Properties of strongly interacting matter

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1 Introduction: fundamental properties of strongly interacting matter

1.1 Basics of Quantum Chromodynamics (Gelis, Rischke)

Four fundamental forces rule the interactions of matter in Nature: the gravitational force, the electromagnetic force, the weak force and the strong force. Except for gravity, for which the quest of a microscopic quantum description has remained somewhat elusive so far, these forces are now fully understood in terms of local quantum field theories. In these field theories, spin-\(\frac{1}{2}\) matter fields carry charges pertaining to the local (gauge) symmetries of the theory and are coupled to spin-1 bosonic fields that mediate the force between the charge carriers. For the weak and strong force, these fields carry also charge.

The quantum field theory that describes the strong force has been discovered in the early 1970’s, following a number of experimental clues. In particular, deep-inelastic scattering experiments led to two crucial observations: (i) the electrical charge of hadrons is not smoothly distributed but is carried by spin-\(\frac{1}{2}\) point-like constituents, and (ii) these constituents are nearly free when probed at very short distances. The simplest quantum field theory, now known as Quantum Chromodynamics (QCD), consistent with these properties and with the multiplets observed in hadron spectroscopy is a non-abelian gauge theory endowed with an internal local \(SU(3)\) symmetry, in which the charged matter fields are the quarks and the mediators of the force the gluons.

Although there are six flavors of quarks (up, down, strange, charm, bottom and top), only the two lightest flavors (up and down) appear in the valence composition of ordinary hadrons. The heavy quark flavors may appear as short-lived quark-antiquark quantum fluctuations in the hadronic wavefunctions and may also be produced in the final state of various reactions.

An important property of QCD is asymptotic freedom: the strength of its coupling decreases at short distance and increases at large distance (in contrast to quantum electrodynamics, where the coupling evolves in the opposite way with distance). This behavior explains both the scaling observed in deep-inelastic scattering experiments and the fact that the force becomes strong enough at larger distance to bind the quarks into hadrons. The latter fact leads to another important property of QCD, confinement: neither quarks nor gluons exist as isolated particles in Nature, and the only stable arrangements are color-singlet bound states, i.e., hadrons, which may either be mesons formed from quarks and antiquarks or (anti-)baryons formed from three (anti-)quarks. Also more exotic states, e.g., made purely from gluons, so-called glueballs, have been suggested to exist. Although there are indications for their existence in the hadron mass spectrum, they have not yet been unambiguously identified. However, despite the fact that confinement prevents a direct observation of quarks and gluons, these particles leave clear imprints in high-energy reactions in the form of jets – collimated streams of hadrons whose direction reflect the momentum of the quark or gluon that initiated them.

Asymptotic freedom has a very profound implication for highly compressed hadron matter: at sufficiently high density, the average inter-quark distance becomes small, and therefore their interaction strength weakens. Above a critical energy density of the order of 1 GeV/fm\(^3\), a gas of hadrons undergoes a deconfinement transition and becomes a plasma of quarks and gluons. Numerical evidence of this transition has been obtained from lattice simulations of QCD, in the form of a rapid increase of the entropy density at the critical density.

\(^1\)To the extent allowed by the spatial resolution of the experiment.
In the cooling history of the Early Universe, the primordial quark-gluon plasma turned into hadrons around $10^{-5}$ seconds after the Big Bang, but this transition has, as far as we know, not left any imprint that is visible in present-day astronomical observations. However, the energy density necessary to form the quark-gluon plasma may be re-created in the laboratory via heavy-ion collisions at sufficiently high energies, inside small volumes of the order of the nuclear size.

1.2 QCD phase diagram (Schmidt, Vento)

Our knowledge of the phase diagram of QCD can be summarized as follows:

(a) In the chiral limit of two-flavor QCD, i.e., for vanishing up- and down-quark masses, a phase transition exists, that separates a phase of broken chiral symmetry at low temperature from a chirally symmetric phase at high temperature. This transition also persists at small, non-vanishing values of the baryon chemical potential. However, since massless quarks cannot be simulated on the lattice, neither the order of the phase transition nor the value of the transition temperature are well determined in the chiral limit, even at vanishing baryon chemical potential. Moreover, an important open question is whether partial restoration of the axial anomaly ($U(1)_A$ restoration) occurs and influences the order of the chiral phase transition.

(b) For QCD with its physical spectrum of non-zero up and down quark masses, as well as a heavier strange quark, the transition from the low- to the high-temperature regime is rapid and accompanied by large changes in the properties of strongly interacting matter. The transition itself, however, is not a phase transition, but a "crossover transition". At vanishing baryon chemical potential this transition occurs at about 155 MeV and restores chiral symmetry up to residual explicit breaking effects arising from non-zero values of the light quark masses. It also shows clear features of a deconfining transition, with the low-temperature regime being best described by ordinary hadronic degrees of freedom, while in the high-temperature phase quarks and gluons emerge as the dominant degrees of freedom.

(c) Properties of strongly interacting matter at very high temperature or baryon chemical potential can be calculated using perturbative techniques. Such calculations show that matter in this asymptotic regime consists of weakly interacting quarks and gluons in the QGP phase. At least for high temperatures and vanishing baryon chemical potentials such calculations can be cross-checked with lattice-QCD calculations.

(d) Close to the crossover region, in particular on the high-temperature side of the crossover transition, strongly interacting matter is strongly coupled. It is not clear that a description in terms of particles, either hadronic or quark/gluon, is of any utility. Approach to equilibrium is very rapid, so transport coefficients are very small. Therefore the behavior of the hot, dense matter created in heavy-ion collisions is strongly collective; in fact, despite large space-time gradients of energy density and local flow velocity in these collisions, strongly interacting matter exhibits properties similar to that of an ideal fluid.

(e) One or more color-superconducting phase exists at asymptotically large net baryon number density and sufficiently low temperature. It is rather likely that this phase is homogeneous, but (also depending on the various charge-chemical potentials) it may display spatial variations of the color-superconducting order parameter when the density is lowered.

(f) Under conditions of vanishing pressure and temperature nuclear matter forms a quantum Fermi liquid with a density of about 1/6 nucleons per fm$^3$. Upon heating, it undergoes a first-order liquid-gas transition, which ends in a critical point of second order when the temperature is increased. The associated critical temperature is rather well established to be around 15 MeV.

Apart from these few anchor points, our knowledge of the phase diagram from first-principles approaches remains scarce, in particular in the experimentally interesting region of intermediate net baryon number densities. At present, these regions are not accessible to lattice-QCD calculations. In order to shed light on their properties, phenomenological studies have been performed. Some use QCD-inspired models; others consider QCD-like theories which avoid some of the technical problems of QCD, such as two-color QCD. To give one example, in QCD with a large number of colors, a new phase, termed the "quarkyonic phase", was proposed at low temperatures and baryon chemical potentials exceeding that of the nuclear matter ground state. In this phase, the order parameter for chiral symmetry breaking undergoes spatial variations. Without stringent controls to judge the quality of model approaches, their results are often inconclusive.
1.3 Equation of state and Thermodynamics (Rischke, Sorin)

The properties of a system in thermodynamical equilibrium are encoded in its grand partition function $Z$ as a function of temperature $T$, volume $V$, and the various chemical potentials for conserved charges, such as the baryon chemical potential $\mu_B$, the isospin chemical potential $\mu_I$, the strange chemical potential $\mu_S$, etc. In order to compute the grand partition function of QCD, various methods are at our disposal, but each one is applicable in a limited region of parameter space only. Due to asymptotic freedom, at asymptotically high temperatures and chemical potentials QCD matter is a weakly coupled gas of quarks and gluons, commonly referred to as quark-gluon plasma (QGP). In this regime of temperatures and chemical potentials, perturbation theory is expected to converge and one can compute the grand partition function in a power series of the strong coupling constant. However, the presence of additional energy scales like the temperature or the chemical potential upsets the traditional power-counting scheme in the coupling constant in vacuum, and resummation techniques are required to compute quantities at a given order in the strong coupling constant. An example is the hard-thermal-loop (HTL) approximation. Self-consistent resummation schemes are defined by specific truncations of the generating functional for $N$-particle irreducible (NPI) vertex functions. These find application e.g. in the region of large baryon chemical potentials and sufficiently small temperatures, where, due to attractive forces between quarks, the QGP becomes a color superconductor and the grand partition function and the color-superconducting gap parameter are derived from the generating functional for 2PI vertex functions.

As one decreases temperature and chemical potential towards values of the order of the QCD scale parameter, $\Lambda_{\text{QCD}} \sim 0.2 \text{ GeV}$, the coupling constant becomes so large that perturbative techniques are no longer applicable and non-perturbative methods must be used to compute the grand partition function of QCD. A non-perturbative approach which is based on first principles is lattice QCD, i.e., the direct numerical evaluation of the grand partition function as a functional integral over gauge-field configurations in Euclidean space-time. This method works very well at any temperature for vanishing baryon chemical potential. However, at non-zero baryon chemical potential the Monte-Carlo sampling of gauge-field configurations performed in order to evaluate the multi-dimensional functional integral fails because of the sign problem of the fermion determinant. To a certain degree, one can circumvent this problem by reweighting techniques or a Taylor expansion around $\mu_B = 0$. Such methods are reliable as long as $\mu_B/T \lesssim 1$. Another issue with lattice QCD is that calculations for physical quark masses are computationally expensive. Nevertheless, by now advances in computing hardware and lattice-QCD algorithms allow for calculations with physical quark-mass parameters, at small but non-vanishing values of the baryon chemical potential, and extrapolated to the continuum limit, which deliver reliable information on the QCD phase diagram and its equation of state.

Recently, effective lattice field theories have been applied to investigate the QCD equation of state and the QCD phase diagram at small $T$ and finite $\mu_B$. These are based on expansions for strong coupling and large quark masses. While the parameters are still far from the physical point, the existence of a liquid-gas transition could be proven, see Fig. 1. These works need to be extended towards realistic values of the quark masses, in order to further explore the low-temperature, nonzero-baryon density region of the QCD phase diagram.

