The “Little Bang” at RHIC and at the LHC

Raimond Snellings
Utrecht University, Princetonplein 5, 3584 CC Utrecht, The Netherlands
E-mail: R.J.M.Snellings@uu.nl

Abstract. One of the fundamental questions in the field of subatomic physics is what happens to matter when densities and temperatures are reached which prevailed in the first microseconds after the Big Bang and which might still prevail in the core of dense neutron stars. At these temperatures and densities, matter is predicted to be in a novel state were quark and gluon degrees of freedom propagate over large distances, in contrast to ordinary matter where the quark and gluons are confined inside hadrons. The aim of heavy-ion physics is to create such a state of matter in the laboratory by colliding heavy nuclei at relativistic energies. At the Large Hadron Collider (LHC) at CERN, lead on lead collisions have recently become available with unprecedented collision energies of 2.76 TeV per nucleon pair. In these proceedings we will discuss how the first anisotropic flow measurements at the LHC contribute to our current understanding of this state of matter.

1. Introduction
To our current understanding, the universe went through a series of phase transitions that mark the most important epochs of the expanding universe after the Big Bang. At about $10^{-5}$ s and at a temperature of about $10^{12}$ K (nearly a hundred thousand times hotter than the core of our Sun), the strong phase transition took place, where the quarks and gluons in the quark gluon plasma became confined into hadrons and where the approximate chiral symmetry was spontaneously broken. These phenomena are still poorly understood from the theory of the strong interaction because they cannot be calculated perturbatively.

At extreme temperatures (large momenta) we expect that the quarks and gluons are weakly interacting and that the QGP would behave as an ideal gas. Better theoretical understanding of non-perturbative QCD phenomena and the QGP comes from lattice QCD (see [1] in these proceedings), where the field equations are solved numerically on a discrete space-time grid. Lattice QCD provides quantitative information on the nature of the QCD phase transition and the Equation of State (EoS) of the quark gluon plasma.

Figure 1 shows the temperature dependence of the energy density as calculated from lattice QCD [2]. It is seen that the energy density $\epsilon$ changes rapidly around $T \sim 190$ MeV, which is due to the rapid increase in the effective degrees of freedom. Also shown in Fig. 1 is the pressure which changes slowly compared to the rapid increase of the energy density around $T = 190$ MeV. It follows that the speed of sound, $c_s = \sqrt{\partial P / \partial \epsilon}$, is reduced during the strong phase transition. At large temperature the energy density reaches a significant fraction (~0.9) of the ideal massless gas limit (Stefan-Boltzmann limit).

Relativistic heavy-ion collisions are a unique tool to create and study hot QCD matter and its phase transition under controlled conditions [3, 4, 5, 6, 7, 8, 9]. As in the early universe,
the hot and dense system created in a heavy-ion collision will expand and cool down. During this evolution the system probes a range of energy densities and temperatures, and possibly different phases. Provided that the quarks and gluons undergo multiple interactions the system will thermalize and form the QGP which subsequently undergoes a collective expansion and eventually becomes so dilute that it hadronizes. This collective expansion is called flow.

Flow signals the presence of multiple interactions between the constituents of the medium created in the collision. More interactions usually leads to a larger magnitude of the flow and brings the system closer to thermalization. Flow is therefore an observable that provides experimental information on the equation of state and the transport properties of the created QGP. The azimuthal anisotropy in particle production is the clearest experimental signature of collective flow in heavy-ion collisions [10, 11, 12, 13, 14]. This so-called anisotropic flow is caused by the initial asymmetries in the geometry of the system produced in a non-central collision. The second Fourier coefficient of the azimuthal asymmetry has been studied in most detail and is called elliptic flow. In these proceedings we will describe the relation between anisotropic flow and the geometry of the collision and the sensitivity to the transport properties. Finally, we will review the anisotropic flow measurements at the LHC, together with the current theoretical understanding of these results.

