4.2 Properties of Strongly Interacting Matter

4.2.1 Introduction

Basics of QCD 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 described 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 interaction. For the weak and strong forces, these fields are also charged under the gauge symmetry.

The quantum field theory that describes the strong force, Quantum ChromoDynamics (QCD), 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-$\frac{1}{2}$ constituents which, to the extent allowed by the spatial resolution of the experiments, are point-like, and (ii) these constituents are nearly free when probed at very short distances. QCD is the simplest field theory consistent with these properties and with the multiplets observed in hadron spectroscopy; it is a non-abelian gauge theory endowed with an internal local $SU(3)$ symmetry, in which the charged matter fields are referred to as *quarks* and the mediators of the force as the *gluons*.

Although there are six flavours of quarks (up, down, strange, charm, bottom and top), only the lightest two (up and down) appear in the valence composition of nucleons. The heavy quark flavours 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.

Two important properties of QCD are *asymptotic freedom* and *colour confinement*: 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). This behaviour 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. Neither quarks nor gluons exist as isolated particles in Nature, and the only stable arrangements are colour-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) or from more than three quarks, have been suggested to exist. For instance, it is believed that tetraquark states have been produced in several experiments. Pentaquarks states have been much more elusive so far, but may have been seen in the products of proton-proton collisions at the LHC. However, despite the fact that confinement prevents a direct observation of quarks and gluons, they 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 hadronic matter under extreme conditions: at sufficiently high nuclear density or temperature, the average inter-parton distance becomes small, and therefore their interaction strength weakens. Above a critical energy density of the order of 0.3 GeV/fm^3, a gas of hadrons undergoes a deconfinement transition and becomes a system of unbounded 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 around the critical energy density. The deconfinement of quarks and gluons is accompanied by a restoration of chiral symmetry, spontaneously broken in the QCD vacuum.

In the cooling history of the Early Universe, the primordial quark-gluon plasma (QGP) turned into hadrons around a few microseconds 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 QGP may be re-created in the laboratory via heavy ion collisions at sufficiently high energies, within volumes of the order of the nuclear size.

QCD phase diagram In equilibrium, the phase structure of nuclear matter is controlled by a small number of local thermodynamical parameters: the temperature T and the chemical potentials associated to conserved quantities, the most important of which is the baryon chemical potential, $\mu_{\rm B}$, related to baryon number conservation. Figure 1 summarizes our present knowledge of the phase diagram in the $T, \mu_{\rm B}$ plane. More specifically:

(a) In the chiral limit of two-flavour 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.

(b) For QCD with its physical spectrum of small but non-zero up and down quark masses and a heavier strange quark, the transition from the low- to the high-

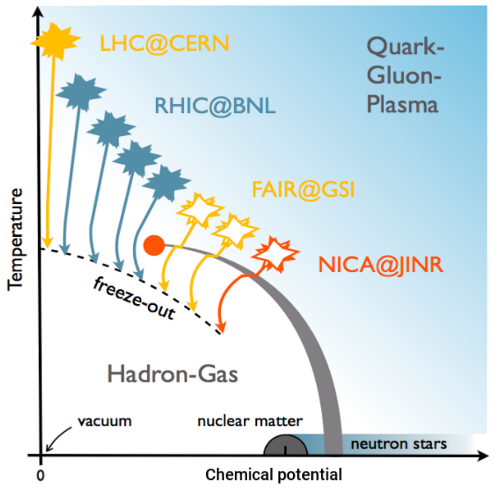


Figure 1: Illustration of the QCD phase diagram. Adapted from J. Phys. Conf. Ser. **432** (2013) 012013, courtesy of C. Schmidt.

temperature regime is rapid and accompanied by large changes in the properties of strongly interacting matter. However, it is presumably not a genuine phase transition but a "cross-over transition". At vanishing baryon chemical potential this transition occurs at about $k_B T = 155$ 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. In this asymptotic regime, nuclear matter 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 cross-over region, in particular on the high-temperature side of the transition, nuclear matter is strongly coupled. In this region, the transport coefficients are very small, implying a strong collective behaviour of the nuclear matter. This has profound consequences on our understanding of heavy ion collisions: despite large space-time gradients in these collisions, strongly interacting matter exhibits properties similar to that of an ideal fluid.

(e) One or more colour-superconducting phases exist at asymptotically large net baryon number density and sufficiently low temperature. It is rather likely that this phase is homogeneous, but it may display spatial variations of the colour-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 0.16 nucleons per fm^3. Upon heating, it undergoes a first-order liquid-gas transition, which ends in a critical point of second order. 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-principle 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, using models that have some resemblance to QCD while avoiding its technical problems. To give one example, in QCD with a large number of colours, a new phase, termed the "quarkyonic phase", was proposed at low temperatures and baryon chemical potentials exceeding that of the nuclear matter ground state. However, without experimental constraints, these model approaches often lead to inconclusive results.

Equation of state, thermodynamics and transport
The equation of state (EoS) and other thermodynamical properties of a system in equilibrium are encoded in its partition function, while its transport coefficients can be extracted from the low momentum behaviour of spectral functions.

In regions of high temperature and/or high baryon chemical potential, a perturbative approach is possible thanks to asymptotic freedom. In regions where the coupling constant is large, non-perturbative calculations are necessary. In the strip where $\mu_{\rm B}/T \ll 1$, one may use lattice QCD. However, lattice QCD fails at large $\mu_{\rm B}$ due to "sign problem": the integrand is not positive definite and thus cannot be sampled by a Monte-Carlo method. Various analytical methods have been developed to circumvent this problem, but they all involve truncations and are therefore approximate. More details on these techniques can be found in Box. 1.

Heavy-ion collisions The idea to collide heavy ions accelerated at ultra-relativistic energies for bringing nuclear matter into the deconfined QGP phase and studying its properties in the laboratory dates back to the

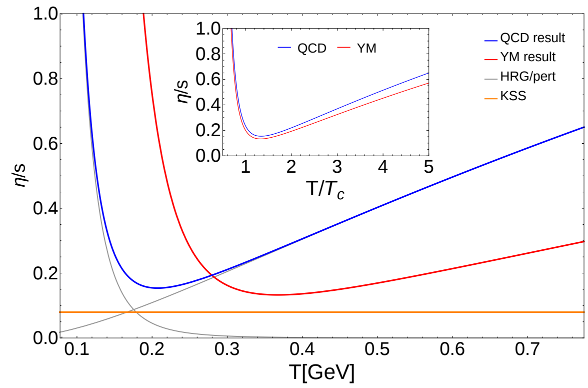
Box 1 - Theoretical tools for calculating the EoS and transport coefficients

At high temperatures or high chemical potentials, asymptotic freedom allows to compute the partition function perturbatively in terms of a power series in the strong coupling constant, provided one resums the large corrections due to collective effects (e.g. Debye screening, Landau damping...).

As one decreases temperature and chemical potential towards values of the order of the QCD scale parameter, $\Lambda_{QCD} \sim 0.2$ GeV, weak coupling techniques are no longer applicable. A non-perturbative first-principle approach is lattice QCD. Calculations with physical quark masses are computationally expensive, but advances in computing hardware and algorithms have rendered them feasible. See the section 4.2.4 for a discussion of the computing resources needed in this area.

This method works very well only for vanishing baryon chemical potential. At non-zero $\mu_{\rm B}$, the fermionic determinant contained in the integrand becomes complex valued, precluding Monte-Carlo samplings. At small baryonic chemical potential ($\mu_{\rm B}/T \lesssim 1$), other methods (reweighting, Taylor expansion, analytic continuation of calculations performed at imaginary $\mu_{\rm B}$) may be used to partially circumvent this problem.

When applied to the calculation of transport coefficients, lattice QCD faces an additional difficulty related to the extraction of a spectral function from an Euclidean correlator, which requires some prior information about the unknown spectral function. A common approach is the Maximal Entropy Method (MEM), a Bayesian method to obtain the most likely spectral function.



Besides lattice QCD, other non-perturbative first-principle methods are functional methods in the continuum, such as Dyson-Schwinger equations (DSEs) or the Functional Renormalization Group (FRG), that do not suffer from the fermion sign problem and can thus be applied at any value of T and $\mu_{\rm B}$. Although a priori exact, these approaches require truncations in practice, which makes them approximate. The figure shows the FRG calculation of the shear viscosity to entropy ratio as a function of temperature (from Phys. Rev. Lett. **115** (2015) no.11, 112002).

early ’80s (see the Box 2 for a timeline of heavy-ion facilities). Pioneering studies at the Brookhaven Alternating Gradient Synchrotron (AGS) and the CERN Super Proton Synchrotron (SPS) promptly demonstrated that the energy deposit and the nuclear stopping in the central rapidity region were quite large. At higher center-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. Nevertheless, the initial energy density in the central rapidity region, inferred from the number of produced particles via Bjorken’s formula, keeps increasing with energy. The net baryon density at mid rapidity approaches zero already at RHIC energy ($\sqrt{s_{\rm NN}} = 200$ GeV), and the initial energy density in central PbPb collisions at the LHC ($\sqrt{s_{\rm NN}} = 2.76$ TeV) is more than an order of magnitude larger than that of the deconfinement transition predicted by lattice QCD. The challenge for the coming years consists in a detailed experimental characterization of the different features of the phase diagram (e.g. the critical endpoint) as well as a determination of the parameters that characterize the hot medium (e.g. its transport coefficients). In this quest, the experimental control variables are the colliding energy, the ions used in the collisions and the centrality of the collisions.

4.2.2 High-temperature matter

In this Section, we focus on the strongly interacting QGP (sQGP) produced in nuclear collisions at the highest available energies. In these collisions, a QGP is formed with high temperature and low baryon chemical potential $\mu_{\rm B}$, i.e., with a minimal excess of quarks over anti-quarks. The QGP produced in these collisions is therefore very similar to the QGP in the early Universe and is in the low $\mu_{\rm B}$ limit where lattice QCD calculations

Box 2 - Timeline of heavy-ion facilities

Bevatron (Billions of eV Synchrotron) : from 1954 to 1993 at Lawrence Berkeley National Laboratory, U.S.
AGS (Alternating Gradient Synchrotron) : since 1960 at Brookhaven National Laboratory, U.S. It is now used as injector for RHIC.
SPS (Super Proton Synchrotron) : since 1976 at CERN. It is now the injector for the LHC.
RHIC (Relativistic Heavy Ion Collider) : since 2000 at Brookhaven National Laboratory, U.S.
LHC (Large Hadron Collider) : since 2009 at CERN.

are reliable.

The goal of the high energy heavy-ion programme is to identify and characterize the properties of the QGP. This programme naturally has two steps: understanding the dynamics of heavy-ion collisions, e.g., via comparison to phenomenological models, and the extraction of fundamental QGP/QCD properties that can be compared to (lattice) QCD results.

Figure 2 illustrates the **three main stages** of a heavy-ion collision: (i) an early non-equilibrium stage, (ii) an expansion stage, and (iii) a final freeze-out stage. An advantage of this modular structure is that it allows for the use of more or less advanced theoretical tools in each stage. In this way the modeling of heavy-ion collisions can be gradually improved and used to constrain further the properties of strongly interacting matter. This picture, and the associated phenomenology, has indubitably evolved over the last 30 years as observables have been identified that are sensitive to specific processes in each phase.