Besides lattice QCD, other non-perturbative first-principles methods are functional methods in the continuum, such as Dyson-Schwinger equations (DSEs) or the Functional Renormalization Group (FRG). While in principle exact, in practice the infinite tower of $N$-point correlation functions that one has to compute in the DSE or the FRG framework needs to be truncated, which renders these methods approximative. On the other hand, the advantage is that they do not suffer from the fermion sign problem and can thus be applied at any value of $T$ and $\mu_B$. Important advances have been made in recent years. These address not only the QCD phase diagram and the equation of state, but also near-equilibrium properties such as first-order hydrodynamic transport coefficients like the shear viscosity coefficient. An example is the calculation of the latter in the framework of the FRG, see Fig. 2.

Recent observations of pulsars with high masses around two solar masses have provided evidence that the equation of state of cold dense baryonic matter in neutron stars must be sufficiently stiff at supersaturation densities so that masses as high as this can be carried by the star without undergoing gravitational collapse. Ongoing are observations of neutron star radii with improved accuracy, in near future also using gravitational wave detectors will hopefully settle the controversial discussion of large ($R > 13\text{ km}$) or small ($R < 11\text{ km}$) radii of neutron stars and provide sufficiently accurate measurements. That is essential for determining the stiffness of cold nuclear matter at high-densities and offers the possibility to obtain direct evidence for a strong first-order phase transition: If high-mass pulsars come in two families, a hadronic one with large radii and a hybrid one of smaller radii with a quark matter core (so called “third family”), separated by an instability in the range between $11.5 \text{ km}$ and $13 \text{ km}$, then the mere
Cold and dense, interacting: onset to nuclear matter

Onset transition to cold nuclear matter

... with very heavy quarks

continuum limit with 5-7 lattice spacings per point

\[
\mu = 20 \text{ GeV}, T = 10 \text{ MeV}, a = 0.17 \text{ fm}
\]

The equation of state for nuclear matter

Effect of binding between baryons:

Transition is smooth crossover:

Binding energy per nucleon:

\[
\mu < m_B \rightarrow 10^{-3}
\]

\[
T > T_c \rightarrow m_B S_{\text{eff}}
\]

\[
n_B/m_B^3
\]

Figure 1: Baryon density as function of baryon chemical potential (both in units of appropriate powers of the baryon mass) for various temperatures. For zero temperature, the liquid-gas transition becomes a first-order phase transition, exhibiting the silver-blaze property of nuclear matter. Figure courtesy of O. Philipsen et al.

Figure 2: The dimensionless ratio of shear viscosity over entropy density as a function of temperature, for pure Yang-Mills theory (red) and full QCD (blue). The conjectured lower bound on this quantity from the AdS/CFT correspondence is given by the orange line (labelled KSS). Grey curves correspond to the results from the hadron resonance gas (labelled "HRG", decreasing with temperature) and from a calculation within resummed QCD perturbation theory (labelled "pert", increasing with temperature), respectively. The insert shows the similarity of the red and the blue curve when plotted against the temperature normalized to the transition temperature \( T_c \). Figure courtesy of J.M. Pawlowski et al.

does not provide indirect evidence for a critical endpoint in the QCD phase diagram.

Computation of the QCD EoS has been one of the major goals in the field of lattice QCD. At zero baryon number density it has been shown very recently with lattice calculations for \( N_f = 2 + 1 \) that the QCD equation of state obtained from the HotQCD and Wuppertal-Budapest collaborations by using two different discretization schemes
agree very well. For hydrodynamic simulations related to NICA energies one needs EoS evaluated in the whole physically allowed baryon/energy density plane. Evaluation of EoS at large $\mu_B$ is a major challenge for lattice QCD. One promising strategy to construct the EoS at nonzero $n_B$ is using Taylor expansion in chemical potentials based on lattice QCD calculations.

The final goal of HIC theory and experiments is to learn about the EoS and transport coefficients of QCD matter. This task includes in particular the quest for the location of the critical endpoint of first order phase transitions. A promising strategy to reach this goal is a Bayesian analysis using a multi-parameter form of EoS and a set of HIC data as priors. For LHC data this has been successfully demonstrated that the analysis yields a most likely EoS parameter range which is in accordance with lattice QCD EoS data. Therefore, a similar strategy shall be developed for the case of high baryon densities, by including the finite baryon chemical potential and a possible critical endpoint. The resulting class of hybrid EoS shall be used within the Three-fluid-Hydrodynamics based event simulation approach appropriate for NICA/FAIR energies (as discussed above) where recent RHIC BES flow data could be included into the set of priors for the Bayesian analysis. By means of presently developing state-of-the-art multi-fluid hydrodynamic model comprising relativistic viscous fluid dynamics and final state hadronic cascade it is planned to assess transport coefficients (shear, bulk viscosity and thermal conductivity) and parameters of the EoS of QCD matter in a Bayesian analysis. For high $\mu_B$ there are no EoS data from lattice QCD available yet for a cross-check, but for the zero temperature extrapolation of the EoS one can determine the mass-radius relations of compact stars and check their consistency with available observational data.

The low value of the shear viscosity coefficient over entropy density ratio $\eta/s$ around the phase transition temperature at low density is reasonably well established and evaluated to be at most a couple of times the AdS/CFT lower limit $1/(4\pi)$. There is a theoretical expectation that the $\eta/s$ ratio is not constant, but depends on temperature, and it has been seen some indications of such temperature dependence in the data. A reliable extraction of the temperature dependence of $\eta/s$, however, requires a complicated analysis of not only all anisotropy coefficients, but the related correlations as well.

In a similar fashion one may expect the $\eta/s$ ratio to depend on chemical potentials as well, although at finite densities the ratio of shear viscosity to entropy is not a good measure of the fluidity of the system, but one should evaluate the shear viscosity to enthalpy density ratio $\eta/w$ instead. The early attempt to extract $\eta/s$ ratio has indeed indicated that not only $\eta/s$ but also $\eta/w$ depends on the baryochemical potential, although a reliable extraction of the temperature and chemical potential dependencies of $\eta/w$ (and $\eta/s$) requires more data and more careful analysis.

Besides its shear viscosity coefficient, the transport properties of matter are characterised by its bulk viscosity and heat conductivity/charge diffusion coefficients as well. The bulk viscosity is estimated to be small everywhere except in the vicinity of the phase transition, but it has been argued that even in that case it could have a significant effect on the final particle distributions. So far there have been no attempts to include effects of heat conductivity/charge diffusion into simulations of the evolution. In collisions at LHC and RHIC energies the created matter is almost charge neutral, and the effect of heat conductivity/charge diffusion can thus be expected to be negligible, but at large densities reached at FAIR and NICA, it should not be ignored. It has been shown that both, viscosity and heat conduction, play an important role for the growth of droplets (spinodal amplification) in first order phase transitions and on 2-particle correlations as observables. They should thus both be included in next generation simulation programs.

Extraction the values of all three transport coefficients from the data requires simultaneous analysis and fit of all the available data. This demanding task requires similar Bayesian approach using model emulators as described previously for evaluating the EoS. The first attempts for using such a strategy have been very promising.

The anomalous transport constitutes the fundamental non-dissipative phenomena deeply related to various fields of high-energy and condensed matter physics. It includes Chiral Magnetic, Chiral Vortical and Axial Vortical Effects which may be studied via particle correlations and hyperon polarisations.

### 1.4 Heavy ion collisions (Bruno, Florkowski)

The idea to collide heavy ions accelerated at ultra-relativistic energies for bringing nuclear matter into the deconfined QGP phase and studying its property in a laboratory dates back to the early ’80. Pioneristic studies at the Brookhaven AGS and the CERN SPS demonstrated, first with light ions then with heavy ones, that the energy deposit and the nuclear stopping in the central rapidity region were as large as one could have hoped. With increasing further
the centre of mass energy, the colliding system enters a new regime characterized by nuclear transparency: the inertia of the colliding nucleons becomes so large that they cannot be completely stopped in the collision as at lower energies. Still, the energy density in the central rapidity region, estimated from the number of produced particles, keep increasing. The net baryon density at central rapidity approaches zero already at RHIC energies ($\sqrt{s_{NN}} = 200$ GeV), and the estimated energy density in central Pb-Pb collisions at the LHC ($\sqrt{s_{NN}} = 2.76$ TeV) becomes an order of magnitude larger than the critical energy predicted by IQCD. The challenge for the coming years consists in the detailed experimental characterization of different regions of the phase diagram, the search for the onset of the transition and the critical point, to be accomplished by varying the colliding energy, the colliding system and the centrality of the collisions.

Theoretical description of soft particle production and evolution in heavy ion collisions proceeds in three steps, which are altogether referred to commonly as the Standard Model of heavy-ion collisions. These three steps include: an early non-equilibrium stage of particle production, the expansion stage described within relativistic viscous hydrodynamics, and the final freeze-out stage.

The processes taking part in the first stage are very often described within simple geometric models (like, for example, the Glauber Monte Carlo approach) which give distributions of the deposited energy density in the transverse plane and longitudinal direction. Such distributions can be used then as initial conditions for the hydrodynamic stage. At present, the early dynamics and subsequent hydrodynamical expansion are included in the event-by-event simulations that allow for inclusion of the fluctuations. The latter are important to reproduce the measured coefficients in the Fourier decompositions of the particle spectra, known as the harmonic flows. The use of hydrodynamics allows us also to describe consistently the phase transition (crossover) process, as the equation of state supplements other hydrodynamic equations. After passing through the phase transition the system consists of hadrons and its description, in the following third stage, is described most commonly with the help of hadron rescattering models such as, for example, UrQMD.

Comparisons between predictions of the Standard Model with the experimental RHIC data have been done to analyse the properties of high temperature low baryon density matter — its shear viscosity coefficient turns out to be close to the AdS/CFT limit, while the equation of state has been confirmed to have the form given by the lattice simulations of QCD. A clear advantage of the Standard Model is its block structure which allows for the use of more or less advanced theoretical tools in a each particular stage. In this way the Standard Model can be gradually improved and used to determine further properties of strongly interaction matter.

