Conclusions of the Town Meeting: Relativistic Heavy Ion Collisions

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On Wednesday 24 October 2018, a Town Meeting was held at CERN to collect input on the section of relativistic heavy ion collisions in the update of the European Strategy for Particle Physics. The meeting featured short presentations of existing and planned future heavy ion experiments at the CERN LHC, the Brookhaven RHIC, the CERN SPS, the FAIR facility in Darmstadt and the JINR in Dubna. In addition, the meeting provided a forum in which individual scientists and groups could contribute with short comments and statements. The meeting counted 421 registered participants that covered all experimental and theoretical activities in the field. The meeting concluded with an open 2-hour discussion of the priorities in the field.

The following text is not endorsed officially by any of the experimental collaborations and facilities mentioned, but summarizes the ***consensus view*** of the scientific community on the priorities of the field, as expressed by the participants of the town meeting. It is submitted to the Open Symposium of the European Strategy Group in Granada, Spain by the convenors of the Town Meeting,

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The study of matter under extreme conditions, aside from its intrinsic interest, is central to our understanding of the early Universe and the evolution of massive stars. At high temperature and density, new states of matter are dominated by quark and gluon degrees of freedom. Such states are studied by colliding heavy ions at ultra-relativistic energies. At the highest energies available at the Large Hadron Collider, the quark gluon plasma (QGP) is created and diagnosed at nearly vanishing (net)baryon density, i.e. under conditions prevailing in the very early Universe. Lower beam energies, currently available at the CERN-SPS, RHIC in Brookhaven and at future facilities such as FAIR in Darmstadt and NICA in Dubna, probe the baryon rich quark matter under conditions encountered in various astrophysical settings.

Considering the fundamental physics questions that are coming into experimental reach in the coming decade, the Town Meeting highlighted the following opportunities for fundamental progress:

1. ***The top priority for future quark matter research in Europe is the full exploitation of the physics potential of nucleus-nucleus and proton-nucleus collisions at the LHC.***

Since its start in 2010, the LHC heavy ion programme has established in PbPb collisions abundant and numerically large signals for dense, collectively evolving matter on transverse momentum scales ranging from ~ 100 MeV to 1 TeV. This has opened a broad phenomenology of strong interaction matter under extreme conditions, including amongst many important features an unprecedentedly detailed characterization of collective flow in all soft observables and of jet quenching in all hard hadronic observables. The wealth of data collected and analyzed by all four LHC experiments bears proof that the properties of strong interaction matter can be accessed with controlled and increasingly precise experimentation in heavy ion collisions at the multi-TeV scale. It also demonstrates the powerful complementarities of the four LHC experiments, ALICE, ATLAS and CMS and LHCb with precision tracking down to very low transverse momenta and particle identification on one side, and excellent capabilities for high-p_T detection on the other.

Within the approved heavy ion programme up to LS4 in 2030, it is foreseen to exploit the currently identified scientific opportunities with PbPb collisions by accumulating an additional

13 nb^{-1} per LHC experiment. This programme after LS2 includes precision studies of the flow of heavy quarks and of open heavy flavor and quarkonia production , the detailed analysis of fluctuations of conserved charges and of quenched jet fragmentation via high statistics photon/Z-jet correlations, and access to signals of electromagnetic radiation from the dense medium. This will enable to fully establish the long-wavelength matter properties of the plasma produced at the LHC, and to get access to the partonic dynamics that underlies the observed surprisingly strong collective phenomena. The Town Meeting observed that a timely completion of the planned upgrades in detector and data acquisition and a timely preparation of the LHC machine are prerequisites for exploiting these opportunities in run 3 and 4.

At the time of the last European Strategy for Particle Physics Update in 2012, the baseline heavy ion programme foresaw pp and pA comparison data to benchmark medium modifications in nucleus-nucleus collisions. Since then, experiments at the LHC have established that signatures of collectivity are only mildly attenuated with decreasing system size and persist in pPb and even in high-multiplicity pp collisions. This major discovery raises fundamental questions about the nature of a unified description of particle production across system size from pp via pPb to PbPb. The resulting novel challenges for the future experimental programme in pPb include a study of the signals of collectivity in all the channels established in PbPb and with comparable precision, as well as the search for the onset of jet quenching phenomena in pPb systems that are expected to accompany collective behavior. Current studies indicate that a total of 6 weeks pPb running (corresponding to 1.2 pb^{-1} for ATLAS and CMS and 0.6 pb^{-1} for ALICE and LHCb) would permit to follow up in a timely fashion on the novel opportunities arising from recent LHC discoveries. It would also yield qualitatively improved constraints on the nuclear parton distribution functions on which our understanding of hard processes in nucleus-nucleus collisions relies. The Town Meeting noted that the scientific rationale for extending in this way the pPb programme without compromising on the approved PbPb programme is compelling.

The LHC experiments have ambitious upgrade plans for LS3 and LS4 that will lead to significant improvements of the sensitivity for key measurements and that will enable new probes such as heavy flavor baryons and electromagnetic radiation. In addition, the use of lighter ion beams will open the possibility of a significant increase of the nucleon-nucleon luminosity after LS4 while still producing ultra-dense matter over a sufficiently large volume. This opens a high-precision era for a broad range of observables that are rare or not accessible at the luminosities currently envisaged for PbPb collisions. For instance, novel very high-Q^2 probes, such as boosted top-decays, will become accessible. A compact, low-mass high-speed all-Silicon next-generation multi-purpose detector could allow one to study luminosities still a factor 50 higher than the upgraded ALICE and give access to a rich physics program ranging from measurements with electromagnetic probes at ultra-low transverse momenta to precision physics in the charm and beauty sector.

