Exploring behaviors of partonic matter forming in early stage of \( pp \) and nucleus-nucleus collisions at ultra-relativistic energies

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The parton yield, (pseudo)rapidity distribution, and transverse momentum distribution in partonic matter assumed forming in the early stage of \( pp \) and nucleus-nucleus collisions at RHIC energy \((\sqrt{s_{NN}}=200 \text{ GeV})\) and LHC energy \((\sqrt{s_{NN}}=5.5 \text{ TeV} \text{ for nucleus-nucleus, } 5.5 \text{ and/or } 14 \text{ TeV for } pp)\) are comparatively investigated with parton and hadron cascade model PACIAE. It turned out that the different parton and anti-parton spectra approach to be similar with reaction energy increasing from RHIC to LHC. We have argued that if the partonic matter forming in Au+Au collisions at RHIC energy is strongly interacting quark-gluon plasma, the one forming in Pb+Pb collisions at LHC energy might approach the real (free) quark-gluon plasma.

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The coalescence (recombination) models\(^1,2,3,4,5,6\) have achieved great successes in relativistic heavy-ion collisions. In these models, different to the string fragmentation model, the relevant degrees of freedom are not "free" quarks but massive (dressed) quarks. The gluons are assumed to convert to quark pairs. It is always as-

The coalescence (recombination) models require the knowledge of parton \( p_T \) and/or \( \eta \) distributions as inputs\(^7\). Similarly, the perturbative quantum chromo-dynamics (pQCD) calculations\(^8,9\) for hadron production in the relativistic elementary and/or nuclear collisions need the intrinsic transverse momentum distribution of parton in the nucleon as well.

Based on the further assumption of different quark and antiquark have same spectrum, coalescence (recombination) models predicted that the elliptic flow parameter \( v_2 \) follows a quark-number \((n_q)\) scaling in \( v_2(p_T/n_q) \) vs. \( p_T/n_q \) for most final state hadrons in the intermediate \( p_T \) region\(^6,7,10,11\). Later, this quark-number scaling prediction has been proved experimentally\(^12,13\). This \( v_2 \) quark-number scaling observation relates the spectrum of final state hadron to the spectrum of initial state parton directly.

Recently, the concept of effective constituent quark has been introduced to connect with the quark coalescence (recombination) picture\(^13,14\). They assume that the hadron's \( p_T \) is composed of its effective constituent quark's \( p_T/n \) \((n \text{ is the number of effective constituent quarks in hadron})\) and the different quark and anti-quark have same \( p_T \) distribution. Then they extracted the \( p_T \) distribution of effective \( u \) (\( d \)) and \( s \) quarks from the ratio of \( \Xi(p_T/3)/\phi(p_T/2) \) and \( \Omega(p_T/3)/\phi(p_T/2) \), respectively, in Au+Au collisions at \( \sqrt{s_{NN}}=200 \text{ GeV} \).

As mentioned in\(^15\) recently that, "... there has been an effort to fully reconstructed jets in heavy-ion collisions in order to provide a direct measurement of the partonic kinematics, independently of the fragmentation process (quenched or unquenched)." In fact, experimentally extracting the partonic observables from final state hadrons with reconstruction method have already become interesting\(^16,17\). So it is important to investigate the properties \((\text{yield, } p_T \text{ distribution, and } \eta \text{ distribution})\) and explore their different behaviors in \( pp \) and nucleus-nucleus collisions at RHIC energy \((\sqrt{s_{NN}}=200 \text{ GeV})\) and LHC energy \((\sqrt{s_{NN}}=5.5 \text{ TeV} \text{ for nucleus-nucleus, } 5.5 \text{ and/or } 14 \text{ TeV for } pp)\) theoretically. These studies might shed light on the way toward QGP.