Successful applications of the perfect fluid hydrodynamics to describe the RHIC data, especially the use of an early starting time in such calculations, have formed an opinion that correct description of the data requires early local equilibration and/or isotropization of the produced matter at times on the order of 0.5 fm/c after the initial impact. The change to a viscous hydrodynamics description suggests a verification of this point of view, since even with the shear viscosity value corresponding to the AdS/CFT limit, the large initial gradients (proportional to the inverse of the initial time) imply substantial corrections to the equilibrium values of the energy-momentum tensor. A natural measure of such effects is the ratio between the longitudinal pressure component $P_L$ (acting along the beam) and the transverse component $P_T$ (acting in the plane transverse to the beam direction). Using, as the first estimate, the Navier-Stokes limit one finds $P_L / P_T = 0.5$ for RHIC initial conditions (initial temperature of 400 MeV at the initial time 0.5 fm/c with $\eta/s = 1/(4\pi)$) and 0.3 for the LHC (initial temperature of 600 MeV at the initial time 0.25 fm/c again with $\eta/s = 1/(4\pi)$). Similar conclusions may be drawn from the AdS/CFT studies. Consequently, the concept of early equilibration is nowadays very often replaced by the concept of so called early hydrodynamization, while the equilibration times (corresponding to reaching local equilibrium where the system is locally almost isotropic in the momentum space) are shifted to more comfortable values of about 2 fm/c. Certainly, replacing one problem by another does not solve the issue of early dynamics whose fundamental theoretical explanation remains a challenge. In particular, the early use of viscous hydrodynamics to describe dynamics of small systems has become lately a highly debated issue.

Dependence on initial geometry

This subsection introduces heavy ion collisions as the experimental tool for exploring some parts of the phase diagram. By varying the energy and type of the colliding system, one has handles to probe different $(T, \mu_B)$ region and search for the onset of the transition and the critical point.

The expansion of the fireball is well described by hydrodynamics, which suggests small values of the viscous transport coefficients (i.e. strong interactions). This also suggests that the system is not too far from thermal
equilibrium fairly quickly. Another important aspect of hydrodynamical modeling is to have a good handle on the initial geometry of the fireball, and its fluctuations.

Some of this material may go into the section 3 if we think it is mostly relevant for the low \( \mu_B \) / high \( T \) regime.

2 Nuclear matter at high temperature and Low \( \mu_B \)

2.1 Big picture: what is the physics we are after?

Note: Some of this is maybe too general and should be moved to the intro of chapter 2; here we should then narrow down a bit to the high-T low \( \mu_B \) case in high-energy collisions

The study of nuclear matter at high temperature and low \( \mu_B \) in high-energy nuclear collisions is aimed at understanding multi-particle states and their QCD dynamics. The strong interaction as described by QCD is one of the fundamental interactions in the Standard Model and it has unexpected properties, since the non-linear aspect of the interaction, related to the non-Abelian nature of the underlying field theory, have no analogy in macroscopic systems. As such, the strong interaction is not part of our intuitive experience of the natural world around us. In fact, the strong interaction only manifests itself on small length scales, mostly at length scales around 1 fm and below, i.e. in the binding of quarks into nucleons such as the proton and the neutron. At high energy density, however, a phase transition to a deconfined state is expected, the so-called Quark Gluon Plasma, in which partons can roam freely over larger distances. In heavy ion collisions, the QGP state has typical size of a (large) nucleus, around 10 fm. Studying the interactions and unraveling the behaviour in realistic multi-parton systems is an exciting endeavor in itself, but also because of connections to other fields of physics, such as cosmology and the properties of neutron stars.

In this Section, we focus on the aspects of nuclear collisions at the highest available energies, where a QGP is formed with high temperature and low baryo-chemical potential \( \mu_B \), i.e. a minimal excess of quarks over anti-quarks: the system is almost matter-anti-matter symmetric, because it is created almost exclusive from the collision energy. The contribution of the mass of the colliding nucleons to the total energy of the system is vanishingly small.

![Diagram of the evolution of the system created in heavy-ion collisions at high temperature and low \( \mu_B \). The main phases and steps are specified on the right side together with the different temperatures driving the transition from the strongly interacting QGP to the hadrons measured in the detectors (successively the critical temperature \( T_c \) for the chiral symmetry restoration, the chemical freeze-out temperature \( T_{ch} \) and the kinetic freeze-out temperature \( T_{fo} \)). Formalisms used to described successfully this evolution are shown on the left side of the schematisation.](image)

Our understanding of the collision normally divides the collision in three stages: the initial or pre-equilibrium
stage, where the initial scatterings and some of the momenta along the beam direction are converted into transverse momentum, followed by the 'thermal stage', in the dynamics can be described as an expanding fluid, and finally the 'freeze-out' where the final state hadrons are formed. This evolution is sketched in Fig. 3. Clearly, a number of different physical processes play a role as the system evolves and it is one of the challenges in the field to identify the processes that dominate the dynamics and to formulate observables that are sensitive to specific processes.

The key areas of interest that can be addressed are:

- Initial scattering and approach to equilibrium; role of gluons; study in small systems? Thermalisation of heavy quarks.
- Properties of the QGP: probes structure; interactions is (close to) thermal system: equation of state, viscosities, transport coeff. Low-momentum observables.
- Hard probes: interactions of fast partons with the QGP; advantage: partly perturbative: a clean way to study multi-parton interactions in QCD.
- Hadronisation: non-perturbative QCD; linked to confinement; various observables (recombination of quarkonia, but also low-momentum correlation observables; statistical model?).

Era of precision measurements: not only a fine characterization of the QGP but detailed understanding of its whole evolution.

nuclear effects Initially thought of as a mere reference for nucleus-nucleus studies, proton-nucleus collisions provided a host of interesting results of their own. None of the individual cold nuclear matter effects are able to describe the data in all kinematic regions, suggesting that a mixture of different effects is at work. Contrary to expectations, there is not yet indication in the forward charmonium data for a non-linear regime at small x, in which the gluon densities would be so high that gluon-gluon recombination effects would become visible. Recent results on excited quarkonium states also challenged a number of preconceived ideas and hint at a significant impact of final-state interactions with comoving particles. It also appears to be crucial that the future LHC programme includes adequate p-p reference runs at the heavy-ion same energies, given the limited understanding and predictability of production models in p-p collisions. A vigorous theoretical effort should also be supported by the community.

Note: this text should be shortened here; the longer versions come back later as well; would be useful to keep here an introduction to the small systems/cold nuclear matter business

heavy flavour In proton-nucleus collisions, open and hidden heavy-flavoured hadrons can be used to probe effects such as the modification of the effective partonic luminosity in nuclei or the multiple scattering of partons in the nucleus before and after the hard scattering. Quarkonia can also be broken through interactions with the cold nuclear matter and the comoving particles produced in the collision. Such effects should also be accounted for in nucleus-nucleus collisions where QGP is produced. During their propagation through the QGP, heavy quarks interact with the medium and lose some of their momentum. This QCD energy loss is expected to occur via both radiative and collisional processes and is predicted to depend on the colour-charge and the mass of the propagating particles. Charm and beauty quarks are therefore complementary probes to (light-flavoured or gluonic) jets. At low $p_T$, heavy quarks could also follow, through their interactions with the medium, the collective expansion of the system and eventually reach thermal equilibrium with its constituents.

The case of quarkonia is even richer since their suppression by thermal effects such as the colour screening or the Landau damping is expected to occur at different temperatures for different states; the less-bound excited states would then "melt" at lower energy densities or, equivalently, smaller centralities. If this mechanism is dominant, the in-medium dissociation rates of these states are expected to provide an estimate of the initial temperature reached in the collisions. At TeV energies, where a large number of charm quarks are produced in each nucleus-nucleus collision, a new production mechanism should be at work and the charmonium production could result from the (re)combination of initially uncorrelated charm-anticharm quarks, during the expansion of the QGP or at the hadronisation stage.

Note: This might fit here, if we make it a bit more general; remove focus on heavy quarks The first Run of the LHC has provided a wealth of measurements in proton-proton (p-p) and heavy-ion (A-A) collisions for hadrons
with open and hidden charm and beauty. The LHC data complement the rich experimental programmes at the Tevatron, the SPS and RHIC, by extending by factors of about 7, 25 and 55 the energies accessible in p-p, A-A and p-A collisions, respectively. The energy increase is particularly relevant to probe small-x nuclear effects, to study bottomonium production, to reach significantly higher pT than at RHIC and, in the case of charmonia, to confirm the (re)combination scenario of charm quarks in the QGP.

Note: We should mention some of the collectivity stuff in small systems here; just to note the 'recent interest'

2.2 Recent Experimental and Theoretical Developments

Note: The casual reader should be able to skip this section to first order; all important developments should be briefly mentioned in the big picture section and the future section (when appropriate); this section 'fills in the details'

From a theoretical point of view, we should at least mention:

- status of initial state description(s);
- convergence in LQCD calculations;
- 3D+1 relativistic viscous hydro;
- transport properties for heavy-flavoured quarks.

lattice (???): wait until the LQCD of section 3 is clear so the content is not duplicated (and the temperature $T_c \sim 155$ MeV should be quickly discussed in the particle yields paragraph anyway).

LHC Run 1 and 2, RHIC high energy (???) (suggestion of BH: maybe MvL for 2 lines stating the colliding energy available and a summary of the event stat for min bias events in AA?)

A. Global Description and Light Flavour Yields

particle yields Analysis of the ratios of hadronic yields within a statistical hadronization model (SHM) has become one of the cornerstones of our understanding of the mechanism of particle production in heavy-ion collisions. With high precision measurements at the LHC such studies enter now a new stage of quantitative predictions [?]. Note: MvL: Not so sure about this; it’s mostly a fit and we have no understanding of what the expected level of precision is (nor a systematic way of improving them) They include nowadays, besides the ratios, also fluctuations of conserved charges measured in the lattice simulations of QCD [?] that are matched with SHM.

