French theory activities in QCD and Hadronic Physics

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1 QCD and hadronic physics

1.1 QCD in a nutshell

Quantum Chromodynamics (QCD) is a quantum field theory of the strong interaction, one of the four fundamental forces in Nature. Any relativistic quantum field theory can be defined by providing information on (i) the field content including the quantum numbers (spin, electric charge, color, etc.), (ii) a Lagrangian describing the local interactions among the different particles, and (iii) the values of the input parameters (masses, couplings, etc.) of the Lagrangian. In the case of QCD, the main freedom resides in specifying the set of matter fields (the quarks). The gauge fields (the gluons) and the structure of the Lagrangian then essentially follow from the symmetry principles of Poincaré invariance (relativity), SU(3)-color gauge invariance, and renormalizability:

$$\mathcal{L}_{\text{QCD}} = \sum_{q=u,d,s,c,b,t} \bar{q}(i\not{D} - m_q)q - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a \,, \tag{1}$$

where $\not{D} := \gamma^\mu D_\mu$ is a contraction of the Dirac gamma matrices with the covariant derviate D_μ given by

$$D_\mu := \partial_\mu \mathbf{I} + ig G^a_\mu T_a \,. \tag{2}$$

Here G_μ is a contraction of the eight gluon fields with the eight generators T_a of the $\text{SU}(3)_c$ group in the 3-dimensional fundamental representation and the field strength tensor $G^a_{\mu\nu}$ defined as

$$G^a_{\mu\nu} = \partial_\mu G^a_\nu - \partial_\nu G^a_\mu - g f_{abc} G^b_\mu G^c_\nu \,. \tag{3}$$

Our goal here is of course not to give an introduction to QCD but to provide a hint of an idea that QCD is a remarkably beautiful theory which can be appreciated once a sufficient mathematical background is acquired. This theory is the starting point to to explain a wealth of phenomena.

The QCD Lagrangian above depends on seven parameters: the gauge coupling g, and the six quark masses $m_u, m_d, m_s, m_c, m_b, m_t$. In order to derive predictions for observables from the QCD Lagrangian it is necessary to provide numerical values for the gauge coupling and the quark masses as external input to the theory. Lacking any theory beyond QCD to calculate the value of these parameters they have to be fixed using experimental information.

The most important parameter is the gauge coupling g which specifies the interaction strength between the quarks and the gluons and the self-interaction of the gluons. The behavior of the theory depends crucially on its value. If g is sufficiently small a pertubative approach is possible where observables can be systematically expanded in powers of g and the terms in this series can be calculated. On the other hand, for large values of g the methods of perturbation theory fail and bound states of the quarks and gluons emerge as relevant degrees of freedom in a new effective Lagrangian.

It turns out that it is difficult and not very meaningful to state a single value for the strong coupling constant g. First of all, the interaction strength is not a constant (despite its name) but depends on the distance scale between the quarks and gluons or, equivalently, on the energy scale of the process. Therefore, the coupling has to be considered as a running cpupling $g(\mu)$ where μ is an energy scale. Still, a fixed value could be a reasonable approximation provided that the coupling doesn't change rapidly with the scale.[1] However, in the case of QCD, the coupling constant changes dramatically from non-perturbative to perturbative values in a transition region characterized by an energy scale $\Lambda_{\rm QCD} \simeq 200$ MeV. Therefore, it is inevitable to take into account the "running" of the strong coupling constant. This is consistently possible in the perturbative regime (energy scales much larger than $\Lambda_{\rm QCD}$) and requires the computation of loop effects leading to a differential equation called **renormalization group equation (RGE)** allowing to compute the coupling as a fonction of the energy scale. The first such calculations lead to the discovery of **asymptotic freedom** (and Nobel prizes for D. Gross, F. Wilczek and D. Politzer in 2004) which means that the strong coupling constant becomes smaller at higher energies/shorter distances and approaches the value zero at UV energies, i.e., QCD asymptotically turns into a free theory.

Concerning the quark mass parameters it would be tempting to identify them with the physical masses (the pole masses) of free propagating quarks. However, as mentioned above, free quarks have not been observed since they are confined in hadrons. It is therefore necessary to say precisely what we mean by a quark mass. If not stated otherwise, we understand by a quark mass the mass parameter appearing in the Lagrangian of QCD which (a priori) is not an observable but defined in a given renormalization scheme. The situation is different for the c, b, t quarks. They are called **heavy quarks** because their masses are much bigger than $\Lambda_{\rm QCD}$ so that α_s evaluated at the scale of the heavy quark mass is in the perturbative region. Therefore, due to asymptotic freedom, it is possible to consider the heavy quarks as quasi free particles and to interpret their masses as physical masses (pole masses) renormalized in the on-shell (OS) scheme. Nevertheless, the use of running heavy quark masses in perturbative calculations often leads to improved theoretical predictions. Again, the running quark masses depend on an energy scale, $m_q = m_q(\mu)$, and the scale dependence is governed by RGEs. The quark masses are extracted from experimental data (for example hadron masses) using either models/effective theories or ab initio calculations using Lattice QCD.

