# Hadron production in p+p, p+Pb, and Pb+Pb collisions with the hijing 2.0 model at energies available at the CERN Large Hadron Collider

Wei-Tian Deng, Xin-Nian Wang, and Rong Xu

Phys. Rev. C **83**, 014915 — Published 31 January 2011
DOI: 10.1103/PhysRevC.83.014915

# Hadron production in $p + p$, $p + Pb$ and $Pb + Pb$ collisions at the LHC energies with HIJING2.0 model

Wei-Tian Deng,[1,2] Xin-Nian Wang,[3,4] and Rong Xu[3]
[1]Frankfurt Institute for Advanced Studies (FIAS) Ruth-Moufang-Strasse 1, D-60438 Frankfurt am Main, Germany
[2]Department of Physics, Shandong University, Jinan 250100, China
[3]Institute of Particle Physics, Huazhong Normal University, Wuhan 430079, China
[4]Nuclear Science Division, MS 70R0319, Lawrence Berkeley National Laboratory, Berkeley, California 94720

The HIJING (Heavy-ion Jet Interaction Generator) Monte Carlo model is updated with the latest parton distributions functions (PDF) and new set of the parameters in the two-component mini-jet model that controls total $p + p$ cross section and the central pseudorapity density. We study hadron spectra and multiplicity distributions using the HIJING 2.0 model and compare to recent experimental data from $p + p$ collisions at the LHC energies. We also give predictions of hadron production in $p + p$, $p + Pb$ and $Pb + Pb$ collisions at the full LHC energy.

PACS numbers: 12.38.Mh,24.85.+p,25.75.-q



## I. INTRODUCTION

The HIJING (Heavy Ion Jet INteraction Generator) Monte Carlo model was developed to study hadron production in high-energy nucleon-nucleon, nucleon-nucleus and nucleus-nucleus collisions [1–3]. It was based on a two-component geometrical model of mini-jet production and soft interaction and has incorporated nuclear effects such as nuclear modification of the parton distribution functions and jet quenching via final state jet medium interaction. It can reproduce most features of hadron production in $p+p(\bar{p})$ and $p+A$ collisions up to the Fermilab Tevatron energies. With some modification of the string configuration in the soft sector of particle production, it can also reproduce the bulk hadron spectra and the approximately the suppression of high $p_T$ hadrons due to jet quenching in central rapidity region of $A + A$ collisions up to the RHIC energies [4–6]. It has been widely used to simulate hadron production in $p + A$ and $A + A$ collisions for designs of new detector systems and provide initial conditions for parton and hadron cascade models such AMPT model [7].

The core component of HIJING is the two-component model for beam parton interaction which was proposed to model the energy dependence of total cross section[8–14] and particle production[15–18] in high energy hadron collisions. The two-component model was also extended [19, 20] and later incorporated in the HIJING model to describe initial parton production in high-energy heavy-ion collisions. In this two-component model, one assumes that parton interaction in high-energy nucleon-nucleon collisions can be divided into soft interaction and hard or semi-hard interaction with jet production. A cut-off scale $p_0$ in the transverse momentum of the final jet production has to be introduced below which the interaction is considered non-perturbative and can only be characterized by a finite soft parton cross section $\sigma_{soft}$. For jet production with transverse momentum $p_T > p_0$, the cross section and jet spectrum are assumed to be given by perturbative QCD parton model. Jet cross sections in collinear factorized perturbative QCD in turn depend on the parton distribution functions (PDF) that are parameterized from a global fit to the available experimental data of deeply inelastic scattering (DIS) of lepton and nucleon, Drell-Yan lepton pair, direct photon and jet production in $p + p(\bar{p})$ collisions.

The two parameters $\sigma_{soft}$ and $p_0$ in HIJING are determined phenomenologically by fitting the experimental data of total cross sections and hadron multiplicity in $p + p/\bar{p}$ collisions, which should depend on the parameterization of nucleon PDF's. In the original version of HIJING, Duke-Own parameterization [21] of PDF's are used to calculate the jet production cross section with $p_T > p_0$ which are adequate for description of jet production at RHIC and maybe Tevatron energies. However, for $p + p$ collisions at much higher energies such as the LHC energies, jet production processes involve initial beam partons with fraction momentum $x \sim 10^{-4}$ where Duke-Owen parameterization of PDF's is no longer valid. More modern parameterizations should be used. In this progress report, we introduce the HIJING 2.0 model in which we use more modern set of parameterized PDF's. We have to perform a global fit of the total cross sections and hadron multiplicities in $p + p(\bar{p})$ collisions to determine the two parameters, $\sigma_{soft}$ and $p_0$, and their energy dependence. We will use the new HIJING 2.0 model to study hadron production in $p+p$ at the LHC energies and compare to the recently published experimental data. We also provide predictions of hadron multiplicities in $p + p$ and $Pb + Pb$ collisions at the full LHC energies.

## II. TWO-COMPONENT MODEL IN HIJING

In the two-component model[1–3, 8–14] incorporated in HIJING, one assumes that events of nucleon-nucleon collisions at high energy can be divided into soft and hard processes with at least on pair of jet production with $p_T > p_0$. The inclusive jet cross section $\sigma_{jet}$ in the leading order (LO) [22]

$$\sigma_{jet} = \int_{p_0^2}^{s/4} \mathrm{d}p_T^2 \mathrm{d}y_1 \mathrm{d}y_2 \frac{1}{2} \frac{\mathrm{d}\sigma_{jet}}{\mathrm{d}p_T^2 \mathrm{d}y_1 \mathrm{d}y_2}, \tag{1}$$

$$\frac{\mathrm{d}\sigma_{jet}}{\mathrm{d}p_T^2 \mathrm{d}y_1 \mathrm{d}y_2} = K \sum_{a,b} x_1 f_a(x_1, p_T^2) x_2 f_b(x_2, p_T^2) \frac{\mathrm{d}\sigma^{ab}(\hat{s}, \hat{t}, \hat{u})}{\mathrm{d}\hat{t}} \tag{2}$$

depends on the parton-parton cross section $\sigma^{ab}$ and parton distribution functions $f_a(x, p_T^2)$ in a parameterized form of experimental data of other high-energy DIS and nucleon-nucleon collisions, where the summation runs over all parton species, $y_1$ and $y_2$ are the rapidities of the scattered partons, $x_1$ and $x_2$ are the light-cone momentum fractions carried by the initial partons, and $K \approx 2$ accounts for the next-to-leading order (NLO) corrections to the leading order jet cross section.