The first stage, which also provides initial conditions (spatial distribution of the deposited energy and pressure, initial flow velocity) for the subsequent hydrodynamical stage, is the least known and is often described by simple geometrical models (e.g. the Glauber Monte-Carlo approach) in which the underlying strong interactions are encapsulated in the inelastic nucleon-nucleon cross-section. More ab-initio descriptions, such as the Colour Glass Condensate (CGC), in which one treats the collision in terms of partonic degrees of freedom (mostly gluons in the relevant kinematical regime for RHIC and LHC) and the QCD interactions, are being actively developed nowadays. Although some observables that have been measured by LHC experiments in PbPb collisions (e.g. J/ψ photo-production) provide evidence for nuclear gluon shadowing, further efforts are required to extract its amount. A more comprehensive study of this regime of large nuclear gluon density will be possible at the Electron-Ion Collider (EIC) currently planned in the USA, by allowing a direct measurement of nucleonic and nuclear structure functions, and in particular the longitudinal one which is most directly sensitive to the gluon content. In the CGC picture, the initial scatterings produce a dense system (made of strong colour fields, the so-called Glasma) that quickly approaches a hydrodynamical regime. It takes less than a fm$/c$ for the system to become a nearly perfect fluid whose expansion can be described by relativistic viscous hydrodynamics.

During the second stage –the fireball expansion–, the bulk evolution is described by relativistic viscous hydrodynamics. Due to the near perfect fluid nature of the QGP, the initial geometrical anisotropy is efficiently converted into a momentum anisotropy of the final particles. Event-by-event fluctuations lead in the final state to significant higher order harmonics (triangular flow and above) of the azimuthal particle distribution, in addition to the 2$^{\mathrm{nd}}$ order one (elliptic flow). Their systematic measurement has recently provided an avenue for constraining initial-state model calculations and transport properties of the QGP both at RHIC and the LHC. Moreover, this bulk evolution provides the substrate for the medium modifications of hard probes, although a better integration of these two aspects of the description is certainly needed.

Hadronisation takes place when the system reaches the pseudo-critical temperature (in the hydrodynamical description, this transition is encoded in the EoS). After hadronisation, the scattering rate decreases quickly and a kinetic description becomes more appropriate than hydrodynamics. This third stage may be described by hadron cascade models such as, e.g. UrQMD. Given the cross-sections for the scatterings between the various hadrons species, this kinetic description can in principle describe the (possibly successive) decoupling of the hadrons from the fireball. The measured relative abundances of hadrons indicate that chemical freeze-out happens at a temperature T_{ch} which is very close to the hadronisation temperature and at nearly zero μ_{B}. Subsequently, the hadrons continue to rescatter elastically until they reach the kinetic freeze-out temperature, T_{fo}, where they decouple and freely stream to the detectors.

Since the last NuPECC long range plan, the Large Hadron Collider (LHC) at CERN has started and completed its first heavy-ion running period, 2010-2013, and begun its second period, 2015-2018. The new LHC data extend the rich experimental programmes at the Bevatron, SPS and RHIC, increasing by factors of

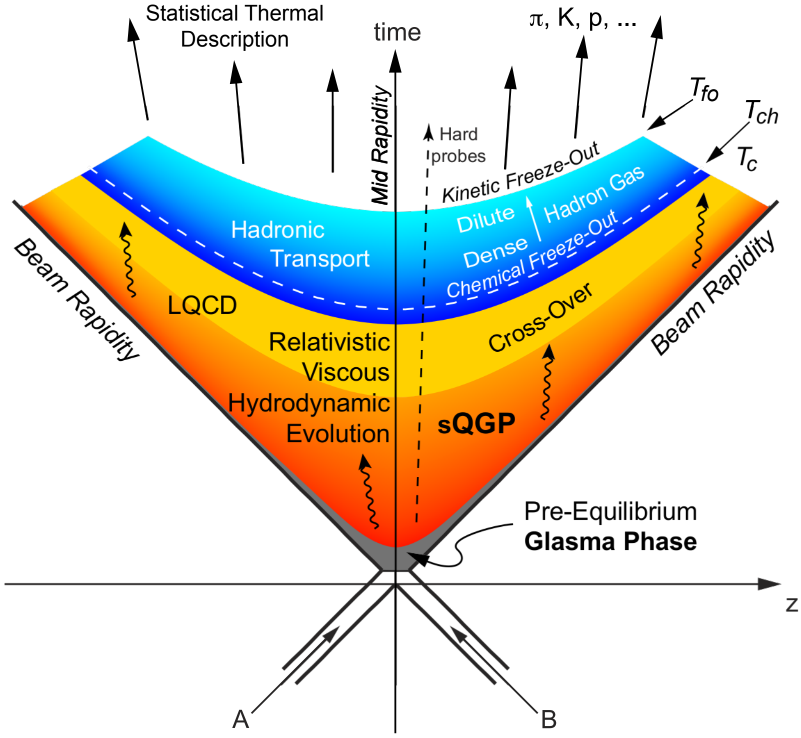


Figure 2: Space-time evolution of the system created in heavy-ion collisions. The different stages are specified on the right side and some theoretical tools used to describe them are listed on the left side.

about 7, 25 and 55 the energies accessible in proton-proton, heavy-ion and proton-ion collisions, respectively. This jump in collision energy has provided abundant access to so-called **hard probes**, whose production is calculable within perturbative QCD and any modification due to the propagation through the medium can be used to probe the QGP properties. At the LHC, the energy loss of heavy charm and bottom quarks can be directly compared for the first time, which allows to test the quark mass dependence of the energy-loss mechanisms. The much more abundant charm production greatly increases the J/ψ production rate by coalescence of c and $\bar{c}$ quarks. The J/ψ yield in PbPb collisions at the LHC is consistent with deconfinement followed by such a recombination. For Υ states, the much larger production cross-section has enabled the first measurement of the dissociation of the 1S, 2S, and 3S bottomonium states individually.

In addition to the rich new set of heavy-ion results from the LHC, unexpected novel insights related to initial state dynamics has come from pp and pPb collisions. It was expected that these collisions would mainly provide a calibration of the initial state and it was therefore surprising to observe large azimuthal anisotropies of the underlying event in these systems. These asymmetries are very similar to those seen in heavy-ion collisions, where they are attributed to the creation of the sQGP perfect fluid.

The LHC has run pPb collisions again in 2016, due to the large interest in small systems, and it is expected that in 2018 there will be a long PbPb run. In 2019-2020, LHC will be shut down to upgrade and prepare the experiments for Run-3. The goal of the heavy-ion upgrades is to be able to handle optimally the factor ~ 10 increase of the event rate to 50 kHz. In the case of the ALICE detector, which is the only dedicated heavy-ion experiment at LHC, the upgraded detector will be able to analyze the full rate of events online, thereby increasing the sensitivity for most measurements by one to two orders of magnitude.

Recent Experimental and Theoretical Developments One of the long-standing puzzles in the field is the question of how the colliding system evolves quickly towards a local isotropic state in momentum space. Two important developments were made recently towards solving this '**fast isotropisation**' puzzle. On the one hand, descriptions of the initial state based on CGC initial conditions have shown that the approach to isotropy in such dense systems is much faster than in the hard-scattering regime. On the other hand, developments within relativistic viscous hydrodynamics have shown that significant deviations from isotropy can be realized even with a small viscosity. These developments offer the perspective of describing via viscous hydrodynamics the full evolution from the initial saturated gluon state to the final freeze-out stage, in an almost seamless fashion.

Unlike hadronic observables, whose prediction is complicated by final state interactions, **photons and dileptons** interact only electromagnetically and therefore escape from the fireball without reinteracting after production. The yield of thermal photons (i.e. the black body radiation from the hot QGP) is very sensitive to the QGP temperature and can be predicted by a combination of QCD perturbative calculations and hydrodynamical simulations. Direct photons have been measured in PbPb collisions at the LHC ($\sqrt{s_{\rm NN}} = 2.76$ TeV). At low p_T, one observes an excess over the non-thermal photons (prompt photons from collisions of the quarks and antiquarks contained in the incoming nuclei, photons from meson decays, etc...) that agrees reasonably well with model predictions of thermal photons (with an initial QGP temperature around $k_B T = 400$ MeV at a time $\tau_0 = 0.4$ fm/c for central collisions).

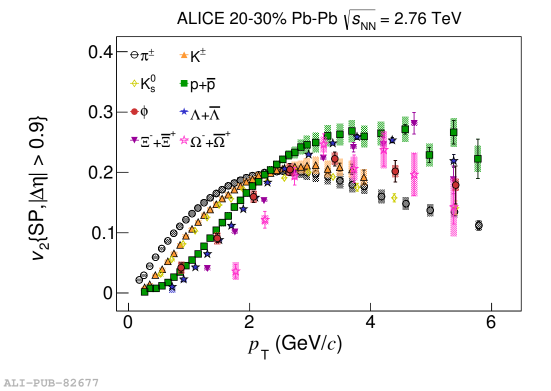


Figure 3: Elliptic flow coefficient as a function of transverse momentum, for various hadron species. From JHEP **06** (2015) 190.

One of the most important discoveries of the heavy-ion programme is that matter produced in heavy-ion collisions behaves as a nearly perfect (inviscid) fluid. This conclusion was already reached based on RHIC data, and the LHC has shown that it also holds for systems with higher initial temperature. Fig. 3 shows the relevant experimental results of the second-order harmonic anisotropy v_2 (elliptic flow) as a function of p_T, for different particles. The results are compatible with calculations of relativistic fluid dynamics (hydrodynamics) in which the fluid has a very low viscosity. Deviations from an ideal fluid may be quantified by the **shear-viscosity-to-entropy-density ratio** η/s. This ratio is estimated by comparing hydrodynamical calculations to the measurements in Fig. 3, leading to a value in the range $1 < \eta/s < 2.5$ in units of $\hbar/(4\pi k_B)$. This value is smaller than that of any other known substance, including superfluid liquid helium, and is very close to the value $\eta/s = \hbar/(4\pi k_B)$ obtained in some exactly solvable field theories in the limit of infinite coupling, suggesting that the QGP is also a strongly interacting medium. 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 offers exciting prospects for determining the bulk viscosity to entropy ratio, ζ/s, from experimental data.

The important question of the **thermalisation of heavy quarks** appears to be partly answered for charm: the positive elliptic flow of charmed hadrons indicates that charm quarks take part in the collective expansion of the QGP. Their degree of thermalization is however not well constrained. For the bottom sector, thermalisation remains an open issue.

Analyses of the ratios of hadronic yields within **statistical hadronization models** (SHM) indicate a temperature of chemical freeze-out just below the hadronisation temperature, and almost zero baryon chemical potential. Nowadays, these models also include, besides the ratios, fluctuations of conserved charges inferred from susceptibilities computed in lattice QCD simulations.

For the high temperature and low $\mu_{\rm B}$ values extracted at the LHC, the yields of matter and anti-matter are almost equal (they differ only by the baryon number of the incoming nuclei, that remains localized at forward rapidities). These collisions are therefore the most abundant source of anti-nuclei in the laboratory. This makes it possible to compare the properties of nuclei and anti-nuclei in order to look for CPT violating effects. This has recently been done in a measurement by ALICE of the mass of anti-nuclei up to anti-deuterons and $^3\overline{\rm He}$. Within the achieved experimental undertainties, no difference was observed, so that this measurement provides the most stringent **constraint on CPT violation** in the strong interaction. It is also remarkable that the yield of these weakly bound objects is perfectly compatible with the SHM predictions, suggesting they are in chemical equilibrium. With the statistics expected in upcoming LHC runs, a similar measurement may be possible for $^4\overline{\mathrm{He}}$.