1.2 Hadronic physics

Hadronic physics can then be defined as the branch of physics which attempts to understand the properties of the hadrons, their structure and interactions in terms of quarks and gluons. The most important hadrons for which we study their structure in terms of quarks and gluons are nucleons, nuclei, pions, and photons (which also have a quark and gluon structure when probed in high energy reactions).

[1]This is the case in Quantum Electrodynamics (QED) where $\alpha_{em} = e^2/(4\pi) \simeq 1/137$ at low energies changes to $\alpha_{em} \simeq 1/128$ at the electroweak scale so that the value 1/137 is still good with 7% accuracy.

1.2.1 Hadron spectroscopy

Hadrons are categorized into two families: baryons, made of an odd number of quarks (usually three quarks) and mesons, made of an even number of quarks (usually one quark and one antiquark). Nucleons (protons and neutrons) are examples of baryons; pions are an example of a meson. "Exotic" hadrons, containing more than three valence quarks, have been discovered in recent years. This includes new states with four quarks (tetraquarks) and five quarks (pentaquarks). In addition, there are also predictions for bound states of just gluons called glueballs which are sought after experimentally. Such states lie outside the conventional quark model classification which was invented in the 1960ths and provide deeper insights into the mechanisms how the quarks are bound together to form hadrons.

1.2.2 Hadron structure

Thanks to asymptotic freedom, observables which depend *only* on large scales can be computed in perturbation theory. However, many observables such as cross sections at high-energy electron–hadron or hadron–hadron colliders are governed by long distance/low energy phenomena related to the structure of the incoming hadrons. In many cases, the cross section is also influenced by dynamics which happens at very short distances/high energies for example when a heavy particle is produced or a final state particle has a large transverse momentum. **QCD factorization theorems** state that in such situations it is possible, up to a power-suppressed error, to separate the physics happening at very different length scales into *independent* factors such that the long distance factors will always be the same, irrespective of the details of the short distance process. Conversely, the short distance factor is free of any long distance physics and can be calculated perturbatively. With other words, whenever a hard (or short distance) scale Q is present (say $Q > 1$ GeV) the hadronic cross section can be written as convolutions of universal **parton distribution functions (PDFs)** $f_i(x, Q)$ with process dependent hard scattering (or short distance) cross sections $d\hat{\sigma}$. For example, the cross section for deep inelastic ep scattering is given by

$$d\sigma(e + p \to e + X) \simeq \sum_i \int_0^1 d\xi\ f_i(\xi, Q)\ d\hat{\sigma}(e + i \to e + X) \tag{4}$$

$$=: \sum_i f_i(\xi, Q) \otimes d\hat{\sigma}(e + i \to e + X) \tag{5}$$

where a sum over all possible partonic subprocesses is implied. Similar formulas hold for Drell-Yan lepton-pair production in pp collisions,

$$d\sigma(p + p \to \ell^+ + \ell^- + X) \simeq \sum_{i,j} f_i(\xi_1, Q) \otimes f_j(\xi_2, Q) \otimes d\hat{\sigma}(i + j \to \ell^+ + \ell^- + X)\,, \tag{6}$$

and other processes like the production of heavy quarks, vector bosons, jets or hadrons at large transverse momenta. In the latter case, universal **fragmentation functions (FFs)**, which are the analogue of the PDFs, describing the transition of the final state quark or gluon into the observed hadron have to be included in the formalism. In each case, the error of the factorization approximation is proportional to a power of Λ/Q where Λ is a typical hadronic scale of a few hundred MeV and it becomes negligible when sufficiently hard scales Q are involved. The PDFs (FFs) are intrinsically non-perturbative objects entailing the long distance physics of the hadronic initial (final) state. They are *universal* in the sense that the same PDFs (FFs) can be used in a large variety of processes. Since the hard scattering cross sections are systematically calculable in perturbation theory, the QCD factorization theorems provide a rigorous framework with predictive power. This pQCD formalism is the theoretical basis for the systematic computation of large classes of observables at present day particle colliders and therefore of paramount importance.

The conventional PDFs $f_i(x)$ describe the probability of finding a parton with momentum fraction x inside a fast moving hadron (in the so called infinite momentum frame). Any dependence on the transverse momentum of the parton has been integrated out. More information about the parton can be obtained if the dependence about the parton transverse momentum $\vec{k}_T$ or the impact parameter $\vec{b}_T$ is retained in a 5-dimensional distribution called **Wigner distribution** $W(x, \vec{k}_T, \vec{b}_T)$. Integrating the Wigner distribution over $\vec{k}_T$ yields a **generalized parton distribution (GPD)** $f_{\text{GPD}}(x, \vec{b}_T)$ while integrating over the impact parameter yields the **transverse-momentum-dependent (TMD) PDF** $f_{\text{TMD}}(x, \vec{k}_T)$. Again, the proper definition of the GPDs and TMD PDFs relies on proper factorization formulas.

Best known are unpolarized (collinear) PDFs inside nucleons but there are also determinations of PDFs inside other hadrons such as pions, photons or nuclei.