2. Anisotropic Flow
Experimentally, the most direct evidence of flow comes from the observation of anisotropic flow. Anisotropic flow is the anisotropy in particle momentum distributions correlated with the plane of symmetry, the so-called participant plane. In more peripheral collisions the plane of symmetry for elliptic flow is approximately the reaction plane, which is defined by the impact parameter and the beam direction $z$ (see Fig. 2). A convenient way of characterizing the various patterns of anisotropic flow is to use a Fourier expansion of the invariant triple differential

![Figure 1. Energy density $\epsilon/T^4$ (full curve) and pressure $3P/T^4$ (dashed curve) as a function of temperature $T$ from lattice calculations (adapted from [2]). The arrow indicates the Stefan Boltzmann limit of the energy density.](image)
Figure 2. Almond shaped interaction volume after a non-central collision of two nuclei. The spatial anisotropy with respect to the $x$-$z$ plane (reaction plane) translates into a momentum anisotropy of the produced particles (anisotropic flow).

distributions:
$$E \frac{d^3N}{d^3p} = \frac{1}{2\pi} \frac{d^2N}{p_t dp_t dy} \left( 1 + 2 \sum_{n=1}^{\infty} v_n \cos[n(\varphi - \Psi_n)] \right),$$

where $E$ is the energy of the particle, $p$ the momentum, $p_t$ the transverse momentum, $\varphi$ the azimuthal angle, $y$ the rapidity, and $\Psi_n$ are the participant plane angles. The Fourier coefficients are $p_t$ and $y$ dependent and are given by
$$v_n(p_t, y) = \langle \cos[n(\varphi - \Psi_n)] \rangle,$$

where the angular brackets denote an average over the particles, summed over all events, in the $(p_t, y)$ bin under study. In this Fourier decomposition, the coefficients $v_1$ and $v_2$ are known as directed and elliptic flow, respectively.

It was realized that viscous corrections can modify significantly the buildup of the anisotropic flow [15]. The shear viscosity determines how good a fluid is⁴, however, for relativistic fluids the more useful quantity is the shear viscosity over entropy ratio $\eta/s$. Known good fluids in nature have an $\eta/s$ of order $\hbar/k_B$. In a strongly coupled $N = 4$ supersymmetric Yang Mills theory with a large number of colors ('t Hooft limit), $\eta/s$ can be calculated using a gauge gravity duality [17]:
$$\eta \leq \frac{\hbar}{4\pi k_B}.$$

Kovtun, Son and Starinets conjectured, using the AdS/CFT correspondence, that this implies that all fluids have $\eta/s \geq \hbar/4\pi k_B$ (the KSS bound.). We therefore call a fluid with $\eta/s = 1/4\pi$ (in natural units) a perfect fluid. The KSS bound raises the interesting question on how fundamental this value is in nature and if the QGP behaves like an almost perfect fluid. In addition, it is argued that the transition from hadrons to quarks and gluons occurs in the vicinity of the minimum in $\eta/s$, just as is the case for the phase transitions in helium, nitrogen, and water. An experimental measurement of the minimal value of $\eta/s$ would thus pinpoint the location of the transition [18, 19].

⁴ a good fluid has a small viscosity and does not convert much kinetic energy of the flow into heat.
Figure 3. a) The interaction volume after a collision of two nuclei. The spatial anisotropy with respect to the participant plane translates into a momentum anisotropy of the produced particles (anisotropic flow). b) For $\eta/s$ is zero. c) For $\eta/s$ equal to two times the KSS bound. (Adapted from [20])

How the initial interaction volume created in a heavy-ion collision expands, due to collective flow, is shown in Fig. 3 [20]. The figure shows the expansion in case of $\eta/s = 0$ (Fig. 3b) and for $\eta/s$ close to the KSS bound (Fig. 3c). The hotspots which are created initially (Fig. 3a) largely survive the expansion in case of $\eta/s = 0$ (Fig. 3b), while the number of hotspots after the expansion with small viscous corrections (Fig. 3c) is strongly suppressed. In the Fourier expansion, Eq. 2, the more viscous expansion leads to very small magnitudes for the $v_n$ coefficients for $n > 2$ and a strongly reduction for $v_2$.

Figure 4. a) The centrality dependence of $v_2$ for three different values of $\eta/s$ [21]. b) The dependence on $\eta/s$ of $v_2(p_t)$ for charged particles [22].

The reduction of $v_2$ as function of $\eta/s$ is shown in Fig. 4a and b. Figure 4a shows for three values of $\eta/s$, between two and three times the KSS bound, the predicted reduction of $v_2$ as function of collision centrality. In Fig. 4b the change in $v_2$ versus transverse momentum is plotted, where the full line is for almost ideal hydrodynamics ($\eta/s \sim 0$) while the three other lines correspond to $\eta/s$ values of up to three times the KSS bound. Different magnitudes of $\eta/s$ clearly lead to a different magnitude of $v_2$ and change its $p_t$ dependence.
Figure 5. a) The eccentricity $\varepsilon$ calculated in a color glass condensate (CGC) model and using a Glauber model [23]. b) The $v_2$ obtained using the CGC or Glauber initial eccentricity [23].

