Quantum Chromodynamics: Theory - Input for the European Particle Physics Strategy Update

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Abstract. This contribution highlights the role of QCD theory in studying the physics of the Standard Model and beyond, as well as opportunities and challenges, as an input to the preparation of the European Particle Physics Strategy Update (EPPSU).

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1. Introduction

The strong interaction and its dynamics contributes to every stage of the evolution of our universe, and plays a critical role in every high energy experiment involving hadron. Quantum Chromodynamics (QCD), a dynamical theory of quarks and gluons, is believed to be the theory of the strong interaction physics, and a necessary part of the Standard Model of particle physics. With its color confinement - the defining property of QCD, no modern detector has ever seen quarks and gluons in isolation, and it has been an unprecedented intellectual challenge to study and to test QCD dynamics without being able to see quarks and gluons.

With its asymptotic freedom, QCD perturbation theory has been extremely successful in interpreting almost all data and phenomena from high energy scattering, in terms of QCD factorization and its capability to describe and predict short-distance dynamics between quarks and gluons. It is this success that has given us the confidence to search for new physics beyond the Standard Model in hadronic collisions with continued improvements of our ability to calculate and to control the precision of QCD calculations.

On the other hand, QCD dynamics is much richer than what we have probed and tested in the asymptotic regime through high energy scattering experiments. Although we are confident that QCD is the right theory for strong interaction physics, there are still many challenging and unanswered questions. What are the properties of high temperature systems of quarks and gluons at the beginning of our universe, and what is their role in the evolution of our universe? How do hadrons and their properties emerge from quarks and gluons and QCD dynamics? How precise could we control QCD calculations to allow us to discover new physics?

The theory community has made tremendous progress in understanding QCD and its dynamics since its introduction about 45 years ago. In addition to the success of precision tests in high energy scattering experiments, lattice QCD has made remarkable progress in calculating and predicting nonperturbative and fundamental hadron properties, such as hadron mass spectrum, axial and tensor charges, and decay properties, as well as predictions on exotic meson and baryon states. Relativistic heavy ion collisions have provided surprises and new opportunities for us to explore the QCD dynamics at high temperature, peeking into the early time of our universe and searching for answers to the question on where did we come from? In this short contribution, we summarize the need and a number of key challenges and opportunities for studying QCD, strong interaction physics and its role in searching for new physics as an input to the preparation of the European Particle Physics Strategy Update (EPPSU).

2. QCD at the LHC

The LHC has completed Run I and Run II, and we have now found every particle of the Standard Model (SM), including the discovery of the Higgs boson from Run I. With the higher energy and integrated luminosity from Run II, it is remarkable that the SM has been doing so well that we have not seen any significant deviations from the SM, as shown for example in Fig. 1. Higgs interactions to the third-generation fermions have been established to a 5σ level of accuracy, as shown for example in Fig. 2. By contrast, establishing the complete Higgs-fermions interaction sector of the SM and exploring the uncharted territory of Higgs self-interactions, as well as

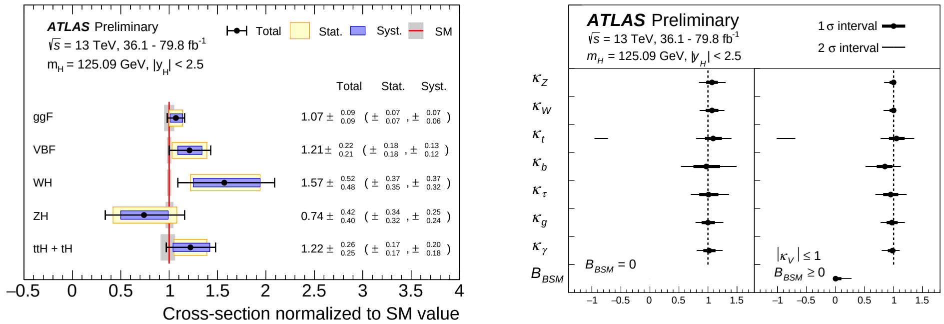

Figure 1. Left: Precision in Higgs cross sections from various production channels normalized to their SM values; Right: Precision in Higgs couplings to various particles [1].