Within the eikonal formalism[8–13, 23], the nucleon-nucleon cross sections can be expressed in the impact-parameter representation as

$$\sigma_{el} = \pi \int_0^\infty \mathrm{d}b^2 \left[1 - e^{\chi(b,s)}\right]^2, \tag{3}$$

$$\sigma_{in} = \pi \int_0^\infty \mathrm{d}b^2 \left[1 - e^{2\chi(b,s)}\right], \tag{4}$$

$$\sigma_{tot} = 2\pi \int_0^\infty \mathrm{d}b^2 \left[1 - e^{\chi(b,s)}\right], \tag{5}$$

in the limit that the real part of the parton-parton scattering amplitude can be neglected. The eikonal functions $\chi(b, s)$ at an impact parameter $b$ is therefore real and can be expressed in term of inclusive jet cross section in pQCD and an effective cross section for the non-perturbative soft parton-parton collisions within the two-component model [1],

$$\begin{aligned} \chi(b, s) &\equiv \chi_s(b, s) + \chi_h(b, s) \\ &= \frac{1}{2} \left[\sigma_{soft} T_{NN}(b) + \sigma_{jet} T_{NN}(b)\right], \end{aligned} \tag{6}$$

where $T_{NN}(b)$ is the nucleon-nucleon overlap function and will be assumed to take the form of the Fourier transformation of a dipole form factor in HIJING.

Within the above eikonal implementation of the two-component model, one can also calculate the nucleon-nucleon cross section [18] for no jet and $j \geq 1$ number of jet production with $p_T > p_0$,

$$\sigma_0 = \pi \int_0^\infty \mathrm{d}b^2 \left[1 - e^{-2\chi_s(b,s)}\right] e^{-2\chi_h(b,s)}, \tag{7}$$

$$\sigma_j = \pi \int_0^\infty \mathrm{d}b^2 \frac{[2\chi_h(b, s)]^j}{j!} e^{-2\chi_h(b,s)}. \tag{8}$$

Their sum gives rise to the total inelastic cross section in Eq.(4). The above eikonal formalism is the base for the Monte Carlo simulation of multiple jet production in $p + p$, $p + A$ and $A + A$ collisions. Both $\sigma_{soft}$ and the transverse momentum cut-off $p_0$ are considered parameters in the HIJING model and are fit to the total and inelastic nucleon-nucleon cross sections and the hadron multiplicity density in the middle rapidity $y = 0$ at each colliding energy.

One can find the detailed description of HIJING model for hadron production in $p+p$, $p+A$ and $A+A$ collisions in Refs. [1]. The main features of HIJING are:

(1) Multiple mini-jet production are simulated according to the above eikonal formalism for each nucleon-nucleon collisions at given impact parameter $b$. The kinematics of each pair of jets and the associated initial and final state radiation are simulated using PYTHIA model[16].

(2) Events without jet production (with $p_T > p_0$) and the underlying soft parton interaction in events with jet production are modeled by excitation of quark-diquark strings with gluon kinks along the lines of the FRITIOF model [24] and the DPM model[14, 25]. In addition, multiple low-$p_T$ exchanges among the end point constituents are included.

(4) A set of impact-parameter-dependent parton distribution functions is used to include nuclear modification of the parton distribution functions inside nuclei.

(5) A simple model for jet quenching is used to study the effect of jet medium interaction in $A + A$ collisions [26].

## III. UPDATES IN HIJING

In the default setting of HIJING 1.0 [1], Duke-Owens parameterization[21] of PDFs in nucleons is used. With Duke-Owens parameterization of PDFs, an energy independent cut-off scale $p_0$ =2 GeV/$c$ and a constant soft parton cross section $\sigma_{soft} = 57$ $mb$ are sufficient to reproduce the experimental data on total and inelastic cross sections and the hadron central rapidity density in $p+p/\bar{p}$ collisions [27]. Duke-Owens parameterization of PDFs is known to be very outdated and one needs to use more modern parameterizations from new global fit to experimental data, especially at the LHC energies when mini-jet production reaches to very small-$x$ region of the parton distribution where gluon distribution is much higher than Duke-Owens parameterization.

Furthermore, with a constant transverse momentum cut-off $p_0 = 2$ GeV/$c$ in HIJING 1.0, the total number of min-jets per unit transverse area could exceed the limit

$$\frac{T_{AA}(b)\sigma_{jet}}{\pi R_A^2} \leq \frac{p_0^2}{\pi} \tag{9}$$

for independent multiple jet production even in central $p+p$ collisions for sufficiently large inclusive jet cross section at high colliding energies, where $T_{AA}(b)$ is the overlap function of $A + A$ collisions and $\pi/p_0^2$ is the intrinsic transverse size of a mini-jet with transverse momentum $p_0$. Therefore, one inevitably has to increase the value of the transverse momentum cut-off $p_0$ to ensure the applicability of the underlying two-component model of independent multiple jet production in the HIJING model.

In the updated version of HIJING 2.0, we will use the Gluck-Reya-Vogt(GRV) parameterization[28] of PDFs, among many modern parameterizations of the PDFs that are available. The gluon distributions in this new parameterization is much higher than the old Duke-Owens parameterization at small $x$ and therefore give much larger inclusive jet cross section at high colliding energies with a fixed value of cut-off $p_0$. One therefore can no longer fit the experimental $p + p/\bar{p}$ data on total and inelastic cross sections using a constant cut-off $p_0$ and the soft parton cross section $\sigma_{soft}$ within the two-component model. One has to assume an energy-dependent cut-off $p_0(\sqrt{s})$ and soft cross section $\sigma_{soft}(\sqrt{s})$ [29]. Fitting the experimental values of the total and inelastic cross sections of $p+p/(\bar{p})$ collisions including those extracted from cosmic experimental and the hadron central rapidity density, we have the following parameterized energy-dependence of the cut-off and the soft parton cross section used in the two-component model of HIJING 2.0:

$$\begin{aligned} p_0 &= 2.62 - 1.084\log(\sqrt{s}) + 0.299\log^2(\sqrt{s}) \\ &\quad -0.0292\log^3(\sqrt{s}) + 0.00151\log^4(\sqrt{s}), \quad (10) \\ \sigma_{soft} &= 55.316 - 4.1126\log(\sqrt{s}) + 0.854\log^2(\sqrt{s}) \\ &\quad -0.0307\log^3(\sqrt{s}) + 0.00328\log^4(\sqrt{s}), \quad (11) \end{aligned}$$

where the colliding energy $\sqrt{s}$ in center-of-mass frame is in units of GeV. Shown in Fig. 1 are the calculated total and inelastic cross sections using both HIJING 1.0 and HIJING 2.0 as compared to the experimental data. The total inclusive jet cross section and non-perturbative soft parton cross sections are also plotted for illustration. With a constant cut-off $p_0 = 2$ GeV/$c$ and soft parton cross section $\sigma_{soft}$ at high colliding energies, HIJING 1.0 already gives larger total cross section than the cosmic data indicate even with the Duke-Owens parameterization of PDFs. With much higher gluon distribution at small $x$ in the GRV parameterization used in HIJING 2.0, one has to introduce a cut-off $p_0$ and the soft parton cross section $\sigma_{soft}$ that increase with colliding energy in order to fit the experimental data on the total cross section. There are, however, some freedom in fixing the values of $p_0$ and $\sigma_{soft}$, which is further constrained by the energy-dependence of the central rapidity density of the charged multiplicities, as shown in Fig. 2. The increasing cut-off as required by the experimental data indicates that multiple mini-jet production below such cut-off are no longer independent and coherent interaction becomes important. This might be taken as an indirect evidence of gluon saturation at very small $x$ inside a proton in proton-proton collisions at very high energies, especially at the LHC energies. An alternative approach to effectively take into account of such gluon saturation is to increase the string tension of soft hadron production as proposed in Ref. [30]. We choose to focus on the change of minijet production in HIJING2.0.