1.3 Key questions in QCD and hadronic physics

There is no doubt that QCD is the correct microscopic description of strong interaction dynamics. The main challenge is to derive reliable predictions for the wide range of observables where the strong interaction is at play. This is highly non-trivial and different approaches are need (pQCD, QCD based effective theories, ab initio lattice calculations).

Some key questions are:

- What is our degree of understanding of QCD?
  - How precisely do we know the parameters of QCD [α_s, Λ_{QCD}, m_q $(q = u, d, s, c, b, t)$]?
  - What is the origin and the dynamics of confinement?
  - What is the origin and dynamics of chiral symmetry breaking?
- What is the structure of hadrons in terms of quarks and gluons?
  - Which hadrons are there?
  - How does the hadron mass arise in terms of its constituents?
  - How does the hadron spin arise in terms of its constituents?
  - How does the hadron decay?
- What is the structure of nuclei in terms of quarks and gluons?
- The QCD phase diagram: What are the roles of quarks and gluons in matter under extreme conditions (high temperature, high density)?
  - Are there novel phases? Phase transitions?
  - What was the behavior of quarks and gluons in the early universe?
  - What is the behavior of quarks and gluons in neutron stars?

2 Theoretical hadronic physics at the IN2P3

In this section we will summarize the research activities of IN2P3 theorists working fully or partly in the field of hadronic physics and related QCD topics, see Tab. 2 for an overview. It is also interesting to see how these activities are embedded in the wider context of the French community active in the GDR QCD. This information can be found in Tab. A in the appendix.

In the following, we will focus on the research of the colleagues whose names are highlighted in bold. The research on B and D decays is mostly in the context of flavor physics and we leave it to the particle physics part to cover these activities. Similarly, the work of van Kolck on nuclear effective field theories (EFTs) is assumed to be represented in the nuclear physics part even if it is relevant for hadronic physics as well.

Lab	Name	Situation	Topics/Keywords
APC Paris	**J. Serreau**	University	IR QCD, QCD phase diagram, χSB
IJCLab Orsay	D. Becirevic	CNRS	Lattice QCD (ETMC), B decays, Flavor physics, Leptoquarks
	B. Blossier	CNRS	Lattice QCD, B, D, Charmonia decays
	S. Decotes-Genon	CNRS	b-hadron decays, flavor physics, CKM, BSM
	S. Friot	University	K/π decay const., χPT, multi-loop, $(g-2)_\mu$, hypergeom. functions
	E. Kou	CNRS	Flavor physics, B physics, hadronic τ decay
	J.-P. Lansberg	CNRS	Heavy quark(-onium) prod., PDFs, TMDs, CNM effects, DPS
	U. van Kolck	CNRS	Nuclear EFTs, χEFT, bound nucleon decay
	S. Wallon	University	GPDs, TMDs, Small-x, Diffractive exclusive processes, Saturation
IP2I Lyon	**G. Chanfray**	University	Neutrino-nucleon interactions, Dense matter
	M. Ericson	Emeritus	Neutrino-nucleon interactions
	H. Hansen	University	Grav. waves, Dense matter, QCD phase diagram, χEFT
	J.-M. Richard	Emeritus	Hadron spectroscopy, Tetraquarks, Pentaquarks
LLR Palaiseau*	**F. Arleo**	CNRS	Coherent energy loss in pA, R_{pA}: DY, J/Ψ, light hadrons, p_T-broad.
LPC Clermont	V. Morenas	University	Lattice QCD, Heavy flavour mesons
LPSC Grenoble	**M. Mangin-Brinet**	CNRS	Lattice QCD (ETMC), $m_{u,d,s,c}$, $F_\pi(Q^2)$, $\langle r^2\rangle_\pi$
	I. Schienbein	University	PDFs, HQ production, FFs, BSM: NLO QCD+PS calc., RGE
Subatech Nantes	**J. Aichelin**	University	HI, QGP, transport models, PJNL: phase diagram, EPOS-HQ
	J. Ghiglieri	CNRS	QGP, shear viscosity/hydrodynam. at NLO QCD, pert. thermal QCD
	P.-B. Gossiaux	University	HI, QGP: energy loss, HQ/Jets, EPOS-HQ, EPOS3-Jet
	T. Gousset	University	HI, QGP: energy loss, jet-correlations, HQ
	M. Nahrgang	University	HI, QGP, HQ, HQ transport, QCD phase diagram
	S. Peigné	CNRS	Coherent energy loss in pA, R^h_{pA}, p_T-broadening
	T. Sami	University	HI, QGP, Critical fluctuations near QCD critical point, energy loss
	K. Werner	University	EPOS3, EPOS-HQ, EPOS-Jet, EPOS and Air Showers, HQ transport

Table 1: IN2P3 theorists working fully or partly on hadronic physics and related QCD topics. The activities of the colleagues highlighted in bold are summarized in this document. For the definitions of the used acronyms see App. B. *: On leave at Subatech Nantes.

