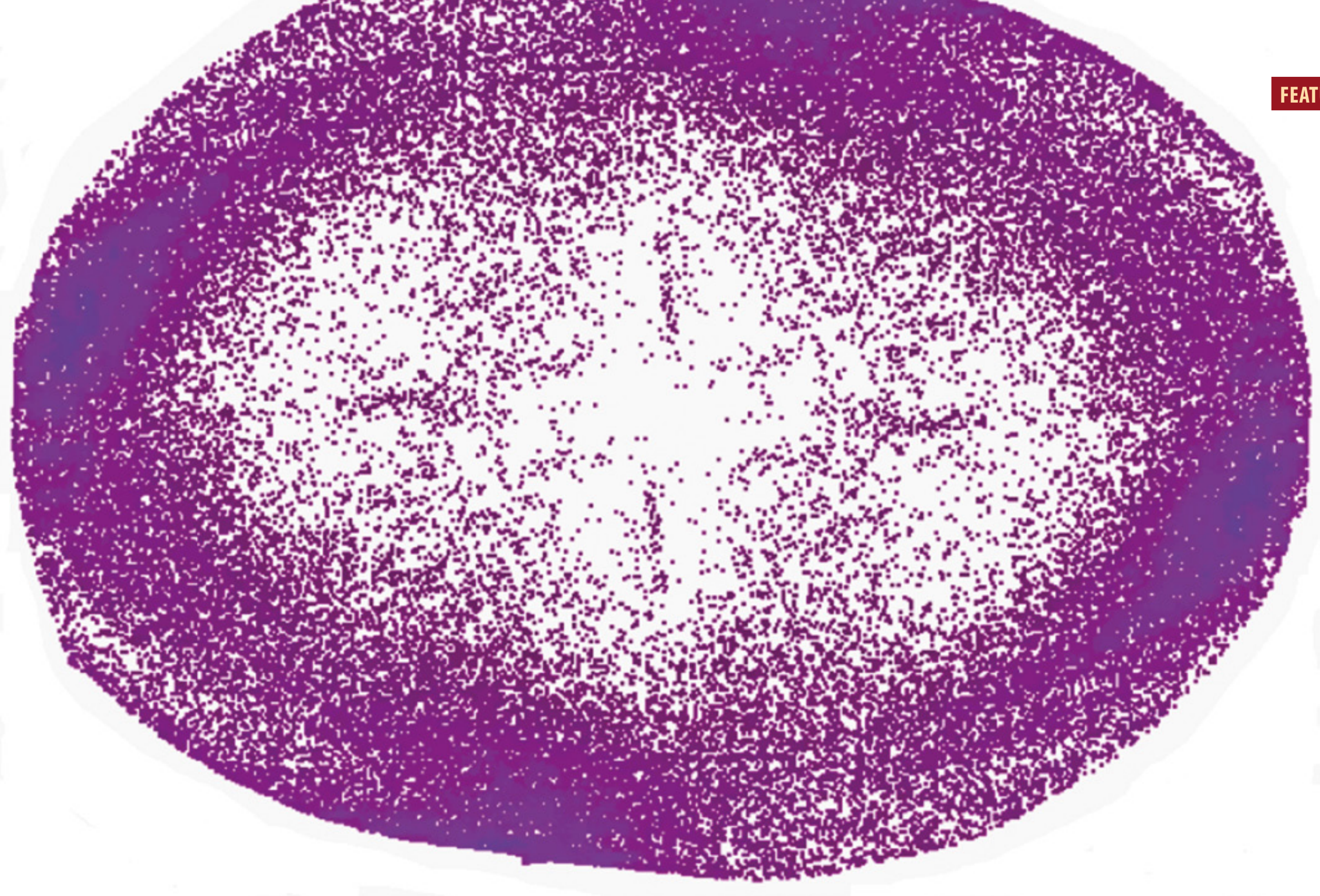

The Quark-Gluon Plasma, a nearly perfect fluid

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We are living in interesting times, where the World's largest accelerator, the Large Hadron Collider, has its most dominant successes in Nuclear Physics: collective matter properties of the Quark-Gluon Plasma (QGP) are studied at a detail which is not even possible for conventional, macro scale materials.