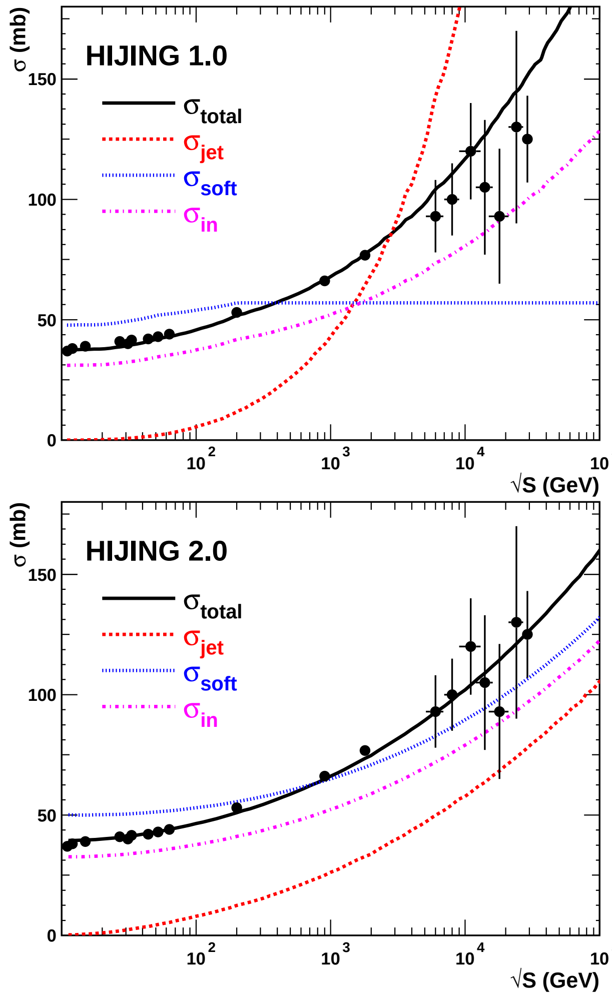


FIG. 1: (color online) Total, soft and jet production cross sections of $pp$ and $p\bar{p}$ collisions. The histogram in left panel are calculated using HIJING 1.0, while the lower using HIJING2.0. The data are from [31–36].

We also show in Fig. 3 the transverse momentum spectra calculated with HIJING 2.0 at different colliding energies as compared to the experimental data. HIJING 2.0 results are all in good agreement with the experimental data.

Note that both HIJING 2.0 calculations and data shown in Fig. 2 are for non-single-diffractive (NSD) events. The definitions of NSD trigger are different in different experiments leading to different central pseudorapidity densities in these NSD events. The NSD triggers in UA5 experiment require at least one charged particle simultaneously in each of the pseudorapidity regions at both ends covering $2 < |\eta| < 5.6$, while Collider-Detector at Fermilab (CDF) NSD events are triggered in $3.2 < |\eta| < 5.9$. The increase of the central pseudorapidity density with energy can be attributed to the increased mini-jet production in high colliding energies.

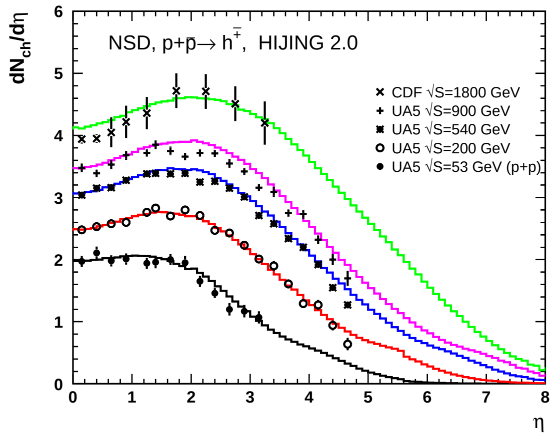


FIG. 2: (color online) Pseudorapidity distributions of charged particles in non-single-diffractive $pp$ at $\sqrt{s} = 53$ GeV, $p\bar{p}$ collisions at $\sqrt{s} = 200,\ 540,\ 900,\ 1800$ GeV as compared to experimental data [37, 38].

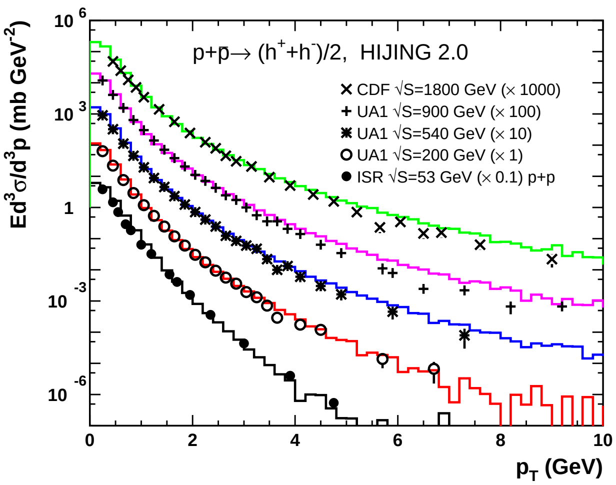


FIG. 3: (color online) Invariant inclusive cross sections of charged particles in $pp$ at $\sqrt{s} = 53$ GeV, $p\bar{p}$ collisions at $\sqrt{s} = 200,\ 500,\ 900,\ 1800$ GeV. The data come from [39–41]. Both the calculation and experimental data are obtained in the region of $|\eta| < 2.5$ for $\sqrt{s} = 200,\ 540,\ 900$ GeV, and $|\eta| < 1.0$ for $\sqrt{s} = 53$ and 1800 GeV.

