Physics Letters B 731 (2014) 87–91

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

# Systematic study of elliptic flow parameter in the relativistic nuclear collisions at RHIC and LHC energies

Ben-Hao Sa [a,*], Dai-Mei Zhou [b], Yu-Liang Yan [a], Yun Cheng [b], Bao-Guo Dong [a], Xu Cai [b]

[a] China Institute of Atomic Energy, P.O. Box 275 (10), Beijing 102413, China
[b] Key Laboratory of Quark and Lepton Physics (MOE) and Institute of Particle Physics, Central China Normal University, Wuhan 430079, China

ARTICLE INFO

*Article history:*
Received 24 October 2013
Received in revised form 30 December 2013
Accepted 10 February 2014
Available online 15 February 2014
Editor: J.-P. Blaizot

ABSTRACT

We employed the new issue of a parton and hadron cascade model PACIAE 2.1 to systematically investigate the charged particle elliptic flow parameter $v_2$ in the relativistic nuclear collisions at RHIC and LHC energies. With randomly sampling the transverse momentum $x$ and $y$ components of the particles generated in string fragmentation on the circumference of an ellipse instead of circle as originally, the calculated charged particles $v_2(\eta)$ and $v_2(p_T)$ fairly reproduce the corresponding experimental data in the Au+Au/Pb+Pb collisions at $\sqrt{s_{NN}} = 0.2/2.76$ TeV. In addition, the charged particles $v_2(\eta)$ and $v_2(p_T)$ in the p+p collisions at $\sqrt{s} = 7$ TeV as well as in the p+Au/p+Pb collisions at $\sqrt{s_{NN}} = 0.2/5.02$ TeV are predicted.

## 1. Introduction

To explore the phase transition from the hadronic matter (HM) to quark–gluon matter (QGM) is one of the fundamental aims of relativistic nuclear collisions. A couple years ago, four international collaborations of BRAHMS, PHOBOS, STAR, and PHENIX at RHIC have published white papers [1–4] to declare their evidences for the discovery of strongly coupled quark–gluon plasma (sQGP). One of the most important signals is the large elliptic flow parameter of produced particles in the Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV.

The measurement of particle elliptic flow parameter $v_2$ is not trivial. Several methods have been proposed, such as the event plane method [5], Lee–Yang zero point method [6], the cumulant method [7], etc. The cumulant method is even distinguished with two-, four-, and six-particle cumulants. The discrepancy among the $v_2$ values measured with the event plane method, Lee–Yang zero point method, and the cumulant method may reach a few of tens percent as shown in Figs. 4 and 5 of [8] and Fig. 11 of [9]. Recently, one even argued that the event plane method is obsolete [10].

On the other hand, the particle elliptic flow parameter $v_2$ is also not easy to investigate theoretically. The conventional (hadronic) transport (cascade) models always underestimated the $v_2$ experimental data in the nucleus–nucleus collisions at RHIC and/or LHC energies. In [11] it was mentioned that the charged particle $v_2$ experimental data is around 0.05 in the Au+Au collisions at highest RHIC energy (estimated from $v_2(\eta)$ in [12]), while the UrQMD model provides only half of this value. They have pointed out that a lack of pressure in the model at this energy may be the reason and that the partonic rescattering has to be taken into account in order to describe the data.

Similarly, the default AMPT model (AMPT_*def*) also underestimated the $v_2$ experimental data in the nucleus–nucleus collisions at RHIC energies [13]. In order to meet with experimental data they updated AMPT_*def* to the AMPT_*sm* with string melting. In the AMPT_*sm* model the hadrons (strings) from HIJING [14] are all melted to the partons. Relying on the rescattering among huge number of partons AMPT_*sm* is able to account for the $v_2$ experimental data, provided the parton–parton cross section is enlarged to ten mb. Of course, the AMPT_*sm* model has to hadronize the partons after rescattering by the coalescence model rather than the string fragmentation in AMPT_*def*.

