Acronym: **Gluodynamics**

Title: Probing the nature of dense gluonic systems

Project duration: 4 years

Principal investigators:

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1 Project summary

Electron-hadron and proton-proton, proton-nucleus, nucleus-nucleus collisions probe hadrons and fluids of strongly interacting matter at different length scales revealing their structure and the emergence of their properties from fundamental degrees of freedom of the strong interaction. Gluons play a key role as dominating contribution to energy, momentum, spin, and as the force mediator. They hence determine the properties of hadrons and strongly interacting fluids. New connections and synergies have recently arisen between hadron structure and QGP (quark-gluon plasma) physics, enabled by new ideas and increasing experimental precision. The teams of P2IO made pioneering contributions at this fruitful interface. Our consortium of 8 P2IO laboratories proposes an in-depth study of new LHC hadron collision data with 10–100 larger statistics in 2021-24 than presently available and of the Jefferson laboratory (JLab) precision data in a new kinematic regime. This effort will be paralleled with theoretical developments bridging the gap between different concepts, heavy-ion and low-x theory, and between experiment and theory via software tools. Our project will promote P2IO as a world-leading environment for Quantum Chromodynamics (QCD) research and will pave the way to leading French construction contributions to the hadron collider projects after 2030 at the Electron-Ion Collider (EIC) in the US and at the LHC.

2 Project description

2.1 Context

The strong interaction, mediated by gluons, is responsible for most of the mass of ordinary matter according to simulations on the lattice, whereas the Englert-Brout-Higgs mechanism (Nobel prize 2013) accounts only for a small fraction of it. The gluonic structure of strongly interacting particles, hadrons, is indeed key for the understanding of the properties of the universe. However, the gluonic sector of hadrons remains largely unexplored at present. Furthermore, strongly interacting thermodynamic systems at high temperatures are governed by fluid dynamics where a description in terms of ordinary hadronic matter becomes inapplicable. At these temperatures, a phase called Quark-Gluon Plasma is produced whose internal structure in terms of its degrees of freedom and the interactions between the latter remain largely unknown. Remarkably, fluid-like behaviour is observed not only in collisions between heavy-nuclei corresponding to comparatively large initial sizes, but it arises dynamically in systems like proton-lead or even proton-proton collisions. The initial conditions of the system evolution are given by the gluon-dominated structure of the incoming hadrons. These boundary conditions play a key role both in the applicability of a fluid description and in the fluid dynamics.

Several theoretical concepts, largely developed in the laboratories of P2IO, allow for a rigorous study of hadron structure. They access either the structure in coordinate space (generalised parton distributions, GPDs), transverse momentum space (transverse-momentum dependent parton distributions, TMDs) or investigate the properties of hadrons in the limit of very large collision energies (colour glass condensate, CGC). In this regime, hadrons are predicted to become dense gluonic objects with qualitatively different properties with respect to dilute hadrons described by GPDs/TMDs. This transition shows drastic changes as the one between the QGP and ordinary matter. The theoretical concepts are most rigorously tested in experiments probing the hadron with electromagnetic probes for which the experimental P2IO groups represent a world-leading expertise. However, the gluonic distributions in coordinate and momentum space are largely unknown since gluons do not interact electromagnetically and information has to be inferred indirectly. Nuclear and proton collision observables are also sensitive to hadron structure. Anisotropies in the angular distribution of the produced

GLUODYNAMICS: probing the nature of dense gluonic systems			
Topics	**Subtopics**	**Institutes**	**Responsibles**
Geometry	nucleon ex nucleon theo nucleus	IPNO, LPT, DPhN, CPHT, IPhT	**C. Muñoz, S. Wallon, L. Massacrier**
Unification	space time tools cross education	CPHT, IPhT, DPhN, IPNO, LLR, LPT	**J.-Y. Ollitrault, C. Marquet, J.-P. Lansberg, H. Moutarde**
Gluometer	force collider force fixed-target radiation	DPhN, LLR, IPNO, IPhT	**M. Winn, F. Fleuret, M. Nguyen**
Future	p/A-p/A collider e-p/A collider In. Stages conference	LAL, DPhN, IPNO, DEDIP, CPHT	**P. Robbe, F. Bossu**

Figure 1: Topical structure of the proposed Flagship project Gluodynamics.

particles can be interpreted as imprints of the hadron geometry in coordinate space, as revealed by scientists of P2IO. The gluon dominated initial-state density and its geometry is hence one of the main ingredients to describe the strongly interacting fluid created in the laboratory. The knowledge of these initial conditions will profit from insights gained in studies of hadron structure and is a prerequisite for precision studies of QCD matter properties. Furthermore, experimental opportunities open up at the LHC to constrain hadron structure.

2.2 Strategic goals on national and international level

The project aims at a positioning of P2IO as a world-leading environment for QCD studies in the funding period 2020–2024 on the experimental and theoretical side. It will be the initial booster to place P2IO as a major site for detector construction and innovative reconstruction concepts for the QCD collider facilities after 2030 at the planned EIC and at the HL-LHC.

2.3 Scientific means and objectives

We propose a systematic study of dense strongly interacting systems, hadrons, and fluid-dynamic systems exploiting modern concepts, new experiments, and their connections. We focus on connecting aspects to reveal the inner workings of QCD within a close collaboration of the P2IO scientists.

Hadron structure sets the initial state of nucleus-nucleus or proton-nucleus collisions evolving in time as a fluid and encodes initial-state correlations between the produced quarks and gluons. In the context of collisions involving hadrons, the description of specific observables cannot be easily attributed to hadron structure or fluid-dynamic concepts due to the imperfection of the high-energy limit and due to the imperfection of the thermodynamic limit. This immanent connection and its challenges shows that these two fields of research are intrinsically intertwined.

The experimental and phenomenological program and part of the theoretical developments will be based on new data with detector and accelerator upgrades at the LHC from 2021 on and the recently started experimental program at 12 GeV CEBAF at Jefferson laboratory (JLab). In order to deepen our understanding of QCD beyond the currently experimentally accessible observables and their precision, simulations and conceptual work on both experimental and theoretical sides are foreseen. This will prepare the P2IO teams to be leading contributors to the future QCD collider programs after 2030 at the EIC and the LHC.

The objectives are organised in 4 work streams:
1) The experimental and theoretical study of nucleon and nuclear **geometry** in electron-hadron reactions at JLab (electron-hadron) and photon-hadron collisions at the LHC (using the electromagnetic field of ions as quasi-real photon source).
2) The **unification** of different theoretical frameworks for the study of hadrons and of ab-initio QCD calculations with hydrodynamics as well as the promotion of software tools being developed within P2IO. 3) The experimental investigation of the gluonic force via **gluometers** at the LHC with quarkonium as forcemeter in collider and in fixed-target mode and in the jets to learn about gluon radiation: The current understanding is limited to a large extent to qualitative insights that can be extended to a deeper understanding by new and more precise observations.

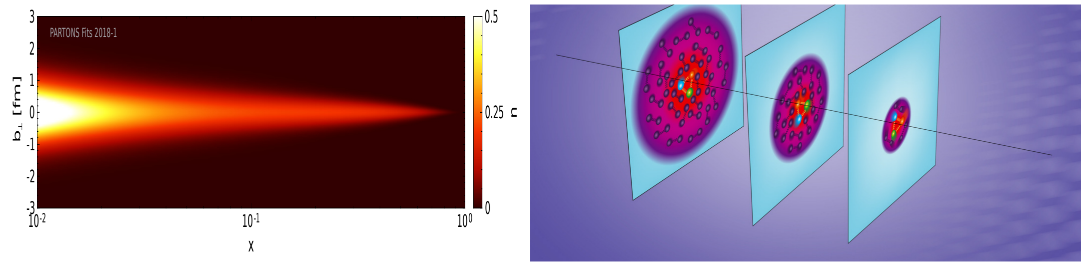

Figure 2: 3D representation of the longitudinal momenta of partons as a function of their transverse position in the nucleon, as obtained from fits of DVCS data from CLAS12 [2, 3].

4) Lay the ground for **future** experimental QCD collider programs in the post 2030 era with dedicated detector simulation studies for future collider facilities as the Electron-ion Collider as well as detector upgrades of LHCb at the LHC: the exploitation of data recorded at future facilities (EIC, LHC) will require optimizations of the detector, read-out and reconstruction chain design.

The four resulting work packages (WP) with their substructure are shown in Fig. 1 and are detailed in the following.

2.4 WPI: Geometry

At JLab, powerful new measurements allowing multi-dimensional studies of the partonic structure of nucleons with deep exclusive processes will require the development of new analysis tools in order to fully exploit the available data and to prepare for the EIC, where these measurements will be extended in the low-x regime. At the LHC, we will study photon-induced interactions. Ultra-peripheral collisions (UPC) are collisions in which nuclei are separated by impact parameters larger than the sum of their radii and therefore hadronic interactions are strongly suppressed. They will be studied within this project to learn about proton and nuclear structure in the very low-x regime. Building on our strengths, we will study photoproduction of vector mesons with simultaneous hadronic interactions. These interactions are interesting to decipher and can give precious insight into the gluon distributions of the incoming Pb nuclei in a complementary fashion. This experimental programme will be interpreted and supported by calculations for new observables in exclusive processes at leading and next-to-leading order as well as by the integration of the measurements into the PARTONS framework and the NLOAccess platform developed first within P2IO.