## IV. HADRON SPECTRA IN $p + p$ AND $A + A$ COLLISIONS AT THE LHC ENERGIES

With the updated HIJING 2.0, we can study hadron production in $p + p$ and $A + A$ collisions at the LHC energies. At the highest energy of $\sqrt{s} = 14$ TeV, mini-jet production involves partons in the very small $x$ region. The increase of the cut-off for independent mini-jet production required to fit the total cross section can be considered as indication of coherence or gluon saturation inside protons at very high energies. This will certainly affect the produced hadron pseudorapidity distribution at the LHC energies. Shown in Fig. 4 is the energy dependence of the central pseudorapidity density of charged hadrons $dN_{\rm ch}/d\eta$ averaged over $|\eta| < 1.0$ as a function of the colliding energy in inelastic $p+p$ collisions from both HIJING1.0 and HIJING 2.0 calculations as compared to experimental data, including that measured in $p + p$ collisions at $\sqrt{s} = 0.9$ TeV and 2.36 TeV from ALICE [45] at the LHC. The central rapidity hadron density in HIJING 2.0 continues to increase with the colliding energy at LHC more or less in a double logarithm form. Because of the larger values of cut-off for mini-jet production, the central rapidity hadron density in HIJING 2.0 is significantly lower than HIJING 1.0 at the LHC energies.

Shown in Fig. 5 and 6 are HIJING results for the pseudorapidity distributions of charged hadrons in $p + p$ at $\sqrt{s} = 0.9$, 2.36 and 7 TeV in inelastic and non-single diffractive (NSD) events. The central rapidity density in NSD events is generally larger than in inelastic events and HIJING results agree with the experimental data reasonably well. Note that CMS [46, 47] experiment uses a different definition of NSD events that gives slightly higher averaged multiplicity than that with UA5 definition of NSD events in HIJING calculations. Another class of inelastic events in ALICE experiments (INEL>0) is defined by requiring at least one charged tracks within $|\eta| < 1$. HIJING results for these type of events (short-dashed lines) are similar to the inelastic events because the lack of double-diffractive events in the Mont Carlo model. Both single diffractive and non-diffractive events in HIJING have finite value of multiplicity in the central rapidity region. This disagrees with the ALICE data [45] which are even larger than the central rapidity density in NSD events. Such discrepancy in trigger dependence of the averaged multiplicity can be fixed when double-diffractive events are included in future improvement of HIJING. However, this is not expected to have a significant influence on particle production in heavy-ion collisions because the fraction of diffractive interactions becomes increasingly smaller in multiple nucleon-nucleon collisions.

Shown in Figs. 7 and 8 are the multiplicity distributions for charged hadrons within different pseudorapidity range in inelastic and NSD $p + p$ collisions at the LHC energies from HIJING calculations as compared to experimental data from ALICE experiment [45]. HIJING results agree reasonably well with the data in low and intermediate multiplicities. However, they fall short of the experimental data at higher multiplicity tails in particular at $\sqrt{s} = 7$ TEV. These high multiplicity events are dominated by multiple jets and they are likely to have final state interaction with each other as indicated by the ridge structure in the two-hadron correlation in azimuthal angle and large rapidity gap observed in CMS experiment [48]. The final state interaction in these high multiplicity events could affect the multiplicity distribution which is not included in current HIJING model.

At high colliding energies, the transverse momentum of produced hadrons should be dominated by hadrons from jet fragmentation, especially at large transverse momentum, as shown in Fig. 9. We compare the HIJING 2.0

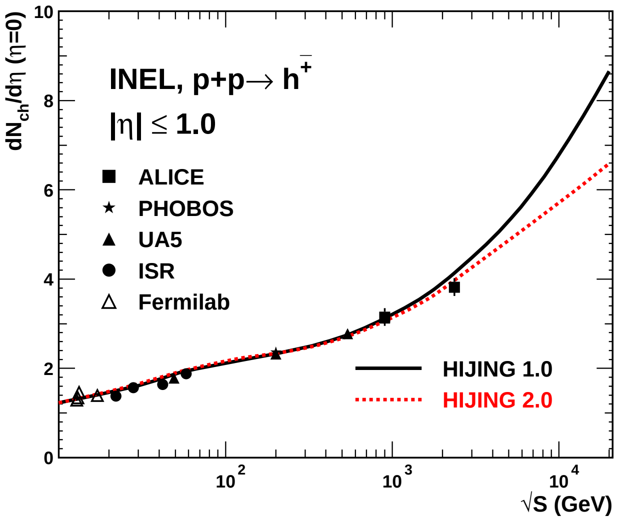


FIG. 4: (color online) Central pseudorapidity density at $\eta = 0$ for charged particles produced in $p + p/\bar{p}$ collisions as a function of $\sqrt{s}$. The experimental data are from [37, 42–45].

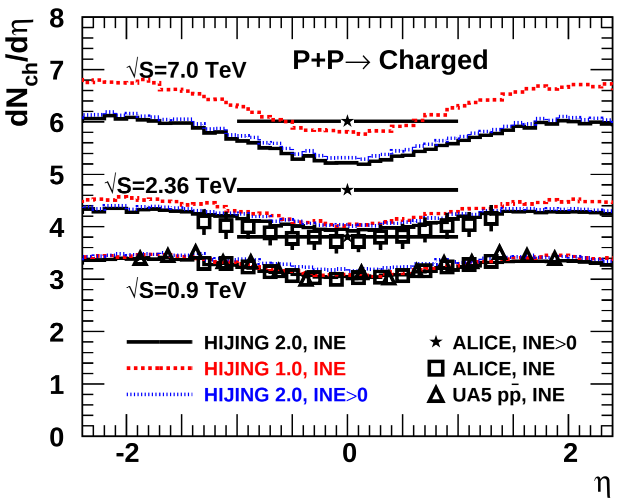


FIG. 5: (color online) Pseudorapidity distribution $dN_{ch}/d\eta$ in inelastic $p + p$ collisions at LHC energies. The experiment data are from UA5[37], ALICE[45] and CMS[46, 47]. Shown in short-dashed lines are the HIJING results for ALICE defined INEL>0 events in which at least one charged tracks are required within $|\eta| < 1$.

results to the ALICE [49] experimental data on charged hadrons within $|\eta| < 0.8$ in inelastic $p + p$ collisions at $\sqrt{s} = 0.9$ TeV and CMS [46, 47] data on charged hadrons within $|\eta| < 2.4$ in NSD $p+p$ collisions at $\sqrt{s} = 0.9$, 2.36 and 7 TeV. The HIJING 2.0 results at $\sqrt{s} = 14$ TeV for inelastic events in $p + p$ collisions are also shown. Within the LHC energy range $\sqrt{s} = 0.9 - 14$ TeV, the transverse momentum spectra at large $p_T$ region becomes apparently harder at higher colliding energies. Even though the cut-off for mini-jet production in HIJING 2.0 is significantly larger than in HIJING 1.0, hadronization from partons as results of initial and final state radiation still fills in the hadron transverse momentum spectra in the intermediate transverse momentum. HIJING 2.0 describes reasonably well the ALICE and CMS experimental data at the LHC energies with the maximum discrepancy of 50% at small $p_T \sim 2$ GeV, as shown in the lower panels in Fig. 9 where the ratios of data over HIJING results are plotted. The transverse momentum spectra in this small $p_T$ region can also be influenced by final-state interaction among jets. We also plot the ratios of charged hadron spectra from NLO pQCD calculation [50, 51] over that from HIJING. HIJING reproduces the NLO pQCD results very well over large $p_T$ range and at different colliding energies.