In the non-center nucleus–nucleus collisions the geometric overlap zone leads to the initial particle spatial asymmetry distribution. It is then dynamically developed to the final hadronic state transverse momentum asymmetry due to the partonic rescattering [11] and the strong electromagnetic field [15], etc. We have pointed out that the transverse momentum $p'_x$ and $p'_y$ of produced particle from string fragmentation are randomly arranged on a circle with radius of $p'_T$ in the PACIAE 2.0 model [16] (in the PYTHIA model [17] originally). Here the observable with superscript ($'$) refers to the string fragmentation local frame distinguished from the without superscript one referred to the nucleus–nucleus cms frame. This symmetric arrangement strongly cancels the final hadronic state transverse momentum asymmetry developed from the initial spatial asymmetry. In the new issue of a PACIAE model

---

* Corresponding author.
*E-mail address:* sabh@ciae.ac.cn (B.-H. Sa).

http://dx.doi.org/10.1016/j.physletb.2014.02.019

(PACIAE 2.1 [18]) we randomly distribute the $p'_x$ and $p'_y$ of produced particle from the string fragmentation on the circumference of an ellipse instead of circle. PACIAE 2.1 is then able to describe the $v_2$ experimental data.

In the next section, Section 2, a parton and hadron cascade model PACIAE, its new issue of PACIAE 2.1, and the definition of elliptic flow parameter are briefly introduced. The calculated charged particle $v_2(\eta)$ and $v_2(p_T)$ are compared with the corresponding experimental data of the Au+Au/Pb+Pb collisions at $\sqrt{s_{NN}} = 0.2/2.76$ TeV in Section 3. Additionally, the predictions for charged particles $v_2(\eta)$ and $v_2(p_T)$ in the p+p collisions at $\sqrt{s} = 7$ TeV and in the p+Au/p+Pb collisions at $\sqrt{s_{NN}} = 0.2/5.02$ TeV are given in the Section 3. The last section is devoted to the conclusions.

## 2. Models

The PACIAE model is based on PYTHIA [17]. However, the PYTHIA model is for high energy hadron–hadron (hh) collisions but the PACIAE model is mainly for nucleus–nucleus collisions. In the PYTHIA model a hh collision is decomposed into parton–parton collisions. The hard parton–parton collision is described by the lowest leading order perturbative QCD (LO-pQCD) parton–parton interactions with the modification of parton distribution function in a hadron. The soft parton–parton collision, a non-perturbative process, is considered empirically. The initial- and final-state QCD radiations and the multiparton interactions are also taken into account. So the consequence of a hh collision is a partonic multijet state composed of the diquarks (anti-diquarks), quarks (antiquarks), and the gluons, besides a few hadronic remnants. It is followed by the string construction and fragmentation, thus a final hadronic state is obtained for a hh (pp) collision eventually.

In the PACIAE model [16], the nucleons in a nucleus–nucleus collision are first randomly distributed in the spatial phase space according to the Woods–Saxon distribution. The participant nucleons, resulted from Glauber model calculation, are required to be inside the overlap zone, formed when two colliding nuclei path through each other at a given impact parameter. The spectator nucleons are required to be outside the overlap zone but inside the nucleus–nucleus collision system. Then we decompose a nucleus–nucleus collision into nucleon–nucleon (NN) collisions according to nucleon straight-line trajectories and the NN total cross section. Each NN collision is then dealt by PYTHIA with the string fragmentation switched-off and the diquarks (anti-diquarks) broken into quark pairs (anti-quark pairs). A partonic initial state (composed of the quarks, antiquarks, and the gluons) is obtained for a nucleus–nucleus collision after all of the NN collision pairs were exhausted. This partonic initial stage is followed by a parton evolution stage, where parton rescattering is performed by the Monte Carlo method with $2 \to 2$ LO-pQCD cross sections [19]. The hadronization stage follows the parton evolution stage. The Lund string fragmentation model and a phenomenological coalescence model are provided for the hadronization. However, the string fragmentation model is selected in this calculations. Then the rescattering among produced hadrons is dealt with the usual two body collision model [16]. In this hadronic evolution stage, only the rescatterings among $\pi$, K, p, n, $\rho(\omega)$, $\Delta$, $\Lambda$, $\Sigma$, $\Xi$, $\Omega$, and their antiparticles are considered for simplicity.