The activities may be grouped together in the following way:

- **Fundamental parameters of QCD:**
  - The strong coupling constant, $\alpha_s(\mu) = g^2/(4\pi)$, is well understood in the perturbative region with energy scales $\mu \gtrsim 1$ GeV. In this region the μ-dependence can be calculated perturbatively using the renormalization group equation.Conversely, at low energies $\mu \sim \Lambda_{\rm QCD}$, α_s becomes large and the common lore is that perturbation theory is not applicable. The precise behaviour of α_s in the so-called infrared (IR) region is still an important subject of research, actively pursued at the IN2P3 by Julien Serreau (APC, Paris). This is an important topic since the large interaction strength in the IR region is intimately connected to the question of confinement.

    Title: A perturbative windodow to the regime of infrared QCD

    French collaborators: Urko Reinosa (CPHT-X Palaiseau), Mathieu Tissier (LPTMC, Sorbonne University)

    International collaborators: Nicolas Wschebor (University of Montevideo), Marcela Pelaez (University of Montevideo)

    Students : Nahuel Barrios (PhD student , Montevideo - Palaiseau)

    Description: Numerical simultations of lattice QCD show that, in the Landau gauge, the coupling constant (defined in the Taylor scheme) stays finite at all energy scales. This is in blatant contradiction with the prediction of a Landau pole in the Faddeev-Popov theory. Not only finite, the coupling constant remains sufficiently small for a controlled perturbative description down to infrared scales.
  - Mariane Mangin-Brinet (LPSC, Grenoble) has been working recently on an extraction of

quark masses from ab initio calculations on the lattice. Note, however, that she was on sick leave for quite some time.

- **Hadron spectroscopy**:
  This line of research is pursued by Jean-Marc Richard (IP2I, Lyon).

- **Perturbative QCD:**
  Jean-Philippe Lansberg (IJCLab, Orsay), Samuel Wallon (IJClab), and Ingo Schienbein (LPSC Grenoble), work within the framework of perturbative QCD which is generally based on a factorization formula such that non-perturbative parts describing the structure of hadrons and perturbatively calculable hard parts are grouped in independent factors. It should be noted that the two pieces (hadron structure, hard part) are both defined in this context and they are intrinsically linked. In order to make progress both parts need to be improved. This research on nuclear PDFs (Schienbein, Lansberg), on TMD PDFs (Lansberg, Wallon), and on GPDs (Wallon) naturally belongs to high energy/particle physics community. However, there are also strong ties to the nuclear physics and heavy ion communities.

  It should be noted that there is a long standing collaboration between I. Schienbein, J.-P. Lansberg and F. Arleo since the days of the Théorie-LHC-France initiative (which ended in 2016). More recently, there have been two IN2P3 theory master projects in which I. Schienbein, J.-P. Lansberg, H. S. Shao are involved: "PDFs and Hard Processes" (2017-2019, PI Schienbein) and "Glue@NLO" (2020-2022, PI Lansberg). S. Wallon is participating in the latter project as well.

  - **NLOACCESS**:
    In the framework of the international **STRONG-2020** consortium two **Virtual Access** infrastructures have been set up. The first of the VA-infrastructures is called **VA1-NLOAccess** coordinated by Jean-Philippe Lansberg. The purpose is to allow for automated perturbative NLO calculations for heavy ions and quarkonia by extending the well-known MadGraph automated on-line code for the novel computation of perturbative QCD cross sections in high-energy hadronic collisions at NLO accuracy, using meson and heavy-ion beams, and for quarkonia final-states by including the HELAC-Onia tool. See: https://nloaccess.in2p3.fr The second infrastructure is called **VA2-3DPartons** led by Hervé Moutarde (CEA, Saclay) with the goal to develop a new combined framework to extract GPDs and TMD PDFs with higher-order fixed and twist corrections, from fits to experimental e-p and p-p data (handled in a Rivet-like format).
  - **Heavy Quarkonia:**
    J.-P. Lansberg is PI of an ANR PRC project "PRECISONIUM" (2021-2025) to work in collaboration with H.-S. Shao and international collaborators towards the following goals: 1. Perform the first truly global NLO analysis of heavy quarkonium data in the NRQCD framework 2. Pioneer NNLO computations for quarkonium production with $2 \to 1$, then $2 \to 2$ processes relevant for lepton-hadron and hadron-hadron colliders 3. Develop the NLOACCESS such that it becomes an integrated framework for quarkonium production at higher orders. This includes work within collinear factorization and TMD factorization.
  - **nCTEQ nuclear PDFs**:
    I. Schienbein is performing global QCD analyses of nuclear PDFs together with other members of the nCTEQ collaboration which was founded in 2006 by I. Schienbein and F. Olness (SMU Dallas). The collaboration has considerably grown over time with current PhD students being in the third generation. Recent work was dedicated to including different data sets in the global analysis: vector boson production data from the LHC, high x deep inelastic scattering (DS) data from JLAB, inclusive hadron production data from the RHIC and the LHC and neutrino-nucleus DIS data from NuTeV, CHORUS, CDHSW. The next steps will be to consider more LHC data (heavy quarks, jets, prompt photons) and to prepare the next big release of nCTEQ nuclear PDFs. On the theoretical side, we plan to switch to NNLO (as it is standard in global analyses of proton PDFs), improve the

parametrization of the nuclear A-dependence of the PDFs, and to reconsider target mass corrections to nuclear DIS structure functions.