The magnitude of $v_2$ does not only depend on the medium properties of interest, but is also proportional to the initial spatial anisotropy of the collision region. This spatial anisotropy can be characterized by the eccentricity, which can be defined by

$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle},$$

where $x$ and $y$ are the positions of the participating nucleons in the transverse plane and the brackets denote an average which traditionally was taken over the number of participants. Calculations have shown that the eccentricity obtained in different descriptions, in particular comparing a Glauber with a Color Glass Condensate (CGC) description, shows that $\varepsilon$ varies by almost 25% at a given impact parameter [23], see Fig. 5a. The elliptic flow, obtained when using these different initial eccentricities is shown in Fig. 5b. As expected, the different magnitude of the eccentricity propagates to the magnitude of the elliptic flow. Because currently we cannot measure the eccentricity independently this leads to a large uncertainty in experimental determination of $\eta/s$.

3. Anisotropic Flow Measurements

Because the magnitude of the anisotropic flow depends strongly on the friction in the created matter the large elliptic flow observed at RHIC provided compelling evidence for strongly interacting matter which, appears to behave like an almost perfect fluid [17]. However, a precise determination of $\eta/s$ in the partonic fluid is mainly complicated by uncertainties in the initial conditions of the collision. In addition, the relative contributions from the hadronic and partonic phase, and the unknown temperature dependence of $\eta/s$ also contribute to the uncertainty. Because of these uncertainties it was not even clear if the elliptic flow would increase or decrease when going from RHIC to LHC energies; a measurement of elliptic flow at the LHC was therefore one of the most anticipated results.

In the left panel of Fig. 6 the ALICE measurement at 2.76 TeV [24] shows that the integrated elliptic flow of charged particles increases by about 30% compared to flow measured at the highest RHIC energy of 0.2 TeV. This result indicates that the hot and dense matter created in these collisions at the LHC still behaves like a fluid with almost zero friction, providing strong constraints on the temperature dependence of $\eta/s$.

The right panel of Fig. 6 shows that the charged particle $p_T$-differential elliptic flow, compared to RHIC, does not change within uncertainties at low $p_T$ [24] which is remarkable because the
Figure 6. Left: Integrated elliptic flow as a function of collision energy. Right: Elliptic flow for three centrality classes measured as function of transverse momentum $p_t$. The bands indicate RHIC results measured by STAR. Figures taken from [24].

Figure 7. The $p_t$-differential elliptic flow for pions, kaons and antiprotons for 40%–50% (left) and 10%–20% (right) collision centrality. The curves are hydrodynamical model calculations. Figures taken from [25].

beam energies differ by more than one order of magnitude. The 30% increase in the integrated flow, shown in Fig. 6, must therefore be due to an increase in average transverse momentum.

In hydrodynamical model calculations this increase in mean $p_t$ is due to a larger transverse flow at higher collision energies. This leads to a more pronounced mass dependence of the elliptic flow. In Fig. 7 we show identified particle $p_t$-differential elliptic flow compared to hydrodynamic model predictions. The hydrodynamic model predictions from [26] (curves in Fig. 7) describe for mid-central collisions very well the measured $v_2(p_t)$ for pions, kaons and antiprotons at low $p_t$ (left panel of Fig. 7). For more central collisions (right panel) the hydrodynamical model predictions well describe the flow of pions and kaons but not that of the antiprotons. This mismatch may indicate a larger radial flow in the data. A full calculation, which includes a hadronic cascade afterburner, provides already a much better description [21] of the data.

4. Higher Harmonic Anisotropic Flow Coefficients

The initial matter distribution as shown in Fig. 3 does not have a smooth almond shape but, instead, a more complex spatial geometry which may possess also odd harmonic symmetry
planes. These are predicted to give rise to odd harmonics like triangular flow $v_3$. These odd harmonics are particularly sensitive to both $\eta/s$ and the initial conditions, and therefore generated strong theoretical and experimental interest [27]. The left panel of Fig. 8 shows that $v_3$ is indeed significant and does not depend strongly on centrality. The magnitude and centrality dependence of $v_3$ is reasonably well described by predictions from a hydrodynamic model calculation with Glauber initial conditions and $\eta/s = 0.08$ (dotted curve), in contrast to a calculation based on MC-KLN CGC initial conditions with $\eta/s = 0.16$, which under-predicts the data (dashed dotted curve). This suggests that the value of $\eta/s$ for the matter created in these collisions is small. To investigate further its hydrodynamic origin, the $p_t$-differential $v_3$ has been measured for pions, kaons and antiprotons, as is shown in the right panel of Fig. 8. It is seen that the mass splitting pattern in elliptic flow is clearly present in triangular flow as well.