The agreement between temperature obtained from the fits to the ratios and the pseudo critical temperature found in the lattice simulations of QCD at zero baryon density [?], indicates that hadronization takes place at the phase transition. This observation further suggests that for finite baryon density the phase transition points may lie close to the points obtained from the experimental analyses of the particle yields. This aspect is intensively studied in the case of low temperature and high density QCD matter.

The overall success of the SHM approach has been discussed widely in the past. Herein, we comment on one particular difference between the SHM predictions and the LHC data for Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [?], namely, the ratio of proton and pion abundances whose experimental value is larger than the SHM result. Several explanations of this particular effect have been given recently (hadronic rescattering, chemical non equilibrium, extra Hagedorn states) but a uniform description of this and other soft hadronic observables is missing. To constrain theoretical models it would be desirable to measure pion spectra with lower transverse momenta using low magnetic fields at the LHC. (WF, BH)

flow (simple estimate of the radial flow with blast-wave models, $T_f$ vs. mean $\beta_T$, the elliptic flow $v_2$ vs. $\sqrt{\langle NN \rangle}$ (extrapolated LHC point in LRP2010): would be great to include both 2.76 and 5.5 TeV values; e-by-e comparison of flow harmonics compared to viscous hydro models as a follow-up to box4 of LRP2010 ? Emphasize that multiple harmonics and correlations can be used to disentangle initial state (Glauber/CGC like etc) vs transport effects (viscosity). (BH,WF)

The explosive behaviour of the system while it expands and cools is evaluated systematically for different colliding systems and centrality (or multiplicity density) intervals. The radial flow can be estimated using a simple blast-wave
picture and looking into the details of the \(p_T\) spectra for identified hadrons. Note: MvL: a bit too much focused on the technology? Using hadron species with different mass, a mean transverse radial flow parameter \(\langle \beta_T \rangle\) is extracted and reflects the transverse collective motion of hadrons after kinetic freeze-out at \(T_{fo}\). Its evolution as a function of centrality translates the cooling of the system while expanding from chemical freeze-out to kinetic freeze-out while hadrons are interacting according to different cross-sections. The maximum value of \(\langle \beta_T \rangle\) obtained for common fits of \(\tau, K\) and \(p\) is close to 0.6 \(c\) for the most central collisions at the LHC: the system is \(\simeq 10\%\) more explosive when compared to most central values at top RHIC energies.

The important question of thermalisation of heavy quarks appears to be partly answered for charm: the positive elliptic flow observed at both RHIC and the LHC indicates that charm quarks take part in the collective expansion of the QGP. The degree of thermalisation is however not yet constrained. For the beauty sector, thermalisation remains a completely open issue.

\[\eta/s, \zeta/s\] One of the most important discoveries of the heavy-ion programme at RHIC is that matter produced in heavy-ion collisions behaves as almost perfect (inviscid) fluid. This behaviour is quantified by the value of the shear viscosity to entropy density ratio, \(\eta/s\), that turns out to be smaller than that of any other known substance, including the superfluid liquid helium. The estimates of the \(\eta/s\) ratio, based on the hydrodynamic modelling of the collisions, suggest the range \(1 < \eta/s < 2.5\) in the units of \(\hbar/(4\pi k_B)\) \([7]\), which is very close to the lower bound obtained from the AdS/CFT correspondance, \(\eta/s = \hbar/(4\pi k_B)\) \([7]\).

More recently, it has been demonstrated that the inclusion of bulk viscosity effects in event-by-event simulations can have an impact on both the flow harmonics and particle spectra \([7]\). This offers exciting prospects for determining the bulk viscosity to entropy ratio, \(\zeta/s\), can be estimated from experimental data.

HBT (global correlated volume and lifetime, possible plot here: correlated volume vs. dNch/deta or tau vs. dNch/deta) (BH)

Basic space-time properties associated to the hot matter system can be inferred from Hanbury Brown–Twiss (HBT) interferometry analyses. Interferences resulting from the wave functions of particles emitted at the moment of hadronization are measured. HBT radii \(R_{out}, R_{side}\) and \(R_{long}\) reflect the spatial extent along perpendicular directions at decoupling and are inversely proportional to the correlation length of the momenta for escaping identified hadrons \([7]\). The volume of the homogeneity region \((V \sim (2\pi)^{3/2}R_{out}R_{side}R_{long}\) with a normalisation assuming gaussian distributions along all dimensions) for charged pions increases linearly with the charged particle rapidity density and the correlated volume extracted in A–A collisions at the LHC at \(\sqrt{s_{NN}} = 2.76\) TeV is roughly 4800 fm\(^3\), about twice the one obtained with a similar analysis at top RHIC energy \([7]\). It basically corresponds to a correlated radius of 10.5 fm which is close to the one extracted phenomenologically from an SHM analysis of the hadron abundances. Note: MvL: next sentence too technical? The duration of the longitudinal expansion of the system i.e. until decoupling time \(\tau_{fl}\), can be estimated by fitting the \(k_{\perp}\) dependence of \(R_{long}\) with fixing \(T_{fo}\). Choosing a value of about \(T_{fo} = 120\) MeV (to be justified within the BW paragraph just before), estimating \(\tau_{l}\) at the LHC gives 10 fm/c so 30\% higher than the one obtained at RHIC (prospects with non-identical hadron correlations).

intermediate \(p_T\) \((\text{range and hadronisation mechanism(s)? ask if (PC) is interested?})\)

(hyper)nuclei production (BH) (cf Nature paper plus quick link to paragraph particle yields).

For the high temperature and low \(\mu_B\) values extracted at the LHC, matter and anti-matter are produced in equal amounts. These collisions are therefore the most abundant source of anti-nuclei in the lab. This makes it possible to compare the properties of nuclei and anti-nuclei to look for CPT violating effects. This has recently been exploited in a measurement by ALICE of the mass of anti-nuclei up to deuterons and \(^4\)He using a time-of-flight technique. No difference was observed, so that this measurement provides the most stringent constraints on CPT violation in the strong interaction \([7]\). It is also remarkable these weakly bound objects appear to be in thermal equilibrium and perfectly compatible with the aforementioned SHM results \([7]\). With the statistics expected in upcoming LHC Runs, a similar measurement is envisageable for \(^4\)He.

B. Collective effects in small systems

hydro – small systems Proton-proton, proton-nucleus, dueteron-nucleus, as well as helium-nucleus collisions have been for long regarded as reference systems for more complicated nucleus-nucleus collisions. In contrast to the latter, such systems were expected to be dominated mainly by initial state effects rather than by the final state interactions described within the hydrodynamic framework. Nevertheless, the multiplicity measured in p+Pb collisions at
Figure 4: Transport coefficient $\hat{q}$, scaled with temperature $T^3$, for a quark with $E = 10$ GeV, as determined by fitting the observed nuclear modification factors $R_{AA}$ measured at RHIC and LHC with a variety of energy loss calculations. The horizontal axis shows the temperature, which is taken from an independent fit of hydrodynamical evolution to particle production at low momentum.[?] 

$\sqrt{s_{NN}} = 5$ TeV is comparable to that produced in peripheral Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, suggesting that the energy deposited in the interaction region in the most violent p-Pb interactions may be similar to that found in the peripheral heavy-ion collisions. In fact, theoretical calculations of the initial distribution of the deposited energy in the transverse plane on an event-by-event basis, suggest the appearance of non-zero eccentricities that may lead to non-zero harmonic flows [?]. Comparison of the flow measurements for small systems confirmed the predictions of hydrodynamic calculations, hinting to common hydrodynamics-like features in various colliding systems at the RHIC and LHC energies.

The results obtained for small systems are intriguing as they call for more solid theoretical understanding. The successes of thermal models and relativistic hydrodynamics applied to heavy-ion collisions are followed now by successes connected with the use of relativistic viscous hydrodynamics in the case of small systems, in the region where this framework has not been expected to be applicable. Note: Should make a remark here about early thermalisation and mean free path vs system size. Ongoing theoretical studies envoking QCD itself, AdS/CFT correspondence, glasma theory, and possible modifications of the very hydrodynamic approach, should be continued and developed in the experimental context to understand better the nature of the space time dynamics of high-energy processes. (WF, BH)

C. Jet production and quenching

In high-energy nuclear collisions, the hard scattering rates in the initial stages of the collisions are sufficient to provide a new category of observables: Hard Probes of the QGP. The initial production of particles with high transverse momentum (quark and gluons) or large mass (heavy quarks and weak bosons) in hard scattering, can be calculated with perturbative QCD techniques. The produced particles propagate through the QGP where they interact with the thermal quarks and gluons, leading to energy loss. Experimental observables that sensitive to the energy loss are used to explore the interaction and the density of the QGP.

The simplest observable in the hard probes category is the nuclear modification factor $R_{AA}$, which has now been measured with good precision at both RHIC ($\sqrt{s_{NN}} = 200$ GeV) and LHC ($\sqrt{s_{NN}} = 2.76$ TeV). The measurements have been systematically compared with a variety of model calculations, which include the effects of collisional and radiative energy loss, with different numerical approximations of the underlying QCD calculations. The results of these comparisons are summarised in Fig. 4, which shows the transport coefficient $\hat{q}$ (the average square momentum transfer per unit medium length) at initial time $\tau_0 = 0.6$ fm/c obtained from fitting full calculations to the mea-
measurements at RHIC and LHC. The results show a good agreement between the different calculations. The transport coefficient is expected to be proportional to the third power of the temperature $T$ with a coefficient of proportionality that depends on the effective number of degrees of freedom and the strong coupling constant $\alpha_S$. The values found at RHIC and LHC are in reasonable agreement with this dependence, indicating that the degrees of freedom in the QGP at RHIC and LHC are similar, despite the different temperatures. The open boxes indicate possible future input from LHC runs at full energy and RHIC runs at lower energies.

The obtained values of $q/T^3$ are in the range 3–5, which is in reasonable agreement with theoretical expectations for a free gas of quarks and gluons. Note: this could be a good place to talk a bit about uncertainties and future improvements.