- **PDFs, TMDs, GPDs on the lattice:** There has been much progress to obtain PDFs, TMDs, GPDs for nucleons, pions and even nuclei from lattice QCD. As is documented in the white paper of the PDFLattice workshop in 2019 [arXiv: 2006.08636] a lot of activity and cross fertilization is to be expected in the next decade between lattice calculations and global QCD analyses. The very precise results of global analyses of proton PDFs will serve as benchmarks for the lattice calculations. Conversely, for the less well-known distributions (strange PDF in the nucleon, PDFs at large x, pion PDFs, TMDs, GPDs) lattice "data" will be used in global fits. There is currently no IN2P3 theorists directly involved in the lattice calculations of pseud- or quasi-PDfs. However, the French community is represented by S. Zafeiropoulos (CPT, Marseille).
- **Open heavy quark production:**
  Heavy quark production is important in various respects. In pp and pA collisions it can be used to constrain the gluon PDF. In heavy ion collisions, heavy quarks are important probes of the QGP. There exist two calculations FONLL (M. Cacciari, LPTHE Paris) and GM-VFNS (I. Schienbein) which are widely usedfor the interpretation of inclusive heavy quark production at the LHC. Both codes have NLO+NLL accuracy and suffer from sizable scale uncertainties. In order to make progress it will be crucial increase the perturbative order. . A fixed order NNLO calculation is now available (Catani et al.) but many phenomenological comparisons with data have yet to come. In the future, a matched NNLO+NLL or beyond would be very helpful for phenomenological comparisons with the wealth of LHC heavy quark data. Currently, we are not aware of any concrete plans but this would be natural research projects either by Catani et al. or in collaboration with them.
- **Production of a photon in association with a heavy quark:**
  Another very interesting process is the associated production of a photon with a heavy quark. In collaboration with Jean-Philippe Guillet (LPATH, Annecy), Francois Arleo, Pol-Bernard Gossiaux, Ingo Schienbein and experimentalists from the ALICE collaboration (R. Guernane, J. Faivre) we have begun to study this process. There are different motivations for $\gamma + Q$ production in pp, pA, and AA collsions. In pp-collisions we hope to improve the perturbative precision compared to existing calculations. Furthermore, in pA this process maybe interesting to extract the nuclear charm PDF. Finally, in AA collisions it is possible to gauge the energy loss of the heavy quark against the medium blind photon. Therefore this is a very interesting observable to study the properties of the QGP.
- **QCD in the high energy limit:**
  Samuel Wallon is studying hadron structure in the high energy limit (small-x) where the density of partons inside the hadron is expected to become large until they overlap. As a consequence several phenomena are expected to be clearly observed: a collective behavior of the partons, non-linear parton evolution, and saturation. Furthermore, in nuclear collisionsi such effects are expected to be amplified.

• **Neutrino-nucleon interactions in the low GeV region:**
The future DUNE long baseline (LBL) neutrino oscillation experiment has the goal to measure CP violation in the leptonic sector, to establish the neutrino mass ordering and to measure the oscillation parameters more precisely. The DUNE collaboration consists of 205 institutions with almost 1300 collaborators. The IN2P3 is actively involved in this collaboration. In order to achieve the physics goals a good understanding of neutrino interactions with nucleons and nuclei for neutrino energies in the low GeV region is important. There is expertise by IN2P3 theorists in this domain: Guy Chanfray (IP2I, Lyon), M. Ericson (IP2I, Lyon), and I. Schienbein (LPSC, Grenoble) with approaches from the nuclear theoy (Chanfray, Ericson) and the high energy physics side (Schienbein). Motivated by the participation of the LPSC Grenoble in the DUNE experiment, I. Schienbein might re-initiate work on neutrino cross sections at the DUNE far and near liquid argon detectors.

- **Fully coherent energy loss**:
  There is a range of effects taking place in pA collisions compared to pp collisions which are not associated to the formation of a hot and dense state of matter in AA collisions. It is important to understand these effects in their own right and in order to a) disentangle them from effects due to the modification of the nuclear PDFs and b) disentangle them from effects due to the formation of a QGP in AA collisions.

  – François Arleo (LLR, Palaiseau on leave at Subatech Nantes) and Stéphane Peigné (Subatech, Nantes) are working on fully coherent energy loss effects in pA collisions with the goal to obtain a theoretical understanding of medium-induced gluon radiation from QCD first principles. This work was funded by an IN2P3 theory master project ("Medium induced gluon radiation", 2017-2019, PI F. Arleo).

    Recent highlights are that there is evidence for a scaling behaviour in the quenching of hadron spectra in LHC $PbPb$ collision data [F. Arleo, Phys. Rev. Lett. 119 (2017) 062302.].Arleo Furthermore, their predictions of the $J/\Psi/$ DY ratio in nuclear collisions might be able to disentangle between energy loss processes and nuclear parton densities [F. Arleo, S. Peigné, Phys. Rev. D95 (2017) 011502(R)].
    Outlook:
    It would then be important to incorporate such energy loss effects in global analyses of nuclear PDFs. This is, however, challenging both on the theoretical side as well as on the practical side and would require dedicated work in the future. In addition, there are plans to investigate fully coherent energy loss in cosmic ray physics.

