Ultra-relativistic Heavy-Ion Collisions: Inputs of the Italian community for the ESPPU 2018–2020

G.E. Bruno [12], A. Dainese [7,@], E. Scomparin [10], G. Usai [17] (Editors), M. Agnello [14], W.M. Alberico [28], B. Alessandro [10], A. Alici [15], F. Antinori [7,30], P. Antonioli [3], S. Arcelli [15], R. Arnaldi [10], A. Badalà [5], R. Barbera [18], L. Barioglio [28], M. Basile [15], F. Becattini [20], F. Bellini [30], S. Beolè [28], A. Beraudo [10], A. Bianchi [28], L. Bianchi [28], G. Boca [24], C. Bonati [26], G. Bonomi [16], E. Botta [28], E. Bruna [10], S. Bufalino [14], M. Buzzegoli [20], P. Camerini [29], F. Carnesecchi [13,3], E. Casula [17], F. Catalano [14], P. Cerello [10], C. Cicalò [4], M.L. Cifarelli [15,13], F. Cindolo [3], F. Colamaria [2], D. Colella [12], M. Colocci [15], M. Concas [14], Y. Corrales Morales [10], P. Cortese [25], S. Costanza [24], A. De Caro [27], G. De Cataldo [2], A. De Falco [17], D. De Gruttola [13,27], M. D'Elia [24], N. De Marco [10], S. De Pasquale [27], S. Del Santo [28], D. Di Bari [12], D. Elia [2], M. Faggin [23], A. Fantoni [1], P. Fecchio [14], A. Feliciello [10], A. Ferretti [28], A. Festanti [30], F. Fionda [31], G. Fiorenza [2], E. Fragiacomo [11], G.G. Fronzè [28], M. Fusco Girard [15], M. Gagliardi [28], M. Gallio [28], P. Giubellino [10,34], P. Giubilato [23], V. Greco [18], F. Grosa [14], E. Grossi [33], D. Hatzifotiadou [3], N. Jacazio [15], J. Klein [10], P. La Rocca [18], R. Lea [29], M.P. Lombardo [6], M. Lunardon [23], G. Luparello [11], G. Mandaglio [22], V. Manzari [2], G.V. Margagliotti [29], M. Masera [28], A. Masoni [4], A. Mastroserio [21], M. Mazzilli [12], M.A. Mazzoni [9], E. Meninno [27], M. Mesiti [22], L. Micheletti [28], V. Muccifora [1], R. Nania [3,13], E. Nappi [2], M. Nardi [10], F. Noferini [3], C. Oppedisano [10], D. Pagano [16], P. Pagano [27], C. Pastore [2], B. Paul [17], S. Piano [11], O. Pinazza [3], S. Plumari [18], R. Preghenella [3], F. Prino [10], M. Puccio [28], G. Puddu [17], L. Ramello [25], I. Ravasenga [14], F. Riggi [19], F. Ronchetti [1], A. Rossi [23], A. Rotondi [24], A. Rucci [26], R. Rui [29], E. Scapparone [3], G. Scioli [15], S. Siddhanta [4], M. Sitta [25], F. Soramel [23], C. Terrevoli [32], A. Trifiró [22], M. Trimarchi [22], S. Trogolo [23,28], G. Trombetta [12], R. Turrisi [7], N. Valle [24], E. Vercellin [28], G. Vino [2], T. Virgili [27], G. Volpe [12], J. Wilkinson [3], M.C.S. Williams [3], V. Zaccolo [29], C. Zampolli [3,30], N. Zurlo [16]

ABSTRACT

This document was prepared by the community that is active in Italy, within INFN (Istituto Nazionale di Fisica Nucleare), in the field of ultra-relativistic heavy-ion collisions. The experimental study of the phase diagram of strongly-interacting matter and of the Quark–Gluon Plasma (QGP) deconfined state will proceed, in the next 10–15 years, along two directions: the high-energy regime at RHIC and at the LHC, and the low-energy regime at FAIR, NICA, SPS and RHIC. The Italian community is strongly involved in the present and future programme of the ALICE experiment, the upgrade of which will open, in the 2020s, a new phase of high-precision characterisation of the QGP properties at the LHC. The community also contributes to the heavy-ion programme of the LHCb experiment. The physics case of a very-high-luminosity programme in the 2030s at the LHC using intermediate-mass nuclei is considered with interest. In addition, there is a growing interest in a possible future experiment at the SPS, which would primarily target the search for the onset of deconfinement using dimuon measurements. The strong expertise of the community in detector development and construction, in particular in the sector of low-material silicon trackers, can serve as a common basis for these new projects at the LHC and SPS. On a longer timescale, the community participates in the ongoing studies for a heavy-ion programme at the Future Circular Collider or the High Energy LHC.

