Understanding the Properties and Stability of Matter

Flavor Physics from the Lattice

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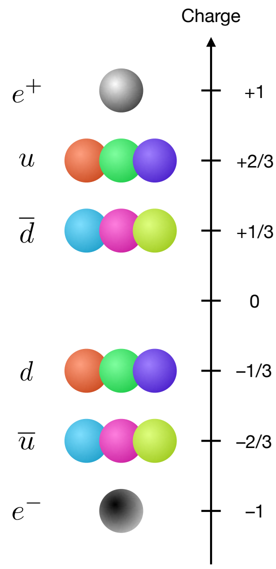
In Short

- The best established theoretical tool to study the low-energy properties of QCD is through the formulation of lattice-regularized QCD and QED and numerical simulations
- Recent progress now allowed us to study the fundamental properties of matter from first principles and make important advances in fundamental aspects of electromagnetism in particle physics
- Quarks are the only fundamental particles that communicate with both the electromagnetic and strong forces. This project will exploit this communication channel and break new ground in the computation of the hitherto unknown electromagnetic contributions to physical observables to confront forth-coming experiments in the precision era.

The current understanding of nature describes four fundamental forces: gravity, electromagnetism, the strong nuclear force and the weak nuclear force. At different length scales, each of these forces has a domain where it is most relevant. Over very large distances, such as celestial mechanics, gravitational forces dominate; at more familiar distance scales, day-to-day objects take their form from electromagnetic interactions and this is the dominant force down to the scale of individual atoms; at the core of atoms are nuclei whose structure are governed by the strong force; finally, at a much shorter distance scale operates the weak nuclear force, including those interactions associated with the Higgs boson. While this distance scale provides a useful characterisation, these forces do not act in isolation of one another and contemporary problems at the fore of the field demand an understanding of their interplay. This proposal will develop an understanding of the transition region between the electromagnetic and strong interaction forces and create new knowledge on the manner in which these forces respond and coalesce.

The three smallest-scale forces are together understood to emerge out of the fundamental interactions of quantum field theory. The elementary constituents of the strong nuclear force are quarks and gluons, which themselves bind together to form the familiar building blocks of nuclear physics, protons and neutrons. The interactions between the elementary quarks and gluons are described by the fundamental relativistic quantum field theory of Quantum Chromodynamics (QCD).

In the standard model of particle physics, the form of these interactions is encoded purely in terms of the symmetries of the elementary fields. With the symmetries classified and the relevant parameters measured, tremendous precision has been achieved in testing the limits of the standard model.



Electromagnetism is understood in terms of Quantum Electrodynamics (QED) which describes the interactions between electrically charged particles (see diagram at left) and photons. The frontiers of experimental measurement and theoretical calculation have successfully tested this theory to better than *parts-per-billion* accuracy. Describing nature to this level of precision is a tremendous feat for humanity.

Owing to the difficulty of performing QCD calculations, the strong force of QCD has not been tested to anywhere near the same degree as QED. Nevertheless, recent progress has seen the theoretical first-principles value for the proton mass – computed from the energy of QCD via Einstein's famous $m = E/c^2$ equation – agree with experiment at an unprecedented accuracy of 2% [1].

The present proposal will address this demand to confront the boundaries of the mathematical description of nature. The study of the dynamically-coupled theories of the strong interactions and the electromagnetic interactions is required. It is performed through the simultaneous simulation of QCD and QED coupled through the electric charge of the quarks appearing in the non-trivial vacuum fields.

For the calculation of hadron masses and matrix elements we follow the program outlined in [2] originally for QCD, and extended to include electromagnetic interactions in [3,4]. This procedure leads us to highly constrained polynomials in the masses and charges of the quarks, which provides us with

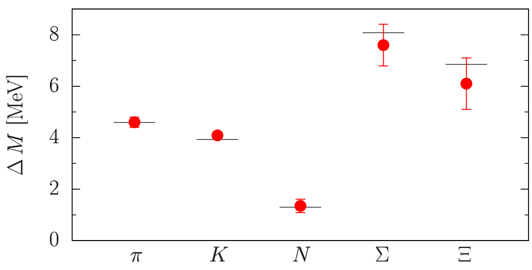


Figure 1: *Mass splittings ΔM of octet pseudoscalar meson and baryon masses compared to experiment.*