- **Heavy Ion physics:**
  There is a wide range of activities in heavy ion physics driven by the members of the Subatech in Nantes, joined by François Arleo who is on leave at the Subatech. The work of M. Nahrgang is also done in collaboration with H. Hansen (IP2I, Lyon). The overarching goal of all activities is to understand the properties of the QGP and, in extension, the QCD phase diagram.

  – **EPOS:**
    Authors: K. Werner, J. Aichelin, P. Gossiaux, T. Gousset, M. Nahrgang
    Many of the projects are linked to the heavy ion collision (HIC) and air shower event generator EPOS which is constantly developed and improved. EPOS is one of the main projects of the theory group at Subatech and highly cited.
    Recent or new developments are:
    * EPOS-LHC has been optimized for pp collisions at the LHC. It is very much used by CMS and ATLAS, and AUGER (cosmic ray physics)
    * EPOS3 contains hydrodynamic expansion of the medium, collective effects and is mainly designed for HIC and collectivity in pp collisions.
    * EPOS-HQ: see below
    * EPOS+PHSD: see below

  – **Advanced fluid dynamics:**

    Authors: M. Nahrgang, T. Sami

    In the past few years, M. Nahrgang and T. Sami together with international collaborators have been working to improve conventional fluid dynamical models to capture more effects in heavy ion collisions, in particular the critical point fluctuations and fluctuation-driven contributions to the transport coefficients involving the following tasks:
    * Propagate additional modes coupled to the fluid dynamical evolution, eg. the chiral order parameter : Non equilibrium chiral fluid dynamics

  * Include thermal fluctuations into the stochastic diffusion equation for net- baryon number near the QCD critical point.

Outlook:
The plan is now to include thermal fluctuation dynamics into the fluid dynamical description. Thermal fluctuations are expected to affect the determination of transport coefficients, the crossover/transition regime and are of importance in small systems, like high-multiplicity pp and pA collisions. The advanced fluid dynamics will then be embedded into a HIC event generator like EPOS.

– **Jet modification in heavy-ion collisions:**

  Authors: Ghiglieri, Gousset, Gossiaux, Weitz

  Jets are one of the key hard probes of the QGP. A wealth of data is coming from the LHC including new jet shape and substructure observables. Therefore, advances in theory and phenomenology are needed.
  The goal is to construct a formalism that smoothly interpolates between vacuum and medium radiation using the expertise in Effective Field Theories and Thermal Field Theory. It is planned to go beyond popular assumptions for important results, such as double-logarithmic enhancements to medium radiation.

  On the MC simulation side, a coupled jet – hydrodynamics scheme has been developped which uses EPOS for the initial state, evolves soft partons hydrodynamically and applies in-medium energy loss to hard partons propagating through the background of soft partons. The hard partons are finallly hadronized and a jet finding algorithm is applied.

– **Quarkonia production in heavy ion collisions:**

  Authors: Gossiaux, Gousset

  Quarkonia production in AA collisions is one of the rare probes able to provide information on the QGP properties before freeze out. There is a conceptual need for modelling including genuine quantum features of emerging bound states. A first work was based on the Schrödinger-Langevin equation and a first implementation in EPOS was dedicated to bottomonia suppression at RHIC and the LHC. In the following, charmonia, usually modelled assuming $c\bar{c}$ statistical recombination at the end of the QGP phase were modeled based on Wigner quasi probabilities, in order to take off-equilibrium effects into account, and implemented in EPOS.
  Outlook:
  There is ongoing work to establish and benchmark a semi-classical (SC) treatment of the many $c\bar{c}$ evolution. For this purpose a SC Monte Carlo will be developped and compared to the previous approach to charmonia. In addition, there are plans to extend the work to heav-light systems and to quarkonia in jets.

– **EPOS-HQ:**
  IN2P3 theory master project (2017-219), renewed in 2020.

  Authors: J. Aichelin, P. Gossiaux, T. Gousset, M. Nahrgang and K. Werner

  The idea is to combine the HIC event generator EPOS which is capable to handle plasma expansion and charm production by a sophisticated model for the heavy quark- plasma interaction (HQ) in order to better understand the properties of the QGP.

  So far the HQ-medium interaction is implemented, quarkonia still need to be treated. The goal is to arrive at a new public version EPOS4 unifying EPOS-LHC and EPOS3.

- **EPOS+PHSD:**

  Title: Dynamical Thermalization in Heavy-Ion Collisions

  The development of the merged EPOS+PHSD approach is one way to study the influence of the initial non-equilibrium stage of the heavy-ion reactions on the final observables. The microscopic understanding of the initial phase of heavy-ion collisions is an intricate problem. In this respect, the EPOS and PHSD approaches provide a unique possibility to address this problem.