Basic space-time properties of the fireball can be inferred from **Hanbury Brown–Twiss (HBT) interferometry** analyses. The volume of the system at freeze-out is found to increase linearly with the charged particle rapidity density at RHIC and the LHC. The largest volume at the LHC ($\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV) is approximately $4800\ \mathrm{fm}^3$, about twice the volume obtained from a similar analysis at top RHIC energy. This volume corresponds to a radius of 10 fm which is close to the one extracted phenomenologically from SHM analyses of the hadron abundances. The HBT analysis also provides information about the duration of the longitudinal expansion of the system. The estimated time until freeze-out at the LHC is about 10 fm/c, which is 30% larger than the value obtained at RHIC.

Two important recent measurements of **parton energy loss** at the LHC are shown in Fig. 4. The left panel, from the CMS experiment, shows an event display of a dijet event in a heavy-ion collision: the red towers in the figure indicate 'jets', i.e., regions with large transverse-energy flow, which are remnants of high-energy quarks or gluons. Without a QGP, the two jets are expected to have equal p_{T}'s. The observed imbalance therefore indicates that (at least) the lowest energy jet has lost a large amount of energy. The emerging picture from jet measurements at the LHC is that the particle distribution inside quenched jets appears to be roughly similar to that in unquenched jets of the same reconstructed energy and that the lost energy is recovered in the form of low momentum particles at large angles (above 0.5 radians). Moreover, there is no complete theoretical understanding of how the large-angle transport comes about, although various theoretical ideas have been proposed, most notably 'anti-angular ordering' and 'democratic branching', which pave the way to a better understanding of these observations. These topics will form the core programme of future research on parton energy loss and jet quenching at the LHC.

Energy loss can be further quantified via the momentum dependence of the **nuclear modification factor** R_{AA}, the ratio of an invariant yield obtained in heavy-ion collisions to an incoherent superposition of the same yield in nucleon-nucleon collisions. Parton energy loss manifests itself by lower-than-unity values of this ratio, at high momentum. The measured nuclear modification factors at the LHC are summarised in the right panel of Fig. 4. A large suppression is observed in central PbPb collisions, where the plasma is larger and hotter. Furthermore, there is a difference between R_{AA} for light hadrons ($\pi^{\pm}$), D mesons (which contain a charm quark) and non-prompt J/ψ from heavy B mesons (which contain a bottom quark) decays. This difference is in line with theoretical models that include interference effects that depend on the velocity, and hence on the mass, of the propagating particles.

An important aspect of the parton-medium interaction is the **path-length dependence** of the parton energy loss. Different energy loss mechanisms have different characteristic path-length dependences: collisional energy loss would give a linear dependence, while radiative loss gives a quadratic dependence (at lowest order) due to quantum-mechanical interference effects in the regime probed in heavy-ion collisions. Even stronger path-length dependences have been obtained in the strong coupling limit and QCD synchrotron radiation. Several measurements have been made to explore the path-length dependence of energy loss, most notably using dijets (and dihadrons) or the azimuthal anisotropy of jet quenching. However, extracting the path-length dependence of the energy loss requires both a dynamical understanding of the medium's density evolution and detailed modeling of the parton-medium interactions. The first aspect is closely related to the emerging global description of the system, while the second is a topic of active theoretical developments. A general trend is that jet quenching studies lead to somewhat larger initial energy densities than those required for the hydrodynamical description of the flow measurements. More precise differential measurements and further developments of the jet quenching theory are needed in order to understand the matching between the descriptions of the soft and hard sectors.

Quarkonia, which are rare bound states of a heavy flavour (charm or bottom) quark and anti-quark, are particularly important hard probes, because the QGP medium is expected to dissolve these bound states leading to an observable suppression. Each charmonium and bottomonium state has a different binding energy and one expects a gradual melting of the more tightly bound states (from less to more bound) as the plasma temperature increases. The in-medium dissociation rates of these states are therefore expected to provide an estimate of the initial (see Fig. 5) temperature reached in the collisions. The LHC data have demonstrated such thermal effects for bottomonia, which seem to exhibit a sequential suppression pattern of the 1S, 2S, and 3S states.

At the LHC, where a large number of charm quarks are produced in each nucleus-nucleus collision, one measures a sizeable increase of J/ψ at low p_{T} relative

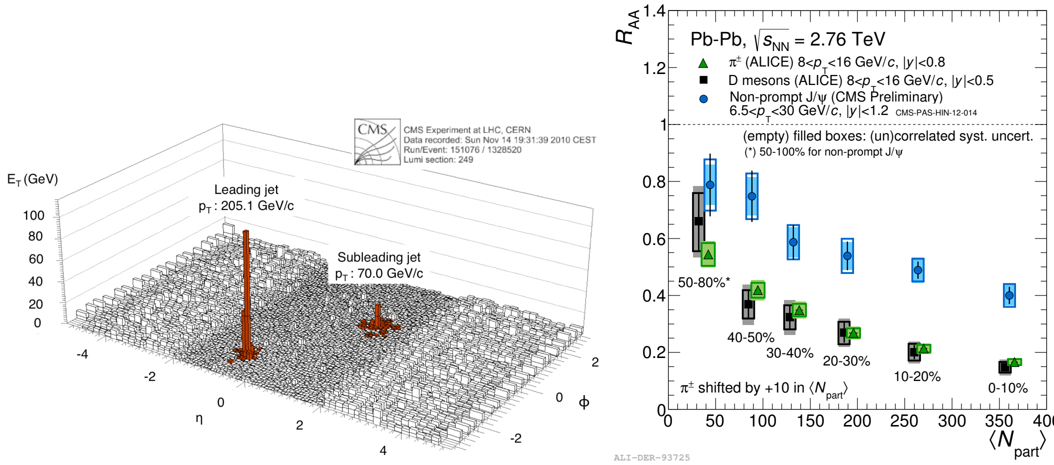


Figure 4: The left panel shows the transverse energy E_T distribution in a single event as a function of the azimuthal angle ϕ and the pseudorapidity η (from Phys. Rev. **C84** (2011) 024906.). The large imbalance in transverse energy of the two jets (marked in red) indicates that at least one of the partons has lost significant energy in the Quark-Gluon Plasma. The right panel shows the event-averaged nuclear modification factor $R_{\rm AA}$ for light hadrons $\pi^{\pm}$, heavier D charm mesons, and non-prompt J/ψ from bottom quark decays (from JHEP **1511** (2015) 205 and JHEP **1205** (2012) 063). The suppression ($R_{\rm AA} < 1$) is stronger for more central collisions (larger $\langle N_{\rm part}\rangle$) and the particle species differences are as expected from the quark-mass dependence of the energy loss.

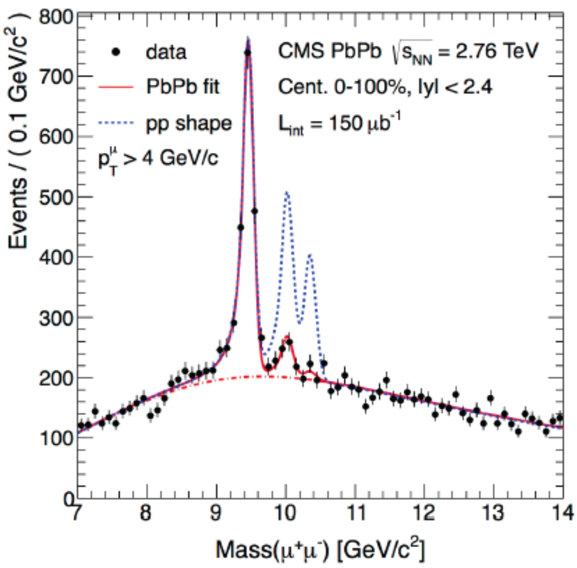


Figure 5: Yield of dimuons in the invariant mass region of the Upsilon states. Points: LHC data in PbPb collisions. Solid line: PbPb fit. Dotted line: rescaled pp invariant mass spectrum. From Phys. Rev. Lett. **109** (2012) 222301.

to the suppression at higher $p_{\rm T}$, and a lower overall suppression than at RHIC. This is compatible with a strong thermal dissociation of charmonia, followed by recombination of charm and anti-charm quarks produced initially in two separate hard scatterings. Whether production takes place throughout the full – or most of the – lifetime of the deconfined state or rather suddenly at the confinement cross-over cannot be disentangled using the existing measurements, but requires a larger set of measurements, including additional quarkonium states.

Collisions of small systems, such as proton-proton, proton-nucleus, deuteron-nucleus, as well as helium-nucleus, have for long been thought to be dominated mainly by initial state effects rather than by final state interactions. Nevertheless, the multiplicity measured in pPb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV is comparable to that produced in peripheral PbPb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV, suggesting a similar deposited energy for a comparable number of participating nucleons. In addition, flow measurements for these collisions of small systems have shown significant multiparticle correlations in the final state. These results for small systems are intriguing and various theoretical explanations have been proposed, ranging from the hydrodynamical expansion of a proton-sized droplet of fluid to correlations inherited from the wavefunctions of the incoming projectiles in a CGC description. These theoretical studies should be continued and developed, accompanied by an active programme of measurements to further explore the similarities and differences between PbPb and pPb collisions, in order to better understand the nature of the space time dynamics of high-energy collisions. Another dimension to study these phenomena would be to explore various combinations of projectiles and geometries, something that could be achieved with a second ion source at CERN.

Future plans and Expected developments The research programme for the properties of the Quark Gluon Plasma at high T and low $\mu_{\rm B}$ concentrates on nuclear collisions at the largest available energies which provide the hottest, densest, and longest lived QGP. The experimental programme is therefore aiming at the full exploitation of the high-energy collisions delivered by the LHC. The most important open questions that will be addressed in the coming years are in four different areas, namely thermalisation/isotropisation at early times, jet modification and energy flow (including flavour dependence), the interplay of hot and cold matter effects in quarkonium production and absorption, and finally the use of electromagnetic observables to probe the initial state temperature and possibly get insight in the mechanism for chiral symmetry breaking. Progress in each of these areas rely on larger data samples for more precise and differential measurements, as well as a continuous dialogue between experimental results and theoretical developments.

As discussed earlier, we now understand the early time development of the collision much better than at the time of the previous Long Range Plan: it is clear that dense gluon field dynamics drives the system towards isotropy much faster than initially thought and that viscous fluid dynamics can accommodate the residual anisotropy. The dense gluon fields in the nucleus may be probed by measurements of forward particle production, which are being performed by LHCb and the forward muon arm of ALICE. In the 2016 pPb run, the LHC has operated at a higher energy and therefore probed larger gluon densities. ALICE is also studying a possible future upgrade with a forward calorimeter, to measure direct photon production, which would provide a direct measure of the gluon density in the nucleus in a new regime.

The discovery of collective effects in pp and pPb collisions poses an important new question: what is the minimum system size or density that can produce flow? This question is the subject of active theoretical work. Experimentally, this will be further explored using pPb collision data recorded during the 2016 run and new analysis techniques that are under development. This programme is expected to lead to an understanding of QCD dynamics that encompasses small and large systems.

In heavy-ion collisions, heavy quarks provide a promising probe of thermalisation, since they are produced early in the collision and then interact with the flowing medium. First results are available, but the large data samples of LHC Run-2 (2015-2018), Run-3 (starting in 2021) and Run-4 are needed in order to achieve the precision required to discriminate different scenarios. The ALICE detector will be upgraded to improve the measurement of heavy flavour flow at low $p_{\rm T}$, a very sensitive probe of thermalisation.

New observables are being explored to improve the determination of QGP properties. In particular event-plane correlations, flow fluctuations and correlations between harmonic coefficients have been shown to be sensitive to the bulk viscosity. In the coming years, the bulk viscosity to entropy ratio, ζ/s, may be estimated from experimental data, so that the two main viscosity coefficients of QGP can be determined. In the future, the shear and bulk viscosities might be found directly from QCD and one will use these values in the hydrodynamic calculations in order to check the overall consistency of the theoretical frameworks.