2.4.1 Experiment nucleon geometry

The recent upgrade of Jefferson Lab to 12 GeV (JLab12) will allow the multi-dimensional study of the partonic structure of matter with unprecedented precision and in yet unexplored kinematic regions. In particular, the JLab groups on the P2IO sites Orsay and Saclay have a world-leading expertise in Deeply Virtual Compton Scattering (DVCS) and other exclusive reactions. Advanced phenomenology in close collaboration with theory colleagues in our consortium will be required to connect the 3D images of nucleons and nuclei at large x measured at Jefferson Lab and the low-x region that will be accessed at an EIC.

The CLAS12 detector in Hall B will measure a large range of exclusive reactions in a wide kinematic domain. We aim to publish final DVCS scattering results from CLAS12 from the proton and the neutron in a wide kinematic domain within the course of the **one of the PhD theses** associated to the gluodynamics project. In parallel, the exceptional resolution and systematic understanding of the Hall C High Momentum Spectrometer analysed by an additional PhD student financed on independent funds will provide the exciting opportunity of performing Rosenbluth (longitudinal/transverse) separations [1] of the DVCS and DVMP (Deeply Virtual Meson Production) cross sections, which will be confronted to the theoretical calculations presented in 2.4.2.

Several detectors have been and are being constructed at P2IO to fulfill the experimental requirements of the approved program. First, a Central Neutron Detector and a Micromegas tracker have been installed in the CLAS12 large acceptance spectrometer to perform DVCS off both protons and neutrons. Secondly, a Neutral Particle Spectrometer (NPS) for Hall C, consisting of a lead-tungsten calorimeter and a sweeping magnet, is under development and expected to be installed in 2020–2021 at JLab to measure DVCS and π^0 production with very high precision.

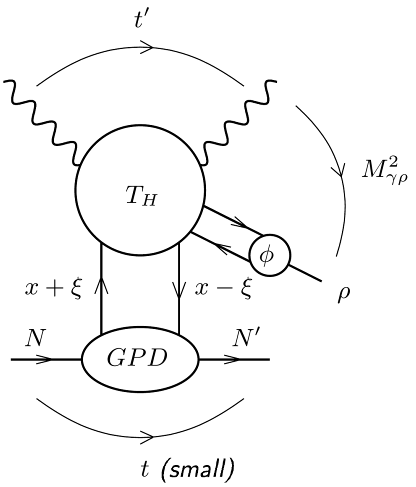

Figure 3: Schematic diagram and kinematic configuration of the $\gamma^{(*)}N \to \gamma$ M N' process will be used to extract GPDs, an otherwise inaccessible information in the chiral-odd sector.

DVCS experiments off hydrogen and deuterium targets are planned in 2020–2021 in Hall B with an active participation of the two involved P2IO teams. The two graduate students are expected to work on the data analysis, which will lead to publications of proton and neutron DVCS beam spin asymmetries at high Q^2 and moderate to large x. After the installation and commissioning of NPS in Hall C in 2021 the first series of experiments will start in 2022. The PhD student co-funded by P2IO will work on the data analysis of the NPS detector that will lead to the measurement of the incident beam energy dependence of the DVCS cross section in the quark valence region.

The NPS calorimeter will also allow one to extend the study of GPDs to TDA (Transition Distribution Amplitudes) by measuring DVCS in the backward region. The experimental feasibility of this idea, first proposed by the theory groups at the Saclay and Orsay sites of P2IO, will be investigated by the Orsay group together with the PhD student co-funded by P2IO. Realistic counting rates will be calculated by implementing the theory models from the theory teams in Orsay and in Palaiseau into the PARTONS framework developed within P2IO. This will be a project that will require a close collaboration and frequent interactions among these 4 groups of P2IO and will give important input into the design requirements of the EIC tracking detectors developed in WPIV, see 2.7.2.

As an additional track of this work package being conducted at the Saclay site sharing the software tools and analysis techniques, a measurement of coherent J/ψ photoproduction in p-Pb to constrain the proton gluon GPDs will be pursued. Furthermore, the so-far in UPC measured incoherent J/ψ production (the Pb serves as photon emitter and the proton breaks up) will be tried to extract from the experimental data in order to constrain proton shape fluctuations. The theoretical understanding and potential extensions will be closely discussed with our P2IO theory colleagues.

The experimental results from CLAS12, Hall C, and the LHC will be the basis of a new release of the PARTONS platform and will be exploited by the NLOAccess framework with a specific branch for hard exclusive reactions.

2.4.2 Theory nucleon geometry

The consortium aims to provide a complete set of predictions at leading and next-to-leading order for $\gamma^{(*)}$N $\to \gamma$ M N' (M being a meson), the hard scale being provided by the initial γ^* (electroproduction) or by the γ M invariant mass (photoproduction). This programme includes as well power suppressed corrections with respect to this hard scale, which should be relevant for precision physics and in order to test the universality of collinear factorization. This process provides a new way of accessing the quark and gluon GPDs insides nucleons, for arbitrary polarizations of initial and final state particles, in both chiral-even and chiral-odd sectors. It is a complementary approach to DVCS and DVMP. One of the most promising point is the fact that in the particular case of a transversally polarized $\rho-$meson, the additional γ in the final state allows one to select the elusive chiral-odd sector of GPDs, at leading power, which otherwise decouples in usual γ^*N $\to$ M N DVMP. As a first step, the feasibility of such studies have been proven by some of us for photoproduction [4, 5] in a leading order analysis, for a set of mesons (ρ^0, $\pi^\pm$, with a possible extension to $\rho^\pm$), whose quantum numbers selects quark exchange in $t-$channel. Besides, the particular case of a $\gamma\pi^0$ final state would be of particular interest since it is directly sensitive to the gluonic content of the nucleon. Since the hard scale of this set of processes can be provided by the γ M invariant mass, UPC at LHC could give access to GPDs in a completely new kinematic regime.

It turns out that the same process, in the high-energy limit, can be viewed as a diffractive process with a rapidity gap between the $\gamma\pi^0$ diffractive state and the proton remnant, with the pomeron quantum numbers in t-channel. This process can then be described in the CGC formalism, using the QCD shock-wave approach which P2IO members have developed for exclusive processes [6]. The very general kinematics of this process (arbitrary t, relative transverse momentum inside the $\gamma\pi^0$) then gives access to a gluonic Wigner distribution. Such a process is therefore very promising, at least theoretically, in order to deepen the unification of the various non-perturbative objects discussed in WPII.

These theoretical developments will be conducted together with a **postdoc** in the P2IO theory team and will be embedded into the PARTONS framework and be made available in the NLOAccess platform for applications from simulation to theory-experiment comparison. They will also allow feasibility studies within the experimental JLab groups in P2IO as well as for the EIC with which we will be in close contact.

2.4.3 Nuclear geometry

ALICE offers unique capabilities to study quarkonium production at low transverse momentum over a wide rapidity range in pp, p-Pb and Pb-Pb collisions. UPC J/ψ production measurements have already brought novel information on hadron structure down to Bjorken $x_{Bj} \sim 4{\cdot}10^{-5}$ as most recently in [7] as well as on the proton structure in UPC collisions in p-Pb collisions [8]. The first indication of J/ψ coherent[1] photoproduction measured by ALICE [9] at forward rapidity in Peripheral Collisions (PC) with nuclear overlap, brings a novel handle, opening a new way to obtain the coherent J/ψ photonuclear cross section by disentangling the contributions from the low- and high-energy photon-nucleus interactions to the coherent J/ψ photoproduction cross section in Pb-Pb. In addition, studies of coherent J/ψ photoproduction as a function of the collision centrality/geometry might become a new tool to probe the Quark-Gluon Plasma [9]. The ALICE upgrade combined with larger delivered luminosities allows one to improve the precision on UPC measurements and extend them to other quarkonia. Thanks to low background in UPC events, it has been demonstrated that semi-forward analyses[2] are possible, allowing for a scan in rapidity of the photoproduction cross section [10], which would provide us with novel indirect information on the gluon dynamics in heavy nuclei. In particular, a possible access to nuclear GPDs will be investigated, in synergy with a CLAS12 ERC team in Orsay (P.I. Raphaël Dupré).

Concerning the quarkonium photoproduction measurements in AA collisions with nuclear overlap, the observed J/ψ excess at low p_T, interpreted as originating from coherent photoproduction, imposes great challenges for the existing coherent photoproduction models, especially in explaining how the broken nuclei satisfy the requirement of coherence. The high statistics Pb-Pb data foreseen in Run3, together with the already collected data in Run2, will permit the measurement, for the first time, of the polarization of the J/ψ excess at forward rapidity by **the P2IO postdoc**, allowing to confirm unambiguously the origin of the excess. The measurement of the excess as a function of centrality will be conducted both at forward and mid-rapidity, to study potential QGP-like effects on the photoproduced J/ψ yield. An observation of a broadening of the excess p_T distribution with increasing centrality would also be an indication that the spectator[3] nucleons in the target are responsible for the coherence. Such kind of studies can be extended at mid-rapidity, thanks to the better p_T resolution, to the measurement of the t-slope[4] of the excess (by a PhD student), which would provide information on the Pb nuclear form factor [11]. The high statistic Run3 data will allow one to extend all the previous studies to $\psi(2S)$ and Υ(1S) for the first time. Benefiting from the fact that the upgraded ALICE will take data in continuous mode with all detectors, a feasibility study of semi-forward photoproduction of quarkonia in PC will be conducted. In case of feasibility, the measurement of the photoproduction cross section in PC over 4 rapidity units will strongly constrain calculations trying to describe this

[1]i.e. the γ emitted by the first Pb nucleus interacts with the second Pb nucleus as a whole.

