considered produced particles. The output of the event-averaged rapidity and transverse momentum distributions are plotted in Figs.1 and 2.

```
      CHARACTER FRAME*8, PROJ*8, TARG*8
      DIMENSION DNDPT(50),DNDY(50)
      COMMON/HIPARNT/HIPR1(100), IHPR2(50), HINT1(100), IHNT2(50)
C....information of produced particles:
      COMMON/HIMAIN1/NATT, EATT, JATT, NT, NP, N0, N01, N10, N11
      COMMON/HIMAIN2/KATT(130000,4), PATT(130000,4)
C....information of produced partons:
      COMMON/HIJJET1/NPJ(300), KFPJ(300,500), PJPX(300,500),
     &  PJPY(300,500), PJPZ(300,500), PJPE(300,500), PJPM(300,500),
     &  NTJ(300), KFTJ(300,500), PJTX(300,500), PJTY(300,500),
     &  PJTZ(300,500), PJTE(300,500), PJTM(300,500)
      COMMON/HIJJET2/NSG, NJSG(900), IASG(900,3), K1SG(900,100),
     &  K2SG(900,100), PXSG(900,100), PYSG(900,100), PZSG(900,100),
     &  PESG(900,100), PMSG(900,100)
      COMMON/HISTRNG/NFP(300,15), PP(300,15), NFT(300,15), PT(300,15)
C....initialize HIJING for Au+Au collisions at c.m.  energy of 200 GeV:
      EFRM=200.0
      FRAME='CMS'
      PROJ='A'
      TARG='A'
      IAP=197
      IZP=79
      IAT=197
      IZT=79
      CALL HIJSET (EFRM, FRAME, PROJ, TARG, IAP, IZP, IAT, IZT)
C....generating 1000 central events:
      N_EVENT=1000
      BMIN=0.0
      BMAX=0.0
      DO 2000 J=1,N_EVENT
         CALL HIJING (FRAME, BMIN, BMAX)
C....calculate rapidity and transverse momentum distributions of
C....produced charged particles:
         DO 1000 I=1,NATT
C......exclude beam nucleons as produced particles:
            IF(KATT(I,2).EQ.0 .OR. KATT(I,2).EQ.10) GO TO 1000
```

```
C.......select charged particles only:
                IF (LUCHGE(KATT(I,1)) .EQ. 0) GO TO 1000
                PTR=SQRT(PATT(I,1)**2+PATT(I,2)**2)
                IF (PTR .GE. 10.0) GO TO 100
                IPT=1+PTR/0.2
                DNDPT(IPT)=DNDPT(IPT)+1.0/FLOAT(N_EVENT)/0.2/2.0/PTR
100             Y=0.5*LOG((PATT(I,4)+PATT(I,3))/(PATT(I,4)+PATT(I,3)))
                IF(ABS(Y) .GE. 10.0) GO GO 1000
                IY=1+ABS(Y)/0.2
                DNDY(IY)=DNDY(IY)+1.0/FLOAT(N_EVENT)/0.2/2.0
1000         CONTINUE
2000     CONTINUE
C....print out the rapidity and transverse momentum distributions:
         WRITE(*,*) (0.2*(K-1),DNDPT(K),DNDY(K),K=1,50)
         STOP
         END
```

5.2 Minimum bias events

Because of the diffused distribution of large nuclei, minimum bias events are dominated by those of large impact parameters with a long shoulder for small impact parameter events. To effectively study minimum bias events, one can generate events uniformly between zero and the largest impact parameter $R_A + R_B$, and then weight the events by a Glauber probability,

$$\frac{1}{\sigma_{AB}} d^2b\{1 - \exp[-\sigma_{in} T_{AB}(b)]\} \tag{30}$$

where σ_{in} is the inelastic cross section for N-N collisions and σ_{AB} is the total reaction cross section for AB collisions integrated over all impact parameters. To obtain the Glauber distribution a routine named FUNCTION PROFILE(XB) has to be called.