In this paper the parton and hadron cascade model, PACIAE\(^18\), is used to investigate systematically the yield, (pseudo)rapidity distribution, and transverse momentum distribution of partons and anti-partons in the partonic matter assumed forming in the early stage of \( pp \) and nucleus-nucleus collisions at RHIC and LHC energies. The discrimination, in the yields, \( \eta \) distributions, and \( p_T \) distributions, between different parton and anti-parton, RHIC and LHC energies, as well as \( pp \) and nucleus-nucleus collisions is discussed. We have turned out that the different parton and anti-parton spectra approach to be similar with reaction energy increasing from RHIC to LHC. It is argued that if the partonic matter forming in the early stage of Au+Au collisions at RHIC energy is a strongly interacting QGP (sQGP)\(^19,20,21,22\), the one forming in Pb+Pb collisions at LHC energy might approach to the real (free) QGP (fQGP).

PACIAE is a parton and hadron cascade model\(^18\) based on PYTHIA\(^23\). PYTHIA is a model for hadron-hadron collisions. The PACIAE model is composed of four stages of the parton initialization, parton evolu-

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A nucleon-nucleon ($NN$) collision in the PYTHIA (PACIAE) model is decomposed into parton-parton collisions. The hard and soft parton-parton collisions are described, respectively, by the lowest-leading-order (LO) pQCD parton-parton cross section \[24\] and an empirical method. The semihard (between hard and soft) QCD $2 \rightarrow 2$ processes are involved as well. Because the initial- and final-state QCD radiation are considered, the PYTHIA (PACIAE) model generates a multijet event for a $NN$ collision. This is followed by Lund and/or Independent Fragmentation model in the PYTHIA model, so one obtains a hadronic state for a $NN$ (hadron-hadron, $hh$) collision. Since above fragmentation is switched-off in the PACIAE model, so one obtains a multijet event (composed of quarks, anti-quarks, and gluons) instead.

A nucleus-nucleus collision in the PACIAE model is decomposed into $NN$ collisions according to the collision geometry. The nucleons in a colliding nucleus are arranged randomly in coordinate space according to the Woods-Saxon distribution (for radius $r$) and $4\pi$ isotropic distribution (orientation). We assume $p_x = p_y = 0$ and $p_z$ equals the beam momentum for every colliding nucleon. Assuming straight line trajectory for nucleons we can calculate the collision time for each $NN$ collision pair provided that the closest approaching distance between two colliding nucleons is less than or equal to $\sqrt{\sigma_{tot}^N/\pi}$ ($\sigma_{tot}^N$ refers to the total cross section of $NN$ collision). If every $NN$ collision is performed with the method in previous paragraph until the collision pair is exhausted, we obtain a initial partonic state for a nucleus-nucleus collision.

TABLE I: Composition of the partonic matter forming in $pp$ and 0-5% most central nucleus-nucleus collisions at RHIC and LHC energies.

| Energy (GeV) | $pp$ | Au+Au | Pb+Pb |
|-------------|------|-------|-------|
|             | 200  | 14000 | 200   | 5500 |
| $d$         | 2.09 | 5.25  | 330   | 244  |
| $\bar{d}$  | 0.237| 3.47  | 27.3  | 112  |
| $u$         | 3.98 | 7.08  | 294   | 226  |
| $\bar{u}$  | 0.234| 3.47  | 27.5  | 112  |
| $s$         | 0.123| 1.19  | 13.5  | 39.6 |
| $\bar{s}$  | 0.106| 1.17  | 12.7  | 39.5 |
| $g$         | 4.82 | 39.8  | 516   | 1351 |

In the parton evolution (partonic rescattering) stage the $2 \rightarrow 2$ LO-pQCD differential cross sections \[24\] are employed. For a subprocess $ij \rightarrow kl$ the differential cross section reads

$$\frac{d\sigma_{ij\rightarrow kl}}{dt} = K \frac{\alpha_s^2}{\hat{s}} \sum_{ij\rightarrow kl},$$