[2]ie. analyses combining a muon in the central barrel and a muon in the spectrometer

[3]ie. the nucleons not participating in the collision

[4]t is the momentum transferred squared, $-t \sim p_T^2$

new phenomenon. The P2IO ALICE team in Orsay has a known expertise in the field of quarkonia, and led the recent Run2 studies of the J/ψ excess in PC[12]. The required software developments and specific data streams will be developed together with the Saclay group in ALICE working on the same signatures as outlined in 2.6.1. On the theory side, it will be explored to which extent the ab-initio geometry calculations developed in 2.5.2 can be confronted with these new measurements and to which extent theoretical calculations developped in 2.4.2 can be extended to the nuclear case.

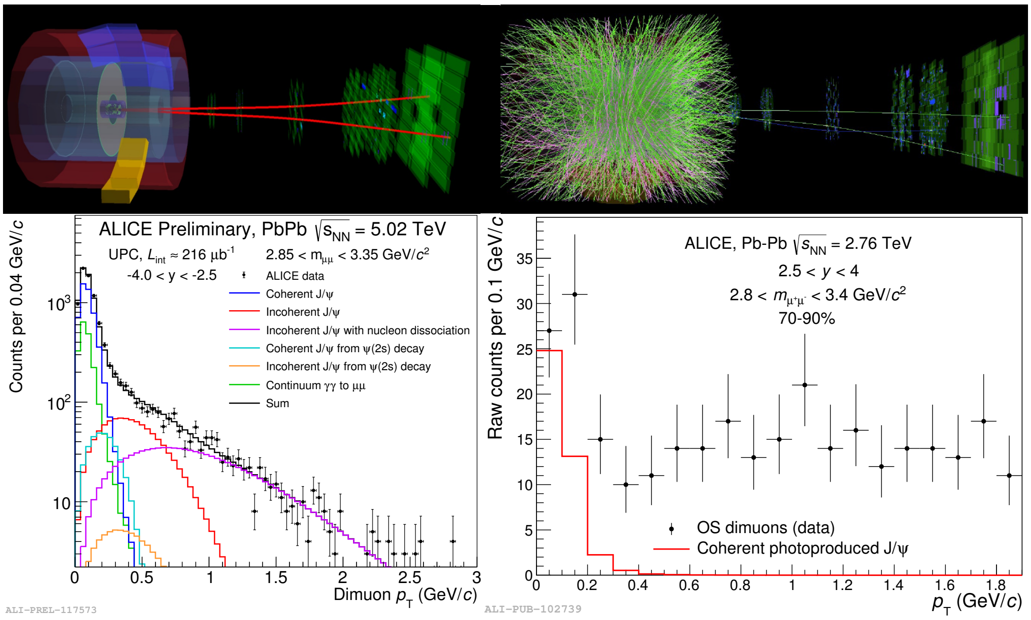

Figure 4: Top left: Pb-Pb UPC event display in ALICE where only two muon tracks are produced forward, and no activity is in the central barrel. Top right : Pb-Pb event display with hadronic activity in the ALICE central barrel and two forward muon tracks. Bottom left: $\mu^+\mu^-$-pair $p_{\rm T}$ in the J/ψ mass region in UPC. The coherently photoproduced J/ψ distribution exhibits a peak at very low $\rm p_T$. Bottom right: $\mu^+\mu^-$-pair $p_{\rm T}$ distribution in the J/ψ mass region, in Pb-Pb events with nuclear overlap (centrality 70-90%). The distribution exhibits an excess at very low-$p_{\rm T}$ which has been interpreted as an evidence for J/ψ coherent photoproduction.

2.5 WPII: Unification

A multidimensional view of hadrons requires a unification programme for different hadron structure concepts and approaches. This programme will connect the variety of analytical expressions and validity ranges in momentum and coordinate space. Furthermore, in the modelisation of hadronic collisions at later times via hydrodynamics, the arbitrariness lies mostly in the initial conditions choices which should be described in the language of this hadron structure description. Recent progress in perturbative QCD made within P2IO allows one to determine the initial conditions from first principles in the nuclear case and to use them as an input to hydrodynamic modelling. This paves the way to a first-principles approach to soft hadron production, for the first time in the history of high-energy physics. Finally, an efficient exchange between theory and experiment in the age of big data requires powerful tools and interfaces as provided by PARTONS and NLOAccess developed in P2IO, which we will promote by providing expert mobility to enlarge the developer and user basis and by providing hardware support.

2.5.1 Concept unification

The investigation of hadron structure is commonly divided into the investigation of a variety of non-perturbative objects, each focusing on different aspects. Most known are parton distribution functions, analysing the compounds of hadrons as a function of the longitudinal momentum carried. GPDs at vanishing skewness add the transverse space coordinate as a second variable[5] whereas TMDs add instead the transverse momentum. In the high-energy limit, the CGC effective field theory is

[5]More precisely, the distance to the center of momentum in the transverse plane is Fourier-conjugated to the momentum transfer on the hadron target.

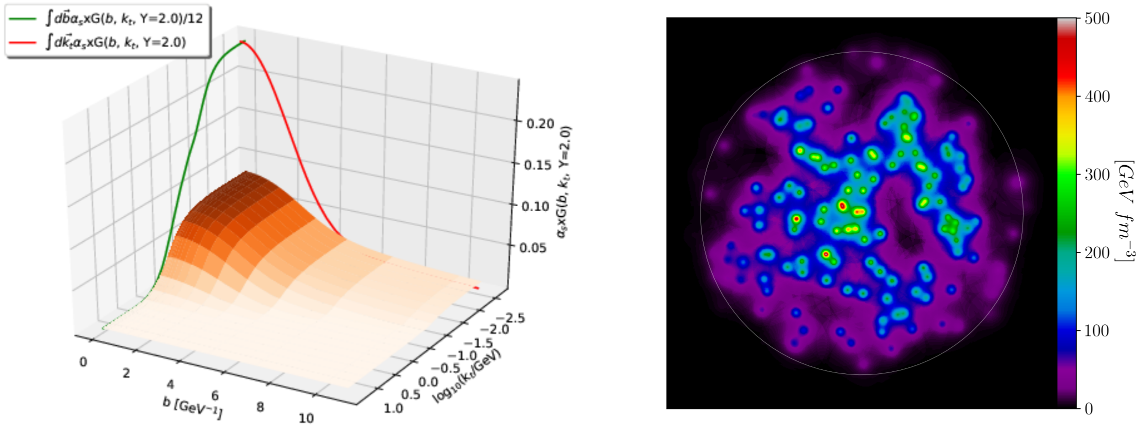

Figure 5: Left: hadron Wigner distribution in the CGC. Right: Energy density profile in the transverse plane right after a central Pb-Pb collision at the LHC, obtained from the ab-initio approach developed within P2IO [taken from Ref. [15]].

the framework of choice to exploit hadron structure. The understanding of the respective kinematic limits and processes for these different concepts and evolution equations and consequently the full exploitation of JLab and LHC data call for a unification programme. This programme will connect the variety of analytical expressions and validity ranges. The P2IO labs are world-leading in the different theory communities and started first pioneering developments in this direction. We, under the lead of CPHT, aim to play a leading role in this endeavour required for the quest of the full multidimensional picture of hadrons and nuclei.

The work program of the **p**ostdoc will be centered around proton-nucleus collisions, also known as *small systems* in the heavy-ion community. Those were originally thought of as control experiments for heavy-ion collisions, but they turned out to produce the same collectivity signals as A+A collisions do. In that case, in the hydrodynamic paradigm (see next sub-section), the initial spatial anisotropies of matter plays a crucial role, and if the same paradigm were to apply to proton-nucleus collisions, the spatial distribution of matter in the proton would as well. We shall investigate this option, implementing for the first time actual GDPs (as opposed to ad-hoc models) in the initialization of hydrodynamics, through the energy momentum tensor.

Should the pA collectivity signals (measured from anisotropies in the momentum distribution of final-state particles) come purely from the QCD dynamics of the initial state, then TMDs would be the crucial objects instead [13, 14]. What is missing in that picture however, is how exactly those intrinsic momentum anisotropies find themselves correlated with spatial anisotropies, and this is the void we plan to fill. Such (semi-)hard/soft correlations will be studied with the help of Wigner distributions, that incorporate both spatial and momentum coordinate, and will be studied at small-x, using Mueller's dipole model and the color glass condensate theory.

2.5.2 Ab-initio initial state and hydrodynamic simulation unification

Relativistic hydrodynamics is by now the standard approach for modeling the bulk of particle production in heavy-ion collisions, as it naturally explains the striking correlation patterns which are observed in experiments. The arbitrariness in hydrodynamic modelling lies mostly in the choice of initial conditions. Recent progress in perturbative QCD, made in particular in the P2IO theory team in Palaiseau, allows one to determine these initial conditions from first principles. More precisely, in the saturation regime of high gluon density, one can predict analytically the energy profile right after the collision, and its event-by-event fluctuations. A collaboration has recently been initiated with the team at IPhT [16] in order to use these first-principles calculations as an input to hydrodynamic modeling as depicted in Fig. 5. The eventual implementation of data-constrained nuclear GPDs into that modeling paves the way to a first-principles approach to soft hadron production, for the first time in the history of high-energy physics.