[@] Corresponding author: `andrea.dainese@pd.infn.it`

[1] INFN - Laboratori Nazionali di Frascati
[2] INFN - Sezione di Bari
[3] INFN - Sezione di Bologna
[4] INFN - Sezione di Cagliari
[5] INFN - Sezione di Catania
[6] INFN - Sezione di Firenze
[7] INFN - Sezione di Padova
[8] INFN - Sezione di Pavia
[9] INFN - Sezione di Roma
[10] INFN - Sezione di Torino
[11] INFN - Sezione di Trieste
[12] Dipartimento Interateneo di Fisica di Bari e INFN - Sezione di Bari
[13] Museo Storico della Fisica e Centro Studi e Ricerche “E. Fermi”
[14] Politecnico di Torino e INFN - Sezione di Torino
[15] Università di Bologna e INFN - Sezione di Bologna
[16] Università di Brescia e INFN - Sezione di Pavia
[17] Università di Cagliari e INFN - Sezione di Cagliari
[18] Università di Catania e INFN - Laboratori Nazionali del Sud
[19] Università di Catania e INFN - Sezione di Catania
[20] Università di Firenze e INFN - Sezione di Firenze
[21] Università di Foggia e INFN - Sezione di Bari
[22] Università di Messina e INFN - Sezione di Catania
[23] Università di Padova e INFN - Sezione di Padova
[24] Università di Pavia e INFN - Sezione di Pavia
[25] Università del Piemonte Orientale, Alessandria e INFN - Sezione di Torino
[26] Università di Pisa e INFN - Sezione di Pisa
[27] Università di Salerno e gruppo collegato INFN
[28] Università di Torino e INFN - Sezione di Torino
[29] Università di Trieste e INFN - Sezione di Trieste
[30] CERN, Switzerland
[31] University of Bergen, Norway
[32] University of Houston, USA
[33] University of Heidelberg, Germany
[34] GSI, Germany

1 SCIENTIFIC CONTEXT AND SCOPE OF THE DOCUMENT

Quantum Chromo-Dynamics (QCD), the theory of strong interactions, is characterised by a rich phase diagram, which is schematically shown in the left panel of Fig. 1 as a function of temperature T and baryon chemical potential μ_B. The elementary coloured degrees of freedom of the theory, quarks and gluons, under ordinary conditions are *confined* in colour-neutral composed objects, mesons and baryons, and get free to propagate over distances larger than the typical size of a hadron ($\sim$ 1 fm) only in an extremely hot or dense environment, like the one present in the early Universe or, possibly, in the core of compact stars. Lattice-QCD simulations and calculations based on chiral effective Lagrangians predict a *cross-over* between hadronic matter and a Quark-Gluon Plasma (QGP) phase in the high temperature and low baryon chemical potential region. They suggest that the transition may become of first order moving towards higher values of the baryon chemical potential. The right-hand panel of Fig. 1 shows the Equation of State (EoS) that relates the pressure P and the temperature T in terms of $P(T)/T^4$, in the $\mu_B = 0$ case. This quantity is characterised by a smooth rise in the effective number of active degrees of freedom as the temperature increases, which represents the transition from hadronic constituents (pions) to quarks and gluons. The cross-over between the hadronic and QGP phase occurs around the critical temperature $T_c \approx 155$ MeV. The transition from QGP to confined hadrons is also associated with the breaking of chiral symmetry. During the thermal evolution of the Universe, the chiral condensate acquired a non-vanishing expectation value $\langle q\bar{q} \rangle \neq 0$ and the baryons got most of their mass: most of the present baryonic mass in our Universe actually arises from the QCD rather than from the electro-weak phase transition.

Experimentally the deconfinement transition is studied using ultra-relativistic heavy-ion collisions (energy per nucleon–nucleon collision in the centre-of-mass $\sqrt{s_{\mathrm{NN}}} \gg 1$ GeV). A schematic cartoon of the evolution of the matter formed in these collisions is displayed in Fig. 2, where the various stages of its dynamics are shown: partonic initial state, pre-equilibrium, colour-deconfined QGP phase, hadron gas phase, free streaming of final-state colourless particles. This research field has by now a 30-years history: starting in the 1980s with exploratory studies at fixed-target facilities at BNL and CERN, then brought to maturity in the following decade, it has reached high-precision levels with experiments at the RHIC collider and, more recently, at the LHC. Evidence for the formation of the QGP has by now been firmly reached [3–9]. In particular, the results from Pb–Pb collisions at the LHC show that a system with an initial temperature that exceeds by more than a factor of two the critical temperature $T_c \approx 155$ MeV for the phase transition from hadronic matter to QGP is produced. It has also been shown that such a system is opaque to hard probes (jets, heavy

