Electromagnetic corrections to baryon masses

Baryon masses with C-periodic boundary conditions

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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

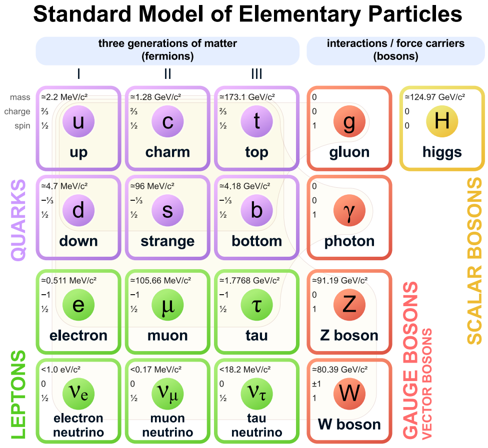

Figure 1: *By MissMJ - Own work by uploader, PBS NOVA, Fermilab, Office of Science, United States Department of Energy, Particle Data Group, Public Domain,* `https://commons.wikimedia.org/w/index.php?curid=4286964`.

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 our 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, *(3)* calculate physical observables. This project is focuses on the third step, in particular on measuring the masses

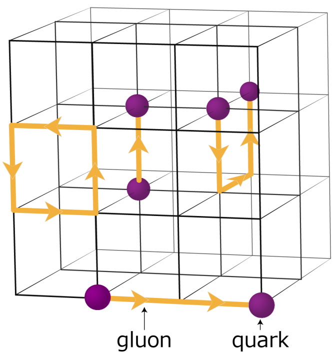

Figure 2: *By Guido Cossu. Lattice QCD+QED is a particular formulation of Quantum Chromodynamics and Electrodynamics, which is based on the idea to replace the continuous spacetime with a lattice, as in a crystal.*

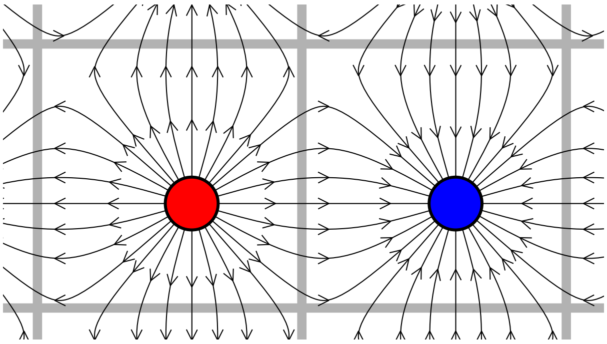

Figure 3: *Pictorial representation of C⋆ boundary conditions. The two grey squares represent two copies of the torus. Particles in one copy of the torus are replaced by their own antiparticles in the other copy.*

of a specific class of hadrons: baryons, such as the proton and the neutron, characterised by being composed by three valence quarks. These results will be obtained with field configurations generated with 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.
This project is part of a long-term research program aiming at calculating isospin-breaking and electromagnetic corrections in hadronic quantities from first principles in lattice QCD+QED [5], these corrections in the case of baryons cause slight shifts in their masses. For example, the proton is slightly lighter than the neutron, due to a combination of these isospin-breaking effects and the electromagnetic self energy of the positively charged proton. These corrections are essential in precision measurements of these masses and we plan to investigate their effects in our project.

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More Information

[1] B. Lucini, A. Patella, A. Ramos and N. Tantalo, *JHEP* **02** (2016) 076. http://arxiv.org/abs/1509.01636

[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.

[5] RC⋆ collaboration, L. Bushnaq *et al.*, *JHEP* **03** (2023) 012 https://dx.doi.org/10.1007/JHEP03(2023)012

[6] RM123 collaboration, de Divitiis *et al.*, *Phys. Rev. D* 85 11 114505 (2013).http://dx.doi.org/10.1103/PhysRevD.87.114505

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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