Conclusions of the Town Meeting: Heavy Ion and QGP Physics at CERN

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On Monday, February 17, 2025, a town meeting was held at CERN to gather input on heavy ion and quark gluon plasma (QGP) physics for the European Strategy for Particle Physics 2026. The meeting included brief presentations on current and upcoming heavy ion experiments at CERN's LHC and SPS, along with future projects at the FAIR facility in Darmstadt and Brookhaven RHIC. It also highlighted CERN's injector and accelerator complex capabilities for providing ion beams to the HL-LHC (with a view to FCC-hh) and future fixed-target experiments. Additionally, the meeting offered a platform for scientists and groups to share comments and statements, including a panel on theory.

The meeting had 279 registered participants representing all experimental and theoretical activities in the field. It concluded with an open discussion on the priorities within the field. The following text, while not officially endorsed by any of the mentioned experimental collaborations or facilities, summarizes the **consensus** of the scientific community on the field's priorities, as expressed by the town meeting participants. It is submitted to the Open Symposium of the European Strategy Group in Venice by the convenors of the meeting.

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Heavy Ion and QGP physics aims at understanding the properties of strongly interacting matter at extreme temperature and density directly from the fundamental interactions of quarks and gluons. At the highest energies available at the Large Hadron Collider, the QGP is created and diagnosed at nearly vanishing baryon density, i.e., under conditions prevailing in the very early Universe. Lower beam energies, currently available at the CERN-SPS and at future facilities such as FAIR in Darmstadt, probe the baryon-rich quark matter under conditions encountered in various astrophysical settings.

1. Physics opportunities at HL-LHC

Over the past decade, the LHC heavy-ion program has yielded groundbreaking results, including: a comprehensive characterization of the nearly perfect fluidity of the quark-gluon plasma through light-flavored hadron spectra, momentum anisotropies, and various correlation measurements; evidence of a novel in-medium hadronization mechanism via hadrochemical abundances and soft charmonium production; detailed insights into quarkonium dissociation and heavy-quark energy loss in the QGP; and an unprecedented study of jet quenching phenomena, which remains the only significant high-pT effect not fully understood theoretically at the LHC. Additionally, the program has led to unexpected discoveries, such as the observation of collectivity across all system sizes, including those in proton-proton collisions.

Despite significant recent progress, important questions remain unanswered, and the scientific opportunities at HL-LHC for studying the quark-gluon plasma (QGP) are not yet explored. For example, the transport of heavy flavor in a nearly perfect non-abelian fluid can be calculated from first principles in quantum field theory, yet the corresponding QGP transport properties remain to be experimentally constrained. Additionally, the expectation that the QGP radiates electromagnetically still needs testing with Lorentz-invariant observables, such as dilepton spectra, where temperature measurements are unaffected by blueshift. This is also a crucial step toward experimentally detecting direct signatures of chiral symmetry restoration in the QCD high-temperature phase through rho and a1 spectral function measurements. Characterizing the QGP through medium modifications of rare hard probes, like Z-boson and high transverse momentum photon tagged jets, will require the integrated luminosity from HL-LHC run 4 and 5. Given the unique potential for progress on these and other fundamental questions, the town meeting concludes that **the top priority for quark matter research in Europe is to fully exploit the physics opportunities presented by nuclear beams throughout the entire HL-LHC program.**

With the upgrades planned for HL-LHC run 4 and run 5, all four major LHC experiments are well-positioned for heavy ion programs that will significantly advance our understanding of fundamental questions in the field and that complement each other. the The upgraded detectors will give access to the 3D structure, microscopic dynamics, and substructure of quark matter. This provides an optimized, multi-pronged approach for the most comprehensive characterization of the QCD high-temperature phase by the end of HL-LHC run 5. Specifically:

- **ALICE 3** is a completely new dedicated high-energy nuclear physics experiment, based on innovative detector concepts, with particle identification and unprecedented pointing resolution over large acceptance in rapidity and transverse momentum. It offers unique opportunities to advance quark matter research in HL-LHC Run 5, in particular via measurements of electromagnetic radiation, heavy flavour, and particle correlations.

