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# Some results from full 2+1 flavor simulations of QCD

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The MILC collaboration has been performing realistic simulations of QCD with 2+1 flavors of quarks. Our simulations allow for controlled continuum and chiral extrapolations. Here I present results for the light pseudoscalar sector: masses and decay constants, quark masses and Gasser-Leutwyler low-energy constants. I will also present some results for heavy-light mesons, decay constants and semileptonic form factors, obtained in collaboration with the HPQCD and Fermilab collaborations.

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## 1. Introduction

It has been a long standing goal to perform nonperturbative simulations of QCD with the effects of the three light quark flavors fully included. The MILC collaboration has made significant advances towards this goal. Employing an improved staggered formalism, so-called "asqtad" fermions [1], simulations with the light $u$ and $d$ quarks, taken to be of equal mass, as light as $1/8$ of the physical strange quark mass $m_s$ have been achieved [2], while the mass of a third quark flavor has been kept close to the strange quark mass. These simulations have been done – some are still being continued – mainly at two lattice spacings of about $a = 0.12$ fm and $a = 0.09$ fm. Some simulations also used a coarser lattice spacing, $a = 0.18$ fm. Multiple lattice spacings are needed to control the extrapolation to the continuum limit, $a \to 0$.

All gauge field ensembles created by the MILC collaboration are made available to other researchers at the "NERSC Gauge Connection". They have been used, for example, by the Fermilab, HPQCD and UKQCD collaborations for the study of heavy quarkonia and heavy–light mesons. The four collaborations joined efforts to validate these QCD simulations by comparing selected, so-called "gold-plated", *i.e.* well controlled, quantities computed on the lattice with their experimentally well known values. Agreement within errors of 1–3% was found [3].

While we have made simulations with lighter u and d quark masses (with $m_u = m_d = m_l$) than have been reached before, simulations at the physical light quark mass value has not been possible so far even with our improved "asqtad" quarks. Hence chiral extrapolations – extrapolations in the light quark mass – are needed to reach the physical value. Due to the so-called taste symmetry breaking of staggered quarks at finite lattice spacings, for accurate extrapolations the chiral perturbation theory, $\chi$PT, had to be adapted to the staggered quark formalism (S$\chi$PT) [4].

A first set of accurate results for light pseudoscalars, from two lattice spacings, one simulation strange quark mass $m_s'$ and several simulation light quark masses $m_l'$, employing the S$\chi$PT formalism for joint chiral and continuums extrapolations, was published in 2004 [5]. There, results were presented for light pseudoscalar (pion and kaon) masses and decay constants, quark mass ratios, and for several Gasser-Leutwyler parameters of $\chi$PT. To obtain the quark masses themselves, one needs renormalization constants. The results, obtained with one-loop $Z$-factors computed by members of the HPQCD and UKQCD collaborations, were published in [6].[1]

During the last year, our simulations have been expanded in several ways. On the coarse, $a = 0.12$ fm lattice, a second simulation strange quark mass $m_s'$ has been used, allowing interpolation to the physical strange quark mass. On the fine, $a = 0.09$ fm, lattice a simulation with a lighter light quark mass, $m_l' \simeq 0.1 m_s$, has been started. This run is currently about 1/3 complete.

## 2. The light pseudoscalar sector

The S$\chi$PT fitting is illustrated in Fig. 1. From such fits we obtain the following (still preliminary) results for the decay constants:

$$f_\pi = 128.1 \pm 0.5 \pm 2.8 \text{ MeV}, \qquad f_K = 153.5 \pm 0.5 \pm 2.9 \text{ MeV}, \qquad f_K/f_\pi = 1.198(3)\left({}^{+16}_{-\ 5}\right),$$

[1]The largest uncertainty in the quark masses comes from the perturbative $Z$-factors. The computation has recently been extended to two-loops [7], reducing this error by about a factor of 2.

where the errors are from statistics and lattice systematics. With experimental data, the lattice QCD value of $f_K/f_\pi$ can be used to extract the CKM matrix element $V_{us}$ [8]. We obtain $V_{us} = 0.2242(^{+11}_{-31})$, with an accuracy comparable to the PDG value. For a more extensive discussion of the present state of our results in the pion and kaon sector see [9].