In the following main program, a range of impact parameters from 0 to $2R_A$ is divided into 100 intervals. For each fixed impact parameter, 10 events are generated for $Au + Au$ at $\sqrt{s} = 200$ GeV/n. Then P_T distribution for charged pions is calculated for the minimum bias events.

```
         CHARACTER FRAME*8, PROJ*8, TARG*8
         COMMON/HIPARNT/HIPR1(100), IHPR2(50), HINT1(100), IHNT2(50)
         COMMON/HIMAIN1/NATT, EATT, JATT, NT, NP, N0, N01, N10, N11
```

```
      COMMON/HIMAIN2/KATT(130000,4), PATT(130000,4)
      DIMENSION GB(101), XB(101), DNDP(50)
C....initialize HIJING for Au+Au collisions at c.m.  energy of 200 GeV:
      EFRM=200.0
      FRAME='CMS'
      PROJ='A'
      TARG='A'
      IAP=197
      IZP=79
      IAT=197
      IZT=79
      CALL HIJSET (EFRM, FRAME, PROJ, TARG, IAP, IZP, IAT, IZT)
C....set BMIN=0 and BMAX=R_A+R_B
      BMIN=0.0
      BMAX=HIPR1(34)+HIPR1(35)
C....calculate the Glauber probability and its integrated value:
      DIP=(BMAX-BMIN)/100.0
      GBTOT=0.0
      DO 100 I=1,101
         XB(I)=BMIN+(I-1)*DIP
         OV=PROFILE(XB(I))
         GB(I)=XB(I)*(1.0-EXP(-HINT1(12)*OV))
         GBTOT=GBTOT+GB(I)
100   CONTINUE
C....generating 10 events for each of 100 impact parameter intervals:
      NONT=0
      GNORM=GBTOT
      N_EVENT=10
      DO 300 IB=1,100
         B1=XB(IB)
         B2=XB(IB+1)
C......normalized Glauber probability:
         W_GB=(GB(IB)+GB(IB+1))/2.0/GBTOT
         DO 200 IE=1,N_EVENT
            CALL HIJING(FRAME,B1,B2)
C......count number of events without any interaction
```

```
C.......and renormalize the total Glauber probability:
                IF (NP+NT .EQ. 0) THEN
                  NONT=NONT+1
                  GNORM=GNORM-GB(IB)/FLOAT(N_EVENT)
                  GO TO 200
                ENDIF
C....calculate pt distribution of charged pions:
                DO 150 K=1,NATT
C.......select charged pions only:
                  IF (ABS(KATT(K,1)) .NE. 211) GO TO 150
C.......calculate pt:
                  PTR=SQRT(PATT(K,1)**2+PATT(K,2)**2)
C.......calculate pt distribution and weight with normalized
C.......Glauber probability to get minimum bias result:
                  IF (PTR .GE. 10.0) GO TO 150
                  IPT=1+PTR/0.2
                  DNDP(IPT)=DNDP(IPT)+1.0/W_GB/FLOAT(N_EVENT)/0.2
150             CONTINUE
200         CONTINUE
300     CONTINUE
C....renormalize the distribution by the renormalized Glauber
C....probability which excludes the events without any interaction:
        IF(NONT.NE.0) THEN
            DO 400 I=1,50
                DNDP(I)=DNDP(I)*GBTOT/GNORM
400         CONTINUE
        ENDIF
        STOP
        END
```

5.3 Events with triggered hard processes

Sometimes, users may want to study events with a hard process. Since these processes, especially with large transverse momentum, have very small cross section, it is very inefficient to sort them out among huge number of ordinary events. However, in HIJING, one can trigger on such events and generate one hard process in each event with the background correctly incorporated. One can then calculate the absolute cross section of such events by using the information stored in HINT(12) (inelastic N-N cross section) and HINT1(59) (cross section of triggered process in N-N collisions). HIPR1(10) is used to specify the P_T value or its range.