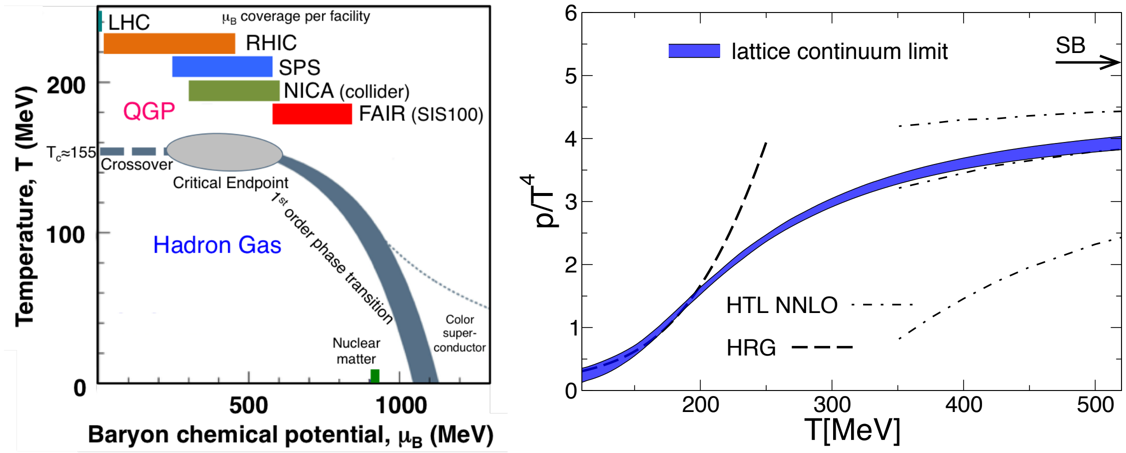

Figure 1: The QCD phase diagram (left panel) and the equation of state $P(T)/T^4$ in the limit of vanishing baryon density [1] measured on the lattice (right panel): the latter is characterised by a rise in the effective number of active degrees of freedom, indicating the cross-over transition to a QGP. The left panel also shows the coverage of various facilities in terms of a range in baryon chemical potential μ_B (the vertical position of the bands does not represent the coverage in temperature) estimated from the corresponding $\sqrt{s_{\mathrm{NN}}}$ ranges using the relation reported in Ref. [2].

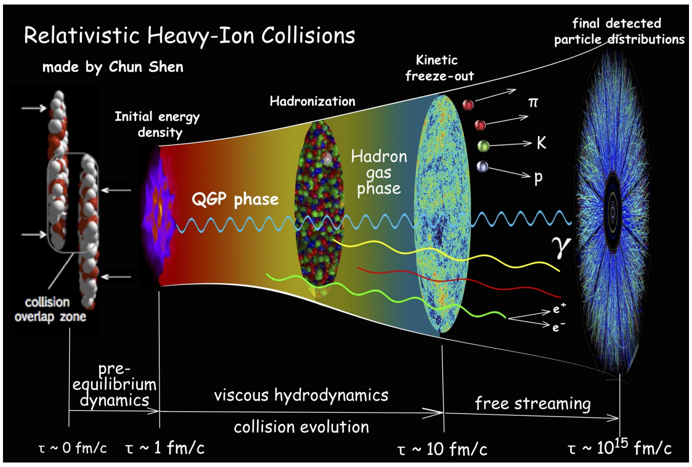

Figure 2: Schematic evolution of ultra-relativistic heavy-ion collisions.

quarks) traversing it, and that quarkonium states are dissociated due to the screening of the colour charge in the QGP.

As shown in the left-panel of Fig. 1, different regions of the phase diagram can be covered by changing the centre-of-mass energy of the collision: indeed, as the energy increases, the initial temperature of the system increases and its baryo-chemical potential decreases (because the baryon number carried by the two incident nuclei has a large separation in rapidity from the central region where the hot system forms). The experiments at the LHC and at the highest RHIC energies are suited to reproduce the conditions of high-energy and low baryon-density present in the early Universe with a cross-over connecting the QGP and hadron-gas phase. Instead, the study of the high baryon density region, where the transition is expected to become of first order and a critical endpoint might be located, is the main motivation of the Beam-Energy Scan at RHIC and of the fixed-target experiments running at the SPS and planned at NICA and FAIR.

A strong and motivated Italian “heavy-ion community” exists since the very beginning of the field. Experimental physicists have played a key role both in the fixed-target experiments with Pb beams at the CERN SPS (WA97, NA50, NA57, NA60) and later on in the design, construction and operation of the ALICE experiment at the LHC. Participation in the heavy-ion programme of the LHCb experiment has also recently started. In parallel, a theory community, significantly growing in the past decade, is providing the field with high-level fundamental and phenomenological studies. In 2014–2016 INFN (Istituto Nazionale di Fisica Nucleare) organised a broad internal discussion on future physics programmes (INFN - What Next?). The future directions for precision studies of the phase diagram of strongly-interacting matter and of the Quark-Gluon Plasma were summarised in a white paper [10]. The present document is largely based on the What Next discussions and documentation. As described in the next section, the future directions identified by the Italian community follow two main research lines for the medium-term future (10–15 years): high energy at the LHC, in the frame of the ALICE and LHCb experiments as well as possible new proposals, and high baryonic density, in the frame of the proposal of a new fixed-target experiment (NA60+) at the CERN SPS. The opportunities offered by a heavy-ion programme at the Future Circular Collider (FCC), or High Energy LHC (HE-LHC), are considered with interest for the longer-term future of the field. Heavy-ion physics presents several connections with the science case for an Electron–Ion Collider (EIC) to be built in the US, which includes QCD studies with nuclei of different sizes. These studies will provide information on the nuclear partonic densities (the initial state of heavy-ion collisions) and multi-parton quantum correlations in a broad range of x and Q^2. The definition of these distributions in the nuclei has important consequences for the estimation of some of the QGP properties, such as the shear and bulk viscosities. The EIC will also improve the understanding of the interaction of quarks and gluons with cold nuclear matter, contributing also to the modelling of partonic interactions in hot QCD matter. Details on the physics potential of the EIC and synergies with heavy-ion collision studies are discussed in the document submitted to the ESPPU by the EIC User Group and in the EIC white paper [11].