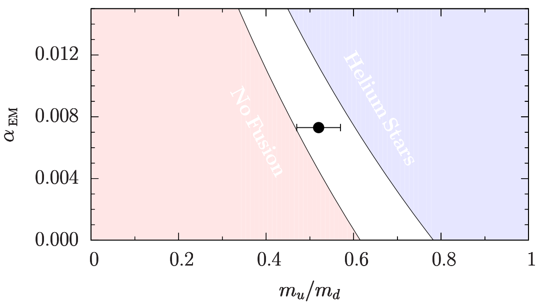


Figure 2: *The allowed ratio of quark masses m_u/m_d against α_{EM}. The solid circle is our result in the $\overline{MS}$ scheme. The region of no fusion is to the left, the region where all hydrogen is converted to helium stars is to the right.*

invaluable information on the pattern of flavor and isospin symmetry breaking. A highlight of our calculations is the evaluation of isospin breaking in the pseudoscalar meson and octet baryon masses. The results are shown in Fig. 1. Good agreement with experiment is found.

Isospin breaking effects are crucial for the existence of our Universe. Our Universe would not exist in the present form if the neutron – proton mass difference would only be slightly different. If it would be larger than the binding energy of the deuteron, no fusion would take place. If it would be a little smaller, all hydrogen would have been burned to helium. Having analytic expressions for the masses of the neutron and proton we can express the allowed region in terms of the fundamental parameters m_u, m_d and α_{EM}, as shown in the right plot of Fig. 2. Not shown are the bounds on α_{EM} from the stability of atoms. It turns out that both α_{EM} and the ratio of light quark masses m_u/m_d are finely tuned. At the physical fine structure constant the ratio is restricted to a narrow region around $m_u/m_d = 0.5$.

One of the few places where tension lies between experiment and the standard model predictions is in the anomalous magnetic moment of the muon, $a_\mu = (g-2)_\mu/2$, where a $3.5\,\sigma$ discrepancy is driving attention. At present, the experimental [5] uncertainty (depicted in Fig. 3 by the BNL line) and the total theoretical uncertainties (blue bars) are of comparable magnitude. The planned Muon $g-2$ Experiment at Fermilab aims to reduce the experimental uncertainty to 140 parts-ber-billion, as indicated in the figure. Thus it is essential to get the theoretical uncertainties down to a comparable precision — this will require the "hadronic vacuum polarisation" (HVP) contributions to be known to better than 0.5%. Reaching this target demands the inclusion of QCD + QED effects to properly understand how the behaviour of quarks are modified when their electric charges are turned on. Having the timely advantage of state-of-the-art ensembles of fully dynamical QCD + QED gauge field configurations, this proposal will produce a detailed account of this *essential* correction.

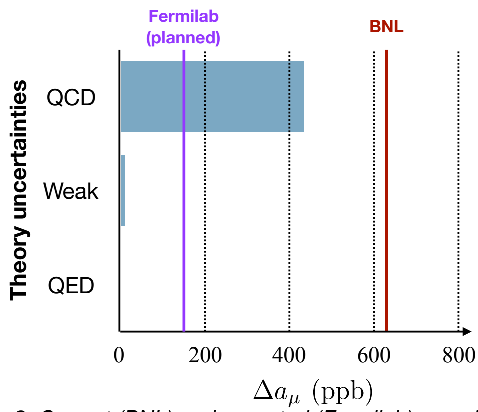


Figure 3: *Current (BNL) and expected (Fermilab) experimental uncertainties for the anomalous magnetic moment of the muon compared with the three sources of uncertainty in the theoretical Standard Model determination.*

This flyer gives only a short impression of the present state of the calculations. For more details the reader is referred to the original work of the collaboration.

More Information

[1] S. Durr *et al.*, *Science* **322** (2008) 1224 doi: 10.1126/science.1163233

[2] W. Bietenholz *et al.*, *Phys. Rev.* **D84** (2011) 054509 doi:10.1103/PhysRevD.84.054509

[3] R. Horsley *et al.*, *JHEP* **1604** (2016) 093 doi: 10.1007/JHEP04(2016)093

[4] R. Horsley *et al.*, *J. Phys. G* **43** (2016) 10LT02 doi:10.1088/0954-3899/43/10/10LT02

[5] G. W. Bennett *et al.* [Muon g-2 Collaboration], *Phys. Rev.* **D73** (2006) 072003 doi: 10.1103/PhysRevD.73.072003

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