The high energy of the LHC has opened up a new area of research, using fully reconstructed jets to probe the properties of the QGP. The results from the first LHC run clearly show a large energy loss, but also pose new questions, in particular about the mechanism for energy redistribution to large angles. The cleanest probe of this process would be to measure events with a hard jet and a hard photon (or Z boson) whose energy is measured and serves as a reference for the initial jet energy. Proof-of-principle measurements of this type have been performed already, but the large data samples of Run-2, Run-3 and Run-4 are needed to provide a quantitative measure of the energy redistribution in these events and consequently discriminate scenarios for parton energy loss in the QGP. In parallel, theoretical tools to calculate multiple parton emissions in QCD are being developed.

In the area of quarkonia, several effects are expected to play a role, including the melting of quarkonia in the QGP, cold nuclear matter effects, such as hadronic co-movers and initial state energy loss, and the recombination of heavy quarks into quarkonia. Future measurements of the excited charmonium states, as well as higher precision measurements of the bottomonium states in pPb and PbPb collisions will help to disentangle these effects.

Direct photon and dilepton measurements provide the cleanest probes of early dynamics, including thermal radiation and potential signals of the chiral phase transition through in-medium spectral functions of the ρ and other vector mesons. These measurements are extremely challenging and require large data samples and low background (gamma conversion) conditions, with no possibility to perform on-line selections of the collisions. Measuring dileptons to identify thermal radiation is one of the most challenging goals of the ALICE upgrades for the period after 2020.

The interest in this field and the opportunities at the LHC are clearly illustrated by the growing community of high-energy nuclear physicists: the European community of heavy-ion physicists, which was initially almost exclusively involved in ALICE, includes at present sizeable groups in both CMS and ATLAS, as well as a starting activity within LHCb. In the coming years, a number of detector upgrades are planned (see Section 4) and the LHC will provide larger collision energies at higher interaction rates. This may allow exploring the temperature and density dependence of the basic properties of hot QCD matter, and refining the hard probe measurements so that they become quantitative tools. An active programme on collective effects in small systems is also under development. We consider it crucial that all these aspects of the LHC programme, including the detector upgrades, are well supported in the coming years.

4.2.3 High-density matter

In parallel to the study of high-temperature QCD matter as described in the preceding section, the interest in nuclear collisions at lower energies has grown substantially over the past decade and has led to a number of experimental programmes at existing facilities and even to new accelerator facilities now under construction (cf. section 4.2.4). The goal of these programmes is to explore the structure of the QCD phase diagram at non-vanishing baryon chemical potential $\mu_{\rm B}$.

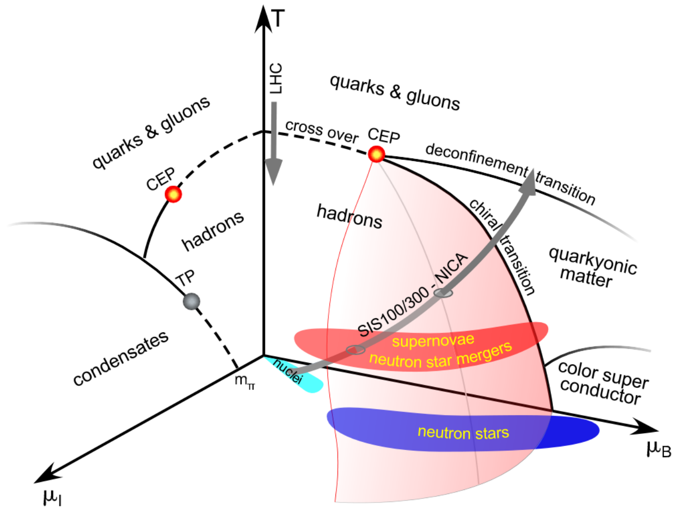
At moderate collision energies, baryon number is transported from the colliding nuclei to the mid-rapidity region, thus creating there a medium with finite net-baryon density. The study of the hadron yields at chemical freeze-out as well as transport models indicate that the net-baryon density (or, equivalently, the baryon chemical potential $\mu_{\rm B}$) increases with decreasing beam energy, with a maximum around 30A GeV, where a density of up to ten times that of the nuclear ground state is reached, i.e., a density which we expect to find in the cores of neutron stars. The corresponding part of the phase diagram can presently not be addressed theoretically by first-principle calculations like lattice QCD (cf. section 4.2.1). QCD-inspired effective models, however, suggest a rich structure as illustrated in Box 3. Its features are a first-order phase transition to deconfined matter, which is separated from the cross-over region at low $\mu_{\rm B}$ by a critical point. Moreover, at large $\mu_{\rm B}$, the restoration of chiral symmetry could fall apart from the transition to deconfined matter, giving rise to a confined phase with partially restored chiral symmetry. This "Quarkyonic" matter appears in the QCD limit of a large number of flavours and can be described as a Fermi gas of confined quarks with baryonic excitations. At very high $\mu_{\rm B}$ and low temperature, it is expected that condensation of quark pairs takes place, leading to the phenomenon of colour super-conductivity. This gives rise to a rich phase structure in that region, depending on the various flavour-colour symmetry structures.

Considering also non flavour-symmetric matter opens additional dimensions to the QCD phase diagram. As an example, hyper-matter (with non-zero strangeness content) in form of single or double hyper-nuclei, where one or several nucleons are replaced by a hyperon, or in form of other multi-strange metastable objects (MEMOS) can be studied in nuclear collisions. Model calculations indicate that the most promising energy range is 5A - 10A GeV. This includes also the clarification of controversial issues like the existence of anti-kaonic nuclear bound states.

Beyond its importance for the understanding of fundamental properties of QCD, the study of high-density matter is also of high interest in the context of astrophysics. The recent discovery of neutron stars with masses of about two solar masses imposes severe constraints on the nuclear EoS, since the appearance of hyperons softens the EoS to an extent that such heavy neutron stars may collapse into black holes. Heavy-ion collisions at moderate energies produce baryon densities similar to those in the core of neutron stars ($\rho/\rho_0 > 5$), albeit at higher temperature and with different net-isospin. They should thus allow to extract features of the EOS which are relevant for the understanding of the stability of neutron stars. Their study hence complements the direct observation of neutron star radii with improved resolution.

Experimental handles for the exploration of the QCD phase diagram

The detection of the landmarks of the phase diagram of strongly interacting matter at large net-baryon densities (e.g., first-order phase transition, critical point) would constitute a breakthrough in our understanding of QCD. There is, however, little quantitative guidance from theory as to the location of these landmarks in



Box 3 - Features of the QCD Phase Diagram at Low Temperature and High Density The 3-dimensional QCD phase diagram at high baryonic $\boldsymbol{\mu_B}$ and moderate isospin $\boldsymbol{\mu_I}$ densities has a rich and yet largely unexplored structure: a critical endpoint separates a smooth cross-over from a first order as well as a chiral phase transition at high baryon densities. New and exotic phases like quarkyonic matter or color superconducting phases might appear at baryonic high densities. At very high μ_B a superfluid color-flavor-locked phase is speculated on. Supernovae are formed at initial proton fractions ≈ 0.4 which reduce to ≈ 0.1 for cold neutron stars. Heavy-ion collisions at FAIR or NICA energies are expected to probe this region as well as the conjectured phase boundaries to quarkyonic or fully deconfined matter.

the phase diagram. The general experimental strategy is thus to scan the $T - \mu_B$ plane by variation of the collision energy and the system size, looking for non-monotonicities or discontinuities in the excitation function of observables sensitive to the properties of the hot and dense matter. In the following, we discuss some of these observables.

The **collective flow of hadrons** is driven by the pressure gradient created in the early fireball, and thus provides information on the dense phase of the collision. In particular, the directed flow v_1 and the elliptic flow v_2 are expected to be sensitive to the details of the phase transition and the softening of the QCD matter EOS, and are important observables for clarifying the role of partonic degrees of freedom. Recently, the STAR collaboration has measured directed flow and elliptic flow in AuAu collisions at energies from $\sqrt{s}_{_{\rm NN}} = 62.4$ GeV down to $\sqrt{s}_{_{\rm NN}} = 7.7$ GeV. A significant difference in the flow of particles and anti-particles is found at lower collision energies, i.e., with increasing μ_B. Moreover, both the sign and the magnitude of this difference are species-dependent. This points to the turn-off of the flow scaling with the number of constituent quarks, which is indicative for partonic degrees-of-freedom. However, at the lowest energy only pions, kaons, (anti-) protons and (anti-) Λ could be identified, and no firm conclusion on the origin of the species-dependent splitting could be reached. The data situation will drastically improve by measuring the flow of identified particles in the FAIR and NICA energy range, including multi-strange hyperons and dileptons. Of particular interest is the flow of particles not suffering from rescattering like Ω hyperons or ϕ mesons, for which no experimental data exist. These measurements will significantly contribute to our understanding of the QCD matter EoS at neutron star core densities.

Particles containing strange quarks are important probes of the excited medium created in heavy-ion collisions. At higher energies, strange particle yields are consistent with those expected from an equilibrated hadron gas. In particular, the equilibration of Ω baryons was taken as a strong argument for the system having undergone a transition to a deconfined state, since it cannot be understood in terms of hadronic two-body relaxation processes in the limited lifetime of the fireball. Following this argumentation, the yields of multi-strange hyperons are indicative for a deconfinement phase transition. This conjecture is supported by microscopic transport calculations modeling both a hadronic and a partonic phase, which find anti-hyperon yields strongly sensitive to a possible QGP phase.

According to hadronic transport models not featuring a partonic phase, multi-strange baryons are produced in sequential collisions involving kaons, Λ and, possibly, higher-mass resonances. Their yields are therefore strongly sensitive to the density of the fireball. This sensitivity is expected to increase towards lower beam energies close to or even below the production threshold in elementary collisions. Measuring the excitation function of multi-strange hyperons ($\Xi^-, \bar{\Xi}^+, \Omega^-, \bar{\Omega}^+$) in AA collisions with different A values is thus most promising to study the compressibility of nuclear matter at high densities and to determine the nuclear EoS.

The data situation for multi-strange hyperons in the SPS and AGS energy range is rather poor owing to the low production cross-sections. An intriguing result, however, has been reported at the lowest energies by the HADES collaboration: in Ar+KCl collisions at $1.76A$ GeV, the measured yield of Ξ^- exceeds the Statistical Hadronization Model expectation by about a factor of 20, which indicates that the production of multi-strange particles is far off equilibrium at low energies. The measurement of these rare probes with high precision at future high rate experiments will decisively improve our knowledge on the nature and properties of the medium they are produced in.

Experimentally closely related to strangeness measurements is the study of **hyper-matter**, which has become a central topic for the attempts to model heavy neutron stars. Of particular importance for the understanding of the stability of such astrophysical objects is information on the hyperon-nucleon (YN) and hyperon-hyperon (YY) interaction. Experimentally, such information can be obtained by measuring YN and YY ($Y = \Lambda, \Xi, \Omega$) correlations, by measuring the production yields and lifetimes of hyper-nuclei such as ${}^{5}_{\Lambda\Lambda}$H or ${}^{6}_{\Lambda\Lambda}$He, or by the search for exotica, like the hypothetical H-dibaryon $(\Lambda\Lambda)_b$ or other strange compound objects.