Future work goes along several directions. The main deliverable is to produce an event generator in 3 dimensions for the initial stage of nucleus-nucleus collisions, which would be an open-source code, and could be included in the NLOAccess portal. This requires to generalize to 3 dimensions the work recently done in collaboration between CPHT and IPhT [15], by including the evolution of the energy density with rapidity. It also requires to bridge the gap between this "initial" stage (we currently compute the energy density right after the collision, at time "0+") and the onset of hydrodynamic behavior, by modeling the thermalisation phase in a robust way. The **hired postdoc** will perform this work, together with the united forces of CPHT and IPhT, which have the relevant expertise. We anticipate that the resulting code will be transparent (both in terms of physics and programming) and efficient (both in predictive power and computing time).

A complementary, broader direction is to explore the phenomenological consequences of this new paradigm by studying a number of observables. We will have a first-principles description of longitudinal correlations (how multiplicities -and also anisotropic flow- in different rapidity windows are correlated), as opposed to "ad hoc" parametrisations currently used. This theoretical picture will be tested against recent data, in particular from CMS. Another class of observables consists of various fluctuation measures, for instance event-by-event fluctuations of the mean transverse momentum.

Finally, we will explore a completely novel direction in synergy with the Gluometer work package: using jet quenching to probe initial stages of the evolution, and its fluctuations. For this purpose, we plan to compute the hard-soft correlation between the energy-momentum tensor and the production of particles, which is directly related to the high-p_{T} second harmonic v_2. This will open the way for further studies, beyond the gluodynamics project, of what imprints of initial fluctuations can be detected with jet sub-structure in heavy-ion collisions.

2.5.3 Software tools for phenomenology, experiment and theory

The increasing complexity of multi-channel experimental data analysis and phenomenology to extract physics information calls for suitable powerful interfaces and tools between theory, phenomenology and experiment. The P2IO laboratories are central world-wide institutions via the set-up of the PARTONS software package [17] and the NLOAccess portal for the study of hadron structure as well as nuclear effects for heavy-ion observables. Initially meant as a flexible, robust, and open-source framework for the theory and phenomenology of GPDs in all kinematic regions (from collider to fixed target settings), the PARTONS framework will be extended to TMDs and will provide event generation features by 2023. This will offer new perspectives on 3D hadron structure studies by a consistent, unified computing framework describing the two main families of 3D parton distribution functions.

The PARTONS framework and the NLOAccess portal are provided technical support (manpower) from the EU H2020 project STRONG-2020, showing their scientific relevance, excellence, and their ability to aggregate knowledge and know-how from different teams or fields around common computing tools. However, this support, designed as a "virtual access infrastructure", covers the actual implementation and maintenance of the software legacy, and the embedding as integral part of upcoming applications. In order to enlarge the user and developer basis, the IPNO[6] and DPhN theory and phenomenology teams will **invite world-leading experts and travel to centres of QCD research** in order to promote and improve these unique lasting contributions to research. Such invitations and travels are absolutely essential for the continuous integration of new models in the PARTONS framework and NLOAccess portal. Indeed such an integration process requires the close collaboration of a software architect and an expert physicist to adapt a new model to the existing structure, and carefully validate it before releasing it to a wide community of users.

The PARTONS framework and the NLOAccess portal have nevertheless slightly different needs. On the one hand, **a dedicated computer** with $\mathcal{O}(100)$ cores allowing for interactive computations with the variety of codes to be included in NLOAccess will be welcome for its smooth running and to avoid to saturate the existing interactive computing resources in the P2IO perimeter. On the other hand, the intricacies of 3D hadron structure model building or of higher-twist corrections to exclusive processes are such that an important part of the software write-up in PARTONS will deal with ongoing theoretical developments. This will require **closer interactions with relevant experts** to properly integrate and document these new components before proceeding with software deployment.

[6] NLOAccess is also strongly based on the know-how of the IPNO computing group which is thus involved in the project.

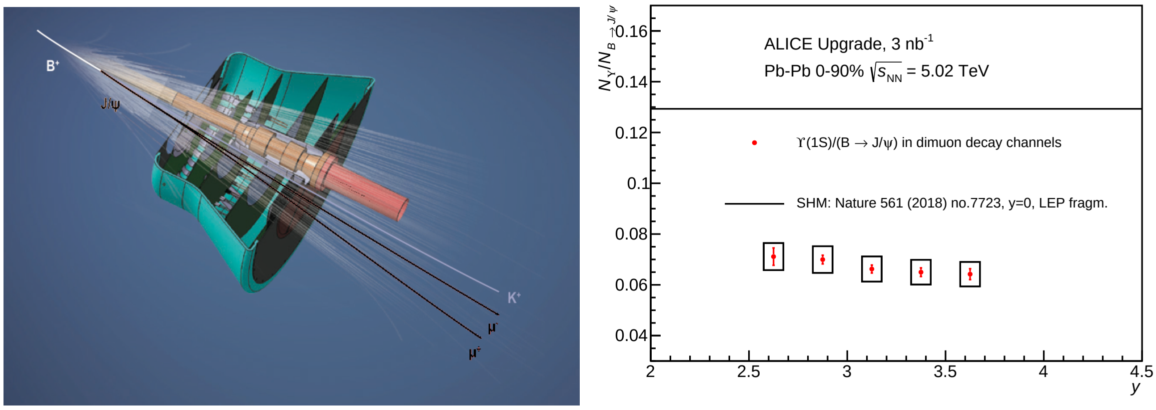

Figure 6: Left: illustration of secondary decay vertex for a $B^+ \to K^+ J/\psi(\mu^+\mu^-)$ which will be resolved statistically by the new MFT detector. Right: Υ over non-prompt J/ψ-ratio integrated over p_T as function of rapidity in Pb-Pb collisions; boxes indicate systematic, error bars statistical uncertainties. The experimental projection for the first Pb-Pb Run 3 measurement is compared with a prediction of [18] assuming a probability of $(1.16 \pm 0.1)\%$ for a b-hadron to decay in J/ψ+X from LEP.

2.5.4 Cross education

In order to bridge potential knowledge gaps and to educate newcomers within the Gluodynamics community about the research fields of the connected areas on a broad basis, in particular in view of conceptual and theoretical aspects, we will organise **a yearly 3-week long lecture series conducted by one theory colleague as well as by one external speaker per edition**. We plan to have one lecture on transverse momentum dependent parton distribution functions in the first year, in the 2nd year a lecture series about thermalisation in heavy-ion collisions, and two still be to defined topics for the last two years. The format consists of one lecture per week for each of the two speakers to allow for various interactions possibilities and to profit from the presence of the visitor. This activity will strengthen the connections between the different communities and to develop new connections and interactions. It will be financed to 50% by Gluodynamics and by institute visitor budgets or other community budgets as the GDR QCD and combined with the Gluodynamics workshops described in Section 2.7.3. This project will be jointly organised by François Arleo, François Gelis, Jean-Philippe Lansberg, Cedric Lorcé, Hervé Moutarde, Jean-Yves Ollitrault and Samuel Wallon in contact with the two PIs.

2.6 WPIII: Gluometer

Bound states of two heavy quarks, charmonia $c\bar{c}$ or bottomonia $b\bar{b}$, are sensitive probes of deconfinement in nucleus-nucleus collisions at the LHC. The investigation of the production characteristics of this hydrogen atom of QCD provided in Run 1 and Run 2 two major insights: ALICE data revealed that quark recombination is at play in the charmonium sector while CMS data showed evidence for a sequential suppression pattern of bottomonium states. However, beyond these qualitative findings, additional measurements as well as further progress on the phenomenological side are required to understand the microscopic mechanism at the origin of the observed patterns. Besides the developments outlined in WPII for the initial state, we contribute experimentally to this quest with new measurements in collider and in the novel fixed-target mode at the LHC.

Furthermore, the strong increase in statistical power will open up new opportunities in CMS with flavour tagged jets, not only to pin down the flavour dependence, but also to unveil, potentially, coherence effects in medium-modified parton showers.

2.6.1 Forcemeter: collider

With the upcoming muon forward tracker (MFT) upgrade of the ALICE muon spectrometer, non-prompt J/ψ measurements will become feasible at forward rapidity in nucleus-nucleus collisions in collider mode at the LHC (Fig. 6). They will allow unique measurements of low transverse momentum open beauty hadron production, a proxy of total beauty production. As in the case of charm, the measurement of the total beauty production provides a natural reference for bottomonium production. In particular, this becomes interesting in view of the recent considerations [18] that even bottomonium states could have already reached their thermal weights in contrast to the common interpretation in the field as implemented in transport calculations. The measurement of hidden over open beauty integrated over p_{T} in a specific rapidity interval will become hence feasible via the measurement of Υ production over non-prompt J/ψ. A projection of this quantity based on the assumptions in the ALICE projections in the HL-LHC YR is provided in Fig. 6 together with a theoretical prediction based on [18]. A cross-P2IO cooperation is the effort towards the calculation of heavy-quark pair production from the Glasma, i.e. the state resulting from the collision of two dense colour field sheets by Francois Gelis within the Gluodynamics project [19]. In addition to this measurement, a feasibility study and potentially a measurement of B_c production with the first Run3 data in the 3-muon decay channel down to low-p_{T} as well as studies of possible low-mass Drell-Yan measurements in pp and Pb-Pb collisions will be carried out. The **postdoc** that will carry out this work with the P2IO teams in ALICE, will benefit from the strong support of the groups, including the collaboration with one PhD student working on the non-prompt J/ψ analysis with the first pp data in 2021. The postdoc will be involved into the upgrade activities concerning the software framework together with the support from WPI. For the B_c study, this project will largely profit from interactions with the CMS P2IO group at the Palaiseau site which works already on the B_c [20]. Furthermore, the theory support for calculations of pure initial-state models of the production ratios in Pb-Pb as well as for the Drell-Yan study is guaranteed via the efforts in WPIII within the NLOAccess portal as well as the ANR ColdLoss (P.I. François Arleo). The investigations of the Drell-Yan and B_c measurement feasibility will be an important input for the discussions on upgrade directions for heavy-ion collisions in view of multi-heavy flavour states, Drell-Yan studies for low-x, and electromagnetic radiation in heavy-ion collisions. These will be discussed closely with the LHCb colleagues since they provide guidance for the studies conducted in WPIV 2.7.1. These future precision dimuon studies and precision heavy-flavour hadron measurements are part of the physics backbone programme of the LHCb upgrade in view of nucleus-nucleus collisions [21].