At the early plans the only dedicated heavy ion detector was ALICE, but as the first results started to arise, also ATLAS and CMS started to invest increasingly more effort into heavy ion research. This change of interest has two aspects. Contrary to early expectations of very high hadron multiplicity the collective flow became more dominant and a larger part of the available energy (of 208 × 2.76 TeV = 574 TeV) is invested into the collective flow, which developed in the QGP. The number of produced final particles is not as high as expected. This made the ATLAS and CMS detectors fully adequate for heavy ion research, and these detectors provided even a more extended rapidity acceptance, complementing the possibilities of ALICE detector well.

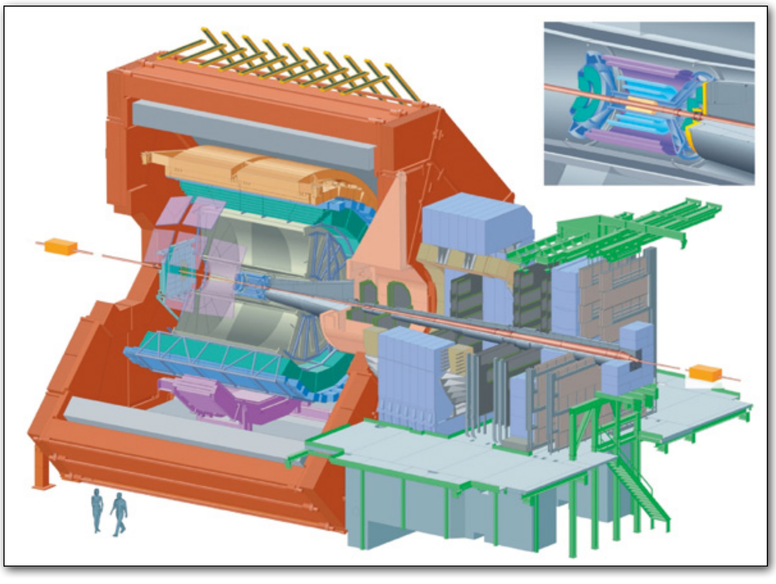
The second aspect was recognized after the very heavy-ion first results [1], where the heavy-ion studies provided new and important insight into the features of QGP. QGP turned out a strongly coupled liquid, with small viscosity, especially at the threshold of the quark/hadron phase transition. The small viscosity, the related fluctuations, and the flow properties arising from these fluctuations enable us to gain insight into the properties of the matter of the early universe, and also the fluctuations observed in the early universe. These new results raised more interest in the ATLAS and CMS collaborations also and their progress in the heavy ion research activity is becoming more important. In recent months the CERN Courier has more and more news about new heavy-ion results.

▲ view of the expanding and rotating Quark-Gluon Plasma from a fluid dynamical calculation (discussed in: L.P. Csernai, V.K. Magas, H. Stöcker, and D.D. Strottman, *Phys. Rev. C* 84, 02914 (2011).)

▲FIG 1: The superconducting magnets of the Large Hadron Collider (LHC) in the 27 km long tunnel. Inside the magnets, in two beam-pipes, lead nuclei are accelerated in opposite directions, which meet each other with 574 TeV energy at the detectors.

Let us start with the most important observations. The emitted hadrons, which reach the detectors, show an explosive process where these particles have large-velocity collective motion, and the major part of the collision energy is in collective flow. The flow is not spherically symmetric, it has azimuthal and longitudinal asymmetries, and these change depending on to what extent the collision is an exactly head on collision of the projectile and the target or not. Already the experiments at the RHIC indicated that the collective flow develops primarily in the QGP phase, because the azimuthal asymmetries were proportional with the number of constituent quarks in the observed hadrons. The centrality of the impact can be estimated based on the observed charged hadron multiplicity in the collision. The large hadron multiplicity of each event enables us to study collisions separately, event by event, and to gain information about the reaction plane direction, centrality, energy spectra, and angular asymmetries.