(1)

where the $K$ factor is introduced for the higher order corrections and the nonperturbative correction as usual. Take the process $q_1 q_2 \rightarrow q_1 q_2$ as an example one has

$$\sum_{q_1 q_2 \rightarrow q_1 q_2} = \frac{4 \hat{s}^2 + \hat{u}^2}{9 t^2}. \quad (2)$$

It can be regularized as

$$\sum_{q_1 q_2 \rightarrow q_1 q_2} = \frac{4 \hat{s}^2 + \hat{u}^2}{9 (t - \mu^2)^2}. \quad (3)$$

by introducing the parton colour screen mass, $\mu=0.63$ GeV. In above equation $\hat{s}$, $\hat{t}$, and $\hat{u}$ refer to the Mandelstam variables and $\alpha_s = 0.47$ stands for the running coupling constant. The total cross section of the parton collision $i + j$ is then

$$\sigma_{ij}(\hat{s}) = \int_{-\hat{s}}^{\hat{s}} dt \frac{d\sigma_{ij\rightarrow kl}}{dt}. \quad (4)$$

With the total and differential cross sections above the parton evolution (rescattering) can be simulated by the Monte Carlo method until the parton-parton collision is ceased (partonic freeze-out).

The hadronization follows parton evolution. In the PACIAE model partons can be hadronized by the string fragmentation scheme or the coalescence picture. As all the simulations are ended after parton rescattering in this paper, we do not describe the hadronization in detail but refer to Ref. \[13\].

After hadronization we obtain a hadron list composed of the spatial and momentum coordinates of all hadrons for a nucleus-nucleus collision. Similar to the parton rescattering above, one calculates the collision time for
each \( hh \) collision pair. Then each \( hh \) collision is performed with usual two-body collision method [25] until the collision pairs are exhausted (hadronic freeze-out).

As we aim at the physics rather than reproducing the experimental data, so in the calculations default values given in the PYTHIA model are adopted for model parameters except \( K=3 \) is assumed. The simulations are all ended at parton evolution (rescattering) stage.

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The transport model results in this paper support above three conjectures.

In Tab. 1 we give the parton chemical composition of partonic matter assumed forming in the early stage of \( pp \) and nucleus-nucleus collisions at RHIC and LHC energies. One sees in this table that:

- Assuming the sum of yields in each column is the total yield of partons in the corresponding reaction. The fraction of gluons in total yield is about 0.420 and 0.422 in \( pp \) and \( Au+Au \) collisions at RHIC energy while those are about 0.648 and 0.636 in \( pp \) and \( Pb+Pb \) collisions at LHC energy. Similarly the momentum fraction carried by gluons in total momentum is about 0.165 and 0.179 in \( pp \) and \( Au+Au \) collisions at RHIC energy while those are about 0.420 and 0.415 in \( pp \) and \( Pb+Pb \) collisions at LHC energy. These results indicate that the QGM forming in the early stage of \( Pb+Pb \) collisions at LHC energy is closer to fQGP than in \( Au+Au \) collisions at RHIC energy.

- In both \( pp \) and nucleus-nucleus collisions the yield of \( d, \bar{d}, s, \bar{s}, \) and \( g \) increases with reaction energy increasing from RHIC to LHC much stronger than \( d \) and \( u \). As the yield of \( d, \bar{d}, s, \bar{s}, \) and \( g \) in \( Pb+Pb \) collision at LHC energy is a few times larger than the corresponding one in \( Au+Au \) collision at RHIC energy, the yield of \( d \) and \( u \) in \( Pb+Pb \) collision is even somewhat less than that in \( Au+Au \) collision in order to meet with the above three conjectures.

- \( d \) and \( u \) yields are about a magnitude larger than \( d \) and \( \bar{u} \), respectively, in \( pp \) and \( Au+Au \) collisions at RHIC energy. But that yield difference drops to two dramatically in \( pp \) and \( Pb+Pb \) collisions at LHC energy. This is consistent with the conjecture of the ratio of anti-parton to parton approaches one in fQGP.