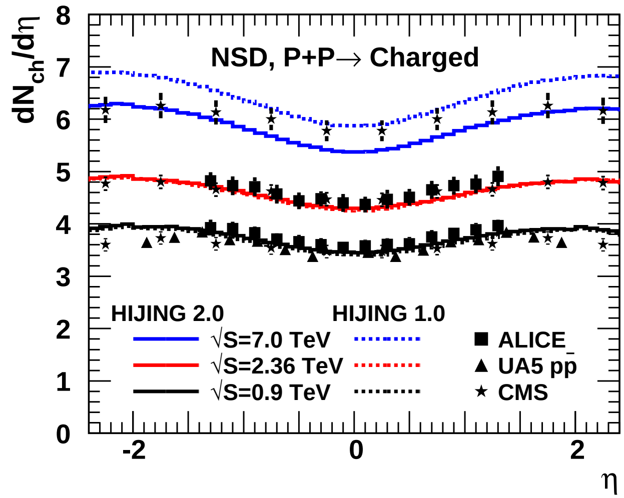


FIG. 6: Pseudorapidity distribution $dN_{ch}/d\eta$ in non-single diffractive (NSD) $p + p$ collisions at LHC energies. The experiment data are from UA5[37], ALICE[45] and CMS[46, 47]. The definitions of NSD events in our calculations and the experimental data from ALICE and UA5 follow that in UA5 experiment as described in the text. CMS [46, 47] uses a different definition.

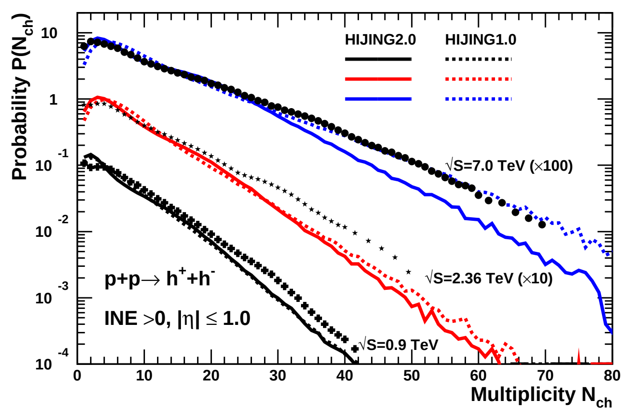


FIG. 7: Multiplicity distributions for changed hadrons within $|\eta| < 1$ in inelastic $p + p$ collisions at LHC energies from ALICE[45] experiment compared to HIJING results.

To describe hadron production in $A + A$ collisions, one should include both the nuclear modification of the par-

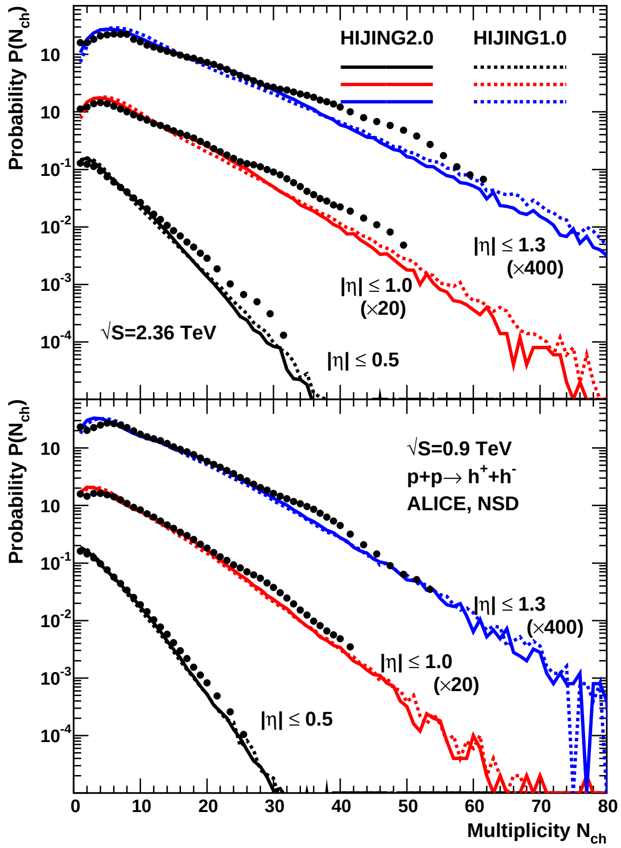


FIG. 8: Multiplicity distributions for charged hadrons within different pseudorapidity intervals in NSD events of $p+p$ collisions at $\sqrt{s} = 2.36$ TeV from ALICE[45] experiment as compared to HIJING results.