QCD energy loss via radiative as well as collisional processes, is expected to depend on the colour-charge and the mass of the propagating particles. Charm and beauty quarks are therefore complementary probes to (light-flavoured or gluonic) jets. At low $p_T$, heavy quarks could also follow, through their interactions with the medium, the collective expansion of the system and eventually reach thermal equilibrium with its constituents.

Open-heavy-flavour studies at RHIC and the LHC allow us to conclude that heavy quarks experience an energy loss in the hot and dense QGP. A mass dependence, with beauty quarks being less affected than charm quarks, seems to emerge from the comparison of data with available theory predictions. This observation crucially depends on the theoretical models, and is still limited to a restricted domain of momenta and centralities.

At low $p_T$, heavy flavour is seen to participate in the elliptic flow, indicating that the partons thermalise in the medium, presumably due to subsequent interactions.

Jets and multi-particle observables

The abundant production of high-momentum partons at LHC, with transverse momenta of up to 100 GeV and beyond, opens up the possibility to study parton energy loss differentially, for example to explore the angular distributions of radiated energy. Such measurements allow to further understand which aspects of QCD dominate the process. Several theoretical developments are ongoing to fully explore this set of observables, such as calculations of angular ordering and non-eikonal propagation, as well as more speculative approaches, using analogies to turbulent flow and strongly interacting systems, using a correspondence between gravitational calculations and quantum field theory.

Should have RAA figure with hadrons and jets, different R; do we also want $AJ$ or some fragment distributions

Figure ?? shows the nuclear modification factor $R_{AA}$ for single particles and jets. Jets are reconstructed showers of partons fragmenting into hadrons. Jets are reconstructed with a typical angular scale, the resolution parameter $R$. In proton collisions, jets reconstructed with a large resolution parameter $R > 0.4$ have been shown to accurately provide the energy and momentum of the fragmenting parton. In Pb–Pb collisions, the nuclear modification factor is below unity, meaning that jet production rates are suppressed compared to the expectation from a simple superposition of nucleon-nucleon collisions. This suppression persists for cone radii up to $R = 0.5$, indicating that there is a sizable redistribution of initial parton energy to angles larger than 0.5 radians. A number of other measurements, confirmed that there is a sizable energy redistribution to large angles, while on the other hand, measurements of the distribution of momentum inside the jet cone show only moderate changes to the jet structure. At the time of writing, it is not fully understood how these two observations are related. Moreover, there is no solid theoretical understanding of how the large-angle transport comes about, although there are various theoretical ideas, most notably ‘anti-angular ordering’ [?] and ‘democratic branching’ [?] which may provide a better understanding of the observations.

Note: an early suggestion was to discuss here also the fact that $R_{AA} < 1$ for jets up to 300 GeV; see whether we can fold that in?

D. Quarkonium production and melting

Heavy-flavour hadrons, containing open or hidden charm and beauty flavour, are important tools to study QCD, not only in the vacuum but also at high temperature. On the one hand, the heavy-quark mass acts as a large energy scale and long distance cut-off so that one can resort to perturbative QCD to treat the partonic production process. Such a reaction also takes place in the early stage of the collision, typically before the thermalisation of the QGP. On the other hand, the hadronisation of a heavy-quark pair into a quarkonium is non-perturbative which can exhibit a complex interplay with cold and hot nuclear matter effects.
The case of quarkonia is even richer since their suppression by thermal effects such as the colour screening or the Landau damping is expected to occur at different temperatures for different states; the less-bound excited states would then “melt” at lower energy densities or, equivalently, smaller centralities. If this mechanism is dominant, the in-medium dissociation rates of these states are expected to provide an estimate of the initial temperature reached in the collisions. At TeV energies, where a large number of charm quarks are produced in each nucleus-nucleus collision, a new production mechanism should be at work and the charmonium production could result from the (re)combination of initially uncorrelated charm-anticharm quarks, during the expansion of the QGP or at the hadronisation stage.

The new experimental data from the LHC is particularly relevant to probe small-x nuclear effects, to study bottomonium production, to reach significantly higher pT than at RHIC and, in the case of charmonia, to confirm the (re)combination scenario of charm quarks in the QGP.

Note: Not sure whether we want to emphasize this; basically a ‘dirt effect’ for quarkonia

In proton-nucleus collisions, open and hidden heavy-flavoured hadrons can be used to probe effects such as the modification of the effective partonic luminosity in nuclei or the multiple scattering of partons in the nucleus before and after the hard scattering. Quarkonia can also be broken through interactions with the cold nuclear matter and the comoving particles produced in the collision. Such effects should also be accounted for in nucleus-nucleus collisions where QGP is produced.

For the quarkonium families, the LHC data demonstrated the presence of thermal effects for bottomonia, which seem to exhibit a sequential suppression pattern. Together with RHIC results, LHC data are compatible with a strong thermal dissociation of charmonia, followed by regeneration. Whether production takes place throughout the full – or most of the – lifetime of the deconfined state or rather suddenly at the confinement crossover cannot be disentangled using the existing measurements.

2.3 Future plans/expected developments

One general observation seems to be that multi-parton systems thermalise much faster than expected from theoretical estimates: this is strongly suggested by the observations of collective effects in small systems, like pp and pPb collisions, but also by the fact that heavy flavour mesons participate in the elliptic flow. + early thermalisation in large systems / hydro fits

bulk viscosity More recently, it has been demonstrated that the inclusion of bulk viscosity effects in event-by-event simulations can have an impact on both the flow harmonics and particle spectra [?]. This suggests that the bulk viscosity to entropy ratio, \( \zeta / s \), can be estimated from experimental data done and the two viscosity coefficients of QGP can be determined by doing detailed comparisons between viscous hydrodynamics predictions and the experimental results. In the future, one might be able also to find the shear and bulk viscosities directly from QCD and use such values in the hydrodynamic calculations to check the overall consistency of our theoretical frameworks.

heavy flavour The main features of the data are in general understood. However, the current experimental precision (statistical) and accuracy (systematic uncertainties) is in most cases still limited. This, along with the lack of precise enough guidance from theoretical models, still prevents definite conclusions on production mechanisms in p-p collisions (for quarkonia), modifications in p-A, and extraction of key quantities for the QGP produced in A-A collisions.

The next steps in the study of heavy-flavour hadron production in heavy-ion collisions will lead to a stage of a quantitative understanding of the data, towards the extraction of the charm and beauty quarks transport coefficients and the temperature history of the deconfined state, including the temperature of the confinement crossover.

The increase in the LHC energy in the Run 2 & 3, up to 13, 8 and 5 TeV in p-p, p-Pb and Pb-Pb collisions respectively, will enlarge by two orders of magnitude the samples of these hard probes whose production is of course rare compared to light hadrons. The forthcoming runs should also be used to obtain more reliable p-p and p-A baselines, at 5 and 8 TeV.

Understanding the quarkonium-production process in p-p collisions will also provide insights on the time over which the heavy-quark remains colourful, which is an important aspect to predict medium-induced effects in p-A and A-A collisions, such as the energy loss. Extracting QGP parameters requires a proper accounting for measured feed-down fractions, a better understanding of the smaller sequential pattern observed in p-A collisions, more Pb-Pb data to properly map out the centrality dependence of the different states, and ultimately the measurement of the...
3 NUCLEAR MATTER AT HIGH $\mu_B$ AND LOW TEMPERATURE

quarkonium elliptic flows.

Lower energy measurements, be they from RHIC or new fixed-target set-ups on the SPS or even on the LHC are also therefore absolutely complementary. All this calls for upgraded or new detectors and a continuous manpower effort, which will allow for the extension of the set of observables and the precision of the measurements over a broad range of collision energies. Only these will enable us to move from qualitative to quantitative interpretations of heavy-flavour-related observables in ultra relativistic heavy-ion collisions.

Yet this would not be enough: this experimental effort definitely needs to be matched on the theory side. The contribution of theory is here of crucial importance, since accurate theoretical guidance and modelling are required to ultimately interpret these results in terms of the QGP properties. Such a stage of quantitative studies of the QGP can therefore only be reached in a close collaboration between experiment and theory.

Afterwards: to be reshuffled

2.4 Recent Experimental and Theoretical Developments at High Temperature and Low $\mu_B$

2.5 Experimental Observables to Explore the High Temperature and Low $\mu_B$ Region

3 Nuclear matter at high $\mu_B$ and low temperature

3.1 General Questions at Low Temperature and High $\mu_b$

Features of the The QCD Phase Diagram at Low Temperature and High $\mu_b$ (Vento, Gelis)

The QCD phase diagram is closely related to the history of the universe and can be probed by heavy ion collisions and compact stars studies. Of particular interest in the study of heavy ion collision experiments are the details of the deconfinement (see Fig.5) and chiral transitions which determine the QCD phase diagram. The phase diagram is conjectured to have a rich phase structure. At low temperature QCD has a vacuum, a hadronic phase and a nuclear matter phase. At high temperatures and/or densities QCD matter develops a qualitatively different phase where quarks are liberated from confinement which is called the Quark Gluon Plasma phase. This has been shown by data taken at RHIC and LHC at high temperature (T) and almost zero $\mu_b$. There is strong evidence from lattice QCD for a crossover transition from the hadronic phase to QGP for small baryon chemical potential $\mu_b$ [?]. The experimental data taken by RHIC imply that near the crossover region matter behaves as a strongly coupled liquid. The crossover nature of the transition justifies the standard scenario of the homogeneous Big Bang nucleosynthesis.

In heavy-ion collisions at lower energies nucleons get into the mid-rapidity region and the nuclear stopping power gives rise to the formation of hot matter at finite $\mu_b$. Lattice studies aimed to extend the simulation to finite chemical potential are limited to small $\mu_b > 0$ due to the so called sign problem prohibiting direct calculations for $\mu_b > 0$. Monte Carlo simulations sample a probability distribution and hence rely on the condition that the statistical weights are positive which does not happen for $\mu_b > 0$. One expects the existence of a critical point at the end of the crossover region. There is no evidence for a phase transition beyond the critical point although Effective Theories suggest the separation between the two phases as a first order phase transition [?]. This scenario is supported by the phase diagram of lattice QCD in the strong coupling limit which can be measured in the full $\mu_b - T$ plane featuring in the chiral limit a tricritical point which may be related to the critical point expected in the QCD phase diagram Strong Coupling[?]. The wishful phase diagram is shown in Fig.6.