  Both EPOS and PHSD contain several steps to simulate the evolution of the hot and dens matter. Here, the first step from EPOS simulating the initial stage of heavy ion collisions is combined with the part of PHSD describing the evolution of the strongly interacting system in the QGP stage (based on off-shell transport equations derived from Kadanoff-Baym equations.) Looking at particle production it is then possible to study observables like the elliptical flow and p_T spectra and to compare them with the full EPOS+Hydro, the full EPOS-Hydro and the full PHSD.

- Work related to the QCD phase diagram in an extended Polyakov-Nambu-Jona-Lasinio (PNJL) model.

A French theorists in the GDR QCD

The French community working on QCD and hadronic physics is very well organized within the GDR QCD. The GDR QCD is the successor of the GDR PH-QCD and has enlarged the scope of the original GDR PH (Physique Hadronique). As a consequence the French community is generally well-connected and this concerns both, theorists and experimentalists. It should be noted, though, that a amall number of theorists working on hadronic physics is not participating in the GDR QCD.

B Acronyms

- BK: Balitsky Kovchegov (small-x, non-linear evolution equation)
- BSM: Beyond Standard Model
- CGC: Color Glass Condensate (an effective theory derived from QCD relevant at small-x)
- χSB: chiral symmetry breaking
- χPT: chiral perturbation theory
- χEFT: chiral Effective Field Theory (EFT describing QCD after chiral symmetry breaking)
- CKM: Cabibbo Kobayashi Maskawa mixing matrix in the quark sector
- CNM: Cold Nuclear Matter (various nuclear effects present in pA collisions)
- DM: Dark Matter
- DPS: Double Parton Scattering
- DSE: Dyson Schwinger Equation
- DVCS: Deeply Virtual Compton Scattering
- DY: Drell-Yan (lepton pair production)
- EPOS: Monte Carlo event generator used for cosmic ray air showers and pp, pA, and AA collisions at LHC and RHIC
- ETMC: European Twisted Mass Collaboration (one of the lattice collaborations)
- FF: Fragmentation Function
- GPD: Generalized Parton Distribution
- HI: Heavy Ion
- HQ: Heavy Quark
- HQET: Heavy Quark Effective Theory
- IR QCD: Infra Red QCD (QCD at mometum scales $\mu \lesssim \Lambda_{\rm QCD}$)
- LR: Left-Right symmetric models
- $\mathcal{N} = 4(2)$ SYM: Supersymmetric Yang Mills theory with 4 (2) supersymmetric generators opposed to real-world QCD which is a non-supersymmetric Yang Mills theory
- NLO: Next-to-Leading Order
- NNLO: Next-to-Next-to-Leading Order
- $\mathrm{N^3LL}$: Next-to-Next-to-Next-to-Leading Logarithm
- PDF: Parton Distribution Functions
- PJNL: Polyakov Jona Nambu Lasinio model (EFT of nucleons and mesons, low-energy approximation of QCD)
- PS: Parton Shower
- $\hat{q}$: one of the transport coefficients characterising the QGP
- QCD at finite T: QCD at finite temperature
- QGP: Quark Gluon Plasma (state of hot and dense quark/gluon matter)
- RG: Renormalization Group
- RGE: Renormalization Group Equation
- SUGRA: Super Gravity
- SUSY: Supersymmetry
- TCS: Timelike Compton Scattering
- TMD: Transverse Momentum Dependent PDFtransverse momentum of the struck quark
- TLRS: Taylor-Lagrange Regularization Scheme
- VBF Higgs: Vector Boson Fusion Higgs (one of the processes to produce the Higgs boson)
- VLQ: Vectorlike quark
- Z': New heavy spin-1 resonance