2 OBJECTIVES AND METHODOLOGY

Advances in the study of high-density and temperature QCD matter and of its phase structure can be pursued by moving towards two well defined directions.

- First, in high-energy studies at the LHC —which provides a QGP with the highest initial temperature, longest lifetime and largest volume— higher-precision data and the investigation of new observables are clearly needed for a complete characterisation of the deconfined state. In particular, the goal is a detailed understanding of the macroscopic properties, structure (degrees of freedom), and inner workings of the QGP. Reaching this goal requires probing this state of matter at multiple length-scales, i.e. with self-generated probes of various types and energies (including real and virtual photons, heavy quarks and jets).
- Second, the phase diagram of strongly-interacting matter is still largely unexplored in the domain of high baryonic densities, which can be studied via experiments at lower collision energies. Among the highlights of these studies, the characterization of the phase transition and the search for the QCD critical endpoint play a prominent role.

The Italian community is involved in preparing the next steps along these two reasearch directions as sketched in the following table and discussed in the rest of this document.

LHC	Pb-Pb $\sqrt{s_{NN}}$ = 5.5 TeV	ALICE, LHCb	2021-2029	High-precision QGP studies at $\mu_B = 0$: ▪ Macroscopic properties ▪ Microscopic constituents ▪ Collectivity/QGP in small systems	Detector development: Silicon trackers with high granularity and ultra-low thickness based on Monolithic Active Pixel Sensors
	Intermediate-mass nuclei		from 2031	~10× luminosity increase	
SPS	Pb-Pb $\sqrt{s_{NN}}$ = 10-17 GeV	NA60+ fixed-target experiment proposal	from 2027	Scan of QCD phase diagram at $\mu_B > 0$: ▪ Caloric curve of phase transition ▪ Chiral phase transition ▪ Search for onset of deconfinement	
FCC	Pb-Pb $\sqrt{s_{NN}}$ = 39 TeV		> 2040	▪ QGP volume 2× LHC ▪ Thermal charm production ▪ Novel QGP probes ▪ Initial-state saturation	

3 HIGH-ENERGY FRONTIER AT THE LHC

3.1 Physics programme in Run 3 and Run 4 with ALICE and LHCb

Heavy-ion collisions at the LHC and at top RHIC energy provide access to the region of the QCD phase diagram at high temperature and vanishing baryon chemical potential. The results from the RHIC programme and the first two Runs at the LHC have revealed the QGP as a strongly-coupled (liquid-like), high-density and low-viscosity medium in which colour charge is deconfined. Experimental research is now moving towards high-precision measurements, in order to constrain the properties of the QGP and determine its equation of state and characteristic parameters —for example: the temperature, the shear-viscosity-to-entropy-density ratio and the transport coefficients.

To provide a strong boost towards high precision, the ALICE Collaboration has undertaken a major detector upgrade programme. This will be implemented during the Long Shutdown 2 (LS2) in 2019–20 with the goal of collecting several samples of Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.5$ TeV during the LHC Runs 3 and 4 for a total integrated luminosity of 13 nb^{-1}, in addition to proton–proton reference samples and data with p–Pb collisions. The ALICE upgrade strategy entails two main items:

- the upgrade of the readout of most of the detectors and a new online-offline system for data compression will enable recording all Pb–Pb events at the projected interaction rate of 50 kHz, thereby increasing by 100× the sample of minimum-bias events with respect to Run 2;
- the new Inner Tracking System (ITS) improves by a factor more than three the precision for the reconstruction of heavy-flavour decay vertices, and the Muon Forward Tracker (MFT) adds such capability also for muon-based measurements.

The ALICE Italian groups are at the forefront of the upgrade activities, with central roles in the design and construction of the new ITS, based on Monolithic Active Pixels sensors (see Section 5), and in the readout upgrade of the Muon Spectrometer, the Zero Degree Calorimeter and particle identification detectors as the Time-Of-Flight and the High-Momentum Particle Identification Detector.

The LHCb detector has participated in the p–Pb and Pb–Pb data-taking in Run-2, although its performance in Pb–Pb is limited to non central collisions by the granularity of the tracking detectors. The major upgrade during Long Shutdown 2 will improve the performance and enable competitive studies, in particular in the sectors of heavy-flavour and quarkonium. In addition, the fixed-target programme in LHCb will continue in Run 3 with the recently-approved SMOG2 project.