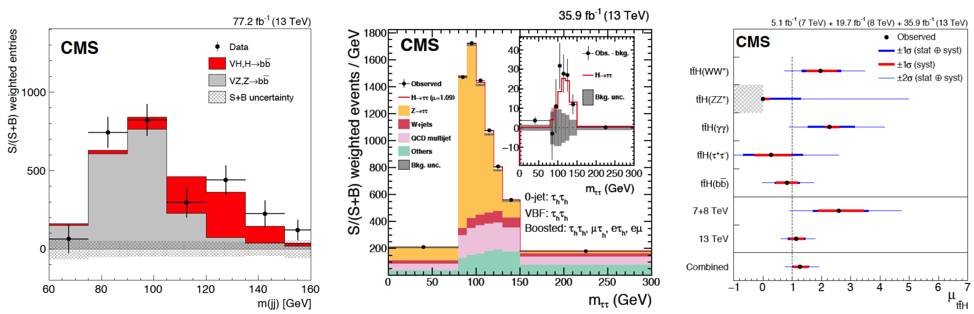

Figure 2. Higgs interactions with the 3$^{\mathrm{rd}}$ generation fermions: $B\bar{B}$ (left), $\tau\tau$ (middle) and $t\bar{t}$ (right)[2].

searching for deviations from the SM and signals for new physics beyond the SM, will require the HL-LHC, HE-LHC and future (lepton and hadron) colliders.

As clearly presented and documented in the most recent edition of the international workshop on QCD@LHC [3], QCD has played, and will continue to play, a key role in virtually all aspects of the LHC physics program and beyond. All analyses of LHC events require an array of methods rooted in QCD, including, while not limited to,

- perturbative calculations of hard processes (involving complex final states with multiple leptons, jets, photons, weak bosons, Higgs) with the current precision frontier at the next-to-next-to-next-to-leading order (N^{3}LO) in the strong coupling for Higgs boson production, and next-to-next-to-leading order (NNLO) for many key $2 \to 2$ partonic subprocesses;
- determination of nonperturbative parton distribution functions (PDFs) from global fits to the LHC and existing lower-energy data, with the current standard at NNLO;
- analytic resummations of logarithmically enhanced large QCD radiative corrections, coming from various regions of phase-space, to all orders in the strong coupling at the leading-logarithmic (LL), next-to-leading-logarithmic (NLL), next-to-next-to-leading-logarithmic (NNLL), and even N^{3}LL accuracy;

- development of parton shower Monte Carlo generators for realistic event simulation indispensable for experimental analyses, aiming toward full next-to-leading-order (NLO) showers.

Owing to the fact that no isolated quarks and gluons have ever been seen in a detector, although we have seen the "footprints" of them in terms of energetic jets, all analyses of experimental events in hadronic collisions rely on QCD factorization theorems that provide formalisms to match the observed particles and their distributions to the quarks and gluons and their dynamics. QCD color confinement demands non-trivial color-entangled soft interactions for all high-energy scattering observables involving identified hadron(s), and QCD factorization of such observables is effectively an approximation for which such non-perturbative color-entanglement is proved to be suppressed. However, some observables, especially important for the precision frontier and for new physics searches, could be more sensitive to such non-perturbative entanglement. For example, precision physics in the top quark sector requires understanding of $t\bar{t}$-pair transverse momentum spectra: a pair of highly boosted top quarks recoiling with small p_T imbalance, which probe subtle QCD color correlations between initial and final states. Also, the precision determination of W-boson mass involves understanding of electroweak boson transverse momentum spectra at low p_T with high precision, including effects beyond NNLO and nonperturbative effects. In general, with observables involving multiple momentum scales, which are very relevant for many precision measurements for signals of physics beyond the SM, QCD factorization calculations could receive large high-order corrections logarithmic in the ratios of various observed scales, as well as non-trivial non-perturbative power corrections because of the nature of color entanglement in QCD.