- The **LHCb Upgrade2**, motivated mainly by the LHCb flavor physics programme, will offer unique opportunities for quark matter research in run 5 at the HL-LHC, in particular with measurements of heavy-flavour and the initial stages in collider mode at forward rapidity and in fixed-target mode.

- The **Phase-2 CMS and ATLAS** feature increased pseudorapidity coverage, high-rate capability and particle identification. They will significantly advance quark matter research by precisely characterizing high-momentum transfer and photonuclear processes that require high statistics.

2. Physics opportunities with fixed-target experiments

At lower center of mass energies, a strongly interacting system with high baryon density is produced. Historically, experiments exploring center-of-mass energies at the CERN SPS at around sqrt(s)=20 GeV provided the first evidence for the production of a new state of matter with many of the predicted features of a QGP. Exploiting recent advances in detector technologies and extending the collision energy range toward even lower energy, there are ample opportunities for a new generation of precision measurements that address central questions about the QCD phase diagram:

The **NA60+ detector** at the CERN SPS will explore for the first time the whole SPS energy range (6<sqrt(s_NN)<17 GeV), addressing open questions in the electromagnetic (thermal dilepton production around T_c, signals of chiral symmetry restoration) and charm sector (onset of charmonium suppression, charm hadronization in a high-muB QGP) with unprecedented event rates. The **CBM detector** at FAIR will allow the exploration of high baryon density towards lower center of mass energies, including the study of electromagnetic processes. **NA61/SHINE** at the CERN SPS will continue exploring QGP-related signatures in light ion systems through comprehensive, large-acceptance hadron measurements.

3. Ions at CERN's accelerator complex

To fully exploit the physics opportunities offered by nuclear beams at the HL-LHC, achieving high integrated luminosities in heavy ion collisions during Runs 4 and 5 is essential. For instance, the ALICE 3 PbPb integrated luminosity target in run 5 is of ~ 30 nb^{-1}. Additionally, a range of scenarios could benefit from further exploring the flexibility of CERN's accelerator complex for nuclear beam delivery to both fixed target and collider experiments. For example, the town meeting noted colliding lighter ion species than lead (such as indium or xenon) or using a 25 ns filling scheme for lead could yield higher nucleon-nucleon luminosity, although with lower QGP effects. Accelerator studies to best inform the choice of the optimal species are encouraged. HL-LHC is also well-positioned to build on recent discoveries and emerging opportunities through dedicated short light ion runs. In some scenarios, it may be beneficial to deliver different ion species to both HL-LHC and CERN's fixed target areas within the same year. The town meeting emphasized that the proposed addition of a second heavy ion source and upgrades to the heavy ion complex would greatly enhance the scientific potential of both the collider and fixed target heavy ion programs.

4. Physics opportunities at FCC-hh

Already in preparation for the 2018 update of the European Strategy for Particle Physics, key parameters of the heavy-ion performance of FCC-hh had been considered. It was established that such a machine would offer unique opportunities for QGP studies in the sector of hard probes and that the QGP created at FCC-hh may be the only one in which phenomena related to thermal charm production can be studied. The town meeting has reiterated these arguments and it concludes:
The **design choices for FCC-hh and its injectors should allow for the possibility to inject heavy ions**, so that questions only accessible at higher center of mass energies or only with future detector technologies can finally be studied as part of the FCC physics programme.

5. Dedicated support for theoretical research

Theoretical work in the field of heavy ion collisions should be guaranteed continuous support, both in its phenomenological aspects (research needed to interpret experimental results and to shape future experimental programs) and in its efforts aimed at understanding from first principles the properties of non-abelian quantum field theories at finite temperature and density.