In head-on collisions there would be no reason to have an azimuthal or longitudinal asymmetry. On the other hand, the new observations for the higher harmonics show [2] that even in central collisions there is a strong azimuthal asymmetry in the emitted hadrons, and this asymmetry arises from the fluctuations of the initial state. In addition in head-on collisions the third harmonic of the azimuthal distribution, v_3, exceeds the second one, v_2, becoming the dominant harmonic component in accordance with a larger contribution from fluctuations with respect to the global collective flow symmetries due to the initial eccentricity. The spectrum of Fourier amplitudes is measured up to n=8, and it is significant up to n=5. The fact that high harmonics have survived the fluid dynamical expansion indicates that the QGP fluid is almost perfect, and does not absorb high-harmonic fluctuations.



▼FIG 2: The ALICE detector is designed to cope with the highest particle multiplicities above those anticipated for Pb+Pb collisions, more than 10000 charged particles in the central Time Projection Chamber. At the present beam energy the number of detected particles is approaching 3000 charged particles in the most violent collisions. The beam energy is planned to be doubled in a few years.

At LHC the study of azimuthal asymmetry due to initial state fluctuations started at full force, and this activity opened a direct connection to theoretical fluctuation studies in the early universe, where the cosmic microwave background radiation has a dominant multipole moment around 200. Just as in the early universe the analysis of these fluctuations provides precious information about the matter and expansion properties.

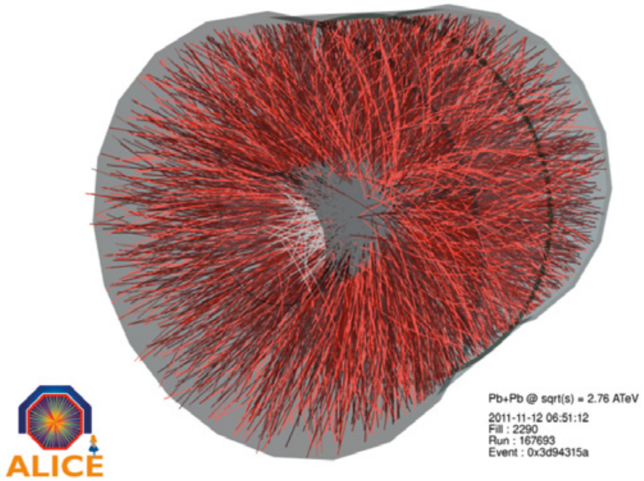
In the case of heavy ions we have an advantage of being able to influence the initial state by selecting different impact parameters. In head-on collisions azimuthal fluctuations can only originate from random fluctuations. At finite impact parameters the eccentricity of the initial state is determined by the global collective symmetries. We now face a challenging task, to separate the observed azimuthal asymmetries based on origin. We have to study whether the asymmetry is caused by initial state fluctuations, by fluctuations developing during the fluid dynamical expansion, or by global collective asymmetry. In low-viscosity matter these special initial states may lead to instabilities and turbulence, which is an exciting possibility.

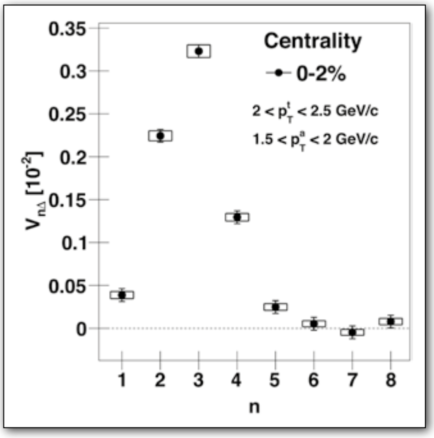
Another important and dominant phenomenon is the jet-quenching through QGP. The increasing collective flow from fluctuations makes these studies more complicated and further effort is needed to separate the earlier detected Mach cone effects around the jets from other fluctuation related correlations. Here also one has to distinguish the Mach cone effects from random fluctuations, which is also a demanding task but not impossible.