Lab	Name	Situation	Topics/Keywords
APC Paris	**J. Serreau**	University	IR QCD, QCD phase diagram, χSB
CPHT Palaiseau	**R. Boussarie**	CNRS	TMDs, Small-x, Saturation, CGC, Diffraction
	C. Lorcé	University	GPDs, TMDs, Nucleon spin and mass
	C. Marquet	CNRS	TMDs, Small-x, Saturation, CGC, Diffraction, Quarkonia
	S. Munier	CNRS	Diffraction, Quarkonia, Parton branching
	B. Pire	Emeritus	GPDs, DVCS, TCS, Diffraction
	U. Reinosa	CNRS	IR QCD, QCD phase diagram, χSB, QCD at finite T
CPT Marseille	**A. Bharucha**	CNRS	B and D decays, BSM: Flavor, Compositeness, DM, SUSY
	J. Charles	CNRS	Lattice QCD, $(g-2)_\mu$, B decays, Flavor, CKM, BSM
	E. De Rafael	Emeritus	Lattice QCD, $(g-2)_\mu$, hadronic vacuum polarization (HVP)
	A. Gérardin	University	Lattice QCD, $(g-2)_\mu$, HVP, B decays, HQET
	M. Knecht	CNRS	K decays, $(g-2)_\mu$, HVP, Compositeness, Higgs-ew chiral L
	L. Lellouch	CNRS	Lattice QCD, $(g-2)_\mu$, HVP, $m_{u,d,s}$, decay constants
	S. Zafeiropoulos	CNRS	Lattice QCD, pseudo-PDFs (nucleon, pion), $\alpha_s^{\overline{\rm MS}}(M_Z)$
DphN Saclay	**C. Mézrag**	CEA	GPDs, pion/kaon valence PDFs from DSE, $\alpha_s^{\rm eff}$
	H. Moutarde	CEA	GPDs, TMDs
IJCLab Orsay	**D. Becirevic**	CNRS	Lattice QCD (ETMC), B decays, Flavor physics, Leptoquarks
	B. Blossier	CNRS	Lattice QCD, B, D, Charmonia decays
	J. Carbonell	CNRS	Few body systems, relativistic bound states
	S. Decotes-Genon	CNRS	b-hadron decays, flavor physics, CKM, BSM
	S. Friot	University	K/π decay const., χPT, multi-loop, $(g-2)_\mu$, hypergeom. functions
	M. Fontannaz	Emeritus	last paper from 2017, prompt photons, photon-jet correlations
	E. Kou	CNRS	Flavor physics, B physics, hadronic τ decay
	J.-P. Lansberg	CNRS	Heavy quark(-onium) prod., PDFs, TMDs, CNM effects, DPS
	U. van Kolck	CNRS	Nuclear EFTs, χEFT, bound nucleon decay
	S. Wallon	University	GPDs, TMDs, Small-x, Diffractive exclusive processes, Saturation
IPhT Saclay	**J.-P. Blaizot**	Emeritus	QGP: fluid dynamics, heavy quark(-onia), $\hat{q}$, diffractive J/Ψ prod.
	F. Gelis	CEA	CGC, initial state of heavy ion collisions
	E. Iancu	CNRS	Small-x, CGC, non-linear evolution, Saturation, Jets in QGP
	G. Korchemsky	CNRS	Conformal theories, scatt. amplitudes, $\mathcal{N}=4$ SYM, $\mathcal{N}=2$ SYM
	D. Kosower	CEA	Conformal theories, scattering amplitudes, $\mathcal{N}=4$ SUGRA
	J.-Y. Ollitrault	CNRS	HI collisions: initial conditions, particle flow, hydrodynamic sim.
	G. Soyez	CNRS	Jets: substructure, in medium, small-x, BK evol., Parton Showers
IP2I Lyon	**H. Hansen**	University	Grav. waves, Dense matter, QCD phase diagram, χEFT
LAPTH Annecy	**J.-P. Guillet**	CNRS	Two-loop integrals, JetPHOX, FFs
	E. Pilon	CNRS	Two-loop integrals, Higgs
	E. Re	CNRS	Precision calc: NNLO+PS, N^{3}LL+NNLO, Higgs, VV, $t\bar{t}$, DY
L2C Montpellier	**J.-L. Kneur**	CNRS	RG improved QCD pressure, Higgs compositeness
LLR Palaiseau	**F. Arleo**	CNRS	Coherent energy loss in pA, R_{pA}: DY, J/Ψ, light hadrons, p_T-broad.
LPC Clermont	J.-F. Mathiot	CNRS	RGEs, TLRS regularization: axial anomaly
	V. Morenas	University	Lattice QCD, Heavy flavour mesons
LPSC Grenoble	**M. Mangin-Brinet**	CNRS	Lattice QCD (ETMC), $m_{u,d,s,c}$, $F_\pi(Q^2)$, $\langle r^2\rangle_\pi$
	I. Schienbein	University	PDFs, HQ production, FFs, BSM: NLO QCD+PS calc., RGE
LPTHE Paris	**M. Cacciari**	University	Higher order QCD/QED, Jets, HQ production, VBF Higgs at NNLO
	B. Fuks	University	BSM: VLQ, DM, Z', LR, Higgs, SUSY, Reinterpret.: MADAnalysis
	H.-S. Shao	CNRS	Heavy quark(-onium) prod., Higher orders, Automation, SM, BSM
Subatech Nantes	**J. Aichelin**	University	HI, QGP, transport models, PJNL: phase diagram, EPOS-HQ
	J. Ghiglieri	CNRS	QGP, shear viscosity/hydrodynam. at NLO QCD, pert. thermal QCD
	P.-B. Gossiaux	University	HI, QGP: energy loss, HQ/Jets, EPOS-HQ, EPOS3-Jet
	T. Gousset	University	HI, QGP: energy loss, jet-correlations, HQ
	M. Nahrgang	University	HI, QGP, HQ, HQ transport, QCD phase diagram
	S. Peigné	CNRS	Coherent energy loss in pA, R^h_{pA}, p_T-broadening
	T. Sami	University	HI, QGP, Critical fluctuations near QCD critical point, energy loss
	A. Smilga	University	Mathematical physics
	K. Werner	University	EPOS3, EPOS-HQ, EPOS-Jet, EPOS and Air Showers, HQ transport

Table 2: French theorist participating in the GDR QCD. IN2P3 laboratories as well as theorists having published in the field of hadronic physics/QCD (see main text) in the past three years are highlighted in bold. Topics/Keywords describe activities in the past few years only.