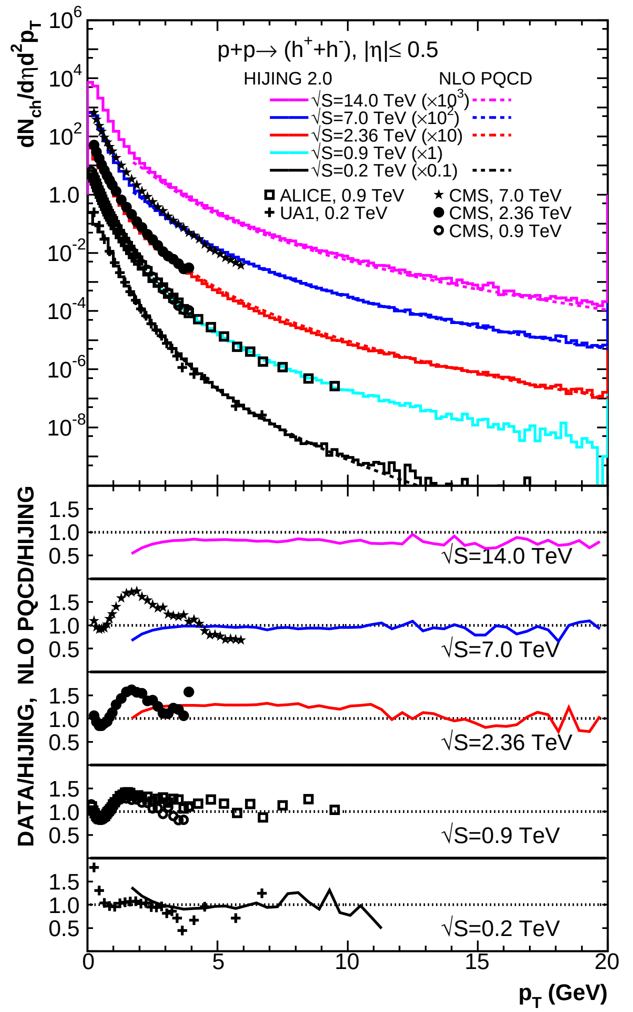


FIG. 9: (color online) Transverse momentum distributions of charged hadron in $p+p$ collisions. The experimental data are from ALICE [49] (open square) for inelastic $p+p$ collisions and CMS[46] (open and closed circle) for NSD $p+p$ collisions at $\sqrt{s} = 0.9$ and 2.36 TeV. The histograms are results from HIJING 2.0.

ton distribution functions and jet quenching in final state interaction. Jet quenching in general suppresses high transverse momentum hadrons [26]. Since the yields of these high transverse momentum partons are relatively small as compared to the bulk part of the initial parton production, its effect on the total hadron multiplicity in $A+A$ collisions will be small as illustrated by other models studies [52–55] of hadron production in heavy-ion collisions at RHIC, most of which have also neglected the effect of final state interaction. With two parameters ($p_0$ and $\sigma_{soft}$) fixed from fit to $p+p$ collisions, the only uncertainty for hadron multiplicity density in $A+A$ collisions is the nuclear modification of parton distribution functions, gluon distributions in particular, at small $x$. We assume parton distributions in nuclei,

$$f_a^A(x,Q^2) = AR_a^A(x,Q^2) f_a^N(x,Q^2), \qquad (12)$$

are given by that in nucleon and the modification factor $R_a^A(x,Q^2)$. This nuclear modification has been studied with data from deeply inelastic scattering (DIS) and Drell-Yan lepton pair production experiments. However, most of parameterizations [56, 57] do not have gluon shadowing strong enough to give the central multiplicity density as measured in RHIC experiments within the two component model as implemented in HIJING model. We will use the HIJING new parameterization [29] which introduced a strong impact-parameter dependence of the parton shadowing in order to fit the centrality dependence of the central multiplicity density at RHIC. The shadowing factor for quarks and gluons are,

$$\begin{aligned} R_q^A(x,b) &= 1.0 + 1.19\log^{1/6}\!A\,(x^3 - 1.2x^2 + 0.21x) \\ &- s_q(b)\,(A^{1/3}-1)^{0.6}(1-3.5\sqrt{x}) \\ &\times \exp(-x^2/0.01), \qquad (13) \\ R_g^A(x,b) &= 1.0 + 1.19\log^{1/6}\!A\,(x^3 - 1.2x^2 + 0.21x) \\ &- s_g(b)\,(A^{1/3}-1)^{0.6}(1-1.5x^{0.35}) \\ &\times \exp(-x^2/0.004), \qquad (14) \end{aligned}$$

respectively. The impact-parameter dependence of the shadowing is implemented through the parameters,

$$s_a(b) = s_a \frac{5}{3}(1 - b^2/R_A^2), \tag{15}$$

where $R_A = 1.12A^{1/3}$ is the nuclear size. The value $s_q = 0.1$ is fixed by the experimental data on DIS off nuclear targets [29] and $s_g = 0.17 - 0.22$ is chosen to fit the RHIC experimental using HIJING 2.0 model as shown in Fig. 10. The form of the impact parameter dependence is chosen to give rise to the centrality dependence of the pesudorapidity multiplicity density per participant pair and the range of values of $s_g$ is allowed by experimental errors at the RHIC energies. With this parameterization of parton shadowing, one can calculate the pesudorapidity multiplicity density per participant pair in $Pb + Pb$ collisions at the LHC energies as a function of the number of participants shown in Fig. 10. As a comparison we also show results from HIJING1.0 as dashed lines in Fig. 10. The range of the gluon shadowing parameter $s_g$ allowed at RHIC leads to much bigger uncertainties in the multiplicity density at the LHC energies. With such strong gluon shadowing constrained by the RHIC data, the effective mini-jet cross section at the LHC energies is still much larger than at RHIC and therefore the minijet component leads to stronger centrality ($N_{part}$) dependence of the central pesudorapidity density of produced hadrons. This strong centrality dependence is very different from other model predictions [58] such as the color glass condensate (CGC) or the limiting fragmentation model. Therefore, the first experimental data on the hadron production at LHC will shed light on the parton/hadron production mechanism in high-energy hadron and nuclear collisions.

To constrain parton shadowing in nucleus, one in principle can also study hadron production in $d+A$ collisions. Shown in the lower panel of Fig. 11 are the pseudorapidity distributions of charged hadrons in $d + Au$ collisions at the RHIC energy $\sqrt{=}$200 GeV for different centralities and minimum-bias events as compared to the STAR data [65]. Within the experimental errors, both HIJING2.0 (solid bands) and HIJING1.0 can describe the data reasonably well. We have followed the definition for the selection of centrality in the STAR measurements. The solid bands in the HIJING2.0 calculation as the variation of the gluon shadowing parameter $s_g$ constrained by RHIC data of $Au + Au$ collisions are too small to be discerned by the $d + Au$ data. Similar situation occurs in $d + Pb$ collisions at the LHC energy as shown in the upper panel of Fig. 11. The change of the pesudorapidity distribution due to variation of the gluon nuclear shadowing parameter is much smaller than in central $Pb+Pb$ collisions shown in Fig. 10. The difference between HIJING2.0 and HIJING1.0 in $d + Pb$ collisions becomes significant only at the highest energy $\sqrt{s} = 5.5$ TeV, reflecting the $p + p$ results in Fig. 4.

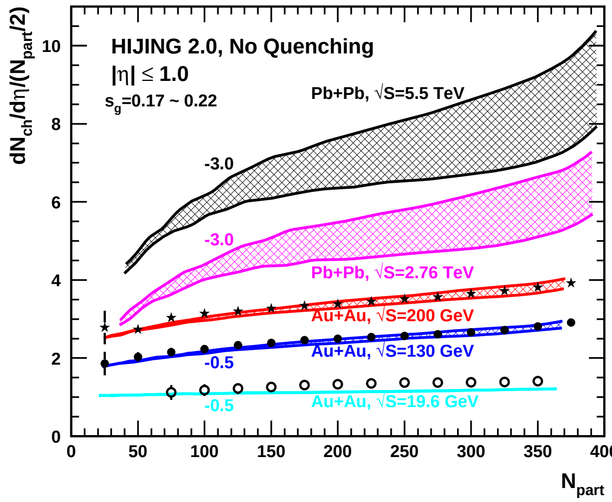


FIG. 10: (color online) Pseudorapidity density per participant pair as a function of the average number of participants in heavy-ion collisions at different energies from HIJING2.0 calculations. Dashed lines are HIJING1.0 results. The experimental data are from Ref. [59]. Note a vertical off-set is applied to each curve for clear illustration.