The higher energy enhanced the production of heavy quarks and thus of heavier hadrons, which makes these studies more interesting. Eventually the heavy-ion reactions may lead to increased "sub-threshold" production of massive elementary particles, due to particle creation in collective mechanisms. New particles like the Higgs, mini Black Holes or WIMPs on the other hand may be difficult to detect, even if they are created, due to the high multiplicity background. This difficulty may be less severe in very peripheral, lower multiplicity events. The LHC is in the energy domain where QGP is dominantly produced even in peripheral reactions. Nevertheless, the plasma finally has to hadronize, so the system will have to undergo a phase transition. This transition is of major interest as the predicted low viscosity [3] should appear at the critical point of the transition [4].

At the Threshold

Fluctuations are becoming dominant due to the low viscosity of QGP. The shear viscosity is minimal at the phase transition threshold [4], where fluctuations are the largest due to the critical fluctuations shown by the well-known critical opalescence. The threshold energy where QGP can be first produced lies below the present LHC energy,





▴ **FIG 3:** The final particles created in a lead on lead collision as reconstructed by the Time Projection Chamber of the ALICE detector. The chamber is filled in by the charged particle tracks rather evenly and densely in a near central collision. As flow fluctuation studies indicate the multipole moments up to 5 can be significantly identified. At higher energy and so higher charged particle multiplicity one can expect to see even higher multipole moments.

◂ **FIG 4:** Multipole moments of the azimuthal distribution of emitted particles in central lead on lead collisions detected by the Time Projection Chamber of the ALICE detector. From ref. [2b].

and according to present expectations it is around the low RHIC and the SPS energies. The present CERN studies could be well complemented by studying a system where the QGP is just created and critical fluctuations in dense hadronic of baryonic matter can be studied. Apart from the drop of collective directed flow due to the rapid softening of the matter at the critical point, there are many other observables, which open new ways of studies. The revolutionary fluctuation studies have an effect on the studies at the critical point also, with many new results coming from the RHIC Beam Energy Scan program. Here the critical fluctuations are being in the focus of present and future research. These show up in the anomalous multiplicity and mass distribution of the produced matter as relics of QGP. These fragments, hypernuclei, anti-baryons, anti-nuclei, antihypernuclei and even anti matter atoms like anti-^4He.

FAIR and NICA

Critical fluctuations, critical dynamics and the relics of QGP can be best generated at the phase transition threshold. The planned Facility for Antiproton and Ion Research (FAIR) in Darmstadt and the Nuclotron based Ion Collider fAcility (NICA) in Dubna are addressing these questions. According to theoretical expectations the production of these exotic nuclear fragments opens in this energy range [5].

Figure 5 shows theoretical predictions for anti-particle cluster production at mid-rapidity ($|y|<0.5$) in collisions of Pb+Pb/Au+Au at center-of-mass energies of $\sqrt{S_{NN}} = 3 - 200$ GeV. The yields of the anti-particle clusters show a monotonous increase with beam energy. They show that, at the highest RHIC energy (and at the LHC) the reconstruction of anti-^4He might be a feasible task.

New accelerators under construction are aiming for the threshold energy of QGP formation, and for the dense baryon matter just below this threshold.

These developments are connected more strongly to perspective and future applications like fusion, safety of fission reactors and other applied nuclear processes. ■

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▾ **FIG 5:** Yields of anti-particle clusters in the mid rapidity region ($|y|<0.5$) of most central collisions of Pb+Pb/Au+Au as a function of the center-of-mass beam energy. Shown are only the results from the thermal production in the UrQMD hybrid model [6] (lines with symbols).