At the precision frontier of the search for new physics, especially important is the evaluation of the theoretical accuracy of our predictions. With the greatly improved precision of experimental measurements, it comes to challenge and demand a better understanding of the approximations of the QCD factorization theorems for evaluating various physical observables, in particular, the role of neglecting nonperturbative and power-suppressed corrections to the factorization formalisms. With the tremendous success of the SM, our effort to search for new physics beyond the SM at the LHC and any future colliders requires a new level of precision in QCD fixed order as well as resummation calculations of short-distance hard processes, and unprecedented accuracy in determining PDFs as achievable in high-energy DIS machines like the LHeC [4] or the FCC-eh [5], along with new challenges to understand and control the theoretical approximations of QCD factorization formalisms.

3. QCD: hadron properties and structure

With remarkable success, QCD describes high energy scattering phenomena observed at the LHC in terms of QCD factorization and the interactions of quarks and gluons at short distances - the asymptotic regime. However, understanding the properties and structure of hadrons in terms of their fundamental constituents requires an understanding of QCD at large distances, sensitive to the rich dynamics of the confinement regime. The mass-scale for the hadron spectrum is characterized by the proton's mass at roughly 1 GeV, which is about 100 times more than the total current quark mass, generated by the Higgs mechanism, of the three valence quarks inside the proton. Understanding the emergence of mass, spin and other hadron properties from the dynamics of quarks and gluons in QCD is an ultimate challenge for QCD theory, and is the main mission of the proposed Electron-Ion Collider (EIC) [6], while understanding the structure of hadrons is also necessary for exploring and searching for signals beyond the SM at the LHC and any of the future lepton-hadron and hadron-hadron colliders.

3.1. Parton distribution functions

Parton distribution functions are indispensable for theory predictions of scattering processes at lepton-hadron and hadron-hadron colliders. Using standard factorisation in QCD, the PDFs are determined by a comparison of theoretical predictions with hard scattering data covering a broad range of kinematics in the momentum fraction x and the hard scale Q^2. Steady progress both in the accumulation and in the analysis of hard-scattering data by experiments at HERA, Tevatron and the LHC, as well as improvements of the relevant theoretical predictions to NNLO in perturbative QCD, have led to an increasingly accurate description of the PDFs of the proton in global fits. Such fits provide the proton composition in terms of the gluon and the individual light-quark flavors u, d and s with a good precision. Simultaneously, they are also able to determine the strong coupling constant α_s and the heavy-quark masses m_c, m_b and m_t at NNLO accuracy in QCD. These results serve as input to high precision predictions for benchmark processes in the SM and cross sections for scattering reactions beyond the SM, measured or being searched for in Run II of the LHC.

The LHC data start to have a significant impact on PDF extractions. For example, uncertainties of PDFs could be the dominant uncertainty source for extracting the mass of the W-boson. With new and more precise data from the LHC, and NNLO calculations becoming available for differential production cross sections for Drell-Yan, Higgs, jets, top, etc., theory is catching up for fitting precision and determination of the PDFs. As shown in Fig. 3, PDFs could be significantly further improved by future HL-LHC data.

A future challenge for the field is the consolidation of PDF determinations, starting from mutually consistent sets of data for hard scattering processes and clarifying observed differences in present PDF analyses, which are sometimes beyond the quoted uncertainties. Progress will come from understanding larger classes of hard scattering cross sections at NNLO accuracy in QCD, which will constrain the PDFs even further. The ultimate goal is to have analyses of compatible sets of precise data with a detailed account of the systematic errors and all known theoretical corrections. This will allow one to measure all non-perturbative PDF parameters and α_s as precisely as possible. Further progress would be possible with high-energy DIS machines, the LHeC [4] or the FCC-eh [5], where N^{3}LO would be required.

3.2. Beyond PDFs: hadron tomography and correlations

Beyond their paramount practical importance for computing hadronic cross sections, PDFs contain a wealth of information about the structure of the proton, ranging from the dominance of gluons at low x to subtle effects like the differences between $\bar{u}$, $\bar{d}$, s and $\bar{s}$ in the sea quark sector. However, PDFs are the result of a strong reduction of information and teach us only about the longitudinal momentum of partons in a fast moving hadron. This restriction is lifted in several types of more general distributions:

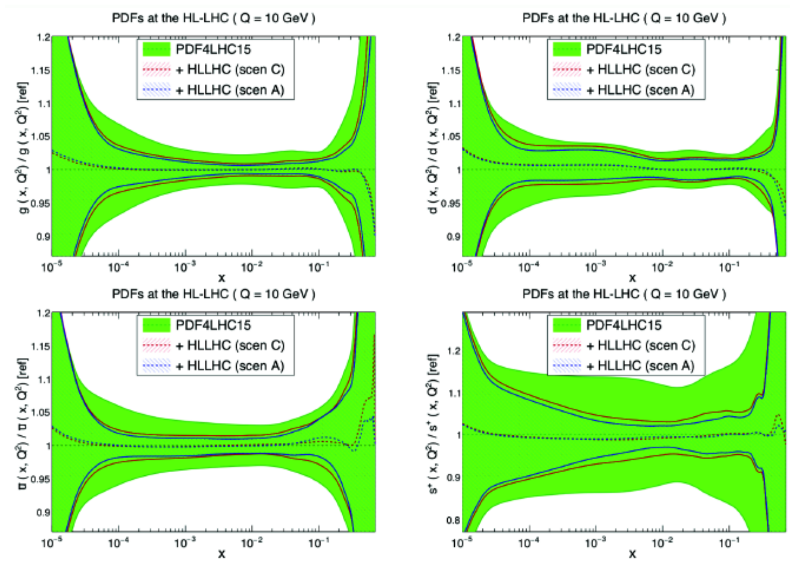

Figure 3. Improvement of PDF determinations with future HL-LHC data (from presentation by R. Thorne at [3]).

Transverse momentum dependent PDFs (TMDs) describe the spectrum of partons both in longitudinal and in transverse momentum. They are of practical importance e.g. for the precise description of the low p_T spectrum for W, Z or H production in pp collisions. The transition between non-perturbative confined motion and perturbative QCD dynamics is exhibited as the parton p_T changes from a few 100 MeV to a few GeV. In the polarised sector, the presence of a transverse direction permits the study of several correlation effects between spin and momentum, some of which are deeply connected with the dynamics of soft gluons and the gauge nature of QCD interactions.

Generalised parton distributions (GPDs) appear in the description of exclusive processes like deeply virtual Compton scattering or meson production at the amplitude level. Measuring the transverse momentum of the outgoing protons in these reactions and performing a Fourier transform, one obtains information about the transverse spatial position of partons inside the target, correlated with their longitudinal momentum. Furthermore, unique information about the spin and orbital angular momentum of partons inside a proton is encoded in its GPDs. Along with the helicity parton distributions obtained from spin asymmetries in high-energy hadronic scattering, this allows one to address the question of how the proton spin is carried by the proton's constituents.

Double parton distributions (DPDs) quantify the joint probability for finding two partons in the proton and are required to compute double parton scattering, i.e. the process in which two parton pairs produce a high-mass system in the same pp collision. Although this mechanism is often suppressed, it can substantially contribute to important final states at the LHC, such as like-sign W pair production. DPDs depend on the spatial distance between the two partons (providing a link with GPDs) and encode a variety of correlation effects, for instance in colour space, that can have important consequences on observables.

The theory of the different distributions and the associated processes stands on firm ground and makes use of powerful concepts such as factorisation and resummation in QCD. Strong connections also exist between the distributions discussed here and theory approaches for QCD in the small x limit. Measurements at running or planned lepton-hadron machines, such as the planned EIC or the LHeC [4], will provide a boon of high-precision data for TMD and GPD extractions in a wide kinematical range, whereas measurements at the LHC will provide increasingly detailed data sensitive to TMDs and DPDs.

Theory will have to address several challenges to keep up with experimental progress and demands. The calculation of higher perturbative orders and of power corrections is highly demanding given the multi-variable nature of the physics, and a suite of software tools will eventually be indispensable to make increasingly complex theoretical expressions available to phenomenological studies and the analysis of experimental data. Input from both non-perturbative QCD methods and experimental data will be needed to map out hadron structure at the detailed level of distributions just discussed. Several groups of theorists in Europe have made essential contributions to the field in the past and will continue to play a prominent role in its future development.