In Fig. 4 we give the pseudorapidity distributions of partons and anti-partons in \( pp \) collisions at \( \sqrt{s}=14000 \) and 200 GeV. One sees in panels (a) and (b) that the fragmentation peaks survive and midrapidity valley appears in the \( \eta \) distribution of \( d \) and \( u \) quarks in \( pp \) collisions at RHIC energy. But the fragmentation peaks approach to disappear and midrapidity valley fills up with energy increasing from RHIC to LHC. However the fragmentation peaks and midrapidity valley are not shown in the \( \eta \) distribution of \( d \) and \( \bar{u} \) quarks. The \( \eta \) distribution
of $u$ quark is higher (RHIC energy) or wider (LHC energy) than $d$ quark because proton is composed of $uud$. However the $\eta$ distribution of $\bar{d}$ quark is nearly the same as $\bar{d}$ in $pp$ collisions at both RHIC and LHC energies.

Globally speaking, we know from Fig. 1 that the $\eta$ distributions of partons and anti-partons in $pp$ collisions at LHC energy is more similar with each other than $pp$ collisions of (a) and (b).

The transverse momentum distributions of partons and anti-partons in $pp$ collisions at LHC energy might approach $fQGP$. If QGM is not possible forming in the early stage of $Au+Au$ collisions at RHIC energy, it might be possible at LHC energy. Therefore if the partonic matter forming in the early stage of $Au+Au$ collisions at RHIC energy is $sQGP$ the one forming in $Pb+Pb$ collisions at LHC energy might move forward to $fQGP$.

In Fig. 3 we compare the different parton and anti-parton $p_T$ distributions approach similar with reaction energy increasing from RHIC to LHC. So one can not rule out the possibility of QGM forming in $pp$ collisions at LHC or higher energy.

The transverse momentum distribution of $d$ ($u$) quark is different from $\bar{d}$ ($\bar{u}$), while the $p_T$ distribution of $s$ and $\bar{s}$ is nearly the same in $pp$ collisions at RHIC energy.

In $pp$ collisions at LHC energy the $p_T$ distribution of $d$ ($u$) is the same as $\bar{d}$ ($\bar{u}$) in the $p_T \geq 2$ GeV/c region. But $s$ and $\bar{s}$ have the same $p_T$ distribution completely.

The slope parameter (apparent temperature) in the $p_T$ distribution of different parton and anti-parton in $pp$ collisions at RHIC energy is larger (lower) than the corresponding one in $pp$ collisions at LHC energy.

These results indicate again that the different parton and anti-parton $p_T$ distributions approach similar with reaction energy increasing from RHIC to LHC. So one can not rule out the possibility of QGM forming in $pp$ collisions at LHC or higher energy.

In Fig. 4 we compare the different parton and anti-parton $\eta$ distributions in $pp$ collisions at $\sqrt{s_{NN}}=5500$ and 200 GeV with the corresponding ones in $Pb+Pb$ and $Au+Au$ collisions at the same cms energy, respectively. A scaling factor is introduced for $pp$ collisions at

FIG. 3: The same as Fig. 1 but for 0-5% most central $Pb+Pb$ and $Au+Au$ collisions at $\sqrt{s_{NN}}=5500$ and 200 GeV instead of $pp$ collisions. The dashed curve has scaled by 2.5 in panels (a) and (b).

FIG. 4: The same as Fig. 2 but for 0-5% most central $Pb+Pb$ and $Au+Au$ collisions at $\sqrt{s_{NN}}=5500$ and 200 GeV instead of $pp$ collisions.
The panel (a), (b), (c), (d), (e), (f), and (g) is, respectively, and the solid and dashed curves for the Pb+Pb and Au+Au collisions, pp collisions. A scaling factor is introduced for the detail.

