IN2P3 Prospective 2020 - GT01 Group Lattice QCD contribution

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Abstract

We present hereafter a small review of the recent progress made by the lattice QCD community followed by a brief description of the different physics topics which could be considered in the future at the IN2P3.

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Context

QCD is the theory of the strong interaction. Its perturbative regime has been extensively studied for many years. However, with the current development of accelerators as well as the theoretical advances in the field, the study of the non-perturbative sector has become mandatory. For instance, many observables theoretically predicted from the Standard Model (SM) encode non-perturbative QCD effects. In addition, the precision related to these non-perturbative effects needs to be controlled in the best possible way, so that the quantitative measurements derived from the experimental data do not suffer from the corresponding theoretical errors which are often the main source of uncertainty nowadays[1]. This can have consequences for Physics beyond the SM searches because should deviations with respect to the SM be observed, classes of new phenomenological models that are compatible with the pattern of deviations can be singled out.

Past achievements

Lattice QCD (LQCD) is the only method currently known to treat QCD from its first principles. By discretizing space-time in a finite volume, it allows performing non perturbative calculations *ab initio*. However, these simulations require heavy computing power.

Over the past ten years, remarkable progress has been accomplished, which is the result of improvements in the algorithms and in the power of the computers at our disposal. We can now take into account u/d quarks as well as s and c quarks in the sea (dynamical quarks). We can include, in our simulations, strong and electromagnetic effects of the isospin symmetry breaking. The predictions have become more realistic, and control over the errors has increased. A wide range of observables have been computed: hadron masses, decay constants, form factors, mixing parameters which characterize weak-decay amplitudes, PDFs, quark masses, etc. As an example, LQCD provides the heavy flavour decay constants for the D, D_s, B and B_s mesons with sub percent precision, and the most precise determination of α_s.

Prospects and opportunities for LQCD

In the years to come, important theoretical improvements in LQCD are expected, which will have a strong impact on the precision of the computed observables. On the numerical side, these include a significant decrease of the statistical errors coming from the simulations on the lattice and the possibility to perform all the necessary extrapolations (i.e. taking the volume of the lattice to infinity and the lattice spacing to zero). On the physics side, these include the possibility to simulate b quarks on the lattice, to work with a pion at its physical mass, to take into account disconnected contributions, to include electromagnetic corrections, to devise methods to study inclusive processes, to deal with states containing several hadrons, etc.

The French LQCD community can contribute to the following topics, of paramount importance for LQCD as well as for particle physics in general:

[1] A striking example comes from the "$g-2$" anomalous magnetic moment of the muon where the discrepancy around $3.5\,\sigma$ between theory and experiment can be reduced in half through the hadronic theoretical uncertainty, which is estimated most satisfyingly in Lattice QCD.

(1) B physics: this domain of research can be performed in close connection with experimentalists from the LHCb experiment or the Belle 2 experiment. Several directions can be considered: the first one concerns the so-called $b \to c$ anomalies, namely the study on the lattice of the ratios $R_{D^{(*)}_{(s)}}$, $R_{J/\psi}$ and R_{Λ_b}. The second one is motivated by the persistent tension in the CKM matrix elements V_{cb} and V_{ub} which requires some further efforts to extract the form factors associated with particular $b \to c$ decays, $B \to \pi$ and $B_s \to K$ decays. A third possible direction can be the study of bottomium $b\bar{b}$ states since they constitute an interesting probe for the dynamics of the strong interaction and can provide constraints for some BSM scenarios.

(2) $g-2$ of the muon: experiments at Fermilab and at J-PARC aim at reducing the error on a_μ by a factor 4. Hence, in order to stay competitive with those experiments, the theoretical uncertainties on the hadronic contributions (such as hadron vacuum polarization, or hadron light-by-light scattering) need to be controlled and reduced by a factor of order 10, which is achievable within the LQCD framework.

(3) Hadron structure: parton distribution functions (PDF), generalised parton distribution functions (GPDF) and distribution amplitudes of nucleons and light mesons will be under deep investigation in future experiments at J-Lab (JLEIC). Hence, theoretical work on the computation on the lattice of these distribution functions will be complementary to the experimental effort in region of the parameter space where the latter has a poor sensibility (for instance at large x-Bjorken).

(4) Neutron Electric Dipole Moment: with an upper bound of around

$$|d_n| < 3 \times 10^{-26}\, e \cdot \mathrm{cm} \qquad (90\%\ \mathrm{C.L.})$$

it is often considered as a particularly stringent constraint on New Physics scenarios. Its SM contribution is mediated by the strong CP-violating term $F\tilde{F}$ or, in other words, the topological charge. Its estimates from lattice simulations is quite challenging but, thanks to recent theoretical developments to circumvent the computation of severe divergent terms, there is good hope to remain competitive with respect to the new experiment led at nEDM@PSI.

(5) Higgs Physics and PDFs: for processes involving hadron initial states (as in pp collisions), a complete high-precision determination of the PDFs, is a crucial input to high-energy measurements in the Higgs sector and for the computation of multi-TeV SM and BSM cross sections.

(6) Algorithmic aspects: large volume simulations need extremely large computer time, for instance several hundred million core hours on Tier-0 and Tier-1 high-performance computing systems. Developing, with the aid of mathematicians or computer engineers, new paradigms is potentially mandatory in order to optimize the cost of acceptance/rejection test in hybrid Monte-Carlo algorithms. A typical example is the release of detailed balance in favour of global balance as advocated to study systems of interacting hard spheres.

Infrastructure

Parts of this program could be undertaken within INP2P3. Indeed, the CC-IN2P3 offers facitilities of outstanding quality to transfer and store the amount of data available to the French lattice QCD community. It also provides computer nodes that are convenient to analyse simulations of intermediate scales, i.e. lattice volumes up to $32^3 \times 64$. For larger simulations, the computing power is made available through calls by the *Grand Équipement National pour le Calcul Intensif* (GENCI).