4. Lattice QCD

The European effort in accelerator based experiment needs to be matched by similar advances in the precision of theoretical predictions. Many processes can be factorized into non-perturbative matrix elements, calculable by Lattice QCD (LQCD), and perturbatively tractable parts. LQCD results are often complementary to experimental efforts. To fully exploit the discovery potential of high energy physics experiments, precise LQCD results are necessary.

European teams are at the forefront of lattice simulations worldwide and organized in collaborations that jointly develop codes and pool computer time to generate gauge ensembles, e.g., the Coordinated Lattice Simulations (CLS) consortium (HU Berlin, CERN, TC Dublin, Krakow, Mainz, UA Madrid, Milano Bicocca, Münster, Odense, Regensburg, Roma I, Roma II, Wuppertal, DESY Zeuthen), the European Twisted Mass Collaboration (ETMC) (Bonn, Cyprus, DESY Zeuthen, Groningen, Lanzhou, Liverpool, Poznan, Roma I, Roma II, Roma III, Valencia) or BMW-c (Budapest, Marseilles, Wuppertal). Once these ensembles have been generated, "measurements" (which are often also computer time intensive) are being taken and analysed by smaller subgroups, just like several experiments share one accelerator. These collaborations have differences in terms of the discretization used, the importance given to the physical quark mass or the continuum limit and the physics questions addressed: spectroscopy, hadron structure, extreme QCD.

To control all sources of systematics and achieve levels of accuracy comparable with high precision measurements, LQCD requires extreme computational resources. Lattice groups have been very successful applying for time on supercomputers. However, the computational needs are in fact so large that in the past the community also developed dedicated computers (e.g., APE, QCDOC, QPACE). Some of this impacted on commercial developments. Due to the exploding costs of ASIC design and manufacturing this has become impossible within current levels of funding. Unfortunately, only very occasionally one European installation enters the top ten list of supercomputers and only a fraction of this time is available for high energy physics applications.

On the physics side, listed below are some examples of the impact and direction of LQCD.

(i) Lattice calculations of decay constants and electroweak formfactors in particular for heavy mesons and baryons resulted in very stringent constraints on the CKM matrix elements and the unitarity triangles. Due to the increasing demand on the precision of such calculations, the inclusion of mass and electromagnetic isospin breaking effects has become necessary and this is an area of active research. The study of electroweak formfactors has also gained momentum recently, in view of hints of possible violations of lepton universality. Lattice calculations of quark masses (other than the top) and the strong coupling parameter provide the most precise values. The latter is also important with respect to the question of vacuum stability. On the theoretical side, the space of technicolor candidate theories for a possible strongly interacting BSM sector is being mapped out by LQCD.

(ii) The crossover line to the quark gluon plasma is being mapped out towards larger values of the baryon density, and the equation of state and other thermal properties like the conductivity and sheer viscosity are being computed with ever increasing precision. Calculations of fluctuations of conserved charges have helped to connect these results to experimental signatures of the freezeout line at RHIC and at the LHC. Further dedicated lattice studies of QCD under extreme conditions are needed in the future.

(iii) Regarding the nucleon structure, Mellin moments of PDFs and GPDs are being computed. Regarding unpolarized PDFs the precision of these studies cannot yet compete with experiment, however, for polarized and transverse PDFs as well as for GPDs, where experimental information is imprecise or sparse, LQCD has started to produce stringent constraints. This is of particular relevance with respect to the planned physics programme at the future electron ion collider. Exploratory studies of double parton distributions and transverse momentum PDFs have been instigated, as well as attempts to compute PDFs as a function of x more directly using perturbative factorization of suitable euclidean space "observables" - matrix elements that are amenable to lattice calculations.

(iv) Many charmed baryons have been discovered recently by LHCb whose masses had been predicted correctly by LQCD. Lattice methods are needed to predict and interpret such experimental findings. In addition to predicting masses and in the case of unstable hadrons, resonance properties, lattice QCD also gives information about the mass decomposition among the parton flavors, as well as the coupling of the gravitational force by computing other elements of the stress-energy tensor. Moreover, first studies on the distribution of the longitudinal and transverse spin among the quarks and gluons exist. Increasing the reliability and precision of these results is another main thrust of LQCD community for the coming years.