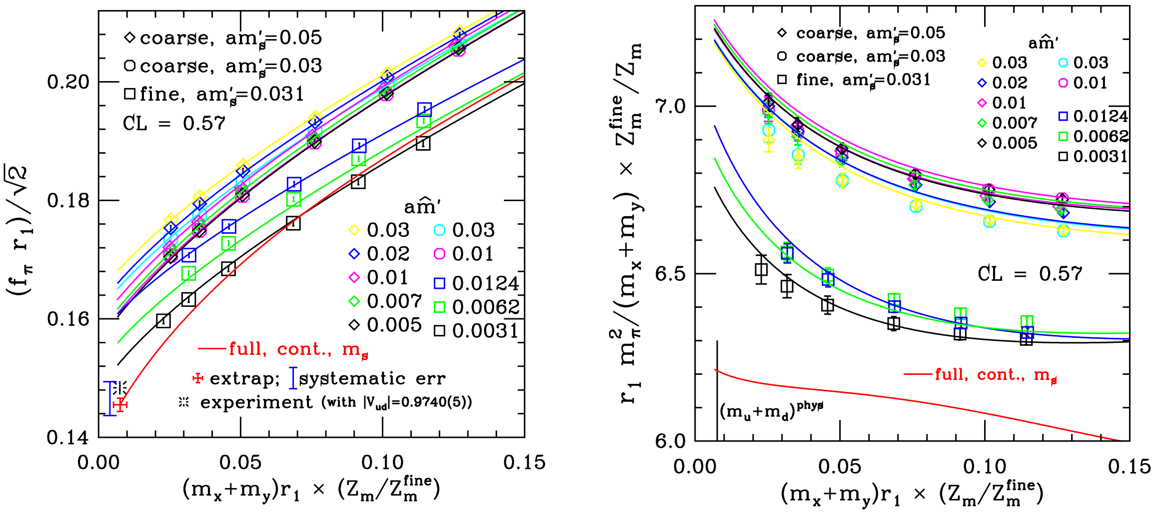


**Figure 1:** Illustration of S$\chi$PT fit showing full QCD points for $f_\pi$ (left) and $m_\pi^2/(m_x+m_y)$ (right). Also shown are the fits extrapolated to the continuum limit, and interpolated to the the physical value of the strange quark mass.

## 3. Heavy-light meson physics

In joint work with the Fermilab and HPQCD collaborations, we used our 2+1 flavor gauge field ensembles to study properties of heavy-light mesons. For the light valence quarks we used "asqtad" fermions, while for the heavy c and b quarks we used clover fermions with the so-called Fermilab interpretation [10]. The use of "asqtad" light fermions allowed us to go much closer to the physical light quark mass values than was achieved before, and use of S$\chi$PT made the remaining chiral extrapolation well controlled. We found [11]

$$f_{D^+} = 201 \pm 3 \pm 17 \text{ MeV}, \qquad f_{D_s} = 249 \pm 3 \pm 16 \text{ MeV}.$$

Our result for $f_{D^+}$ was a prediction, being made before CLEO-c announced its measurements $f_{D^+} = 223 \pm 17 \pm 3$ MeV [12].

We also computed the form factors for the semileptonic decays $D \to K l \nu$, $D \to \pi l \nu$ [13] and $B \to \pi l \nu$. The $B$-decay form factor is needed to extract the CKM matrix element $V_{ub}$ from experiment, while the $D$-decay form factors can be used for determinations of $V_{cs}$ and $V_{cd}$, or, since those CKM matrix elements are quite well determined, for a validation of the lattice QCD calculations. In Fig. 2 we show a comparison of our results with recent measurements by the FOCUS collaboration [14].

## 4. Conclusions

Our QCD simulations with 2+1 flavors of quarks have, with all errors well controlled, reached hitherto unprecedented accuracy for many quantities. This has pushed lattice QCD calculations to

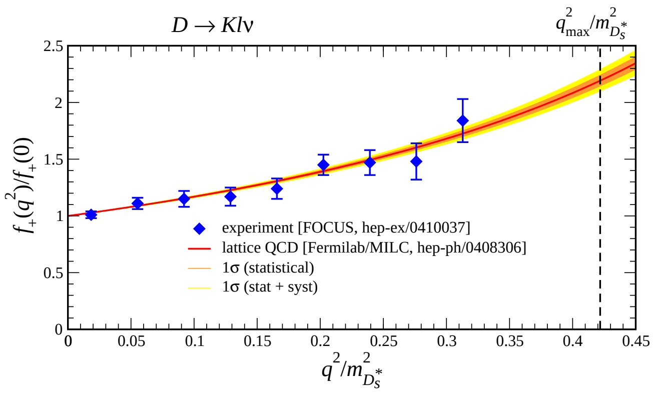


**Figure 2:** Comparison of the shape of the form factor $f_+(q^2)/f_+(0)$ with experiment [14].

the point where they can have an impact on current experimental physics programs, for example, in the determination of the CKM matrix. For a determination of the entire CKM matrix with lattice QCD, based on the MILC ensembles of gauge field configurations, as the only theoretical input see [15].

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