In the current version, both large P_T jets (IHPR2(3)=1) and direct photon production (IHPR2(3)=2) are included. In the following, we give an example on how to generate a pair of large P_T jets above 20 GeV/c in a central $Au + Au$ collision at $\sqrt{s} = 200$ GeV/n.

```
        CHARACTER FRAME*8, PROJ*8, TARG*8
        COMMON/HIPARNT/HIPR1(100), IHPR2(50), HINT1(100), IHNT2(50)
C.....switch off jet quenching:
        IHPR2(4)=0
C.....switch on triggered jet production:
        IHPR2(3)=1
C.....set the pt range of the triggered jets:
        HIPR1(10)=-20
C....initialize HIJING for Au+Au collisions at c.m.  energy of 200 GeV:
        EFRM=200.0
        FRAME='CMS'
        PROJ='A'
        TARG='A'
        IAP=197
        IZP=79
        IAT=197
        IZT=79
        CALL HIJSET (EFRM, FRAME, PROJ, TARG, IAP, IZP, IAT, IZT)
C....generating one central event with triggered jet production:
        BMIN=0.0
        BMAX=0.0
        CALL HIJING (FRAME, BMIN, BMAX)
C....print out flavor code of the first jet:
        WRITE(*,*) IHNT2(9)
C....and its four momentum:
        WRITE(*,*) HINT1(21), HINT1(22), HINT1(23), HINT1(24)
C....print out flavor code of the second jet:
        WRITE(*,*) IHNT2(10)
C....and its four momentum:
        WRITE(*,*) HINT1(31), HINT1(32), HINT1(33), HINT1(34)
```

```
      STOP
      END
```

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Appendix: Flavor Code

For users' reference, a selection of flavor codes from JETSET 7.2 are listed below. For full list please check JETSET documentation. The codes for anti-particles are just the negative values of the corresponding particles.

Quarks and leptons

1	d	11	e^-
2	u	12	ν_e
3	s	13	μ^-
4	c	14	ν_μ
5	b	15	τ^-
6	t	16	ν_τ

Gauge bosons

21	g
22	γ

Diquarks

		1103	dd_1
2101	ud_0	2103	ud_1
		2203	uu_1
3101	sd_0	3103	sd_1
3201	su_0	3203	su_1
		3303	ss_1

Mesons

211	π^+	213	ρ^+
311	K^0	313	K^{*0}
321	K^+	323	K^{*+}
411	D^+	413	D^{*+}
421	D^0	423	D^{*0}
431	D_s^+	433	D_s^{*+}
511	B^0	513	B^{*0}
521	B^+	523	B^{*+}
531	B_s^0	533	B_s^{*0}
111	π^0	113	ρ^0
221	η	223	ω
331	η'	333	ϕ
441	η_c	443	J/ψ
551	η_b	553	Υ
661	η_t	663	Θ
130	K_L^0		
310	K_S^0		

Baryons

		1114	Δ^-
2112	n	2114	Δ^0
2212	p	2214	Δ^+
		2224	Δ^{++}
3112	Σ^-	3114	Σ^{*-}
3122	Λ^0		
3212	Σ^0	3214	Σ^{*0}
3222	Σ^+	3224	Σ^{*+}
3312	Ξ^-	3314	Ξ^{*-}
3322	Ξ^0	3324	Ξ^{*0}
		3334	Ω^-
4112	Σ_c^0	4114	Σ_c^{*0}
4122	Λ_c^+		
4212	Σ_c^+	4214	Σ_c^{*+}
4222	Σ_c^{++}	4224	Σ_c^{*++}
4132	Ξ_c^0		

4312	Ξ'^0_c	4314	Ξ^{*0}_c
4232	Ξ^+_c		
4322	Ξ'^+_c	4324	Ξ^{*+}_c
4332	Ω^0_c	4334	Ω^{*0}_c
5112	Σ^-_b	5114	Σ^{*-}_b
5122	Λ^0_b		
5212	Σ^0_b	5214	Σ^{*0}_b
5222	Σ^+_b	5224	Σ^{*+}_b

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Figure Captions

Fig. 1 The rapidity distribution of charged particles produced in central $Au + Au$ collisions at $\sqrt{s} = 200$ GeV/n, obtained from the example program for fixed impact parameter.

Fig. 2 The transverse momentum distribution of charged particles in central $Au + Au$ collisions, obtained from the example program for fixed impact parameter.