On a technical level the future research in LQCD should include: (1) increased control over the continuum limit, (2) flavour singlet observables with full non-perturbative renormalization to schemes that are also defined in the continuum, (3) inclusion of electromagnetic effects, (4) resolving matrix elements including resonances by use of finite volume methods, (5) higher order perturbative matching to the MS scheme, (6) exploration of techniques to compute inclusive observables, (7) exploration of coordinate space methods, e.g., for the direct computation of PDFs, (8) development of new techniques to compute higher Mellin moments, (9) development of new methods to push towards larger baryon densities, and (10) global fits including experimental and lattice input.

To achieve these aims a dedicated European computational infrastructure for lattice QCD with long term career prospects for software developers and maintainers is of prime importance, especially, for the HL-LHC effort. This, if supported by adequate computer and human resources, will allow the LQCD community to make a major impact on the particle and hadron physics phenomenology. In many cases LQCD predictions will exceed the accuracy that can be reached in present and future experimental measurements.

5. QCD at finite temperature and nuclear collisions

The understanding of QCD at high temperatures and densities, where symmetries of the theory become modified and coloured partons turn into asymptotic degrees of freedom, is the goal of the heavy-ion programmes at RHIC and the LHC. The most recent experimental data and theory developments can be found in the presentations in the 2018 Quark Matter [7] and Hard Probes [8] conferences. At present, a heavy-ion collision is commonly pictured as two Lorentz-contracted nuclei that cross producing an abundance of partons. Those partons interact to quickly create ($\tau \lesssim 1$ fm/c) a collective state or medium with energy density exceeding that required for the transition from the confined, chiral-symmetry broken hadronic phase to the Quark-Gluon Plasma (QGP). The behaviour of this medium can be described macroscopically using relativistic hydrodynamics with a very low shear viscosity - an *almost perfect fluid*. The medium expands and cools down to hadronisation when the final particles, then rescattering and decaying, are produced.

The structure of protons and nuclei (see Sections 2 and 3), both their number and transverse distribution, determines the initial stage of hadronic collisions. Nuclear parton densities (nPDFs) in the collinear framework have been extracted from global fits comprising fixed target (NC and CC DIS and DY) and collider data (hadrons from dAu at RHIC and electroweak bosons and jets from pPb at the LHC), see the talk by H. Paukkunen in [8]. The impact of LHC data is modest and nPDFs are presently subject to large uncertainties everywhere and unconstrained for $x < 10^{-3}$. Future improvements [8, 9] rely on the inclusion of heavy flavour forward data, of larger statistics electroweak bosons and Drell-Yan and top data (although this possibility would be better exploited at the HE-LHC and the FCC-hh) in pPb during Run 3 or 4, and of dijet and exclusive vector meson production in ultraperipheral collisions (where gluon GPDs can be constrained). Clarifying the production mechanism and the scale dependence will be crucial for the use of heavy quarks and quarkonia.

There has been much progress in developing a QCD theory of thermalisation and hydrodynamization. At present, there are difficulties to obtain the fast isotropisation required for a successful description of experimental data when the expansion of the system is taken into account. On the other hand, both weak (including both elastic and inelastic processes) and strong coupling (using the AdS/CFT correspondence) approaches lead from a wide range of initial conditions to a behaviour describable by hydrodynamics even for large momentum anisotropies. Therefore, the present debate focuses less on thermalisation but on how a behaviour macroscopically describable by hydrodynamics emerges from the microscopic QCD dynamics.

Hydrodynamic models, based on a gradient expansion truncated to first or second order, provide a successful description of AA, pA, dAu, ^{3}He Au and even pp collisions at RHIC and the LHC if initial conditions are carefully chosen and rescattering after hadronisation is included. They are being improved by attempting a consistent resummation to all orders using either the AdS/CFT correspondence or the link to transport equations (e.g. anisotropic hydrodynamics). Finally, statistical methods are applied for the extraction of transport coefficients (shear and bulk viscosity and relaxation times) from a comparison to experimental data.