2.6.2 Forcemeter: fixed-target

P2IO is at the origin of the new and unique LHCb fixed-target program at the LHC whose main goal is to thoroughly test the in-medium QCD force modification between heavy-quarks and provide key input to characterize the phase transition. Thanks to the excellent detector performances, including particle identification, LHCb offers the unique opportunity to precisely measure, within a wide 3-units rapidity range, open and hidden charm production, including P-waves states such as χ_c, at intermediate energies (70–110 GeV), which is the ideal place to probe the so-called charmonium sequential suppression pattern induced by the different melting temperatures of the $c\bar{c}$ states.

In addition, the study of charm production in proton-nucleus collisions on various nuclear targets is needed for a correct interpretation of the charmonium suppression patterns observed in heavy-ion collisions. This is also crucial to understand the physics mechanisms underlying charmonium production. Several effects can be studied in proton-nucleus collisions, such as the interaction of the $c\bar{c}$ pair with the target nucleons leading to a break-up of the charmonium states, parton shadowing (or anti-shadowing) in the target nucleus that may suppress (or enhance) the probability of charmonium production, gluon saturation effects, bound state interaction with the comoving hadrons and coherent parton energy loss. The magnitude of these effects and the interplay between them are currently not well understood. Thanks to the strong theoretical expertise available on these subjects within P2IO labs, synergy efforts between P2IO experimentalists and theorists will lead to substantial improvement in our understanding of these so-called Cold Nuclear Matter effects, once high luminosity proton-nucleus samples will be recorded and analysed.

A first measurement of charm production in proton-nucleus collisions has been already performed with statistically limited p-He and p-Ar data samples, demonstrating the accuracy of the program [22]. During the course of the project, the study of already recorded p-Ne and Pb-Ne data (see Fig. 7) will be performed, and a high luminosity campaign will start in 2021, thanks to the upgrade of the gas target.

The required **postdoc** will participate to the data taking and analysis of the high luminosity proton-nucleus and nucleus-nucleus samples. She/He will contribute to the analysis of these data with a particular focus on MC simulations which will form a strong synergy with the upgrade simulation

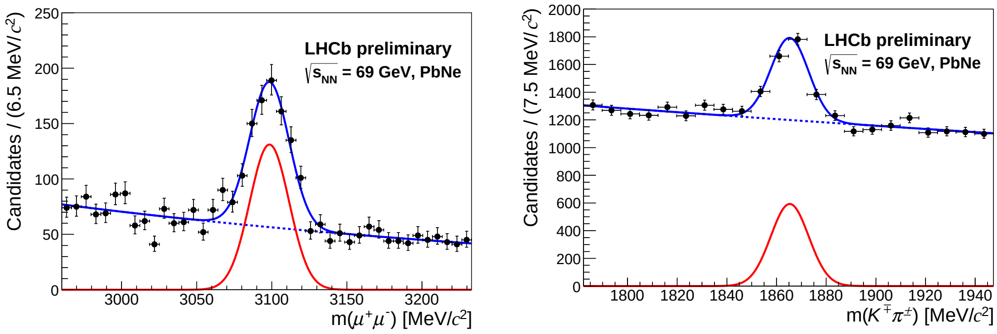

Figure 7: Invariant-mass distributions fitted by an unbinned maximum likelihood in $\sqrt{s_{NN}} = 69$ GeV PbNe collisions; Left: $J/\psi \to \mu^+\mu^-$; Right: $D^0 \to K^-\pi^+$. The dashed blue line corresponds to the combinatorial background, the red line to the signal and the solid blue line to the sum of the two.

activity presented in WPIV 2.7.1. In particular, the calorimeter optimisation will profit from the experiences gained in the analysis and simulation of $\chi_c \to J/\psi + \gamma$. In this context, the NLOAccess portal will be very useful to provide theoretical predictions from different production models in this seldom explored phase space.

2.6.3 Radiation

The interaction of hard-scattered partons with the quark-gluon plasma proceeds largely via gluon radiation (bremsstrahlung). This leads to the phenomenon known as jet quenching, whereby the yields of high p_T hadrons and jets are suppressed in nucleus-nucleus collisions compared to the expectation from proton-proton collisions. This process is the QCD analog of QED energy loss by charged particles in normal matter. By studying this process one learns both about the nature of QCD radiation at large color charge density and high temperature and about the transport properties of the Quark-Gluon plasma itself.

Many of the state-of-the-art studies of jet quenching have been conducted using the CMS experiment, which features large acceptance calorimetry and tracking, as well as readout and trigger capabilities. The CMS heavy-ion group of P2IO at the Palaiseau site has participated in many of these jet quenching studies including the first observation of the dijet imbalance [23] and the first measurement of b-tagged jets in heavy-ion collisions [24].

The CMS P2IO heavy-ion group has also performed a wide variety of quarkonium measurements, including the pioneering measurements of the Υ states [25], which revealed a larger suppression of the excited states, compared to the fundamental one. In the J/ψ sector, CMS specializes in measurements at large p_T. Notable results include the measurement of the nuclear suppression factor [26] and elliptic flow parameter v_2 [27] of high p_T. These high p_T studies are complementary to the coverage of the ALICE and LHCb experiments. Whereas low p_T measurements are thought to be sensitive to the Debye screening of the Quark-Gluon Plasma, as well as confounding effects such as charm recombination, at large p_T there is emerging evidence that jet quenching may also play a role. CMS and LHCb have recently measured the jet production associated to J/ψ at large $p_T$in pp collisions, which they have shown to be much larger than expected by existing models [28, 29]. This is demonstrated in Figure 2.6.3 (left), which compares the event generator PYTHIA8 and preliminary results for the distribution of the fragmentation variable z, which is the ratio of the J/ψ p_T to its parent jet p_T. The fact that J/ψ tend to carry a smaller fraction of the jet momentum than foreseen by models may indicate that J/ψ production is occurring at later times than previously thought, as part of a parton shower, as illustrated in Fig. 2.6.3 (right). This picture is supported by new model calculations including parton shower effects in Ref [30]. Late production of J/ψ in turn that these J/ψ-jets should be quenched, an aspect that has not been considered in models of nuclear effects on the quarkonium states.

This project attributes **one year of a post-doc** to work on the CMS heavy-ion program at the interface of quarkonium and jet quenching studies. The deliverable is an article focusing on high p_T quarkonia and their associated production. For example, a promising direction could be to study the substructure of jets containing quarkonia. Such a study would benefit from the expertise of Gregory Soyez, who is at the forefront of the development of jet substructure methods (e.g., as author of the

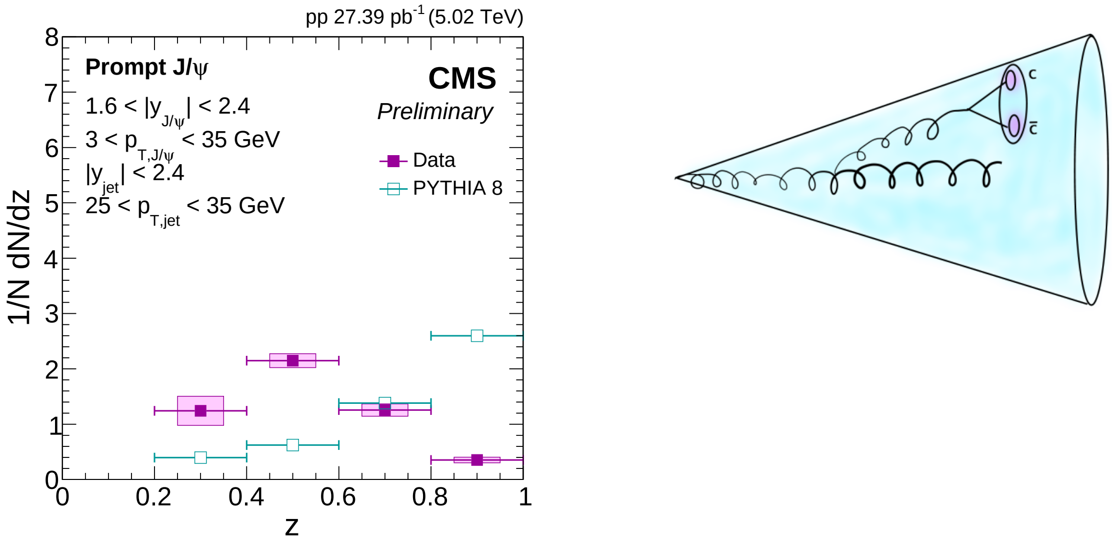

Figure 8: Left: The z distribution of J/ψ-jets in pp collisions at 5 TeV, compared to Pythia [29]. Right: An illustration of low z J/ψ production, where the J/$\psi$is produced in a parton shower.

so-called SoftDrop technique [31])".