.

## A. Conclusions

We have updated HIJING Monte Carlo model with modern parton distribution functions for the nucleons and the new set of parameters within the two-component model for mini-jet production in high-energy nucleon-nucleon collisions. Because of the large gluon distribution at small $x$ in the GRV [28] parameterization of the nucleon's PDFs used in HIJING 2.0, one has to introduce an energy-dependent transverse momentum cut-off $p_0$ for the mini-jet production and the soft parton interaction cross section $\sigma_{soft}$ in order to describe the energy-dependence of the total, inelastic cross sections and the central rapidity hadron density in high-energy $p + p(\bar{p})$ collisions. The updated HIJING 2.0 model is shown to describe the existing experimental data on hadron production from ISR energy up to Fermilab Tevatron energy. The HIJING 2.0 results are also shown to be in good agreement with the recently published hadron spectra in $p + p$ collisions at the LHC energies ($\sqrt{s}$=0.9, 2.36 TeV), except for events with INEL¿0 trigger because of the lack of double-diffractive events in the model of soft interaction in HIJING. We also give the HIJING 2.0 predictions for $p + p$ collisions at $\sqrt{s} = 7$ and 14 TeV. With a model parameterization for nuclear modification of the parton distribution functions, we also give HIJING 2.0 prediction of hadron multiplicity in central $Pb + Pb$ and minimum-bias events of $d + Pb$ collisions at the LHC energies $\sqrt{s} = 2.75$ and 5.5 TeV/n.

This is the first step of the upgrade to the HIJING model. Jet quenching description in current HIJING model is very schematic. The next stage of upgrade of HI-

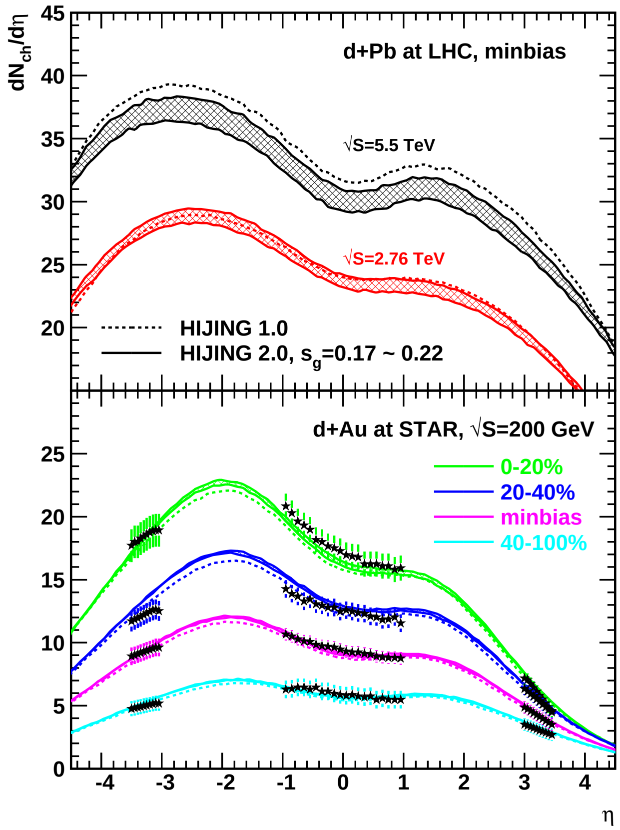


FIG. 11: (color online) Pseudorapidity distributions of charged hadrons in $d+Au$ collisions at the RHIC energy $\sqrt{s}=200$ GeV/n (lower panel) and $d+Pb$ collisions (upper panel) at the LHC energies. The solids lines are HIJING2.0 results with the bands corresponding to the variation of gluon nuclear shadowing parameter $s_g = 0.19-0.24$. Data at the RHIC energy are from STAR experiment [65].

JING will be focused on jet quenching in dense medium incorporating the most recent development [60–64] in the theory of parton propagation and multiple interaction in dense medium.

### Acknowledgement

We thank H. Z. Zhang for providing the NLO pQCD results of transverse momentum spectra. We would like to thank M. Gyulassy for helpful discussions and P. Jacobs and J. Schukraft for discussions about ALICE experimental data. This work was supported in part by the National Natural Science Foundation of China under the project No. 10525523, No. 10825523, MOE of China under Project No. IRT0624, and the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Division of Nuclear Physics, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231. W.-T. Deng was also financially supported by Helmholtz International Center for FAIR within the framework of the LOEWE program launched by the State of Hesse during the completion of this work.