As we just mentioned the standard scenario contemplates a first order phase transition beyond the critical point. But there is no proof of this conjecture. Another possibility that has been contemplated is that we have a region with an inhomogeneous chiral condensate instead of a sharp boundary [?]. In some Nambu Iona Lasinio models two second-order phase transitions have been found from homogeneous to inhomogeneous dynamically broken to unbroken phase. These features have been also discussed in the large $N$ limit and show up in holographic models and in the quarkyonic matter picture in real QCD. It has been argued that some features of hadro-production in relativistic heavy ion collisions may be explained by the existence of three forms of matter: hadronic-nuclear matter, quarkyonic matter and QGP [?]. These forms of matter meet at a triple point in the QCD phase diagram. Quarkyonic matter
Figure 5: The deconfinement transition: The quantity $s/T^3$ is a measure of the number of degrees of freedom, where $s$ is the entropy. The quarks and gluons act as unconfined above critical temperature.

Figure 6: The QCD phase diagram

is an exotic form of matter which can be understood as a quark Fermi sea with baryonic Fermi energy. A good physical model of quarkyonic matter is what happens with the crystalline phases of the Skyrme model. Ordinary matter can be represented by a Skyrme crystal with a certain crystal structure. When compressed ordinary matter, this Skyrme crystal, has a phase transition which is purely chiral to another crystal structure or an inhomogeneous phase [?]. Finally a second phase transition at higher densities will melt the crystal and liberate the quarks to form QGP.

This picture can be enriched at low temperature and very high density. Before all condensates melt away and QGP is realized condensation of quark-quark pairs can take place leading to color superconductivity. Color superconductivity allows for a very rich phase structure in that region depending on the various flavor-color symmetry structures, the so called Color-Flavor Locking scenarios [?].

Critical Endpoint $\mu_b$. Is there a 2nd order critical end point (of a 1st order phase transition), or is there rather a Lifshitz point, associated with an inhomogeneous (crystalline) phase? (Rischke, Friese, Vento, Gelis)

If the phase transition density is not very high we may have quark matter in the neutron star core at 5-10 nuclear
matter density ($\mu_B$). Between the phase boundary and the crossover transition we have a Critical Point (CP). The location of the CP is sensitive to the details of the models and determines the shape of the phase diagram.

Can one find the critical point experimentally? In heavy-ion experiments one might get the phase space trajectory to pass close to the CP. The critical point is characterized by thermodynamic fluctuations which are accessible experimentally [7]. The signal of a CP would be a nonmonotonic behavior of fluctuations. In the case of heavy-ion collisions one would see, for example, a bump in the fluctuations of the number of final state pions emitted in different collision events. In an ideal experiment, the correlation length would go to infinity and one would have a large enhancement of fluctuations near the critical point. In realistic heavy ion collisions, however, the size of correlation length is limited by the critical slowing down. By most estimates, the correlation length is quite modest and the magnitude of the variation of the fluctuations is limited by the size of the correlation length. However, simple arguments show that statistical fluctuations become more and more non-Gaussian as one approaches the critical point, so the higher moments grow faster with the correlation length than the corresponding powers of quadratic fluctuations. Thus these higher moments may be better signals to watch for in experiments [7].

The search for the critical point and the complete understanding of the QCD phase diagram is one of the main motivations in the physics program at BES (RHIC) and of the future CBM/FAIR experiment in Darmstadt, the NICA project in Dubna and heavy-ion facilities at J-PARK.

The Strange Dimension $\mu_B$ (Sorin, Rischke, Friese)

How far can we extend the chart of nuclei towards the third (strange) dimension by producing single and double hypernuclei? Does strange matter exist in the form of heavy multi-strange objects?

The formation of hypernuclei has been simulated by Botvina et al. [PLB 742 (2015)]7. They find that the production cross section rises in the region of energies 5 - 10 AGeV and then saturates. Extending such studies to other multi-strange metastable baryonic objects (MEMOs) in general it was found that the energy range at NICA and FAIR, together with the dedicated high luminosities at these facilities, is ideally suited for such studies of exotic composite objects [Steinheimer et al., PLB 676 (2009) 126] that shall deepen our insights to the multidimensional aspects of QCD phase diagrams. This includes also clarification of controversial questions like the existence of antikaonic nuclear bound states. According to statistical model analysis [Andronic, Braun-Munzinger & Redlich, NPA 765 (2006) 211], the excitation functions of single- and double-$K^-$ clusters should peak at NICA fixed target and NICA collider energies (or corresponding energies at the FAIR facility), respectively.

Charm Production at Threshold Energies $\mu_B$ (Friese, Vento, Gelis)

What is the production mechanism of charm quarks at threshold beam energies, how does open and hidden charm propagate in cold and in hot and dense nuclear matter.

The interest in hadrons containing charm quarks in the medium is motivated by their unique role in the diagnostic of the highly excited medium created in high energy heavy-ion collisions. As their mass is much larger than the temperature of the medium, charm quarks can only be produced in primordial hard processes in the first stage of the collisions. They thus probe the created medium during the entire evolution process. Suppression of charmonium states due to Debye screening by free colour charges was in fact the earliest proposed signature for a deconfined medium [7]. The energy dissipation of the heavy quarks is considered the most promising probe for the characterization of the QGP formed in the early stages of the collision. After hadronisation, the then-formed charmed hadrons continue to interact with the medium through collisions with lighter hadrons. Understanding of this late-stage interactions is indispensable for a reliable characterisation of the QGP phase.

Corresponding studies were so far carried out at SPS, RHIC and LHC, where charm is produced with sizable cross section. The results indicate that at the later stages of the fireball evolution a high degree of thermalization of the heavy quarks with the bulk medium consisting of light quarks and gluons is achieved. The large measured elliptic flow $v_2$ underlines that heavy quarks take part in the collective motion of the bulk medium [7, 7].

At lower collisions energies, where a medium with high net-baryon density is formed, no experimental data on charm production in heavy-ion collisions are available. In the near future, however, several machines and experimental programmes will give access to charm observables in this energy domain. Of particular interest is the question how far down in collisions energy the observations at RHIC and LHC, attributed to the formation of a QGP, continue to hold. Heavy hadrons will thus be ideal probes to study the QCD phase transition at GSI-FAIR and J-PARK [7, 7].

Moreover, the production mechanisms for charmed hadrons at lower collision energies may differ from those rel-
relevant at RHIC and LHC. Model predictions of the charm yield in this regime vary substantially, owing partly to the large uncertainty in the $c\bar{c}$ production cross section, but also to the details of the formation of charmed hadrons. Because of the steep excitation function, the sensitivity to the details of the production mechanisms is largest near the kinematic threshold. Measurements of the yields of charmed hadrons at such energies can thus be expected to give decisive input to the theoretical understanding in this area.

3.2 Unique Features of Experimental Facilities to Explore Low Temperature/High $\mu_B$

Hades (Salabura)

HADES is currently the only experiment studying properties of strongly interacting matter with rare and penetrating probes at the low-energy frontier. The experiment has recently reached an important milestone measuring Au+Au collisions at 1.23 AGeV. For the first time at such low energy, a complete measurements of strangeness production, i.e. $\Lambda$, $K^{(+,0,-)}$, $\phi$ and low-mass dileptons have been performed, supplementing results previously obtained by HADES with the medium-size collision system (Ar+KCl) and with p+Nb collisions [?], [?], [?].

![Figure 7: HADES results from Au+Au at 1.23 AGeV: (left panel) Centrality dependence of $\Lambda$, $K$ and $\phi$ production. (right panel) Invariant mass distribution of dielectrons (40% most central collisions). The data is compared to a cocktail of electron pairs from meson decay after freeze-out.](image)

The centrality dependence of the multiplicity of hadrons carrying strangeness (see Fig. 7-left) shows a stronger than linear increase with $A_{part}$, as it is expected from multi-particle collisions lifting the available energy above the production threshold. The observed $\phi/K^-$ ratio suggests that about 30% of $K^-$ originate from $\phi$-decay. Its production requires an energy $\simeq 500$ MeV above the threshold in single $NN$ collision. This observation questions interpretations assuming strangeness exchange reactions to be the dominant process for $K^-$-production at these energies. Moreover, the observed $\phi$ meson multiplicity appears to be in agreement, as well as the measured yields of $K$’s and $\Lambda$’s, with the Statistical Hadronization Model (SHM - Thermus[?]). It is remarkable that there is no canonical suppression of the $\phi$ in this model due its $s\bar{s}$ content. These findings naturally rise a more general question about the mechanism of strangeness production in heavy-ion collisions at SIS energies, even more, if the results on the double strange cascade $\Xi(1321)$ production in A+A and p+A collisions is included, which show a sizeable enhancement above predictions from SHM and transport models calculations [?]. Recently is has been argued, that the formation and decay of heavy baryon-resonances could be a source of strangeness production, for which branching ratios, however, are purely constrained [?].

The invariant mass distribution of dielectrons measured in Au+Au collisions at 1.23 AGeV is shown in the right
The yield is normalized to the number of produced neutral pions and compared to a cocktail obtained assuming the decay of mesons after freeze-out. A clear enhancement above this cocktail is observed and can be explained by assuming emission from a thermalized fireball. This contribution is calculated by coarse-graining UrQMD and utilizing emission rates based on strict vector meson dominance and a strong medium modification of the $\rho$-meson $[?]$. The $\rho$ modification is mainly driven by a strong coupling to baryonic resonance hole states ($\Delta(N^+) - N^{-1}$). The strong excess yield is understood to stem from a high density and a substantial temperature in the central region of the fireball and a substantial lifetime of this extreme state ($\simeq 10 fm/c$). While in the case of strangeness production high-mass resonances produced in multi-particle (or multi-step) processes might be instrumental, in the case of dileptons it is the decay of resonances via intermediate $\rho$’s which provides an explanation for the observations. A detailed microscopic understanding of this (baryonic) resonance dynamics is a base in the search for new exotic phases and a related, likely first-order phase transition. Such an interpretation of the low-mass excess is also supported by earlier results from $p + Nb$ $[?]$ and $Ar + KCl$ $[?]$ collisions.