The PACIAE 2.0 model [16] is mainly different from AMPT_*sm* as follows:

1. The partonic initial state is obtained by breaking the strings from PYTHIA in PACIAE 2.0, but by breaking hadrons from HIJING in AMPT_*sm*.
2. The $gg \to gg$ elastic scattering cross section is utilized in the parton rescattering in AMPT_*sm* but specific scattering cross section is used for individual $qq$ $(gg)$ scattering processes in PACIAE 2.0.
3. In the AMPT_*sm* model the partons after rescattering are hadronized by the coalescent model but by string fragmentation in the present PACIAE calculations.

Because of the first difference, the number of initial partons in PACIAE 2.0 is much less than the one in AMPT_*sm*. Hence the strength of partonic rescattering effect in the former is not as strong as that in the later. Therefore relying on partonic rescattering only the PACIAE model is hard to describe $v_2$ experimental data, unlike AMPT_*sm*. The rearrangement for the transverse momentum $x$ and $y$ components of the particles from string fragmentation, mentioned above, is then required.

The spatial overlap zone formed in non-center nucleus–nucleus collision is almond-like, which is always assumed to be an ellipse with a half-minor axis of $a_r = R_A(1-\delta_r)$ along the $x$ axis (axis of impact parameter) and a half-major axis of $b_r = R_A(1+\delta_r)$ along the $y$ axis (here $R_A$ refers to the radius of nucleus provided a symmetry nucleus–nucleus collisions is considered). Originally this initial spatial asymmetry may develop dynamically into a final hadronic state momentum asymmetry due to the parton rescattering and the strong electromagnetic field, etc. Unfortunately, in the PYTHIA (PACIAE 2.0) model once the transverse momentum $p'_T$ of the produced particle from string fragmentation is randomly sampled according to the exponential and/or Gaussian distribution, its $p'_x$ and $p'_y$ components are randomly arranged on a circle with radius of $p'_T$, i.e.

$$p'_x = p'_T \cos(\phi'), \qquad p'_y = p'_T \sin(\phi'), \tag{1}$$

where $\phi'$ refers to the azimuthal angle of particle transverse momentum. This symmetry arrangement strongly cancels the final hadronic state transverse momentum asymmetry developed dynamically from the initial spatial asymmetry. As a prescription to minimize this cancellation, in PACIAE 2.1 [18] we randomly distributed $p'_x$ and $p'_y$ on the circumference of an ellipse with half-major and minor axes of $p'_T(1+\delta_p)$ and $p'_T(1-\delta_p)$, respectively, instead of circle. I.e.

$$p'_x = p'_T(1+\delta_p)\cos(\phi'), \qquad p'_y = p'_T(1-\delta_p)\sin(\phi'). \tag{2}$$

We know from ideal hydrodynamic calculation [20] that the integrated elliptic flow parameter of final hadronic state is approximately proportional to the initial spatial eccentricity of nuclear overlap zone. Therefore we assume that the introduced deformation parameter of $\delta_p$ here can be related to the deformation parameter of $\delta_r$ in the initial spatial phase space, i.e.

$$\delta_p = C\delta_r \tag{3}$$

where $C$ is an extra model parameter instead of $\delta_p$. We also know that the spatial eccentricity of nucleon distribution in the initial overlap zone, reaction plane eccentricity for instance [21], can be expressed as

$$\begin{aligned} \epsilon_{rp} &= \frac{\sigma_y^2 - \sigma_x^2}{\sigma_y^2 + \sigma_x^2}, \\ \sigma_x^2 &= \langle x^2 \rangle - \langle x \rangle^2, \\ \sigma_y^2 &= \langle y^2 \rangle - \langle y \rangle^2, \end{aligned} \tag{4}$$

where $\langle \cdots \rangle$ denotes the average over the nucleon spatial distribution. This spatial eccentricity should be identical with the geometrical eccentricity [22]