The extraction of medium properties from the modification of the yields of hard probes (large transverse momentum hadrons and jets - *jet quenching*, and heavy quarks and quarkonia) has also greatly advanced [8]. Methods ranging from transport equations to density matrix evolution are applied to describe the fate of quarkonium in the medium, the main remaining uncertainties being the understanding of the formation of bound states and of their interaction with the medium, which demand non-perturbative input. The description of the energy loss of hard partons in a QCD medium includes now coherence both in the rescattering with medium constituents and between emitters in a QCD cascade and has been extended to NLO, using different techniques including soft-collinear effective theory (SCET). Modern jet techniques are now applied in heavy-ion collisions. For the extraction of transport coefficients of the QCD medium, uncertainties remain related to the lack of a simultaneous description of vacuum and medium-induced radiation, and of a satisfactory description of the interplay between the energetic parton and medium (i.e. the medium response to the passage of a jet). There is also a large activity aimed to develop Monte Carlo models that contain all these ingredients, see the talks by L. Apolinário and T. Luo in [8].

Collisions of small systems – dAu at RHIC, pPb and pp at the LHC – are the hottest topic in the field (see also Sections 2 and 3). They show characteristics (all measured ones except the jet quenching [9]) that in heavy-ion collisions are taken as signatures of the creation of a dense hot partonic medium. The most prominent of them is the two-particle correlations that are long range in rapidity and peaked at 0 and π azimuthal angle – the so-called *ridge*. All these characteristics vary smoothly as a function of the event multiplicity from pp to PbPb. Most common explanations are either at weak coupling in the framework of the Color Glass Condensate (CGC, initial state), or considering the formation of a medium to which hydrodynamics can be applied (final state). As stated above, weak and strong coupling approaches lead to hydrodynamisation even for large momentum anisotropies. Present efforts lie in merging initial state models with kinetic theory describing the stage prior to the application of hydrodynamics. Besides, these heavy-ion like phenomena challenge the standard view of particle production in pp and ask for a dynamical framework encompassing all system sizes, see the talk by T. Sjöstrand in [7].

Concerning finite temperature QCD, there have been advances both using perturbative techniques and on the lattice (see the talk by M. D'Elia in [7]). Transport coefficients and photon emission have been computed to NLO, and bulk properties like pressure to NNLO/N^{3}LO. Photon and dilepton emission are now computed in models that consider both QGP and hadron gas phases, see the talk by J. Ghiglieri in [8], but the large observed photon azimuthal asymmetries are still problematic. Lattice calculations (see Section 4) have progressed in the determination of bulk properties, the EOS, observables like fluctuations of conserved charges relevant for the search of the critical point in the phase diagram and the effects of magnetic fields, now with physical quark masses and improving the continuum limit. Problems remain for finite chemical potential, for characterising the QCD transition as a function of quark masses, and determining of dynamic properties (colour screening, transport coefficients) and the effects of chiral symmetry restoration.

Concluding, the heavy-ion field is centred on many body aspects that are not the main focus of other branches of QCD, the small systems problem and the understanding of the initial stages of the collision presently being the key open questions. A high future activity is guaranteed by the experimental programmes in the 2020's: AuAu at RHIC and pPb and PbPb at the LHC, the possibility of a fixed-target programme at the LHC [10], and the proposals for the 2030's: electron-nucleus collisions at the EIC [6] and the LHeC [4] and AA at the LHC [9].

6. Summary

QCD distinguishes itself from all other known theories and corresponding forces for having two remarkable yet seemingly contradicting properties: *asymptotic freedom* and *confinement* of the color force. It is these two properties that make QCD a fundamental theory very rich in dynamics, covering the strong interaction physics at all distance scales from the region of sub-femtometer distance ($\lesssim 0.1$ fm), where *asymptotic freedom* defines a "weak" sector of the strong force, and enables us to perform increasingly precise computations, to the regime of femtometer scales (0.1-10 fm) where *confinement* characterizes the strength, the richness, and the uniqueness of the "strong" sector of the strong force. QCD dynamics influences every observable or event in high energy collisions involving identified hadrons, plays a critically important role in our effort to search for new physics beyond the SM, and is still a best kept secret of the SM of all known forces. A sustained support of QCD theory, phenomenology and lattice is necessary to fully exploit the discovery potential of running and future experiments.

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