Within the the CERN workshop on HL-LHC Physics, the high-density QCD physics programme using the LHC heavy-ion and proton beams in Run 3 and Run 4 was recently reassessed and extended in scope [12], with the contribution of all four large LHC experiments and theory groups, and in particular of the Italian heavy-ion community. The following four major research goals have been identified.
1) Characterising the macroscopic or “long-wavelength” properties of the QGP with unprecedented precision. The long-wavelength behaviour of hot and dense QCD matter can be described in terms of fluid and thermodynamic concepts and it is experimentally investigated using multi-differential azimuthal measurements of low-momentum hadron production, as well as of electromagnetic radiation. For example, the temperature of the early stage of the QGP will be determined by ALICE with an accuracy of about 20% by measuring thermal radiation. As another notable example, the heavy-quark diffusion coefficient D_s at a temperature of 1–2× the QCD critical temperature T_c will be constrained with a 2× improved accuracy using D and B meson production measurements.
2) Accessing the microscopic parton dynamics underlying QGP properties. The nature of the effective constituents of QCD matter and its characteristic length scales can be studied experimentally with high precision, using high-statistics hard probes. Multi-differential jet, heavy flavour and quarkonium measurements are among the main avenues for these investigations. For example, measurements of the production of charmonium and bottomonium states with different binding energies give access to a well-defined set of length scales for the study of the QCD force in a colour-deconfined medium via the characterisation of the mechanisms of melting and regeneration. ALICE and LHCb will have unique potential for charmonium measurements. The microscopic dynamics of the QGP and of hadronization in general will also be studied, by ALICE in particular, using precise measurents of heavy-flavour meson and baryon production as well as of light nuclei and hyper-nuclei.
3) Developing a unified picture of QCD particle production from small (pp) to larger (pA and AA) systems. Recent discoveries of collective patterns and strangeness enhancement in particle production in pp and p–Pb collisions question both the view of pp collisions as a superposition of quasi-independent parton–parton scatterings and the view of nucleus–nucleus as the only colliding system in which a QGP can form. These questions motivate the proposal [12] of increased luminosity goals with pp and p–Pb collisions to carry out a programme of high-precision studies of rare probes at high multiplicity. Example studies that require very large integrated luminosity include the comparison of collective-like properties (the so-called “flow”) of heavy quarks and quarkonium in small and large systems and the searches for thermal radiation and partonic energy loss. ALICE is at the forefront in these studies.
4) Probing initial-state nuclear parton densities in a broad (x, Q^2) range. A major goal in this context is the study of the presently-uncovered small-x region below 10^{-4} where parton phase-space saturation could

set in, using charmonia in γ–Pb collisions (ALICE and LHCb), and forward Drell-Yan (LHCb) and photons (ALICE) in p–Pb collisions. These studies, besides their intrinsic interest, are crucial inputs for the initial conditions of heavy-ion collisions.

3.2 Prospects for new initiatives

The Pb–Pb data samples of Runs 3 and 4 will grant high-precision studies for a broad set of physics observables. However, a major increase of luminosity for heavy-ion collisions would open new opportunities in the sectors of both "ultra-hard" (or "ultra-rare") probes and of "ultra-soft" particle production and radiation. The most convenient approach to largely increase the luminosity is the usage of nuclei lighter than Pb as a colliding system, because the main limiting effect for the luminosity, bound-free pair production, decreases with the seventh power of the atomic number. Clearly, nuclei much smaller than Pb imply a reduction of the volume and lifetime of the QGP system, and for this reason Pb–Pb remains the highest priority for Runs 3 and 4. Lighter nuclei have been identified within the HL-LHC Physics workshop as an appealing case for extending the programme in Run 5 (starting in 2031), with the optimal ion species to be identified by future studies and ^{40}Ar or ^{78}Kr taken at the moment as working examples [12]. A Ar–Ar programme of three months in Run 5 would provide an integrated luminosity equivalent, for rare signals that scale with the number of nucleon–nucleon collisions, to about one order of magnitude more than that of Pb–Pb in Runs 3 and 4.

A number of key physics topics that could be addressed with the higher luminosity granted by lighter nuclei require detector capabilities similar to those specific of the ALICE experiment, namely low-p_{T} tracking, ultimate vertexing resolution, hadron identification, detection of photons and electrons down to very low p_{T}. An extended rapidity coverage would in addition have a strong impact. These topics include the study of the soft electromagnetic radiation (real and virtual photons), the production of light (hyper-)nuclei with $A > 4$, the X,Y,Z exotic states, multi-charm baryons and charm-beauty mesons, excited charmonium and bottomonium states (χ_c and χ_b).

With the LS2 upgrade the ALICE detector will reach the maximum readout-rate performance for a spectrometer based on a TPC, due to the intrinsic limitations induced by the space-charge (ions) accumulated in the drift volume, which introduces large spatial distortions. For this reason, a first conceptual design for a new fast, ultra-light and granular detector has been conceived within the ALICE Collaboration [13,14]. The detector should be capable of recording the full luminosity that can be achieved with lighter ion collisions and it should at the same time exceed the tracking precision and particle identification capabilities of the ALICE upgraded detector. The concept is based on a tracker consisting entirely of CMOS Monolithic Active Pixel Sensors (MAPS). In the barrel the three innermost layers would have a spatial resolution of $\approx 1\,\mu$m, a material budget per layer as low as 0.05% of the radiation length (X_0), and would be placed inside the beam-pipe. Charged-particle identification would be provided by the determination of the specific energy loss in the middle layers and by the time-of-flight measurement in a set of layers with high precision timing capability ($\sigma_{\mathrm{t}} \approx 25\,\mathrm{ps}$) positioned at about 1 meter from the beam-pipe. Planar layers in end-cap geometry would extend the acceptance up to a rapidity $|y| \approx 4$. The barrel would be equipped with a pre-shower consisting of a 2–3 X_0 high-granularity digital sampling calorimeter to identify electrons down to few hundred MeV by a detailed imaging of the initial shower.