The one year of post-doc salary attributed by the Gluodynamics project will be complemented with funding from another project to offer at least a two year contract to the candidate. During the same time frame, the group will also receive financing for at least one year of a post-doctoral appointment from the LHC-Combine package of the European STRONG2020 infrastructure project (P.I. Raphaël Granier de Cassagnac) and the COLDLOSS project, financed by the ANR (P.I. François Arleo). Both of these projects have close thematic links to the gluodynamics project. In particular, the COLDLOSS project aims at quantifying the gluonic density of large nuclei through the effects of medium-induced gluon radiation and energy loss on hard processes in pA collisions. LHC-Combine aims to perform combinations measurements from the various heavy-ion experiments, including quarkonium and jet studies.

2.7 WPIV: Future

At higher energies and luminosities, particle multiplicities will increase dramatically. New ideas will need to be found to still be able to perform meaningful data analyses in these conditions. New techniques will have to be designed, tested, and implemented to efficiently recognize the patterns associated to particles in tracking detectors or in calorimeters. Advanced detector technology including timing information as well as algorithms using CPU accelerators, like FPGA co-processors, are promising methods for this application. Feasibility studies both for LHCb for heavy-ion collisions as well as the future detector at the EIC will be conducted during the course of the project, with the help of the detector, electronics, and computing departments of the involved labs.

2.7.1 Future hadron collider

A proposal is currently emerging to upgrade the LHCb detector to run at higher luminosities [21], during the High Luminosity phase of the LHC accelerator. The physics case of this proposal is based, at the moment, mainly on the operation of the detector with pp collisions. However it would be essential to be able to record and analyse also nucleus-nucleus collisions in order to continue the analyses conducted during this project since the LHCb experiment proved to be a versatile detector, capable of providing precise data that benefited the physics goals of the project. A first important step is to estimate the performances of the foreseen design of the detectors. This would be achieved from realistic simulations of the QCD physics processes considered in the project. The experience

Detector	Maximum occupancy in most central PbPb at $\sqrt{s_{NN}} = 5$ TeV
VELO (Upgrade I)	4 %
VELO upgrade (Upgrade II)	1 %
SciFi (Upgrade II)	25%

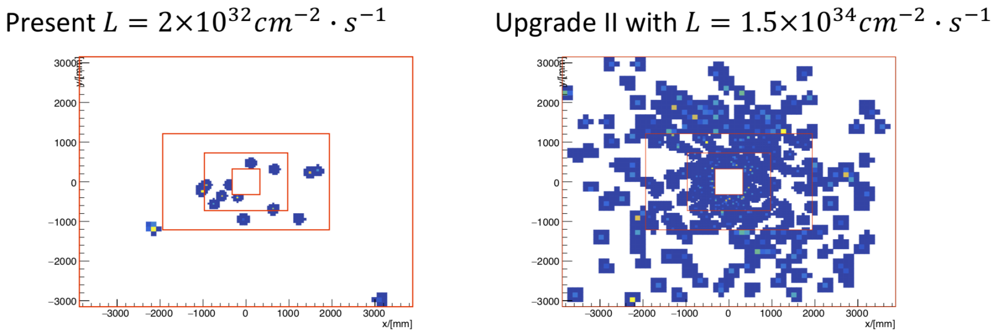

Figure 9: Upper panel: Estimated occupancy in tracking detectors after Upgrade 1 and Upgrade 2 in LHCb [21]; Lower panel: Simulation of energy deposits of electrons and photons in the electromagnetic calorimeter of LHCb with current (left) and upgrade II (right) luminosity.

gained in the other work packages of the project concerning data analyses will be crucial for the interpretation of the simulation.

The following step is to find improvements to the envisaged detector design, in order to reach the performances required for nucleus-nucleus measurements. Since the LHCb detector was originally designed with low multiplicity events in mind, changes will be mandatory to adapt it in the best possible way to the high multiplicity environment required by the project. While running at higher luminosities at the LHC will necessarily imply an increase of multiplicity seen in pp collisions by the experiment, as shown in Fig. 9, use of precise timing in the detector readout will mitigate strongly the effects of the occupancy increase in the performances. However, this will not help for nucleus-nucleus collisions. The step will also be based on simulation. The results of the design improvement studies will necessarily show that not only detector design must be adapted but also that reconstruction algorithms must be improved to analyse high multiplicity events. One promising way is to use CPU accelerator assisted (FPGA, GPUs) reconstruction algorithms. Within WPIV, prototypes will be designed to prove the feasibility and gain of such an approach.

Important decisions concerning the design of the detector will be taken in the next two years, and it is crucial to make progress within these two years to influence the design. In particular, a framework TDR will be written to detail the characteristics of the detector at the end of 2021, that the work from this work package will guide. This is mandatory in order to include a nucleus-nucleus physics program where the P2IO laboratories will play a major role. This will also allow one to maintain on a long term the visibility acquired. With the Gluodynamics funding, it will be possible to offer a **2-year post-doc position**, where the work will be shared between the simulation studies conducted in WPIV and physics analyses conducted in WPIII. This will greatly enhance the potential to attract excellent candidates to work in the project.

2.7.2 Future electron-hadron collider

With the high luminosities and the higher centre-of-mass energies that the future Electron Ion Collider will provide, hadron structure physics will enter in the precision measurement era, in particular for the gluon dominated processes. To achieve high luminosities, the current preliminary accelerator designs for the EIC focus on delivering a bunch crossing at about 0.75 GHz [32]. This imposes very tight constraints on detector design in terms of timing and background suppression.

Precise charged particle tracking is essential to reach the physics goals of EIC. Micro-pattern gaseous detectors (MPGDs) are considered among the best choices for tracking detectors, both in the central and the forward detection regions. In the central region, i.e. $|\eta| \lesssim 1$, low material budget MPGDs will be considered either as tracking detection elements or as readout planes for Time

Projection Chambers (TPCs). Monte Carlo simulations will be conducted in order to establish the detector requirements for the two solutions in terms of spacial resolution and occupancy. The study of exclusive and semi-inclusive reactions at EIC will also demand stringent requirements on calorimetry. At forward rapidity, the need of high energy resolution and radiation hardness will likely require the use of crystal or glass ceramic materials. Simulations will be performed to identify other regions where compact and homogeneous calorimetry will be beneficial. Ongoing R&D at P2IO on PWO crystals and new glass ceramic samples will determine the ultimate performance in terms of light yield and homogeneity of these materials. Simulations of the dose from synchrotron radiation produced by the electron beam and from secondary particles produced in the beam pipe and surrounding material are needed to better define the requirements in terms of radiation hardness. Optical bleaching procedures are under study at P2IO to recover the optical properties of crystals from electromagnetic radiation. Also, beam tests of increasingly larger prototypes are helping characterize the contribution of the energy-independent term to the energy resolution.

The simulations will also be important to evaluate the need of fast data acquisition and reconstruction algorithms to be implemented in CPU accelerators in collaboration with the other WPIV participants. Simulations of the exclusive and semi-inclusive reactions under theoretical study in WPI will be performed with realistic background conditions to establish the signal purity and possible detector features needed.

A TPC solution as main tracking device would offer the possibility not just to track particles but also to identify their nature. On the other hand, the high gain needed for precise energy deposition measurements could lead to higher ion back flow (IBF) in the drift region that causes distortions of the drift electric field. Ongoing R&D studies at P2IO are focusing on the development of low IBF Micromegas MPGDs for the TPC readout planes. The optimisation for low-IBF and high gain will need simulation studies focusing on the evaluation of the particle identification (PID) performance needed. The results of this study will be discussed with the TPC experts of the ALICE experiment. Machine learning algorithms will be developed to maximise the PID efficiency and studies will be performed on the feasibility of the implementation of such algorithms on dedicated hardware.

The approval of the EIC is soon due and the EIC User Group is promoting physics and detector performance studies that will culminate in the publication of a conceptual design report (CDR) in 2021 [33]. The simulation studies proposed in WPIV will need the dedicated full time of **a post-doctoral researcher** on tracking and PID and timely results will be crucial for establishing the P2IO laboratories among the major contributors to the EIC detector developments and hence to physics analyses.

Following the results of the postdoctoral work, simulations of the full detector will be available to optimize the whole detector set-up performance. High resolution calorimetry is also crucial for exclusive and semi-inclusive physics. P2IO has a proven expertise for this type of instrumentation and will strongly participate in these developments for EIC.

2.7.3 Initial Stages conference and intertopical workshops

This unique synergistic scientific program will allow one to dive deep into the structure of hadrons as well as strongly interacting matter. It will consequently progress our understanding of the underlying mechanisms of the strong interaction and the smallest fluids on earth. In order to promote the projects visibility, we plan to **host the Initial Stages conference** by the end of the 4 years funding period. Initial Stages is an expanding conference series, after Quark Matter one of the largest conferences in the field of heavy-ion physics, founded in 2013 focusing on the questions of the initial state. It is hence ideally suited to demonstrate the progress within the P2IO laboratories and to promote it as a centre of QCD physics. In addition, we plan to organise **2 international intertopical workshops** which combine the different subjects of the Gluodynamics project. These workshops will be organised to be adjacent to 2 out of the 4 lecture series discussed in section 2.5.4.

3 Project impact

This unique synergetic scientific program will allow improving our understanding of the underlying mechanisms of strong interaction and the smallest fluids on earth. Furthermore, it will prepare the local community to the upcoming experimental and theoretical challenges at the EIC and the HL-LHC. The project will have a **high scientific impact** on international level thanks to the unique

P2IO landscape with its combination of world-leading theoretical and experimental experts on hadron and heavy-ion physics.