NA61/Shine (Bruno)

The NA61/SHINE (SPS Heavy Ion and Neutrino Experiment) is a fixed-target experiment at the CERN SPS for the study of hadron production in hadron-proton, hadron-nucleus and nucleus-nucleus collisions. The main detectors are four large volume Time Projection Chambers (two of them in super-conducting magnets) and two Time-of-Flight walls, inherited by the former NA49 experiment. Its main physics goal is the study of the onset of deconfinement and the search for the critical point of strongly interacting matter $^2$. These goals are being pursued by investigating proton-proton, proton-nucleus and nucleus-nucleus collisions at different beam momentum from 13$A$ to 158$A$ GeV/$c$, with the programme illustrated in figure 8. Most of the data for the reference systems, namely p-p, p-Pb and Be-Be, have been collected and analyzed successfully. The first results from the light mass system (argon-scandium collisions) are expected very soon. The energy scan of the intermediate (xenon-lanthanum) and heavy (lead-lead) systems is scheduled for this year and the next one. The approved programme extends to 2017, but the Collaboration is considering a detector upgrade, which include a silicon vertex detector for open charm measurements, and a proposal for an extension of the programme by a few years.

![Figure 8: Data taking schedule for the strong interaction program of NA61/SHINE at the SPS and its proposed extension (in gray). The size of the box indicates the statistics of the collected data sample, either already collected (in green) or expected (in red).](image)

STAR (van Leeuwen, Hippolyte)

The STAR collaboration at RHIC has been performed a beam energy scan from top energies down to $\sqrt{s_{NN}} = 7.7 GeV$, and plans to improve the statistical significance of the data in a second scan.

$^2$NA61/SHINE has also a rich program for a precise hadron production measurement. To this scope $p + C$ and $\tau + C$ interactions have been studied in the past year to provide improved calculations of the initial neutrino beam flux in the long-baseline neutrino oscillation experiments as well as more reliable simulations of cosmic-ray air shower.
**NICA@JINR (Sorin)**

The Nuclotron-based Ion Collider fAcility (NICA) at the Joint Institute for Nuclear Research (JINR) in Dubna designed for energy range $\sqrt{s_{NN}} = 4 \text{–} 11 \text{ GeV}$.

The NICA accelerator facility will support world-leading programs in long base line relativistic nuclear physics and particle spin physics, radiobiology, applied research and education. It will be unique among accelerator facilities worldwide in its flexibility to support multiple research programs based on particle beams of the frontier parameters. The main goal of the project is a study of hot and dense strongly interacting matter in heavy ion (up to Au) collisions at centre-of-mass energies up to 11 $\text{AGeV}$ that corresponds to maximum achievable baryon chemical potential. It will be realized in two modes of operation: collider and extracted beams, with two detectors: MPD and BM@N. An average designed luminosity in the collider mode is $10^{27} \text{cm}^{-2}\text{s}^{-1}$ for Au. Extracted beams of various nuclei species with maximum momenta of 13 GeV/c (for protons) will be available. A study of spin physics with NICA extracted and colliding beams of polarized protons and deuterons is foreseen as well. The NICA facility (Fig. 9) includes: the injection complex, the Booster, the upgraded superconducting (SC) accelerator Nuclotron and two storage rings with two interaction points. The injection complex provides a wide set of ion species up to the heaviest one, Au, at energy of 3.2 MeV/u with the designed intensity of $2 \times 10^{9}$ particles per cycle. The NICA facility contains also the source of polarized ions with the existing linac LU-20 accelerating light ions up to 5 MeV/u that provide direct injection of polarized protons and deuterons into Nuclotron. The Booster synchrotron should accelerate ions up to 600 MeV/u. The magnetic ring of 211 m long is placed inside the window of the Synchrophasotron yoke. The upgraded Nuclotron should provide proton, deuteron (including polarized) and multi-charged ion beams with the maximum energies: 6.8 GeV/u for $A/Z = 2$ and 5.5 GeV/u for Au. The collider ring 503.04 m long has a racetrack shape and is based on double-aperture (top-to-bottom) superferric magnets - dipoles and quadrupoles.

Figure 9: Scheme of the elements of the NICA accelerator facility under construction. The Nuclotron SC accelerator is operating and the SC magnet factory has started mass production for the two collider rings and the booster ring.

The NICA accelerator facility is being developed in three stages:

1. Construction of the new injector, the booster-synchrotron and commissioning of the BM@N detector with planned start of operation for fixed-target experiments in 2017, based on the Nuclotron providing $^{197}$Au$^{79+}$ ions with a kinetic energy in the range of 1 - 4.5 GeV/u and protons up to 12.6 GeV;

2. Construction of the collider, the beam transfer line from Nuclotron to the collider and the multi-purpose detector (MPD). The two SC collider rings have a circumference of 503 m each and in order to reach the design luminosity of $10^{27} \text{cm}^{-2}\text{s}^{-1}$ for Au ions, electron and stochastic cooling systems will be constructed. The mass production of the magnets (prototypes tested in 2013) is scheduled for 2016 - 2018. The MPD detector is presently being designed;

3. Polarized ion beams (starting with deuterons, based on experience with Nuclotron since the beginning 1990-ies) and construction of the spin-physics detector (SPD) at the second interaction point, opposite to the MPD.
The construction of the collider buildings and the transfer channels was started in November 2015. The mounting of the collider elements, transfer channel and MPD parts is planned to be started beginning 2019. The start-up version of the project is planned for the end of 2019 and the completion of the NICA commissioning in the project mode is planned for 2023.

**BM@N (Sorin, Schmidt)**

The BM@N experiment at the Joint Institute for Nuclear Research (JINR) in Dubna is a fixed target experiment in preparation at the Nuclotron to study heavy-ion collisions at gold beam energies up to about 5.5 AGeV.

BM@N (Baryonic Matter at Nuclotron) is the first fixed-target experiment at the accelerator facility NICA. The aim of the experiment is to study interactions of relativistic heavy ion beams with energy from 2 to 5.5 AGeV with fixed targets. At Nuclotron energy the nucleon densities in a baryon dominated fireball produced by a collision of two gold nuclei exceed the saturation density by a factor of 3 - 4. The BM@N experiment is well suited for studies of strange mesons and multi-strange hyperons which are produced in nucleus-nucleus collisions close to the kinematic threshold. Heavy-ion collisions are a rich source of strangeness, and the coalescence of lambda-hyperons with nucleons can produce a variety of light hyper-nuclei. The planned interaction rate of the BM@N experiment running in the gold ion beam is up to 50 kHz (Fig. 10). The gold ion beam is planned in the beginning of 2019. The carbon, argon and krypton beams are foreseen in 2017. The experiment (Fig. 11) combines high precision track measurements with time-of-flight information for particle identification and total energy measurements for the analysis of the collision centrality.

**MPD@NICA (Sorin, Schmidt)**

The Multi-Purpose Detector (MPD) at the collider facility NICA at JINR in Dubna at energies of $\sqrt{s_{NN}} = 4 - 11$ GeV.

A comprehensive scan of the QCD phase diagram at NICA will be performed with beam species from protons to gold by varying the c.m.s. collision energy from 4 to 11 AGeV. Systematic measurements of the production of hadrons, (multi)strange hyperons, leptons, gammas, and light (hyper)nuclei will be conducted with the MPD (MultiPurpose Detector) experiment over a broad range of pseudorapidity ($\eta$), transverse momentum ($p_T$), and event centrality. The MPD (Fig. 12) being 9 meters long and 6.5 meters in diameter has a full azimuthal coverage and consists of several subsystems comprising precise trajectory measurements, advanced secondary vertex reconstruction, sophisticated event characterization, and excellent particle identification capability. The MPD phase-space coverage ($|\eta| < 3$, $0 < p_T < 3$ GeV/c, and full azimuth) and high event rates (up to 10 kHz, see Fig. 10) make it the ideal detector to study event-by-event fluctuations, azimuthally sensitive observables, as well as measure rare in this energy range probes such as di-leptons, $\phi$, $\Xi$, and $\Omega$.

**CBM@FAIR (Hermann, Schmidt)**
Physics at the Compressed Baryonic Matter (CBM) \cite{CBM} experiment at the future Facility for Antiproton and Ion Research in Darmstadt at the SIS100.

The research program on dense QCD matter at the Facility for Antiproton and Ion Research (FAIR) in Darmstadt will be performed by the Compressed Baryonic Matter (CBM) experiment. Part of the CBM start-up version is the large acceptance spectrometer HADES experiment, which is well suited for reference measurements with proton beams and heavy-ion collision systems with moderate particle multiplicities, i.e. Ni+Ni or Ag+Ag collisions at the lowest SIS100 energies. CBM itself is a second generation heavy-ion experiment. Its main feature is the combination of a large-acceptance, fast detector and a high-speed data read-out system capable to record very high interaction rates. This enables the experiment to measure observables which are rare in high $\mu_B$ energy domain. Examples are the flow of identified (anti-) particles, higher moments of event-by-event multiplicity distributions of conserved quantities, multi-strange (anti-) hyperons, dileptons and particles containing charm quarks. The combination of high-intensity beams with a dedicated high-rate detector system provides worldwide unique conditions for a comprehensive study of QCD matter at the highest net-baryon densities achievable in the laboratory.
3.3 Experimental Observables to Explore the Low Temperature/High $\mu_B$ region

Collective Behavior and Hydrodynamics (Hermann, Schmidt)
Collective behavior and hydrodynamical description: flow of identified particles including multistrange hyperons and dileptons, comparison with models and extraction of the EoS.

Multi-Strangeness (Hermann, Schmidt)
Excitations function of multi-strangeness, sub-threshold production and sensitivity to the density of the fireball.

Lepton Pairs (Gelis, Salabura)
Leptons pairs: sensitivity to chiral symmetry restoration, onset of deconfinement and critical endpoint.