5. Summary

In these proceedings, we have shown that anisotropic flow is one of the most informative observables in heavy-ion collisions. The current theoretical understanding of the experimental data is rapidly improving as is our understanding of the dynamics in heavy-ion collisions and the properties of the new state of matter, the quark gluon plasma. The new high quality data from the LHC recently became available and already shows that the properties of the created matter at the LHC can be studied with unprecedented precision.

Acknowledgements
The author would like to thank Ante Bilandzic, Michiel Botje, Mikolaj Krzewicki and You Zhou for their contributions. This work is supported by NWO and FOM.
References

[1] T. Hatsuda, these proceedings.
[2] A. Bazavov, T. Bhattacharya, M. Cheng et al., Phys. Rev. D80, 014504 (2009).
[3] See F. Gelis, T. Hatsuda, C.A Salgado, J. Schukraft and W.A. Zajc, these proceedings.
[4] Edward V. Shuryak. Phys. Rept. 61:71–158, 1980.
[5] G. F. Chapline, M. H. Johnson, E. Teller, and M. S. Weiss. Phys. Rev. D8:4302–4308, 1973.
[6] T. D. Lee and G. C. Wick. Phys. Rev. D9:2291, 1974.
[7] T. D. Lee. Phys. Rev. D19:1802, 1979.
[8] John C. Collins and M. J. Perry. Phys. Rev. Lett. 34:1353, 1975.
[9] Robert D. Pisarski and Frank Wilczek. Phys. Rev. D29:338–341, 1984.
[10] J. Y. Ollitrault, Phys. Rev. D 46, 229 (1992).
[11] S. A. Voloshin, A. M. Poskanzer and R. Snellings, in Landolt-Boernstein, Relativistic Heavy Ion Physics, Vol. 1/23 (Springer-Verlag, 2010), p 5-54. arXiv:0809.2949 [nucl-ex].
[12] U. W. Heinz, arXiv:0901.4355 [nucl-th].
[13] P. Huovinen and P. V. Ruuskanen, Ann. Rev. Nucl. Part. Sci. 56, 163 (2006)
[14] D. A. Teaney, arXiv:0905.2433 [nucl-th].
[15] D. Teaney, Phys. Rev. C68, 034913 (2003).
[16] M. Luzum, P. Romatschke, Phys. Rev. C78, 034915 (2008).
[17] P. Kovtun, D. T. Son, A. O. Starinets, Phys. Rev. Lett. 94, 111601 (2005).
[18] L. P. Csernai, J. I. Kapusta, L. D. McLerran, Phys. Rev. Lett. 97, 152303 (2006).
[19] R. A. Lacey, N. N. Ajitanand, J. M. Alexander et al., Phys. Rev. Lett. 98, 092301 (2007).
[20] S. Jeon et al., Phys. Rev. Lett. 106, 042301 (2011).
[21] U. W. Heinz, C. Shen, H. Song, [arXiv:1105.3226 [nucl-th]].
[22] M. Luzum, P. Romatschke, Phys. Rev. C78, 034915 (2008).
[23] T. Hirano, U. W. Heinz, D. Kharzeev et al., J. Phys. G G34, S879-S882 (2007).
[24] K. Aamodt et al. [ALICE Collaboration], Phys. Rev. Lett. 105, 252302 (2010)
[25] M. Krzewicki, [ALICE Collaboration], [arXiv:1107.0080 [nucl-ex]].
[26] C. Shen, U. W. Heinz, P. Huovinen, H. Song, [arXiv:1105.3226 [nucl-th]].
[27] K. Aamodt et al. [ALICE Collaboration], arXiv:1105.3865 [nucl-ex].
[28] B. H. Alver, C. Gombeaud, M. Luzum, J. -Y. Ollitrault, Phys. Rev. C82, 034913 (2010)