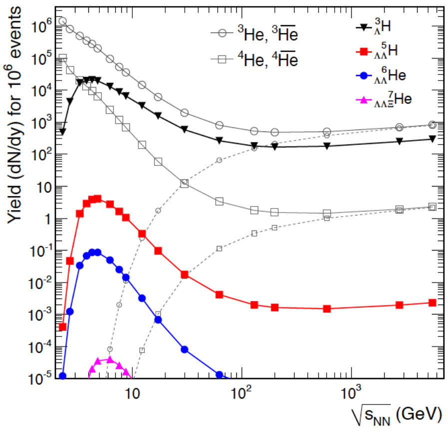


Figure 6: Energy dependence of hypernuclei yields at midrapidity for 10^6 central AuAu collisions as calculated with the Statistical Hadronization Model. The predicted yields of ^{3}He and ^{4}He nuclei are included for comparison. From Phys. Lett. B **697** (2011) 203.

In heavy-ion collisions, hyper-nuclei may be produced by the coalescence of hyperons with nucleons or light nuclei in the final stage of the reaction. Thermal model calculations show that the most promising energy range is the FAIR/SIS-100 regime (Fig. 6). Still, the expected yields for hyper-nuclei or strange dibaryons are very low and necessitate high-rate experiments. As an example, the CBM experiment promises to measure e.g., ${}^{5}_{\Lambda\Lambda}$H and ${}^{6}_{\Lambda\Lambda}$He in large quantities, which would represent a breakthrough in hyper-matter physics, as up to now only six candidates for double-Λ hyper-nuclei events have been found, and only one ${}^{6}_{\Lambda\Lambda}$He event has been unambiguously identified.

The **dilepton radiation** carrying undistorted information from the fireball is an excellent tool to study properties of the strongly interacting matter in various aspects. Thermal radiation in the low-mass region (LMR) ($M < 1\,\mathrm{GeV}/c^2$) is saturated by spectral functions of the light vector mesons weighted by the temperature distribution and integrated over the collision time. It is a measure of the total lifetime of the fireball and hence can serve as a chronometer of the collision. Dileptons in the LMR are also a sensitive observable to study chiral symmetry restoration as a function of T and μ_{B}. In the QCD vacuum, spectral functions of hadrons show splitting of parity doublets (i.e ρ and a_1) induced by the spontaneously broken chiral symmetry, which is predicted to vanish at high energy densities. A consistent explanation of the thermal dilepton rates in the LMR, measured at SIS-18 (HADES), SPS (NA60/CERES) and RHIC energies, is given by the radiation from a strongly medium-modified ρ meson. As an example, Fig. 7 shows the dielectron spectrum measured by HADES in AuAu collisions at 1.23A GeV. The microscopic description is based on hadronic many-body theories with a dominant role played by the ρ-baryon interactions. The underlying connection to the chiral symmetry is provided by the QCD and Weinberg sum rules relating the spectral functions of the vector (ρ) and the axial-vector (a_1) mesons with the quark and gluon condensates which can be calculated by lattice QCD. Using such connections, it was shown for vanishing μ_{B} that the evolution of the a_1 spectral function with temperature is consistent with chiral symmetry restoration close to T_c.

The intermediate-mass region (IMR) from 1 to 3 GeV/c^2 provides an estimate of the temperature of the fireball at its early stage and hence can serve as a thermometer. Furthermore, the mass spectra are Lorentz-invariant and thus not affected by the collective expansion. On the other hand, transverse momenta and flow observables provide information on collective effects. At SPS and RHIC energies, the main contribution to IMR are given by QGP radiation, correlated heavy flavour decays and charm annihilation. At lower energies, however, the charm contribution is decreased, and radiation from multi-pion annihilation, in particular a_1-π fusion and axial-vector mixing can be expected. It is there-

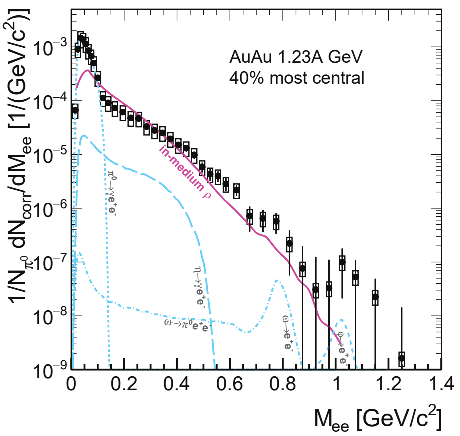


Figure 7: HADES results from AuAu at 1.23 AGeV: Invariant mass distribution of dielectrons (40% most central collisions). The data are compared to a cocktail of electron pairs from meson decays after freeze-out and contribution from in-medium ρ. From: HADES collaboration (priv. comm.), in preparation.

fore of utmost importance to provide high quality data at these energies in both the LMR, where the effects of baryons on the ρ meson are especially strong, and the IMR, where no data exist.

The interest in **charmed hadrons** is motivated by their unique role in the diagnostic of the highly excited medium created in high-energy nuclear 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 deconfinement. 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 (cf. section 4.2.2). After hadronisation, the then-formed charmed hadrons continue to interact through collisions with lighter hadrons. Understanding of this late-stage interactions is indispensable for a reliable characterisation of the QGP phase.

Studies investigating charm production were so far carried out at SPS, RHIC and LHC, where charm is produced with sizable cross-section. The results on charmonium indicate that at the later stages of the fireball evolution a significant 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 of D mesons underlines that heavy quarks take part in the collective motion of the bulk medium.

At lower collisions energies, where a medium with high net-baryon density is formed, the production mechanisms for charmed hadrons are likely to differ from those 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, where no experimental data on charm production in heavy-ion collisions exist yet. 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 in the high-μ_{B} domain.

Event-by-event fluctuations of conserved quantities such as baryon number, strangeness and electrical charge can be related to the thermo-dynamical susceptibilities of the matter under investigation and thus are the prime tool to search for critical phenomena as expected in the vicinity of the QCD critical point, where the susceptibilities diverge in the limit of infinite matter. Hence, large non-statistical fluctuations are expected in heavy-ion reactions if matter is created at T and μ_{B} close to the critical point. It has to be noted, though, that the finite size of the system created in the collision limits the correlation length even near the critical point, such that quantitative predictions on the size of the fluctuations are not at hand. Simple arguments, however, show that the event-wise distributions become more and more non-Gaussian when approaching the critical point, such that higher moments grow faster with the correlation length than the quadratic ones. Higher moments (skewness, curtosis) are thus expected to be more sensitive to critical behaviour than just the width of the distributions.

Measurements have been performed by the STAR collaboration in order to search for the QCD critical point at beam energies down to $\sqrt{s_{NN}} = 7.7$ GeV. Figure 8 depicts the (volume-independent) product $\kappa\sigma^2$ of moments of the net-proton multiplicity distribution as a function of the collision energy, measured in central AuAu collisions. There are indications for a deviation from the Poisson expectation at the lowest measured energies. These data clearly call for a high-precision measurement of higher-order fluctuations at

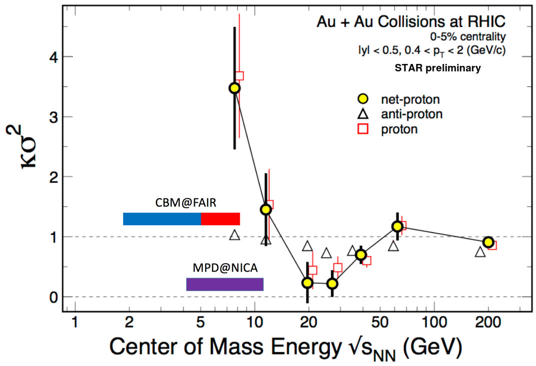


Figure 8: Energy dependence of the product of moments $\kappa\sigma^2$ of the net-proton multiplicity distribution (yellow circles) for top 0-5% central AuAu collisions. The Poisson expectation is denoted as dotted line at $\kappa\sigma^2 = 1$. From arXiv:1601.00951v2 [nucl-ex]. The solid bars indicate the energy ranges accessible by FAIR and NICA, respectively.

lower beam energies in order to search for the peak in $\kappa\sigma^2$ as expected in the presence of a critical point.

Current experimental activities

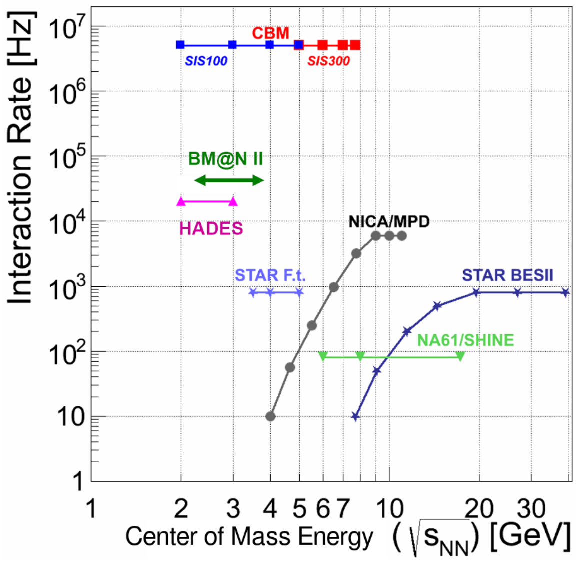
HADES at SIS-18 (GSI) is presently studying properties of strongly interacting matter with rare and penetrating probes at the low-energy frontier. The experiment has recently reached an important milestone by measuring AuAu collisions at 1.23A GeV. For the first time at such low energy, a complete measurement of strangeness production, i.e. Λ, $K^{(+,0,-)}$, ϕ, and low-mass dileptons has been performed. The results indicate the formation of a long-lived system where sub-threshold particle production and dilepton radiation is confined to the high-density phase of the collision. These results supplement those previously obtained by HADES with the medium-size collision system Ar+KCl and with p+Nb collisions where also the double-strange Ξ^- hyperon was measured. HADES also conducts a hadron physics programme with proton and pion beams focused on the role of baryon resonances in strangeness and dielectron production.

NA61/SHINE is a fixed-target experiment at the CERN SPS for the study of hadron production in hadron-proton, hadron-nucleus and nucleus-nucleus collisions. Its main physics goal is the study of the onset of deconfinement and the search for the critical point of strongly interacting matter. These goals are being pursued by investigating proton-proton, proton-nucleus and nucleus-nucleus collisions at different beam momentum from 13A to 158A GeV. Up to now, data from p+p, Be+Be and Ar+Sc collisions were taken at six different beam energies. The energy scan with medium-size (Xe+La) and heavy (Pb+Pb) systems are scheduled for the years 2017 and 2018. Beyond its approved programme, the collaboration plans for a detector upgrade including a silicon vertex detector for open charm measurements at the higher SPS energies and an extension of the programme by a few years.

NA61/SHINE has also a rich programme for a precise hadron production measurement. In this context, p+C and π+C interactions were studied in the past years 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.

Future plans

In the near future, two major accelerator facilities will come into operation, which will open up new possibilities for the exploration of high-density QCD matter with heavy-ion experiments (cf. section 4.2.4). The Facility for Anti-Proton and Ion Research (FAIR), currently under construction in Darmstadt, will in its first stage provide nuclear beams up to 14 GeV per nucleon for symmetric nuclei and 11 GeV per nucleon for heavy ions with the SIS-100 synchrotron. In a later stage, a second accelerator (SIS-300) will extend the energy range to about 45 GeV per nucleon. At this facility, the **Compressed Baryonic Matter Experiment (CBM)** will measure both hadronic and leptonic probes with a large acceptance in fixed-target mode. For this next-generation experiment, the emphasis is put on very high rate capability, with the ambitious design goal of 10 MHz peak rate. Such interaction rates will overcome the limitations in statistics suffered by current experiments and permit the measurement of extremely rare probes like e.g., yields and flow of identified anti-baryons, in particular multi-strange hyperons, intermediate-mass lepton pairs, 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. CBM is expected to start operation in 2022. The nuclear collision programme at FAIR is complemented by the HADES spectrometer moved to the SIS-100 accelerator, 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 lower SIS-100 energies.