A possible first step in the direction of an ultra-light and granular tracker could be the development and construction of a new inner barrel (the three layers at radius below 4 cm) to replace in Run 4 (from 2027) the inner barrel of the ITS upgrade, which is presently under construction. The concept, described in an Expression of Interest [15], consists of an inner barrel made of curved wafer-scale ultra-thin silicon sensors arranged in truly cylindrical layers, featuring the unprecedented low material budget of 0.05 % of X_0 per layer, with the innermost radius of only 18 mm. This modification of the ALICE ITS would strongly improve the measurements of charm-baryon production and low-mass dielectrons.

The Italian ALICE groups consider with high interest these new initiatives and are willing to contribute to the R&D for next-generation MAPS-based detectors. These R&D activities can have a strong synergy with other projects, for example the NA60+ proposal, as discussed in Section 5.

4 LOW-ENERGY FRONTIER: A NEW EXPERIMENT AT THE SPS

Experimental information on the large-μ_B region of the phase diagram is still poor and its study represents a natural evolution of ultra-relativistic heavy-ion physics. The NA60+ project aims at measuring the properties of the QGP and the nature of the phase transition by performing an energy scan in the range accessible to the CERN SPS (beam energies in the range 20–160 GeV/nucleon, corresponding to $\sqrt{s_{\mathrm{NN}}} \sim 6\text{–}17\,\mathrm{GeV}$). The experiment could address several fundamental open questions, and in particular: (i) can a signal of the first-order phase transition to QGP be detected? (ii) can the restoration of chiral symmetry be accessed experimentally? (iii) what are the transport properties of the QGP at high-μ_B?

These questions can be addressed by an experiment based on a muon tracking system and a sophisticate vertex spectrometer. With this apparatus the dimuon invariant mass spectrum can be studied from threshold up to the J/ψ mass region and beyond, discriminating between prompt and non-prompt sources, while the vertex spectrometer can also be used to detect hadronic decays of particles containing strange and charm quarks. Its layout is conceptually similar to that of the past NA60 experiment [16], which took data in 2003–2004 with indium and proton beams on various nuclear targets at top SPS energy and performed accurate measurements of muon pair production.

Coming to the observables related to the physics questions listed above, the nature of the phase transition can be investigated by studying the evolution of the temperature of the system, for various collision energies, as a function of its energy density. The temperature can be precisely extracted by a measurement of the mass spectrum of the thermal muon pairs in the mass region 1.5–2.5 GeV, while the energy density is estimated via charged multiplicity measurements in the vertex spectrometer. In this way a "caloric curve" for the phase transition can be measured and the flattening related to a first order transition can be observed, if present. The feasibility of the temperature measurement via thermal dimuons was clearly demonstrated by NA60, which obtained at top SPS energy an average temperature of about 200 MeV.

The approach to the restoration of chiral symmetry, expected in proximity of the phase transition to QGP, should modify in a detectable way the spectral function of the vector/isovector mesons (ρ-a_1). A strong broadening of the ρ was already observed by NA60, and it is considered a manifestation of chiral restoration. Additionally, while the a_1 cannot be directly observed in the dilepton spectrum, chiral mixing of the vector and axial vector spectral functions is expected to increase the dilepton yield by $\sim 30\%$ in the mass region 1–1.5 GeV. This is a direct manifestation of chiral restoration and NA60+ aims at measuring the related yield excess for the first time. Such a study is particularly intriguing at low beam energies where the contribution of the QGP phase, which would constitute a background to this measurement, becomes less important.

When decreasing the incident beam energy, the initial energy density of the created strongly interacting system also decreases, while the net baryon content increases, leading to a high-μ_B QGP if the critical temperature is attained. At high energy, it has been shown that such a system can selectively melt the quarkonium states according to their binding energy, via a colour screening mechanism in the QGP. At low energies, one should therefore observe the suppression effect to become weaker and then disappear when the initial temperature of the system does not exceed the critical temperature. By measuring the J/ψ or $\psi(2\mathrm{S})$ decay to $\mu\mu$, and possibly the $\chi_c \to \mathrm{J}/\psi\gamma$ process, one could therefore track the onset of the deconfinement transition.

In addition to charmonium measurements, also the detection of open charm mesons and baryons represents an important observable in the low SPS energy range. Their hadronic decay products can be measured in the vertex spectrometer, while an indirect measurement via muon pairs from simultaneous semileptonic decays of meson or baryon pairs is also feasible. Indeed the charm diffusion coefficient is predicted to be larger in the hadronic phase at temperatures approaching the critical temperature T_c from below than in the QGP phase at temperatures larger than T_c, and the system is expected to spend a relatively longer time in the hadronic phase when the collision energy becomes lower. For what concerns hadronization mechanisms, recombination effects could lead to a large enhancement of the Λ_c/D ratio. The enhancement could be larger at low SPS energy than at RHIC and LHC energies, because of the larger baryon content of the system.

In order to access all the observables detailed above, a Pb ion beam intensity $\sim 10^7\,\mathrm{s}^{-1}$ impinging on a $\approx 4\,\mathrm{mm}$ Pb target is required, leading to interaction rates of the order of 1 MHz. This choice is dictated in particular by the need of a high precision for the temperature measurement and by the relatively low charmonium production cross section at SPS energy. This intensity can be reached using the existing ECN3 underground experimental hall in the CERN North Area.