![Graph](image)

FIG. 5: Comparing pseudorapidity distributions among pp collisions at \( \sqrt{s} = 5500 \) and 200 GeV and 0-5% most central Pb+Pb and Au+Au collisions at \( \sqrt{s_{NN}} = 5500 \) and 200 GeV. The panel (a), (b), (c), (d), (e), (f), and (g) is, respectively, for \( d, d, u, \bar{u}, s, \bar{s}, \) and \( g \). In any of these panels the solid and open circles are for the Pb+Pb and Au+Au collisions, respectively, and the solid and dashed curves for the pp collisions. A scaling factor is introduced for pp collisions, see text for the detail.

![Graph](image)

FIG. 6: The same as Fig. 5 but for transverse momentum distributions and no scaling factor is introduced.

\( \sqrt{s} = 5500 \) and 200 GeV. That is 100 and 100 in panel (a), 30 and 150 in (b), 50 and 50 in (c), 30 and 150 in (d), 30 and 150 in (e), 30 and 150 in (f), and 30 and 100 in (g). We see in Fig. 5 that, in globally speaking the shapes of parton and anti-parton \( \eta \) distributions in pp collisions are similar to the corresponding ones in nucleus-nucleus collisions at the same cms energy. That is because in the PACIAE model the nucleus-nucleus collision is decomposed into \( NN \) collisions and the \( NN \) collision decomposes further into parton-parton collisions. Meanwhile, we consider only 2 → 2 parton-parton scattering processes and among these processes the elastic scattering is dominant.

Similarly, one compares the different parton and anti-parton \( p_T \) distributions in pp collisions at \( \sqrt{s} = 5500 \) and 200 GeV with the ones in Pb+Pb and Au+Au collisions at \( \sqrt{s_{NN}} = 5500 \) and 200 GeV in Fig. 6 respectively. However, in Fig. 6 we do not introduce any scaling factor. The same conclusion about the similarity discussed in the last paragraph may emerge if one examines the shapes of parton and anti-parton \( p_T \) distributions in Fig. 6. Meanwhile, one sees in Fig. 6 that the discrepancy in slope parameter (apparent temperature) between pp and nucleus-nucleus collisions at the same cms energy decreases with cms energy increasing.

In summary, we have used a parton and hadron cascade model, PACIAE, to investigate systematically the yield, (pseudo)rapidity distribution, and transverse momentum distribution of partons and anti-partons in partonic matter assumed forming in the early stage of pp and nucleus-nucleus collisions at RHIC and LHC energies. The discrimination, in the yields, \( \eta \) distributions, and \( p_T \) distributions, between different parton and anti-parton, RHIC and LHC energies, as well as pp and nucleus-nucleus collisions is discussed. We have turned out that the different parton and anti-parton approach to have similar spectrum with reaction energy increasing from RHIC to LHC. This is consistent with the fact of the (dressed) mass effect decreases with momentum (reaction energy/temperature) increasing. This result seems not supporting the assumption of different quark and anti-quark have the same \( p_T \) distribution at RHIC energy. We have also argued that if the partonic matter forming in the early stage of Au+Au collisions at RHIC energy is sQGP, the one forming in the Pb+Pb collisions at LHC energy might approach fQGP.

The transport model results of this paper seem to support that the fQGP may properly have following physical features:

- Gluons carry more than half fraction in total momentum (energy).
- Ratio of anti-parton to parton approaches one.
- Flavor balance, such as
  \[
  u : d : s : c... \approx 1 : 1 : \gamma_s : \gamma_c...,
  \]
  and
  \[
  \bar{u} : \bar{d} : \bar{s} \bar{s}... \approx 1 : 1 : \gamma_s...,
  \]
  \((\gamma_s \geq 0.3 \text{ and } \gamma_c \geq 10^{-11} \text{ for instance})\) is expected.

These physical features might shed light on the searching for fQGP.

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