Box 4 - Overview on experiments exploring the high-density region Existing and future experiments will map out the phase diagram at different energies and interaction rates: the beam energy scan of STAR at RHIC connects the low and high μ_B regions. The future MPD experiment at NICA will measure excitation functions in the region of highest baryon densities. Both experiments, however, suffer from the collider-typical decrease of luminosity at lower beam energies. The future experiment CBM at FAIR will run at substantially higher interaction rates. However, to fully map the region of high μ_B an upgrade of the SIS-100 to SIS-300 is mandatory. NA61 is a fixed target experiment at the SPS, which, however, is limited in rate by the TPC employed. HADES and BM@N cover a similar, - lower-, energy range. They have, however, a quite different focus with respect to observables.

The new accelerator complex NICA at JINR Dubna will allow to study hot and dense strongly interacting matter at centre-of-mass energies up to 11 GeV per nucleon pair in collider mode. **MPD** is a collider experiment designed to perform a comprehensive scan of the QCD phase diagram with beam species from protons to gold by varying the c.m.s. collision energy from 4 to 11 GeV per nucleon which complements the RHIC beam energy scan towards lower energies. The MPD acceptance ($|\eta| < 3$, $0 < p_T < 3$ GeV/c, and full azimuthal coverage) and relatively high event rates (up to 10 kHz, see Box 4) make it an ideal detector to study event-by-event fluctuations and azimuthally sensitive observables. The unique feature of MPD as a collider experiment is the invariant acceptance at different beam energies as compared to fixed-target experiments. This, however, is counter-balanced, as for all collider experiments, by a sizeable decrease in interaction rate at lower energies (see Box 4). Thus, the study of rare probes such as dileptons, ϕ, Ξ, and Ω, is restricted to the higher beam energies. MPD will start operation in a staged approach, with first beams in the NICA collider expected in 2019 and reaching its full capabilities by 2023.

Extracted beams from the NICA facility will also allow a fixed-target programme in a limited energy range but with higher interaction rates. The **BM@N** experiment, currently being constructed, plans for data taking at the NICA nuclotron with heavy beams up to 4.5 GeV per nucleon from 2019 on. It will measure yields and flow of identified hadrons at interaction rates of up to 50 kHz.

Outside Europe, the STAR collaboration plans a second phase of the RHIC beam energy scan programme (BES-II) in the years 2019-2020, with increased statistics owing to an upgrade of the RHIC accelerator with electron cooling, and with improved detector performance resulting from an upgrade of the existing time-projection chamber. The programme focuses on fluctuation and flow measurements in search for the QCD critical point. While being less sensitive at low energies because of limited statistics, BES-II will extend the energy range accessible by FAIR and NICA to higher energies and is thus complementary to the FAIR and NICA plans. In addition, STAR also plans to take data in fixed-target mode by inserting a target in the beam halo. This would give access to bulk probes in the low-energy range.

Together with the programmes at SPS and RHIC, the new experiments at FAIR and NICA will provide a complete coverage of the energy range relevant for the investigation of QCD matter at large net-baryon densities, albeit with varying sensitivity depending on the accessible interaction rates. The running and planned experiments show a large degree of complementarity, e.g., in terms of acceptance or run mode (fixed target / collider). The experimental landscape is summarised in Box 2, showing the coverage in energy range and interaction rates of the various experiments.

Beyond the future experiments already under construction as outlined above, there are plans for further experimental projects, which are yet in a conceptual stage. The project **NA60+** aims at a high-precision study of thermal radiation and charmonia by the measurement of muon pairs in fixed-target nuclear collisions at the SPS, with an experimental concept similar to that of the NA60 detector. Such measurements would be complementary in energy range to the muon programme of CBM, and complement the programmes of RHIC-BES, NA61 and MPD in the same energy domain, which do not have access to muon measurements. Furthermore, plans for a heavy-ion physics programme at J-PARC, Tŏkai, are currently under consideration. These would add an additional heavy-ion accelerating scheme to the current facilities, providing extracted heavy-ion beams up to 19 GeV per nucleon for fixed-target experiments. The aim is also to arrive at very high beam intensities, comparable to those at FAIR.

4.2.4 Facilities, computing and instrumentation

Facilities and Experiments Several facilities in Europe are currently operating, in construction or in discussion, to provide heavy-ion collisions at various energies, to explore different regions of the phase diagram. We give a brief overview of the facilities and the relative experimental programmes for the next decade. We start from facilities which are existing and operating (the LHC), continue with those whose realization is already approved and on-going (FAIR and NICA), and then discuss further plans which are under exploration for the future (NA60+ at the SPS, AFTER at the LHC, the Future Circular Collider).

LHC Run-3 and Run-4 and relative upgrades LHC experiments made terrific steps forward in the comprehension of the QGP using Run-1 (2009-2013) data. The higher statistics which is being recorded during the on-going Run-2 (2015-2018) will further solidify the physics programme which was planned for the first inverse nanobarn of integrated luminosity. Nevertheless, the precise determination of several observables in PbPb interactions and the study of the rarest probes require a higher integrated luminosity. With a ten time larger data sample and upgrades of the detectors, the experiments will address the following topics (among others): the study of charm and bottom quark production down to very low transverse momenta and their possible thermalization in the medium; the elliptic flow of prompt J/ψ, the measurement of the J/ψ polarization and the study of the ψ(2S) with uncertainties as low as 10$\%$ down to zero p_T; a precise investigation of the jet structure as well as jet-photon and jet-Z^0 correlations; the study of the production of light nuclei, hyper-nuclei, and the search for exotic compound hadrons; the measurement of low-mass dileptons to give a determination of the temperature of the source emitting the thermal dileptons: an integrated luminosity of 10 nb^{-1} would allow a statistical precision of about 10$\%$ and a systematic uncertainty of about 20$\%$.

The main strategy to increase the luminosity in the PbPb Run-3 and Run-4 at the LHC is to increase the total number of lead nuclei stored in the machine. This goal can be achieved by reducing the bunch spacing within the PS batches and/or decreasing the SPS kicker rise time to reduce the bunch spacing in the SPS. A peak luminosity exceeding $6 \cdot 10^{27}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ can be achieved. The actual schedule foresees 2.85 nb^{-1}/year integrated luminosity, starting from 2021. The LHC schedule for the present Run-2 and the future runs is shown in Fig. 9, which emphasizes the heavy-ion periods and reports the integrated luminosity requested by the ALICE experiment.

From 2021 on the LHC will operate at the nominal center-of-mass energy of 14 TeV for proton-proton and of 5.5 TeV per nucleon pair in PbPb collisions, and will make a significant step forward in the luminosity. The long shutdown LS3 will prepare the machine and the experiments to a further jump of a factor 10 in proton-proton luminosity, with the High-Luminosity LHC entering operation in 2026 with two runs presently foreseen (Run-4 and Run-5). Concerning PbPb collisions, for Run-3 and Run-4 the experiments have requested a total integrated luminosity of more than 10 nb^{-1} (e.g., 13 nb^{-1} requested by ALICE) compared to the $\sim$ 0.1 nb^{-1} recorded in Run-1 and the expected $\sim$ 1 nb^{-1} of Run-2. During Run-3 and Run-4, reference samples with pp collisions at 5.5 TeV will also be collected, as well as a sample with pPb collisions at 8.8 TeV. The possibility of extending the programme to collisions of nuclei lighter than Pb (e.g. Ar-Ar or O-O) is under discussion.

The ALICE Collaboration is preparing a major upgrade of the experimental apparatus that will operate during Run-3 and Run-4. The upgrade strategy was driven by the following requirements: - Improvement of the track reconstruction performance in terms of spatial precision and efficiency, in particular for low-momentum particles to select more effectively the decay vertices of heavy-flavour mesons and baryons, and study better the production of low-mass dielectron pairs;
- Increase of the event readout rate up to 50 kHz for PbPb collisions with a minimum-bias selection, providing the highest efficiency for low-momentum processes. This luminosity enables recording during Run-3 and Run-4 of a sample of minimum-bias collisions two or-

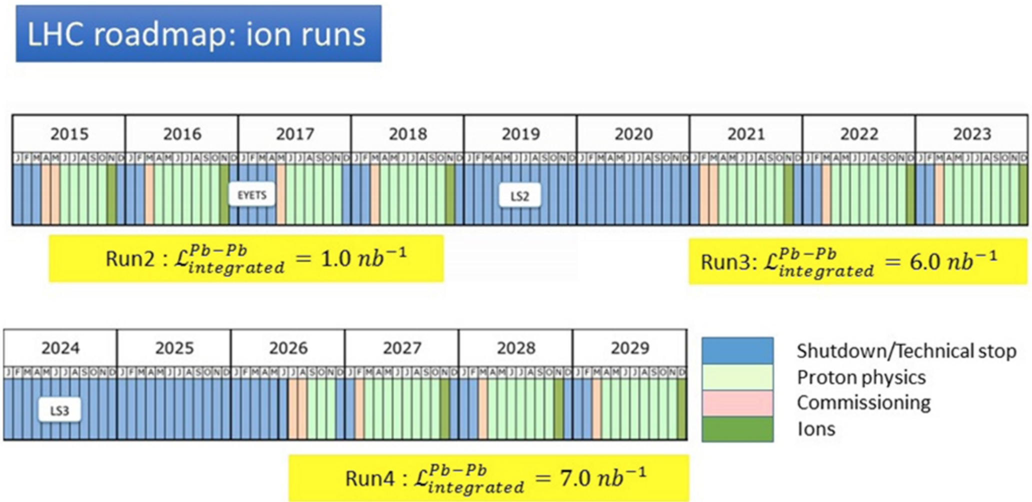


Figure 9: The LHC schedule for the next runs

ders of magnitude larger compared to Run-2;
- Consolidation of the particle identification capabilities of the apparatus, which are crucial for the selection of heavy-flavour, quarkonium, dilepton, and nuclei decay products at low momentum.

The ALICE upgrade programme entails the following changes to the apparatus: a new Inner Tracking System (ITS) with seven layers equipped with Monolithic Active Pixel Sensors (MAPS), a Muon Forward Tracker (MFT) made of five planes of the same MAPS used in the ITS, new readout chambers for the TPC based on the Gas Electron Multiplier (GEM) technology and a new Fast Interaction Trigger detector (FIT) based on Cherenkov radiators and scintillator tiles at forward rapidity around the beam pipe. The upgrade includes the readout electronics of most of the detectors to record PbPb interactions at a rate of up to 50 kHz, and a new integrated Online/Offline system for data readout, compression and processing to reduce the volume of data by more than one order of magnitude before shipping them to permanent storage.