Precisely this interchange between theory, phenomenology, experimental analysis, and simulation studies for the future is required to progress in the quest for the nucleon structure and the Quark-Gluon Plasma, i.e., probing QCD in its extremes. The combination of hadron structure and heavy-ion expertise on the experimental and theoretical side is **innovative**. In particular, we aim not only at sharing common tools and methods, which is required to exploit the available opportunities, but also to advance our fields based on the recent scientific insight of the other field directly. The materialisation of such an effort is based on the unique capabilities assembled in P2IO.

The project represents the starting point for a **longterm vision** of QGP and hadron structure physics within P2IO. In particular, it provides the starting impulse for the experimental QCD projects being online after 2030 and the corresponding theoretical and phenomenological groundwork that is needed to fully profit from this wealth of new precision data and the potential merging of the fields of heavy-ion and nucleon structure analysis in the very long run.

The **local community** has proven a strong collaborative spirit within successful national and international collaborations as well as community efforts as the HL-LHC Yellow report, H2020 call, EIC UG, GDR QCD, GDR InF. The solidification and the expansion of these ties, required for scientific advance, are enabled by this transversal project.

The possibility to attract young talents from around the world is central to the scientific excellence and the **visibility of P2IO**. It will be strongly improved by this project. A further enhancement of the P2IO visibility will be guaranteed by the organisation of the international Initial Stages conference, which is at the heart of the project topics, and topical workshops. The P2IO laboratories are leading in providing community software support for theory and phenomenology computations that are boosted by the presented effort. On the local structural level, the project is suited to promote further cooperation for the future within and between the three major sites beyond purely scientific grounds, most emblematically demonstrated by the cooperation on future detector developments paving the way towards technological advance.

4 Project organisation

4.1 Delivrables

The list of the project delivrables are detailed in Table 1. They are associated to specific contact persons to ensure clear responsabilities. As lined out in the corresponding subpackages, these delivrables represent the clearly envisageable results and legacies and are not meant to represent the full scientific production within or in close contact to the Gluodynamics project. In many cases, further directions and connecting aspects that will be enabled with the hired manpower are explicitly explained in the different work package texts.

4.2 Involved personal

The project involves 41 permanent, 10 post-docs and 6 doctoral students from 8 P2IO institutes equivalent to about 19.325 Full-Time-Equivalents (FTE) per year averaged over the full funding period of 4 years. The detailed distribution is given in Table 2 and Table 3. In case the case of doctoral students, postdocs and CDDs, the table includes only persons that have already started or that are already funded excluding future funding applications. For the future work-package, the large FTE numbers of the permanent staff proponents despite the early finalisation of the listed delivrables are to be understood in the following way: Gluodynamics is meant to provide the starting impetus for these large scale hardware projects in view of a strong P2IO participation and the realisation of physics opportunities related to Gluodynamics within these experiments. They will last beyond the concerned funding period and will have to be supplemented by other funding schemes during and after the Gluodynamics project duration if a strong participation of P2IO can be secured.

4.3 Detailed schedule

A detailed overview of the different milestones for the delivrables of the project are given in Table 4. In particular, for the non-technical tasks related to software and hardware developments and the

WP	Delivrable	Description	Finalisation	Contact
I	nucleon-ex 1	DVCS off proton/neutron (CLAS12)	T2–2023	C. Muñoz
I	nucleon-ex 2	L/T Rosenbluth separation DVCS (Hall C)	T4–2023	C. Muñoz
I	nucleon-ex 3	UPC pPb (in)coherent	T2–2022	M. Winn
I	nucleon-theo 1	$\gamma^{(*)}N \to \gamma M N'$: NLO & CGC	T4–2021	S. Wallon
I	nucleon-theo 2	$\gamma^{(*)}N \to \gamma M N'$: power corrections & applications	T4–2023	S. Wallon
I	nucleus-ex 1	forward PC coherent	T1–2023	L. Massacrier
I	nucleus-ex 2	semi-forward/central PC coherent	T4–2023	L. Massacrier
II	uni-space 1	GPD input in hydro initialization for small systems	T4–2021	C. Marquet
II	uni-space 2	QCD correlations between momentum and spatial anisotropies	T4–2023	C. Marquet
II	uni-time 1	3D ab-initio initial state generator	T4–2021	J.-Y. Ollitrault
II	uni-time 2	impact of initial stage on high-p_t v_2	T4–2022	J.-Y. Ollitrault
II	uni-tools 1	Inclusion in NLOAccess of codes from the project	T4–2023	J.-P. Lansberg
II	uni-tools 2	Inclusion in PARTONS of codes from the project	T4–2023	H. Moutarde
III	force-collider 1	non-prompt J/ψ and Υ PbPb measurements	T4–2022	M. Winn
III	force-collider 2	B_c PbPb or DY measurement	T4–2023	M. Winn
III	force-fixed-target 1	J//ψ and D^0 measurement in p-Ne & Pb-Ne Run 2	T2–2021	F. Fleuret
III	force-fixed-target 2	J//ψ, $\psi(2S)$, χ_c and D^0 measurement in Run 3 p-A and Pb-A	T4–2022	F. Fleuret
III	radiation 1	high-p_T quarkonium + jet Run 3 measurement	T4–2022	M. Nguyen
IV	hh collider 1	framework TDR calorimeters	T4–2021	P. Robbe
IV	hh collider 2	realistic heavy-ion simulations for LHCb Upgrade 2	T1–2022	P. Robbe
IV	e-h collider 1	CDR EIC detector	T4–2021	F. Bossu
IV	e-h collider 2	realistic simulations for exclusive reactions at the EIC	T1–2022	F. Bossu

Table 1: List of delivrables with short summary and contact. The parts 'unification: cross education' and conference are not put into this scheme due to their different nature.

required flexibility based on the hired personal skills and interest, these timelines are to be understood as indicative and will be revised within the project progress.

4.4 Coordination

The project is steered by the two project contacts Cyrille Marquet and Michael Winn. Overall project meetings will be held every 6 months to keep informed about the progress on the different topics.

In addition to the Initial Stages conference, 2 intertopical workshops are planned to boost the cooperation between different work packages and QCD physics close to the project focus as well as in order to stimulate the local landscape with external inputs. They will be put adjacent or overlapping with the 2 editions of the yearly lecture series.

The work package responsibles are asked to provide feed-back to the project contacts in adequate time distance to ensure not only progress, but also to open up potential new cooperation lines besides the directions already pointed out in this document.

5 Financial needs

The most important requirement to realise the project is the additional manpower that is required to fully exploit the available experimental data and theory opportunities in view of gluonic systems in hadron structure and QGP physics, in particular at intersection points between these two communities to let emerge a united community prepared for the next large scale projects.

The budget distribution of the overall project by contacts and topics is given in Tab. 5 and in Tab. 6 by institutes and purpose. The tasks and their specific manpower needs have been detailed in the respective sections and are summarised in Tab. 3. Furthermore, the work package unification requires additional funds to bring the different communities together. In particular, the unification tools budget consists of 20 kEuro funds for inviting guest scientists and allowing travel possibilities for the PARTONS software project. The NLOAccess project requires in the same spirit 15 kEuro as well as 5 kEuro for the computer hardware mentioned in the detailed proposal. The unification cross education budget is reserved for four 3-weeks-long lectures held by external guests financed by 50 % by Gluodynamics according to the concept introduced in the corresponding section 2.5.4. In addition, the work package Future requires 10 kEuro additional funds for FPGA prototypes in view of accelerated data reconstruction. The conference and workshop budget of 20 kEuro is devoted to the Initial Stages conference and the 2 bi-yearly workshops that will be combined with the guest lecturer stays in an interdisciplinary spirit. Related fundings from running grants, ANRs and H2020 European Union funds are mentioned in the detailed scientific project presentations.

Institute	Name	Role		WP	FTE
CPHT	Cyrille Marquet	PI, WP leader	theo	**II**,IV,I	60 %
	Stéphane Munier	Contributor	theo	I,II	25 %
	Cédric Lorcé	Contributor	theo	I,II	25 %
	Bernard Pire*	Contributor	theo	I,II	50 %
IPhT	Jean-Yves Ollitrault	WP leader	theo	II	60 %
	Edmond Iancu	Contributor	theo	II	10 %
	Francois Gelis	Contributor	theo	II	20 %
	Gregory Soyez	Contributor	theo	II,III	10 %
	Jean-Paul Blaizot*	Contributor	theo	II	15 %
IPNO	Christophe Suire	Contributor	ex	**I**, III	30 %
	Laure Massacrier	WP leader	ex	**I**,III	30 %
	Carlos Muñoz	WP leader	ex	**I**,IV	60 %
	Bruno Espagnon	contributor	ex	I	20 %
	Jean-Philippe Lansberg	WP leader	theo	**II**,I,III	25 %
	Laure-Amélie Couturier	Contributor	comput.	II	15 %
	Vicent Lafage	Contributor	comput.	II	15 %
	Raphael Dupré	Contributor	ex	I	10 %
	Dominique Marchand	Contributor	ex	I	20 %
	Silvia Niccolai	Contributor	ex	I	60 %
	Zaida Conesa del Valle	Contributor	ex	I,III	20 %
DPhN	Michael Winn	PI, WP leader	ex	**III**, I, IV	60 %
	Francesco Bossu	WP leader	ex	**IV**,I	50 %
	Hervé Moutarde	WP leader	theo	**II**,I	30 %
	Franck Sabatié	Contributor	ex	I,IV	10 %
	Maxime Defurne	Contributor	ex	I,IV	30 %
	Javier Castillo	Contributor	ex	III,IV	25 %
	Alberto Baldisseri	Contributor	ex	III,IV	15 %
	Andrea Ferrero	Contributor	ex	III	15 %
	Stefano Panebianco	Contributor	ex	III,IV	15 %
	Andry Rakotozafinadrabe	Contributor	ex	III,IV	15 %
DEDIP	Maxence Vandenbroucke	Contributor	ex	IV	20 %
	Stephan Aune	Contributor	ex	IV	15 %
LAL	Patrick Robbe	WP leader	ex	**IV**	50 %
	Yasmine Amhis	Contributor	ex	IV	10 %
	Daniel Charlet	Contributor	ex	IV	10 %
LLR	Frédéric Fleuret	WP leader	ex	**III**, IV	60 %
	Matt Nguyen	WP leader	ex	**III**	50 %
	François Arleo	Contributor	theo	III	15 %
	Raphael G. d. Cassagnac	Contributor	ex	III	20 %
	Emilie Maurice	Contributor	ex	**III**, IV	50 %
LPT	Samuel Wallon	WP leader	theo	**I**,II	60 %