As briefly stated above, this rich physics programme can be addressed by an experiment which includes a high-resolution vertex spectrometer, consisting of five silicon pixel tracking planes immersed in a 1.2 Tm dipole field. The tracker will be based on a new generation of CMOS Monolithic Active Pixel Sensors (MAPS), developed in close synergy with the ALICE experiment, immersed in a dipole magnetic field. The goal is to obtain very large area sensors up to $\approx 14 \times 14\,\text{cm}^2$, with a thickness of $50\,\mu$m or less. The vertex spectrometer will be followed by a thick absorber (mainly graphite) that will filter out hadrons and finally by a muon spectrometer, with a toroidal magnet and several large planes of tracking and triggering detectors. For the four tracking planes, the use of GEM detectors providing spatial resolution $< 100\,\mu$m, time resolution < 10 ns and sustaining high particle rates (the current requirement is $\sim 10\,\text{kHz/cm}^2$) is currently foreseen, with a total surface of the order of $100\,\text{m}^2$. Finally, for the muon triggering detectors, which will be placed behind a further hadron absorber, the default choice is the use of Resistive Plate Chambers (RPCs), which provide good resistance to ageing and can sustain the expected maximum rate of $\sim 100\,\text{Hz/cm}^2$.

Finally, we point out that this physics programme can be uniquely pursued at the CERN SPS. The other comparable facilities under construction (FAIR and NICA) are either lacking the necessary interaction rate (NICA) or reach too low energy (SIS100 at FAIR) to address all the physics topics detailed above. Similarly, the beam energy scan programme at RHIC (BES-II) covers the same energy range as the CERN SPS, but with interaction rates lower by orders of magnitude.

At present a study group is established with physicists from the following institutions: Cagliari (INFN), Kolkata (Saha institute), Lyon (IPNL), Munich (TUM), Padova (INFN), Rice University, Stony Brook University, Tohoku University (Japan), Torino (INFN). The Italian groups, which played a key role in the past NA60 experiment, are also leading the effort in this preparation phase.

A dedicated input on this project is submitted to the ESPPU2018–2020 [17] and a Letter of Intent to be sent to the CERN SPSC is in preparation.

5 LIGHT-WEIGHT SILICON TRACKERS BASED ON MAPS: EXPERTISE, FUTURE DEVELOPMENTS AND SYNERGIES

In recent years, a major achievement in silicon detectors has been the development of the CMOS Monolithic Active Pixel Sensors (MAPS), with the sensor and the frontend readout implemented on a single silicon substrate. Presently, the state of the art is the pixel sensor ALPIDE developed for the ALICE experiment, consisting of a 15×30 mm^2 sensor that features a pixel size of 27×29 μm^2 with a thickness of only 50 μm. Similar small-size sensors are usually mounted edge-to-edge on top of a printed circuit board, which provides the power distribution and data bus, to form the basic block (the “module”) to build large area detectors.

The Italian community gave an important contribution to the development of the ALPIDE project and will pursue in the coming years a further significant development towards large-area and ultra-thin MAPS detectors, as detailed in the following.

In the production processes of any CMOS circuitry, including image sensors, the largest field of view that is used in the photolithographic steps defines the reticle, whose size is normally a bit larger than a few cm in both directions. The emerging stitching technology [18], which allows an image sensor that is larger than the field of view of the lithographic equipment to be fabricated, can offer the possibility to construct large area sensors. Sensors of $\sim 15 \times 15$ cm^2 can be manufactured, the size limit of the process being imposed by the wafer size itself. The possibility to replace traditional modules made of more small-size sensors with single large sensors where power distribution is managed internally would mainly eliminate the need of a support, confining to the sensor edge the interconnection to the outside world. With a flex circuit for power distribution at the periphery, the material budget for such tracking stations might drop to 0.05 % of X_0 or less.

A silicon pixel tracker based on large area sensors excluding all services and mechanical support structures from the acceptance would be a breakthrough, for both collider and fixed-target experiments. For the former, the flexible nature of thin large-area silicon sensors opens the possibility to produce an almost transparent detector in barrel geometry with truly cylindrical shape. The possible usage of these detectors for the three innermost layers of the ALICE ITS or for a completely new experiment is discussed in [15] and in [14], respectively, and briefly in Section 3.2. Naturally, a first use case of this kind of detectors in fixed-target mode would be the NA60+ project described in Section 4. The operation at high interaction rate requires dedicated studies to increase the radiation tolerance of this technology, which also go in the direction of making it a possible choice for experiments at future colliders. Therefore, dedicated R&D programmes for improving the radiation hardness, the tolerable interaction-rate and for developing ultra-fast timing capabilities are very promising and should be supported in Europe with the highest priority. Furthermore, cheap large-area pixel sensors are also very attractive for medical applications or astrophysical measurements.

6 FURTHER PERSPECTIVES: HEAVY-ION PROGRAMMES AT FUTURE HADRONIC COLLIDERS

The Italian heavy-ion community takes part in the CERN-based group working on the heavy-ion physics case at the FCC-hh [19, 20] and at the HE-LHC [12]. These are clearly long-term projects, with possible operation periods starting in the 2040s, but the community considers important to keep nuclear beams in the baseline design of the machine and to continue bringing a contribution of ideas on heavy-ion physics and QGP studies also beyond the present conceptual design phase.