The Town Meeting identifies the above novel arguments for continuing beyond LS4 the exploitation of the LHC for the study of the properties of strongly interacting matter, and gives strong support for further pursuing these plans.

2. ***At lower center of mass energies where the highest baryon densities are reached, advances in accelerator and detector technologies provide opportunities for a new generation of precision measurements that address central questions about the QCD phase diagram.***

Former fixed target experimental programs at the Brookhaven AGS and the CERN SPS have explored the beam energy range between 2 to 200 GeV/nucleon to characterize the transition from a hadronic to a partonic state of matter produced in the collision. At present, the NA61/SHINE experiment at the CERN SPS and the RHIC Beam Energy Scan program continue characterizing to this end fluctuations in hadronic distributions. The Town Meeting

notes that rare penetrating (electro-magnetic) probes as well as cumulants of net-charge fluctuations are of central importance to explore the QCD phase diagram in the region of large baryon density. So far, they are almost unexplored in the energy range between SIS 18 and the top SPS energy.
In the coming years, SIS 100 at FAIR will allow the HADES and CBM collaborations to access these and other rare probes, such as multi-strange hyperons and hypernuclei, at gold beam energies up to 11 GeV/nucleon with unprecedented reaction rates up to 10 MHz. On the same time scale as CBM at SIS100, the NICA project at JINR in Dubna will provide a similar energy range in a collider geometry at the average luminosity of 10^{27} / cm^2 s^{-1}, and it will also enable fixed target experiments with E_{Lab} = 2 – 4.5 GeV/nucleon. The Town Meeting notes that the scientific programs of CBM at FAIR, the collider experiment MPD at NICA and the fixed target experiment BM@N will offer important complementarities for the study of QCD matter at the highest baryon densities.
The Town Meeting also observed that the CERN SPS would be well-positioned to contribute decisively and at a competitive time scale to central open physics issues at large baryon density with proposals like NA60+. In particular, the CERN SPS will remain also in the future the only machine capable of delivering heavy ion beams with energies exceeding 30 GeV/nucleon, and the potential of investigating charm production and rare penetrating probes at this machine is attractive.

3. ***The complementarity of LHC and RHIC is an essential resource in efforts to quantify properties of the Quark-Gluon Plasma.***

At the LHC, measurements constraining the long-wavelength properties of strong interaction matter (such as viscous QGP transport coefficients and parton energy loss parameters) have been collected in recent years with unprecedented precision at low and high p_T. At RHIC energies, the range of $p_T > 10$ GeV remains almost unexplored today, and measurements of rare and electromagnetic probes warrant higher precision. As the temperature dependence of transport properties can be accessed experimentally by varying the center of mass energy over a logarithmically wide range, the combined analysis of LHC data and future high precision data from RHIC offers a qualitatively novel handle on the temperature dependence of properties of hot and dense matter. The Town Meeting observes that the recently approved sPHENIX proposal targets these opportunities by bringing greatly extended capabilities to RHIC, including mid-rapidity hadronic calorimetry, momentum resolution and a high rate data acquisition suited to fully exploit the RHIC luminosity. In addition, upgrades currently being implemented will allow STAR to continue providing in the coming years valuable complementarities at lower energy between the RHIC beam energy scan program and planned European efforts to study the QCD phase diagram at large baryon density.
Additional opportunities for studying nuclear collisions at center-of-mass energies close to those reached at RHIC could arise with the use of the LHC in fixed-target mode. The Town Meeting notes with interest first results in fixed target mode obtained with the SMOG system in LHCb, and fully supports the exploration of these opportunities within the AFTER, ALICE and LHCb collaborations.

4. ***Dedicated investments in theoretical research are needed to fully exploit the opportunities arising from the upcoming precision era of nuclear research at collider and fixed target energies.***

The dynamical understanding of relativistic heavy ion collisions requires the combination of a broad range of different techniques and theoretical concepts. In particular: Finite temperature lattice QCD provides a unique source of ab initio calculations of non-perturbative QCD matter properties. QCD-based modeling of heavy ion collisions is a prerequisite for linking future high-precision data to fundamental properties of dense QCD matter. Perturbative QCD techniques are needed at the multi-TeV scale for the quantitative analysis of quenched high- p_T processes in nuclear collisions and of nuclear parton distributions. The Town Meeting notes that progress in all these directions is required to fully exploit the opportunities of the upcoming precision era. In addition, theoretical research in high energy nuclear physics has profited in the recent past from exploring concepts of other active research fields, including applications of string theory to the study of strongly coupled plasmas, or adaptations of cosmological fluctuation analyses to the corresponding measurements in heavy ion collisions. This interplay with the wider theoretical physics community is worth further developing, as it provides not only an intellectual enrichment of nuclear physics, but also a natural communication channel via which the most important discoveries of the LHC heavy ion programme are disseminated to the wider scientific community.

To best address the opportunities arising from the upcoming precision era in nuclear physics, the Town Meeting emphasized in particular the need of giving dedicated support to phenomenological computing in Europe on a level comparable to what has been implemented successfully in the US in recent years. This support should also facilitate the interplay between the currently distinct scientific communities modeling proton-proton and nucleus-nucleus collisions, thus providing a framework for addressing the challenges arising from the LHC discovery of collectivity in small systems. Furthermore, a timely implementation of the roadmap towards exascale computing in finite temperature lattice QCD is needed to fully exploit the opportunities arising from the improved experimental control over in-medium spectral functions, fluctuation measures and transport coefficients. This also requires support for the development and optimization of software for newly emerging processor and hardware architectures.