QED Corrections to Hadron Physics

Towards QCD+QED Simulations with C* Boundary Conditions at physical QED coupling

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In Short

- Hadron physics at (sub)percent precision
- Electromagnetic corrections
- C* boundary conditions in finite volume
- Simulations of Lattice Chromodynamics and Electrodynamics
- `openQ*D` simulation code

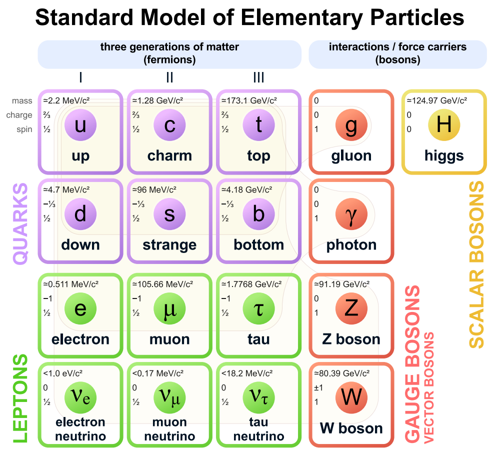

Figure 1: *By MissMJ - Own work by uploader, PBS NOVA, Fermilab, Office of Science, United States Department of Energy, Particle Data Group, Public Domain,* `https://commons.wikimedia.org/w/index.php?curid=4286964`.

The grand goal of Particle Physics is to understand what the Universe is made of, at its smallest and most elementary level. Elementary particles are the building blocks of all matter, including owr own body. Even though ordinary matter around us comes with an incredible variety of forms and properties, when looking very closely, one realizes that it is actually made only of a handful of components. The list of all elementary particles is shown in figure 1, and their properties and behaviour is described by a theory called *Standard Model*. The discovery of the Higgs boson in 2012 represented a great success for the Standard Model and for our understanding of Nature at its most fundamental level. However our knowledge is far from complete. For instance we know that a very abundant form of matter exists in the Universe, the *dark matter*, which is not described by the Standard Model. Its name comes from the fact that dark matter have never been observed directly, however the indirect effects of its existence are apparent in a large number of astrophysical observation. The existence of dark matter itself implies that the Standard Model is not the whole story, and must show cracks if one looks close enough. In order to do this, physicists need very precise experiments but also very detailed understanding of the Standard Model.

This project focuses on a particular sector of the Standard Model, i.e. *Quantum Chromodynamics*, which studies *quarks* and *gluons*. These elementary particles interact in a very complicated way and form a large variety of composite particles, called *hadrons*. Protons and neutrons are examples of hadrons. The long-term goal of this study is to understand the properties of hadrons at very high level of precision.

Electromagnetic interactions, which are due to exchange of photons between quarks, produce small effects in hadron physics. However these corrections become phenomenologically relevant when the target precision is at the percent level. By using Lattice QCD+QED (see figure 2), a particular formulation of Quantum Chromodynamics and Electrodynamics, it is possible to use computer simulations to calculate these small effects. The details of the setup that will be used in the proposed simulations can be found in [1]. Lattice simulations are articulated in three main steps: *(1)* choose (or tune) the parameters of the simulations, *(2)* generate the configurations of the fields describing gluons and photons, *(3)* calculate physical observables. This pioneering project is focused on the first two steps. In order to generate

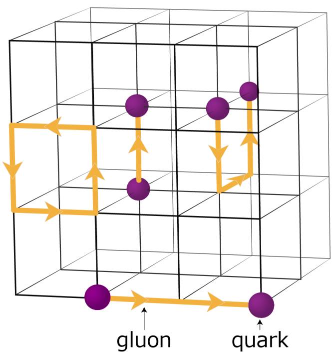

Figure 2: *By Guido Cossu. Lattice QCD+QED is a particular formulation of Quantum Chromodynamics and Electrodynamics, which is based on the idea to replace the continuous spacetime with a lattice, as in a crystal.*

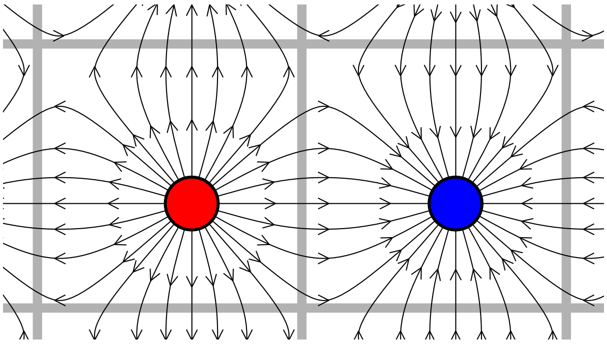

Figure 3: *Pictorial representation of C⋆ boundary conditions. The two grey squares represent two copies of the torus. Particles in one copy of the torus are replaced by their own antiparticles in the other copy.*

the field configurations, we will used the publicly-available openQ∗D simulation code [2], which has been developed by the RC⋆ collaboration. Several team members are also developers of the openQ∗D code.

Going a bit more technical, the signature and innovative ingredient of our project is the use of C⋆ boundary conditions, which are illustrated in figure 3. Roughly speaking, the system lives on a torus, and whenever a particle travels around the torus, it is replaced by its antiparticle. C⋆ boundary conditions allow for a local and gauge-invariant formulation of QED in finite volume and in the charged sector of the theory. See [4] for a comparison with other available methods. The proposes project is the first part of a long-term research programme aiming at generating QCD+QED configurations, and at using them to calculate physical observables (c.f. [5]) for a discussion of how to calculate hadron masses in this setup). Since electromagnetic effects are very small, we simulate at unphysically large value of the fine-structure constant, which controls the interaction strength between the photon and any charged particle, and in particular quarks. This strategy has been also successfully used by other collaborations [6,7], and it has the effect to amplify isospin-breaking corrections. Real-world observables are ultimately obtained by interpolation to the physical value of fine-structure constant. On the gauge configuration generated, we are calculate the masses of a number of hadrons, such as proton, neutron, charged pion, charged and neutral kaons, D mesons, Ω^- baryons [8,9].

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More Information

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[2] RC⋆ collaboration, openQ∗D simulation code for QCD+QED with C⋆ boundary conditions. GitLab: https://gitlab.com/rcstar/openQxD. CSIC: https://dx.doi.org/10.20350/digitalCSIC/8591.

[3] RC⋆ collaboration, I. Campos, P. Fritzsch, M. Hansen, M. K. Marinkovic, A. Patella, A. Ramos et al., http://arxiv.org/abs/1908.11673.

[4] A. Patella, *PoS* **LATTICE2016** (2017) 020. http://arxiv.org/abs/1702.03857.

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[8] RC⋆ collaboration, J. Luecke et al., *PoS Lattice2021* (2022), 293. http://dx.doi.org/10.22323/1.396.0293.

[9] RC⋆ collaboration, M. E. B. Dale, L. Bushnaq, I. Campos, M. Catillo, A. Cotellucci, P. Fritzsch, J. Lücke, M. K. Marinković, A. Patella and N. Tantalo, *PoS Lattice2021* (2022), 373. http://dx.doi.org/10.22323/1.396.0373.

Project Partners

DESY, Zeuthen, Germany — Dipartimento di Fisica, Università di Roma Tor Vergata, Italy — Institut für Theoretische Physik, ETH Zürich, Switzerland — Instituto de Física de Cantabria & IFCA-CSIC, Spain — IRIS Adlershof, Humboldt-Universität zu Berlin, Germany — School of Mathematics, Trinity College Dublin, Ireland — Sezione di Tor Vergata, INFN, Italy.

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