The other major LHC experiments have planned rich heavy-ion programmes, also taking profit of the major upgrades of the detectors scheduled up to LS3. For instance CMS will upgrade the pixel system, the inner tracker, the trigger and the data acquisition systems, among other upgrade projects. These improvements will allow the full exploitation of the high luminosity heavy-ion running for jet quenching analyses and will improve the heavy-ion reconstruction performance to about the level of the current pp reconstruction algorithms. Moreover, very precise measurements of the production of quarkonium states and electroweak bosons will be achieved, as well as new measurements never attempted before, as the production of top quark in heavy-ion collisions. The LHCb experiment has joined the LHC heavy-ion programme at the end of the Run-1, and has performed key measurements of charm and quarkonia in p-Pb collisions. LHCb has excellent capabilities complementary to those of the ALICE experiment in the measurement of p-A collisions. In 2015, LHCb has started to explore their capabilities in PbPb collisions at 5 TeV and to test the possibility of performing fixed-target measurements at the LHC with the **SMOG** system. A gas is injected in the beam pipe, to collide with the LHC beams: various nuclei were tested so far (... give ...), demonstrating the feasibility of such a programme. SMOG results are extremely promising and show the absence of impact of the gas injection on the LHC. In view of these observations, the ALICE detector, in particular its muon arm, could also offer very interesting opportunities in the fixed-target mode which remain to be investigated. LHCb has planned a large upgrade of its detector during LS2, namely its tracking system. LHCb will certainly make important contributions to the heavy-ion programme at the LHC during Run-3 and Run-4. Proton-lead collisions at the highest LHC energies are also of interest, since they allow to explore the formation of a semi-classical state of gluon fields, the Color Glass Condensate.

Currently, the heavy-ion programme at the LHC is effectively restricted to the use of one ion type per year: the setup time of the current **ion source** at CERN is of a couple of weeks. Therefore different ions can be used, but both a switch between different types and having collisions between different ions is practically not possible within the normally foreseen four weeks of heavy-ion programme per year. Recently the possibility to study collisions between lead ions and deuteron or $^3\mathrm{He}$, in addition to p-Pb, was considered with great interest. Also the possibility to having asymmetric collision systems (as Cu-Au was done at RHIC) could be studied. A second ion source is in discussion at CERN, in connection to medical applications too. That might provide light ions like deuteron and $^3\mathrm{He}$, although that might take until 2030.

Very large new facilities are currently under construction: FAIR and NICA.

Using the current GSI facilities as injector chain, the **FAIR** centre (in Darmstadt, Germany) will comprise two synchrotrons and a complex system of storage rings that will provide both internal and external beams for a variety of physics programmes, ranging from QCD matter physics over hadron physics with anti-proton beams and nuclear structure physics with rare-isotope beams to applied and plasma physics with ultra-high intensity, bunched beams. Among these programmes, heavy-ion collision physics is one of the major scientific pillars of the FAIR project. For this research field, the accelerator complex will deliver a large variety of extracted, fully stripped ion beams (e.g., p, C, Ca, Ni, Ag, Au) with unprecedented intensities of above 10^9/s, thus enabling fixed-target experiments with extreme reaction rates. In the first stage of FAIR, planned to start operation in 2022, the SIS-100 synchrotron with a bending power of 100 Tm will accelerate heavy ions to 11A GeV, symmetric nuclei up to 15A GeV and protons up to 29 GeV. At a later stage, a booster ring (SIS-300) with 300 Tm bending power or more will be installed in the same tunnel. Beams injected from the SIS-100 will be accelerated to 35A GeV (heavy ions), 45A GeV (medium-size ions) and 90 GeV (protons). Apart from the extension of the energy range, the SIS-300 will enable a highly parallel operation of the various physics programmes of FAIR, thus substantially increasing the available experiment time for each of those.

The nuclear collision programme at FAIR will be conducted by the **CBM experiment**, currently being designed to operate both at SIS-100 and, later, at SIS-300, and the **HADES** detector, which is currently in operation at the SIS-18 accelerator at GSI and which will be moved to the SIS-100 beam line. CBM will be a next-generation experiment being able to cope with the complex event topologies typical for heavy-ion reactions at very high interaction rates of up to 10^7 collisions per second, more than two orders higher than that of other existing or planned detectors in the field. To achieve this ambitious goal, rigorous R&D on innovative technologies for detectors, electronics and data processing was performed over the last decade, with the emphasis on fast and radiation-hard detectors and electronics.

The backbone of CBM is a low-mass *Silicon Tracking System (STS)* based on double-sided silicon strip sensors, which is hosted in the aperture of a dipole magnet of about 1 Tm bending power. In order to achieve the design goal of a momentum resolution of 1.5%, the readout electronics will be placed outside of the acceptance and will be connected to the sensors with low-capacity, ultra-thin cables. The tracking capabilities of CBM will be enhanced by a *Micro-Vertex Detector (MVD)*, using the Monolithic Active Pixel Sensor (MAPS) technology to determine secondary vertices of open charm decays and to enhance the background rejection capabilities for dielectron studies. The envisaged interaction rates require a time resolution of 10 μs or below and sufficient radiation hardness to stand more than $10^{13}\,\mathrm{n_{eq}}/\mathrm{cm}^2$, figures which after several years of R&D are now within reach.
The major technological challenges for the *Time-of-Flight Detector (TOF)*, using multi-gap Resistive Plate Chambers, and the *Transition Radiation Detector (TRD)* based on MWPC readout is the development of highly granular and fast gaseous detectors which can stand the CBM environment in particular for the inner part covering forward emission angles. Several advances in detector technology allow now to operate these detectors at very high rates and with good resolution.
The flexible and modular design of the CBM detector system allows for both hadronic and leptonic observables. The latter, i.e., dielectrons and dimuons are addressed with a *Ring Imaging Cherenkov (RICH)* detector, comprising a radiator and a UV photon detector realized with multi-anode photomultipliers for electron identification, and a *Muon Chamber System (MuCh)* for muon identification, consisting of a GEM-instrumented hadron-absorber made of graphite and iron plates. Furthermore, an *Electromagnetic Calorimeter (ECAL)* based on lead-scintillator layers will be used to measure photons and neutral mesons (π^0, η) decaying into photons. The detector setup is completed by a forward calorimeter, the *Projectile Spectator Detector (PSD)*, providing measurements of centrality and reaction plane.

A particular challenging feature of CBM is the processing of the large amount of raw data delivered by the detector systems, which requires an online reduction of the data rate by more than two orders of magnitude when running at the highest interaction rates.

As most of the rare key observables of CBM have rather complex signatures not allowing for a conventional hardware trigger, CBM employs a novel data acquisition system with trigger-less electronics, shipping time-stamped raw data to an online computing farm. There, event reconstruction and data selection will be performed in real-time by dedicated software. This necessitates very fast and highly parallel algorithms which reconstruct 4-d event topologies (i.e., in space and time), coping with the temporal event overlap at high rates. Prototypes of such algorithms have been developed in the past years, providing a step towards the required performance.

In parallel to the construction of FAIR, the accelerator facilities at JINR Dubna are being substantially enlarged by the **NICA project**, which will support world-leading programmes in relativistic nuclear physics and particle spin physics, radiobiology, applied research and education. The main goal of the project is the study of hot and dense strongly interacting matter in heavy-ion collisions (up to Au) at centre-of-mass energies up to 11A GeV. Both colliding and extracted beams will be delivered to the experiments MPD and BM@N, respectively (see below). The study of spin physics with beams of polarized protons and deuterons is foreseen as well.

The NICA accelerator facility is being developed in three stages. The first stage comprises the 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 $^{197}\mathrm{Au}^{79+}$ ions with a kinetic energy in the range of 1 - 4.5 GeV/u and protons up to 12.6 GeV. In the second stage, the collider, the beam transfer line from the Nuclotron to the collider, and the multi-purpose detector (MPD) will be constructed. The two SC collider rings have a circumference of 503 m each. In order to reach the design luminosity of $10^{27}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ for Au ions, both electron and stochastic cooling systems will be provided. The mass production of the magnets (prototypes were tested in 2013) is scheduled for 2016 - 2018. The construction of the collider buildings and the transfer channels was started in November 2015. The mounting of the collider elements, the transfer channel and parts of MPD is planned to be started beginning 2019. The start-up version of the project is planned for the end of 2019, the completion of commissioning for 2023. In the final stage of NICA, polarized ion beams (starting with deuterons, based on experience with the Nuclotron since the beginning 1990s) and the construction of the spin-physics detector (SPD) at the second interaction point, opposite to the MPD, are planned.

QCD matter physics at the new collider will be studied by the **MPD** detector, being designed to record heavy-ion induced reactions at intermediate reaction rates (see Box 4). The detector system, housed in a 0.66 T superconducting solenoid, will measure charged hadrons, electrons and photons. In its first stage the MPD will comprise a *Time Projection Chamber (TPC)* with a design similar to the existing ALICE TPC covering a pseudorapidity range $|\eta| < 1.2$. The chamber is designed for a momentum resolution below 3% in the range $0.1\,\mathrm{GeV} < p_t < 1\,\mathrm{GeV}$ and a dE/dx resolution below 8%. A multi-gap resistive plate *Time-of-Flight Barrel (TOF)* supplements the particle identification of the TPC with a design time resolution of below 100 ps. The start time for the time-of-flight system is provided by a *Fast Forward Detector (FFD)*, which also provides a L0 collision trigger. The FFD converts forward photons in a lead converter. The ensuing Cherenkov light is detected in MCP photomultipliers providing a high-resolution timing signal. An *Electro-Magnetic Calorimeter Barrel (ECAL)* will provide electron and photon identification with an energy and time resolution of $\approx 2.5\%/\sqrt{E}$ and 80 ps, respectively. The current design of the ECAL is of the so-called "shashlyk" type (lead-scintillator sandwich). Finally, a lead-scintillator *Forward Hadron Calorimeter (FHCAL)* will serve for centrality and event plane determination. In a second, later stage the MPD detector will be supplemented by a silicon-based *Inner Tracker* and *end-cap detectors* (tracker, time-of-flight and EM-calorimeters) which will make it a versatile 4π heavy-ion detector.

The **BM@N** fixed-target experiment will make use of extracted beams from the upgraded Nuclotron. The experiment combines high precision track measurements with time-of-flight information for particle identification and uses total energy measurements for the analysis of the collision centrality. The charged track momentum and multiplicity will be measured with a set of two coordinate planes of *GEM Detectors* (Gaseous Electron Multipliers) located downstream of the target in the analyzing magnet and the *Drift/Straw Chambers* (DCH, Straw) situated outside the magnetic field. The GEM detectors sustain high particle rates of particles and can be operated in the strong magnetic field. The design parameters of the *Time-of-Flight detectors* based on Multi-Gap Resistive Plate Chambers (mRPC) with a strip read-out allow to discriminate between hadrons (π, K, p) as well as light nuclei with momenta up to few GeV produced in multi-particle events. A *Zero Degree Calorimeter* (ZDC) is designed for the analysis of the collision centrality by measuring the energy of forward going particles. Processes with electro-magnetic probes $(\gamma, e^{\pm})$ in the final state will be measured by an *Electro-Magnetic Calorimeter* installed behind the outer drift/straw chambers and the mRPC wall.

In addition to the existing facilities and those under construction, other proposals and major projects are being worked on and discussed in the scientific community.

AFTER@LHC is the project of a fixed-target experiment at the LHC for hadronic, spin and heavy-ion physics based on four crucial advantages of the fixed-target mode with TeV beams: high luminosities, an access to target rapidities (y), target versatility and polarisation. This allows for extremely precise studies of most hard probes in many colliding systems over the whole $y < 0$ region thanks to the boost. These, along with an ambitious spin programme, complement the scope of RHIC and the Electron Ion Collider project. To name a few, AFTER@LHC gives access to measurements, at an energy between RHIC and SPS, of the entire bottomonium family, of a complete set of charm observables down to low p_T (*e.g.* ψ, χ_c, D,D+D, ψ+D and the corresponding ratios), of the Drell-Yan process in pA, Pbp and PbA collisions to check, for the first time, the nuclear PDF factorisation. In addition it will allow to study azimuthal asymmetries over the entire negative y to understand their origin and to measure the temperature dependence of the shear viscosity. AFTER@LHC also offers a unique range of opportunities for p-A studies at large x where many nuclear effects remain poorly understood.