Table 2: The list of involved permanent personal at the P2IO Laboratories. (*: Emeriti)

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Institute	type	years	theo/ex	WP	primary supervisor	FTE
CPHT	**postdoc P2IO**	T4–20 - T3–22	theo	**II**,I	C. Marquet	100%
	postdoc X	T1–20 - T4–21	theo	**II**,I	C. Marquet	50%
IPhT	**postdoc P2IO**	T1–21 - T1–22	theo	**II**,III	J.-Y. Ollitrault	100%
IPNO	**PhD P2IO**	T4–20 - T3–23	ex	**I**	C. Muñoz	50%
	postdoc P2IO	T2–21 - T2–23	ex	**I**,III	C. Suire	100%
	PhD	T4–20 - T4–23	ex	**I**,III	L. Massacrier	100%
	PhD	T4–21 - T3–23	ex	I	C. Muñoz	100%
	PhD	T1–20 - T3–20	theo	II	J.P. Lansberg	30 %
DPhN	**postdoc P2IO**	T1–21 - T4–22	ex	**III**,I	M. Winn	100%
	postdoc P2IO	T2–20 - T1–23	ex	**IV**,I	F. Bossu	100%
	PhD	T1–20 - T3–22	ex	I	M. Winn	50 %
	PhD	T1–20 - T3–22	ex	III	J. Castillo	50 %
LAL	**postdoc P2IO**	T2–20 - T1–23	ex	**IV**,III	P. Robbe	100%
LLR	**postdoc P2IO**	T1–22 - T1–22	ex	III	M. Ngyuen	100%
	postdoc P2IO	T1–21 - T1–22	ex	**III**, IV	F. Fleuret	100%
LPT	**postdoc P2IO**	T1–21 - T4–22	theo	I	S. Wallon	100%

Table 3: The list of involved non-permanent personal at the P2IO Laboratories including requested personal in bold.

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Delivrable	Milestone	Finalisation
nucleon-ex 1	preliminary result: DVCS BSA proton	T4–2022
nucleon-ex 1	data-taking: CLAS12	T1–2023
nucleon-ex 1	publication: DVCS CLAS12	T2–2023
nucleon-ex 2	data taking: NPS in Hall C	T1–2022
nucleon-ex 2	publication: Hall C data	T4–2023
nucleon-ex 3	feasibility: incoh. J/ψ pPb UPC	T2–2021
nucleon-ex 3	publication: UPC J/ψ pPb Run 2	T2–2022
nucleon-theo 1	publications: LO processes	T1–2021
nucleon-theo 1	publications: NLO & CGC LO	T4–T021
nucleon-theo 2	publication: phenomenology	T2–T022
nucleon-theo 2	publications: power corrections	T1–2023
nucleon-theo 2	publication: NLO/CGC integration in PARTONS/NLOAccess & feasibility CLAS12/LHC/EIC	T4–T023
nucleus-ex 1	publication: PbPb forward rapidity low-p_T J/ψ excess polarization (Run2 + potentially Run3)	T1–2022
nucleus-ex 1	publication: Excess for other quarkonia and J/ψ excess in most central PbPb collisons (Run 3)	T1–2023
nucleus-ex 2	software dev. & feasibility, potential publication of semi-forward low-p_T J/ψ excess	T1-2022
nucleus-ex 2	publication: low-p_T J/ψ excess at midrapidity as function of centrality, t-slope	T3–2023
uni-space 1	publication: eccentricity fluctuations in small systems	T4–2020
uni-space 1	publication: small-systems hydro with GPD input	T4–2021
uni-space 2	publication: Wigner distribution from dipole cascade	T4–2022
uni-space 2	publication: anisotropies of particle production in small systems	T4–2023
uni-time 1	publication: CGC energy-momentum tensor with GPDs	T4–2020
uni-time 1	publication: longitudinal correlations and conserved charges/p_T fluctuations	T2–2021
uni-time 1	publication and code: 3D model	T4–2021
uni-time 2	publication: energy density/particle production correlation in CGC	T4–2021
uni-time 2	publication: high-pt v_2 with soft/hard correlation	T4–2022
uni-tools 1	software: access via NLOAccess to codes for the project	T3–2020
uni-tools 1	software: projects codes online in NLOAccess	T4–2023
uni-tools 2	software: interface between GPD models in PARTONS and uni-space 1 & open source access to fit results on 3D nucleon structure	T4–2021
uni-tools 2	software: GPD and TMD models from Wigner distributions & inclusion in PARTONS of project codes	T4–2023
force-collider 1	software development: for Run 3	T2–2021
force-collider 1	preliminary result: non-prompt J/ψ PbPb	T2–2022
force-collider 1	publication: Υ/(non-prompt J/ψ) PbPb	T4–2022
force-collider 2	feasibility: DY/B_c	T4–2021
force-collider 2	publication: DY or B_c	T4–2023
force-fixed-target 2	data taking: proton-nucleus 2021	T3–2021
force-fixed-target 2	data taking: Pb-nucleus 2021	T4–2021
force-fixed-target 2	publication: charm production with Run 2 data	T2–2021
force-fixed-target 2	publication: charm production with Run 3 data	T4–2022
radiation 1	data taking: PbPb 2021	T4–2021
radiation 1	publication: 2021 data	T4–2022
hh-collider 1	software development: simulation set-up for heavy-ion conditions	T4–2020
hh-collider 1	optimisation: detector layout heavy-ions in HL-LHC phase	T4–2021
hh-collider 1	framework TDR: contribution calorimeters LHCb Upgrade 2	T4–2021
hh-collider 2	realistic heavy-ion simulations for LHCb Upgrade 2	T1–2022
eh-collider 1	requirement definition TPC	T2–2020
eh-collider 1	design choices: for TPC and optimisation for CDR	T2–2021
eh-collider 2	realistic simulations for exclusive reactions at the EIC	T2–2021

Table 4: Detailed overview of milestones for the different delivrables.

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WP		Institutes	Contact	budget/kEuro
Geometry	nucleon-ex	**IPNO**, DPhN	C. Muñoz	55
Geometry	nucleon-theo	**LPT**, DPhN, CPHT	S. Wallon	110
Geometry	nucleus-ex	**IPNO**, DPhN, IPhT	L. Massacrier	110
Unification	uni-space	**CPHT**, LPT, IPhT	C. Marquet	110
Unification	uni-time	**IPhT** CPHT	J.-Y. Ollitrault	110
Unification	uni-tools	**IPNO**, **DPhN**	J.-P. Lansberg & H. Moutarde	20+20
Unification	cross education	**CPHT**, **DPhN**, **IPhT**, **IPNO**, **LLR**	C. Marquet & M. Winn	3+3
Gluometer	force-collider	**DPhN**, IPhT, LLR, IPNO	M. Winn	110
Gluometer	force-fixed-target	**LLR**, LAL, IPNO	F. Fleuret	55
Gluometer	radiation	**LLR**, IPhT	M. Nguyen	55
Future	hh collider	**LAL**, LLR, DPhN	P. Robbe	120
Future	e-h collider	**DPhN**, IPNO	F. Bossu	110
Future	conf./workshops	**CPHT**, **DPhN** & all	C. Marquet & M. Winn	10+10

Table 5: Financial requirements for the project with topical structure.

Site	Institute	Purpose	Budget/kEuro	Institute sum
Orsay	IPNO	personal support NLOAccess	165 20	185
	LAL	personal hardware	110 10	120
	LPT	personal	110	110
Saclay	IPhT	personal	110	110
	Irfu/DPhN	personal support PARTONS conference/workshops lectures	220 20 10 3	253
Palaiseau	CPHT	personal conference/workshops lectures	110 10 3	123
	LLR	personal	110	110

Table 6: Financial requirements per institute and site. The total budget amounts to 1,011,000 Euros.

CPHT

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DIRECTION DE LA RECHERCHE FONDAMENTALE
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C.E.A.

IPNO

Michel GUIDAL
Directeur
INSTITUT DE PHYSIQUE NUCLEAIRE D'ORSAY

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LLR

Irfu/DPhN

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Chef du Département
de Physique Nucléaire

LAL

Fabien CAVALIER
Directeur par intérim
Laboratoire de l'Accélérateur Linéaire

LLR

LPT

Sébastien DESCOTES-GENON
Directeur du LPT
ORSAY