[1] X. N. Wang and M. Gyulassy, Phys. Rev. D **44**, 3501 (1991).
[2] M. Gyulassy and X. N. Wang, Comput. Phys. Commun. **83**, 307 (1994).
[3] X. N. Wang, Phys. Rept. **280**, 287 (1997).
[4] S. E. Vance, M. Gyulassy and X. N. Wang, Phys. Lett. B **443**, 45 (1998).
[5] S. E. Vance and M. Gyulassy, Phys. Rev. Lett. **83**, 1735 (1999).
[6] V. T. Pop, M. Gyulassy, J. Barrette, C. Gale, X. N. Wang and N. Xu, Phys. Rev. C **70**, 064906 (2004).
[7] B. Zhang, C. M. Ko, B. A. Li and Z. w. Lin, Phys. Rev. C **61**, 067901 (2000).
[8] T. K. Gaisser and F. Halzen, Phys. Rev. Lett. **54**, 1754 (1985).
[9] P. L'Heureux, B. Margolis and P. Valin, Phys. Rev. D **32**, 1681 (1985).
[10] G. Pancheri and Y. N. Srivastava, Phys. Lett. B **182** (1986) 199.
[11] L. Durand and P. Hong, Phys. Rev. Lett. **58**, 303 (1987). L. Durand and H. Pi, Phys. Rev. D **38**, 78 (1988).
[12] J. Dias de Deus and J. Kwiecinski, Phys. Lett. B **196**, 537 (1987).
[13] R. C. Hwa, Phys. Rev. D **37**, 1830 (1988).
[14] A. Capella, U. Sukhatme and J. Tran Thanh Van, Z. Phys. C **3**, 329 (1979).
[15] T. K. Gaisser, F. Halzen and A. D. Martin, Phys. Lett. B **166**, 219 (1986).
[16] T. Sjostrand and M. van Zijl, Phys. Rev. D **36**, 2019 (1987). T. Sjostrand, Comput. Phys. Commun. **39**, 347 (1986).
[17] W. R. Chen and R. C. Hwa, Phys. Rev. D **39**, 179 (1989).
[18] X. N. Wang, Phys. Rev. D **43**, 104 (1991).
[19] J. P. Blaizot and A. H. Mueller, Nucl. Phys. B **289**, 847 (1987).
[20] K. Kajantie, P. V. Landshoff and J. Lindfors, Phys. Rev. Lett. **59**, 2527 (1987). K. J. Eskola, K. Kajantie and J. Lindfors, Nucl. Phys. B **323**, 37 (1989).
[21] D. W. Duke and J. F. Owens, Phys. Rev. D **30**, 49 (1984).
[22] E. Eichten, I. Hinchliffe, K. D. Lane and C. Quigg, Rev. Mod. Phys. **56**, 579 (1984) [Addendum-ibid. **58**, 1065 (1986)].
[23] A. Capella and J. Tran Thanh Van, Z. Phys. C **23**, 165 (1984) [Erratum-ibid. C **25**, 102 (1984)].
[24] B. Andersson, G. Gustafson and B. Nilsson-Almqvist, Nucl. Phys. B **281**, 289 (1987). B. Nilsson-Almqvist and E. Stenlund, Comput. Phys. Commun. **43**, 387 (1987).
[25] J. Ranft, Phys. Rev. D **37**, 1842 (1988). J. Ranft, Phys. Lett. B **188**, 379 (1987).
[26] X. N. Wang and M. Gyulassy, Phys. Rev. Lett. **68**, 1480 (1992).
[27] X. N. Wang and M. Gyulassy, Phys. Rev. D **45**, 844 (1992).
[28] M. Gluck, E. Reya and A. Vogt, Z. Phys. C **67**, 433 (1995).
[29] S. Y. Li and X. N. Wang, Phys. Lett. B **527**, 85 (2002) [arXiv:nucl-th/0110075].
[30] V. Topor Pop, M. Gyulassy, J. Barrette, C. Gale, S. Jeon and R. Bellwied, Phys. Rev. C **75**, 014904 (2007).
[31] U. Amaldi and K. R. Schubert, Nucl. Phys. B **166**, 301 (1980).
[32] M. Bozzo *et al.* [UA4 Collaboration], Phys. Lett. B **147**, 392 (1984).
[33] G. J. Alner *et al.* [UA5 Collaboration], Z. Phys. C **32**, 153 (1986).
[34] N. A. Amos *et al.* [E710 Collaboration], Phys. Rev. Lett. **63**, 2784 (1989).
[35] R. M. Baltrusaitis *et al.*, Phys. Rev. Lett. **52**, 1380 (1984).
[36] T. Hara *et al.*, Phys. Rev. Lett. **50**, 2058 (1983). L. Durand and P. Hong, Phys. Rev. Lett. **58**, 303 (1987).
[37] G. J. Alner *et al.* [UA5 Collaboration], Z. Phys. C **33**, 1 (1986).
[38] F. Abe *et al.* [CDF Collaboration], Phys. Rev. D **41**, 2330 (1990).
[39] B. Alper *et al.* [British-Scandinavian Collaboration], Nucl. Phys. B **87**, 19 (1975).
[40] C. Albajar *et al.* [UA1 Collaboration], Nucl. Phys. B **335**, 261 (1990).
[41] F. Abe *et al.* [CDF Collaboration], Phys. Rev. Lett. **61**, 1819 (1988).
[42] W. Thome *et al.* [Aachen-CERN-Heidelberg-Munich Collaboration], Nucl. Phys. B **129**, 365 (1977).
[43] J. Whitmore, Phys. Rept. **10**, 273 (1974). W. M. Morse *et al.*, Phys. Rev. D **15**, 66 (1977). C. P. Ward *et al.*, Nucl. Phys. B **153** (1979) 299.
[44] R. Nouicer *et al.* [PHOBOS Collaboration], J. Phys. G **30**, S1133 (2004).
[45] K. Aamodt *et al.* [ALICE Collaboration], Eur. Phys. J. C **65**, 111 (2010); Eur. Phys. J. C **68**, 345 (2010).
[46] V. Khachatryan *et al.* [CMS Collaboration], JHEP **1002**, 041 (2010).
[47] V. Khachatryan *et al.* [CMS Collaboration], Phys. Rev. Lett. **105**, 022002 (2010).
[48] V. Khachatryan *et al.* [CMS Collaboration], JHEP **1009**, 091 (2010).
[49] K. Aamodt *et al.* [ALICE Collaboration], Phys. Lett. **B** **693**, 53 (2010).
[50] B. W. Harris and J. F. Owens, Phys. Rev. D **65** (2002) 094032.
[51] H. Zhang, J. F. Owens, E. Wang and X. N. Wang, Phys. Rev. Lett. **98**, 212301 (2007).
[52] X. N. Wang and M. Gyulassy, Phys. Rev. Lett. **86**, 3496 (2001).
[53] K. J. Eskola, K. Kajantie and K. Tuominen, Phys. Lett. B **497**, 39 (2001).
[54] Z. W. Lin, S. Pal, C. M. Ko, B. A. Li and B. Zhang, Phys. Rev. C **64**, 011902 (2001).
[55] D. Kharzeev and M. Nardi, Phys. Lett. B **507**, 121 (2001).
[56] K. J. Eskola, V. J. Kolhinen and C. A. Salgado, Eur. Phys. J. C **9**, 61 (1999).
[57] M. Hirai, S. Kumano and M. Miyama, Phys. Rev. D **64**, 034003 (2001).
[58] N. Armesto *et al.*, J. Phys. G **35**, 054001 (2008).
[59] S. S. Adler *et al.* [PHENIX Collaboration], Phys. Rev. C **71**, 034908 (2005) [Erratum-ibid. C **71**, 049901 (2005)].
[60] M. Gyulassy and X. N. Wang, Nucl. Phys. B **420**, 583 (1994).
[61] R. Baier, Y. L. Dokshitzer, A. H. Mueller, S. Peigne and D. Schiff, Nucl. Phys. B **484**, 265 (1997).
[62] U. A. Wiedemann, Nucl. Phys. B **588**, 303 (2000)

[63] M. Gyulassy, P. Levai and I. Vitev, Nucl. Phys. B **594**, 371 (2001)

[64] X. F. Guo and X. N. Wang, Phys. Rev. Lett. **85**, 3591 (2000); X. N. Wang and X. F. Guo, Nucl. Phys. A **696**, 788 (2001).

[65] B. I. Abelev *et al.* [STAR Collaboration], arXiv:nucl-ex/0703016.