Charm (Friese, van Leeuwen, Hippolyte)
Charm: production mechanism in the non-pertubative regime (FAIR).

Heavy Flavors (Vento)
Heavy Flavor at High Baryon Density

The interest in heavy quark hadrons in the medium is motivated by their unique role in the diagnostic of the highly excited medium created in high energy heavy-ion collisions. The good understanding of the vacuum properties of heavy quark states is one of the reasons why they are thought to be good probes for medium effects. So far experiments have focused on increasing the collision energy from 200 GeV at RHIC to several TeV at LHC. In the near future several machines will explore the region of high baryon density in order to investigate the critical point in the QCD phase diagram.

Heavy quarks are produced in the primordial quark collisions of the nuclear reactions and therefore they probe the created medium during the entire evolution process. The energy dissipation of the heavy quarks is considered the most promising probe for the characterization of the QGP formed in the early stages of the collision. The two main processes through which a heavy quark looses energy are elastic collisions and the radiative loss due to the interaction of heavy quarks with the light quarks and gluons of the medium. However to make the characterization of the QGP reliable the role of the hadronic phase must be taken into consideration. When the system cools down hadronization takes place and the resulting heavy-flavor mesons can be detected. They suffer collisions with light mesons ($\pi, K, \bar{K}, \eta$) rearranging their momentum until freeze-out and then creating a nuclear modification ratios $R_{AA}$ different from 1 and a finite elliptic flow $v_2$. At RHIC and LHC, $R_{AA}$ for (open) heavy flavor, shows a large
suppression at high transverse momenta. This indicates that at the later stages of the fireball evolution a high degree of thermalization of the heavy quarks with the bulk medium consisting of light quarks and gluons is achieved. The large measured elliptic flow $v_2$ underlines that heavy quarks take part in the collective motion of the bulk medium [?, ?].

At low-intermediate energies and high densities close to the critical point experimental studies have not been jet carried out. Theoretical studies for dense matter tend to indicate that the elliptic flow does not change much with respect to that of high energies and low density. On the other hand $R_{AA}$ might change a lot depending on the initial state parametrization of the quark momentum distribution. Thus the results of the various calculations are not conclusive. The experimental study and subsequent theoretical analysis in this case will help understand the degree of thermalization of the heavy quarks and their corresponding transport properties. If the relaxation time is long enough to not fully thermalize but short enough to undergo no significant re-interactions with the medium, heavy hadrons will be ideal probes to study the QCD phase transition at GSI-FAIR and J-PARK [?, ?].

Hypermatter

Since the recent very accurate mass measurements of two 2-solar-mass neutron stars the interaction of hyperons in matter has become a central topic for the attempts to model heavy neutron stars. The problem is that hyperons are expected to appear at densities which are somewhat larger than the nuclear-matter saturation density, but which are still below the central density of a typical neutron star. The appearance of hyperons softens the EoS to an extent that neutron stars with masses of order two solar masses should not exist. Thus, to understand role of hyperons in matter, experimental access to hyperon-nucleon ($YN$) and hyperon-hyperon ($YY$) interaction is indispensable. However, $YN$ or $YY$ interaction are notoriously difficult to measure, as there are obviously no hyperon targets. Beams of multi-strange particles are possible in principle, but due to the relatively short decay length of hyperons ($c\tau < 10$ cm) they have to be boosted to several 100 GeV/c to allow for an identification of hyperons by beam-defining elements [?]. However, at these energies (elastic) scattering is suppressed and hence the determination of the scattering length from a partial-wave analysis not feasible. As “tools” to investigate the properties of hypermatter one is left with the following possibilities:

(1) to measure $YN$ and $YY$ correlations: Femtoscopy is a well established tool to determine the source size of a fireball created in heavy-ion collisions. If the source size is comparable to the interaction range of the particles under consideration, one expects substantial effects of the particles’ final-state interaction on the correlation function [?].
However, the bound \( \Lambda \Lambda \) states only at unphysical pion masses. Extrapolation to physical masses yielded an unbound \( H \)-dibaryon. However, the \( H \)-dibaryon is predicted as a resonance by some models \([?, ?]\), which motivates the search for the \( H \)-dibaryon as a resonant structure in the correlation function \([?]\). Common to all three tools is that the corresponding particles or event type is very rare. Present measurements (Ref. ALICE, STAR, NA49, KEK) due not allow unambiguous conclusions due to insufficient statistics. CBM is designed as a next-generation, high-rate experiment operating at energies which imply high baryonic densities. Model calculations (Ref Andronic, Steinheimer) show that in this energy range the production of hypermatter, i.e., light single or double hypernuclei and multi-strange objects is maximized. According to Fig. X one would expect to measure events have been found, and only one \( \Lambda \Lambda \) event has been unambiguously identified.

**Fluctuations** (van Leeuwen, Hippolyte)

Fluctuation of conserved quantities: search for the critical end point .

### 3.4 Models for the description of matter at “very” high high High \( \mu_b \): phase transition, signatures to identify the state of matter? (Sorin, Rischke, Gelis, Friese, Vento)

At “very” high \( \mu_b \) and relatively low temperatures it is expected that the phase diagram of QCD may exhibit a region of coexistence of hadronic and quark matter (“mixed phase”), characteristic for a first order phase transition and delimited by a critical endpoint (CEP), analogous to the liquid-gas phase transition of water or of nuclear matter. Measuring the CEP position in the QCD phase diagram is a key goal for the beam energy scan programs at RHIC, CERN-SPS and future dedicated experiments like FAIR-CBM and NICA-MPD. Most of the models for the phase transition use a Maxwell construction to obtain the limits of a mixed phase region between separately developed models for the hadronic and the quark matter equations of state (EoS) and necessarily fail to predict a critical point. The estimates for the phase transition region vary in a broad range from high densities \((8.5 - 17 \, n_0)\), see [Khvorostukhin et al. EPJCB 48 (2006) 531]) to rather low densities \((2.5 - 3.2 \, n_0)\), see [Fischer et al. Arxiv:1603.03679 (2016)]). Heavy-ion collision event simulation based on the HSD/PHSD transport theory [Bratkovskaya EPJWoC 97 (2015) 00006] is suitable for modeling a crossover transition but not yet developed for a first order phase transition.

In the molecular-dynamics based description the UrQMD simulation of the initial and final stages without [Auvinen and Petersen, PRC 88 (2013) 064908] and with [Karpenko et al. PRC 91 (2015) 064901] viscosity effects “sandwiches” a hydrodynamic description of the first order phase transition in the expansion stage of a hot, dense fireball but cannot appropriately address the baryon stopping regime of heavy-ion collisions at energies up to \( \sqrt{s} \sim 10 GeV \), i.e. The case of NICA and FAIR energies. An adequate description of the baryon stopping regime of a heavy-ion collision is provided by a three-fluid hydrodynamics based event simulation [Batyk et al. (in preparation, 2016)] that can take into account a first-order phase transition already in the early compression stage [Ivanov, PRC 87 (2013) 064904].

In this description a characteristic signature of a first-order phase transition in the EoS as compared to a crossover transition or a purely hadronic EoS is a characteristic change in the curvature of the net proton rapidity distribution at midrapidity in the c.m. energy range of \( 4 - 8 \, AGeV \) which is robust against kinematic acceptance cuts of the NICA-MPD experiment [Ivanov and Blaschke, PRC 92 (2015) 024916]. A new event generator “THESCoN” based on three-fluid hydrodynamics model [Ivanov, PRC ] is being developed
with unique capabilities to address a first order phase transition in the baryon stopping phase of HIC at high $\mu_B$ and low temperature for NICA and FAIR energies. Simulations are presently being prepared for publication, the "smoking gun" signal as a benchmark test is the irregularity (wiggle) in the energy scan of the midrapidity curvature for the net proton rapidity distribution [Ivanov and Blaschke, PRC (2015)]. Other interesting signals concern multipolar flow observables for identified particles and effects of baryon vorticity, hydrodynamic helicity and polarization [Baznat et al., JPCS 668 (2016), PRC (2016)]. The process of identifying Physics targets for the exploration of a possible first order phase transition in the region of the QCD phase diagram accessible to NICA and CBM and the possible observable effects of a “mixed phase” has been conducted since 2009 and culminates this year in the release of the “NICA White Paper” as a Topical Issue of the European Physical Journal A (2016).

4 Computing, facilities and instrumentation

4.1 Computing

FAIR computing

The data challenge imposed by the two big data producers at FAIR, CBM and PANDA, is similar in scale to those of the LHC experiments. The rapid technology development in terms of the density of compute power and the bandwidth available for data storage, however, led to a shift of paradigm for the design of the experiments. High-rate data taking is enabled not by hardware triggers, but by reconstructing and selecting physically interesting data in real-time. As a consequence, FAIR computing differs from the conventional approach in two aspects: the maximal archival rate is limited not by output bandwidth, but by the cost of storage media; the interaction rate limit is determined not by the detector and electronics capacities, but by the computing power deployed online for data selection. Thus, large on-site compute facilities and storage capacities are decisive for the physics reach in terms of collected event statistics.

For modern experiments, online computing is not an optional add-on for the increase of sensitivity, but an integral prerequisite for the operation. This has also consequences for the offline compute model and needs. The online clusters will be composed of commercial off-the-shelf hardware, which can also be used for offline computing in the experiment downtimes. As an example, the online cluster of CBM will comprise the equivalent to about $10^5$ CPU cores, comparable in size to the entire LHC grid compute resources. In general, offline computing will shift away from the GRID approach to a small number of big data centres connected by high-speed networking, which offer computing access to a regionally defined group of users.

To make efficient use of modern computing hardware, both for online and offline purposes, parallel programming is indispensable. The needed software skills exceed those that nowadays can be assumed for the average physicist. This situation calls for an increased effort in training on modern programming technologies, but also for the development of adequate data processing frameworks by experts, shielding the physics user from the complexity of parallel computing paradigms. An example of such efforts is the common development of the FAIR and ALICE experiments in the context of the ALFA framework.

4.2 Facilities

4.3 New instrumentation

5 Recommendations

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