The energy $\sqrt{s_{\mathrm{NN}}}$ for Pb–Pb collisions is 39.4 TeV at the FCC and 10.6 TeV at the HE-LHC. The estimate of the integrated luminosity per month at the FCC is larger by factors 10–30 than that of future LHC runs. The increase in the centre-of-mass energy and integrated luminosity with respect to the LHC opens up novel opportunities for physics studies of the QGP [19]. The main scientific motivations to carry out measurements with heavy ions at these future high energy colliders can be summarised as follows.
1) Novel access to QCD thermodynamics and QCD equilibration processes. The QGP formed at higher energy is initially denser and hotter, and expands for a longer duration and over a larger volume, thereby developing stronger collective phenomena. Both the initial energy density and the volume of the system are expected to increase by a factor about two from $\sqrt{s_{\mathrm{NN}}} = 5.5$ TeV to 39 TeV, up to values of about 40 GeV/fm^3 (at $\tau = 1$ fm/c) and 11000 fm^3, respectively. The QGP temperature could reach values ($T \sim 1$ GeV) where charm quarks start to contribute as active thermal degrees of freedom in the QGP equation of state.
2) Characterisation of dense QCD matter through novel hard-scattering processes. The higher energies provides a much larger abundance of hard-scattering processes than at the LHC, as well novel probes like the top quark and, potentially, the Higgs boson. The thermal production of charm quarks in scatterings between quark and gluon constituents of the hot QCD medium is expected to be as large as 80% of the initial production and it represents a novel observable sensitive to the medium temperature evolution.
3) Exploration of parton densities in a new, ultra-dense kinematic domain. The higher centre-of-mass energies allows one to explore a wide previously-uncharted kinematic range in the (x, Q^2) plane, down to $x \sim 10^{-6}$, where saturation is expected to set in.

An important topic to be investigated in the near future is the possibility to design and operate a general purpose detector for pp collisions also for a heavy-ion programme. Some of the requirements may be conflicting (e.g. high-p_{T} vs. low-p_{T} performance): the possibility to operate a general-purpose detector with lower magnetic field for heavy-ion collisions may be considered. On the other hand, the need to have an extended coverage up to $\eta = 5$–6 is a common requirement for both the pp and heavy-ion programmes. As discussed in the previous section, the expertise of the Italian heavy-ion community on silicon pixel detectors could be precious for the design and development of a low-material central detector with high spatial and timing precision for both particle tracking and identification.

7 SUMMARY

We conclude this document by summarising the main development lines in the study of the phase diagram of strongly-interacting matter with heavy-ion collisions and by presenting our view of the possible contributions by the Italian community. The experimental exploration of the phase diagram will continue in two parallel directions:

High-energy experiments. At LHC and at top RHIC energy, where the high-temperature/low-baryon-density region of the phase diagram is covered, the experiments will move towards high-precision measurements, in order to constrain the properties of the QGP and determine its equation of state and characteristic parameters.

Low-energy experiments. The continuation of the SPS heavy-ion programme and the new experiments at the low-energy facilities NICA and FAIR will explore the region of the phase diagram with moderate-to-high baryonic density, the search for the onset of deconfinement and for the critical endpoint.

Our present view on the future involvement of the Italian heavy-ion community in these studies is summarised in the following.

- At the LHC, the Italian community is strongly involved in the ongoing upgrade of the ALICE experiment in view of physics in Runs 3 and 4 with 100-fold increased samples and enhanced detector performance. The increasing participation in the LHCb heavy-ion and fixed-target programmes is an important added value for the community. There is interest in the possible extension of the heavy-ion programme to Run 5, using lighter ions to achieve a large luminosity increase. This would open new opportunities in the sectors of both "ultra-hard" (or "ultra-rare") QGP probes and of "ultra-soft" particle production and radiation. The Italian ALICE groups participate in the conceptual design of a fast and ultra-light new experiment based on next-generation monolithic pixel sensors. R&D activities in this direction will be pursued, building on a long-standing expertise.
- A proposal of a new fixed-target experiment at the SPS, currently denoted NA60+, is being prepared. This project targets novel high-precision measurements of thermal radiation (dimuons), light vector mesons, open charm and charmonia, in order to search for the onset of deconfinement and the restoration of chiral symmetry. In view of the required interaction rates and beam energy range, such an experiment can only be carried out, among the existing or future facilities, at the SPS. The Italian community plays a leading role in the finalization of a proposal and the formation of an international collaboration. The construction of the experiment should be pursued after the LHC Run 3.
- Heavy-ion collisions at the FCC-hh or HE-LHC are regarded as an interesting long-term opportunity. The Italian community supports the studies on the physics potential and detector requirements for heavy ions at these machines.
- The Italian theory community is involved in several aspects of the study of the QCD phase diagram. In the scope of lattice-QCD simulations, the activity encompasses the main hot topics, namely the study of the phase transition at finite baryon chemical potential, the search for the critical endpoint and the determination of the QGP transport coefficients. Italian theory groups also play a central role in the study of heavy-quark in-medium dynamics. These activities will be instrumental for the interpretation of future high-precision LHC measurements in terms of properties of the QGP. All these studies will profit from the fruitful interaction between the theory and the experimental heavy-ion community, which should be further strengthened in the future.

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