The project **NA60+** aims at high-precision measurements of thermal radiation, light vector mesons and charmonia via the detection of muon pairs to explore the phase diagram at moderate-to-high baryonic density and to look for chiral symmetry restoration, the onset of deconfinement and the critical endpoint. It consists in a beam energy scan at the CERN SPS from 20 to 160 GeV per nucleon with a fixed target detector, complementary to SIS-100, SIS-300 and NICA. It complements NA61 focused on hadronic observables. The NA60+ experimental concept is similar to that of the previous NA60 experiment at the SPS with a vertex spectrometer, a hadron absorber and a muon spectrometer with a readout system of several tens of kHz. NA60+ will have unique capabilities to perform the above mentioned studies, in the energy range of the RHIC energy scan and NICA.

In February 2014, CERN launched an international design study for a **Future Circular Collider (FCC)** to assess the feasibility and physics potential of a new hadron collider providing proton-proton collisions at a center-of-mass energy of 100 TeV, in a 80-100 km tunnel near Geneva. The study aims at a possible starting time in 2035-2040. The operation with heavy ions is part of the accelerator design studies. The center-of-mass energy per nucleon pair would be 39 TeV and 63 TeV for PbPb and proton-Pb collisions, respectively. Even in a conservative injection scenario, the new accelerator could provide an integrated luminosity as high as 33 nb^{-1} per month of running. The higher collision energy and the increased integrated luminosity open tremendous opportunities in the investigation of the QGP at vanishing baryon chemical potential. A medium which is initially denser and hotter will be created, which will also have a longer expansion time, over a larger volume: stronger collective effects and novel qualitative phenomena may become accessible. Hard processes will become available in much larger abundance, thanks to both the higher center-of-mass energy and the larger statistics: this not only holds for heavy quarks and high-momentum jets, but will also allow to study the interaction of the top quark with the QGP, to probe the time evolution of the QGP density and the role of colour coherence. Collisions at the FCC will also allow to probe saturated parton densities in a totally new ultra-dense kinematic region. The possibility of a heavy-ion physics programme at the FCC is currently being discussed.

Computing resources All present and future research projects dedicated to study the properties of strongly interacting matter require large computational resources. Adequate computing power and infrastructures are needed both by theory and experiments.

Computing infrastructure for theory will require large-scale resources to cope with the demanding requests driven by high-precision calculations. Numerical simulations by lattice-regularized Quantum ChromoDynamics (**lattice QCD** in the following) have developed rapidly and very successfully in the last years. By implementing non-perturbative techniques, lattice QCD calculations provide estimates of the QCD EoS and the critical behavior at vanishing chemical potential, and important developments to extend to the non-zero potential regime and the determination of transport coefficients are taking place.

These computations employ high performance computers with the power of the Pflop/s order and involve the use of accelarators like GPUs. The resource needs grow with a doubling time of approximately 1.5 years, consistently with Moore's law, and will continue growing rapidly in the coming years. The planned future developments require more numerous or larger computational resources: multi-GPU architectures and resources with many thousands of GPUs or new many-core CPU architectures are needed to carry out computations approaching the chiral limit, calculations of higher order cumulants, thermal masses and transport properties. At the same time, appropriate support for software developments must be secured: new software will be needed to exploit fully the new hardware architectures especially as most of them will have more complex memory hierarchies. Moreover important progress can be achieved with the development of new and optimized algorithms.

As far as the **computing for experiments** is concerned, in the coming years the existing infrastructures for physics analysis and simulation, like the WLCG used for the ALICE experiment at the CERN LHC, have to be maintained and scaled up to meet the demands in the next decade.

High-luminosity accelerators and advanced detector technologies result in a dramatic increase of data sizes (several orders of magnitude) and bandwidth into the computing systems. Both the upgraded detectors of the ALICE experiment at the LHC for Run-3 and Run-4, and the two big data producers at FAIR, CBM and PANDA, will provide data outputs in the order of Terabytes/s. New and by now matured technologies like distributed cloud systems and the availability of high-bandwidth wide area networks offer new opportunities for international collaborations, however require further development of the computing models. In addition the rapid technology development in terms of the density of compute power and the bandwidth available for data storage, led to a shift of paradigm for the design of the experiments. High-rate data taking will be not enabled by hardware triggers, but by reconstructing and selecting physically interesting data in real-time. This requires a significant investment in the online computing systems: large on-site computer facilities and storage capacities will be decisive for the physics reach in terms of collected event statistics.

The strong development of online computing has also consequences for the offline computing models 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. In general, offline computing will shift away from the GRID approach, towards 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. In the recent years, we have seen a significant common development effort between the major experiments and nuclear physics laboratories. The FAIR experiments and the ALICE experiment at the CERN LHC have embarked to develop a common software framework (ALFA), based on the successful experience with the FairROOT framework developed at GSI. This new open-source framework will be the basis of the experiment-specific software developments for the next decade. The new framework enables the experiments to fully exploit the capabilities offered by modern computing systems and reduces the development and maintenance costs.

New computing solutions are continuosly emerging: in the last decade, the architecture of computing systems has rapidly changed, mainly driven by the demands of the digital economy. The transition from single-core to multi-core architectures with wide vector processing units, accelerator cards like GPUs, the availability of commercial high-speed networks as well tiered memory and storage solutions changed the way in which algorithms need to be implemented. On the infrastructure side, modern data center facilities characterized by a high performance coupled with a low power usage are required. As an example, the “Green Cube”, currently under construction at GSI, is an energy and cost saving, high performance data center: it will accomodate powerful energy-efficient supercomputers, taking advantage of a new water cooling concept, whose capacity will exceed 10 MW.

Meeting the future computing demands of the nuclear physics community in a cost-effective way, needs fully exploiting the capabilities of the rapidly evolving computing landscape.

Forthcoming detector challanges and new instrumentation High intensity facilities proposed for the next years require outstanding detectors to cope with the high interaction rate, measurement precision and particle identification capability. Detector R&D is a key tool for a successful planning of the next generation of nuclear physics experiments exploring the QCD phase space.

GEM-based high resolution TPC The operation of a traditional Time Projections Chamber (TPC), e.g., with Multi-Wire Proportional Chamber (MWPC) based readout plane and gating grid, has a principal limit of the triggered rate of few kHz. The expected increase of the LHC luminosity after the LHC long shutdown 2 in 2019/20 (LS2) to 50 kHz in PbPb collisions, implies that a gated TPC is no longer a sensible mode of operation. An alternative readout scheme based on gas-electron multiplier (GEM) foils, which will allow for non-triggered, high rate operation, has been chosen by ALICE. Readout chambers with GEM stacks feature inherent suppression of the ion back flow (IBF) into the drift region. IBF is responsible for track distortions, whose magnitude depends on the quasi-static charge density created by the ions drift region. The ALICE collaboration showed that the IBF can be limited to 1%, achieving a dE/dx resolution of about 5-6%, as in conventional MWPC-based TPCs.

Precise vertexing and tracking accuracy in high particle density Tracking with high space accuracy and precise vertexing capabilities in relativistic heavy-ion collision experiments represent a challenge due to the very high particle density. In the next years, the two larger high energy nuclear physics experiments at European facilities, ALICE at CERN and CBM at FAIR, will adopt CMOS Monolithic Active Pixel Sensors (MAPS) for vertexing and tracking in the proximity of the interaction point. After an intense R&D effort, this technique showed a space resolution better than 10 μm, a power consumption $<$100 mW/cm^2, and radiation hardness at a total integrated dose up to few Mrad. The ALICE time schedule foresees the installation of these new detectors during the LHC LS2 (2019-2020).

Ultra fast silicon detectors for 4D tracking Ultra fast silicon detectors (UFSD) are a promising device, taking advantage of the intense R&D performed in the CERN RD50 collaboration and INFN Gruppo V. UFSD aim at providing a 4D event reconstruction with a space resolution ranging between 20 and 50 μm and a time resolution of 10-20 ps. Such an excellent time resolution requires large and fast signals. The basic idea is to use n-on-p low-gain avalanche detectors (LGAD) with a high ohmic p bulk with a p+ implant extending several microns underneath the n-implant. The p+ plant provides a large electric field, 300 kV/cm, allowing avalanche multiplication and high drift velocity, while thin devices ensure large signal slope dV/dt (slew rate) and are less sensitive to total dose radiation effects. Test beam results based on 300 μm thick device showed a time resolution of 120 ps; according to detailed simulations this time resolution corresponds to about 30 ps for a 50 μm thick device presently in construction. This device can be used for particle identification in Time of Flight (TOF) detectors, fast triggering and forward physics.

Compact RICH detectors Future HI experiments have to foresee detectors with PID capability, too. Cherenkov detectors are successfully used in several experiments and many Ring Imaging Cherenkov detectors (RICH) are planned in the next years. Important progress has been reached by CBM at FAIR, that includes a gas RICH to identify electrons up to 8 GeV/c. Photons generated in the CO_2 radiator (typically 20 hits/ring) will be detected by 1,100 multi-anode photomultipliers. At high momentum, radiators with a low refractive index are required, resulting in a small number of photoelectrons. This could drive up the detector length and cost. At few GeV silica aerogel offers an affordable solution while beyond 10-15 GeV/c other solutions should be considered. Compact RICH can be built using gas under pressure, as pressurized octafluorotetrahydrofuran (C_4F_8O), and an appropriate focusing geometry. Recently more than 10 photoelectrons have been obtained with a 1 m long prototype RICH using C_4F_8 as radiator and a GEM stack structure to detect photons. A clear π,K,p separation up to 32 GeV/c has been obtained by a prototype exposed to the Fermilab beam test facility.

Silicon Calorimeters The study of electrons and gammas at high rapidities in collider experiments requires compact, highly segmented and fast calorimeters with imaging capability, to associate the energy depositions with the showers originating from individual particles. Electromagnetic showers have to be confined in small volumes to avoid overlaps and therefore a proper segmentation is required. Silicon detectors coupled with a tungsten absorber are a good candidate, coping with all the above requirements. In addition silicon calorimeters show a very good radiation hardness. Several calorimeters relying on few tens of layers and segmentations of few squared millimeters have been developed in several R&D projects: a good linearity coupled with a satisfactory energy resolution (σ/E) ranging between 15%/$\sqrt{E}$ to 30%/$\sqrt{E}$, depending on the sampling fraction, has been achieved. Silicon calorimeters have been proposed by the experiments ALICE at the LHC (FOCAL) and PHENIX at RHIC (MPC-EX).

4.2.5 Recommendations

Experimental programme

- Continuation of the heavy-ion program at the LHC with Runs 3 and 4, and the planned experiment upgrades
- Continuation of the on-going programs at intermediate energies: HADES at SIS18, NA61 at the SPS
- Construction of SIS-100 at FAIR and realization of the CBM experiment. Continue supporting developments for SIS-300
- Construction of NICA at JINR and realization of the BM@N and MPD experiments
- Continue studies for AFTER@LHC, NA60+, and a heavy-ion program at the Future Circular Collider

Theory developments

- Guarantee continuous support to theory (theoretical support needed to interpret the results and to provide feedback to the experimental programme)
- Foster close collaboration between theory and experiments

Miscellaneous

- Computing: secure resources to face the increasing needs in computing power and data storage, both by theory and by experiments. Invest in developments of new technology and algorithms
- Continue at all times R&D of detectors employing new techniques to reach faster signal production and collection, to handle higher data rates, and higher radiation levels