Lattice QCD calculation of neutral D-meson mixing matrix elements[†]

E. T. Neil[*1,*2] for the Fermilab Lattice and MILC Collaborations

The various weak decays of heavy quark flavors provide a stringent test of the electroweak sector of the Standard Model, and can be of great importance in constraining models of new physics beyond the Standard Model (BSM) which have non-trivial flavor structure.[1)] In order to interpret experimental results for these decays, it is essential to disentangle the electroweak or BSM effects of interest from the contributions due to the strong force (QCD). Lattice QCD provides a way to numerically calculate the required strong matrix elements at high precision and with full control of systematic effects.

We consider the process of mixing between the neutral D^0 and $\bar{D}^0$ mesons, which is not a decay but does involve flavor-changing weak processes (the charm quantum number changes by $\Delta C = 2$ units.) The presence of down-type quarks in Standard Model contributions to this process through box diagrams allows D mixing to provide unique and complementary information on potential new physics compared to kaon and bottom-quark mixing and decay. Furthermore, the contributions of bottom quarks to D mixing are highly suppressed, which in turn suppresses CP violation from the Standard Model; searches for CP violation in D mixing are therefore very sensitive to new physics.

Our calculation uses lattice gauge theory to compute the set of five QCD matrix elements $\mathcal{O}_1$ through $\mathcal{O}_5$ which contribute to D-mixing. We use a set of gauge ensembles generated by the MILC collaboration with $N_f = 2+1$ dynamical quarks, using the "asqtad" improved staggered fermion formulation and tadpole-improved Luscher-Weisz gauge action. We study 14 ensembles with different values for the lattice spacing a and average pion mass M_π^{RMS}; global fits using staggered chiral perturbation theory then allow us to extrapolate simultaneously to the physical quark mass point and the continuum limit.

Following a careful analysis of sources of systematic error, we obtain for the five matrix elements in the $\overline{\mathrm{MS}}$-NDR scheme at $\mu = 3$ GeV the values $\langle \mathcal{O}_1 \rangle = 0.0805(55)(16)$, $\langle \mathcal{O}_2 \rangle = -0.1561(70)(31)$, $\langle \mathcal{O}_3 \rangle = 0.0464(31)(9)$, $\langle \mathcal{O}_4 \rangle = 0.2747(129)(55)$, $\langle \mathcal{O}_5 \rangle = 0.1035(71)(21)$, where the first error bar shows the combined statistical and systematic error, and the second shows the estimated uncertainty due to quenching of the charm quark in our simulations.

We can apply our matrix element results to place constraints on models of new physics, using the experimental measurements[3)] of D-mixing. As an example, we consider a specific model[2)] in which the Higgs boson has flavor-violating couplings to quarks and leptons. Integrating out the Higgs field at low energy gives an effective Hamiltonian

$$\mathcal{H}^{\mathrm{NP}}_{\Delta C=2} = -\frac{Y_{uc}^{\star\,2}}{2m_h^2}\mathcal{O}_2 - \frac{Y_{cu}^2}{2m_h^2}\bar{\mathcal{O}}_2 - \frac{Y_{cu}Y_{uc}}{m_h^2}\mathcal{O}_4 \qquad (1)$$

where in front of the operators we show Wilson coefficients at the scale m_h. The Wilson coefficients are run down to a renormalization scale of 3 GeV at which our lattice QCD matrix elements are computed, and then used to convert to an experimental prediction for the D-mixing parameter x_{12} based on the size of the Yukawa couplings Y_{cu} and Y_{uc}. The resulting constraints are shown in Fig. 1.

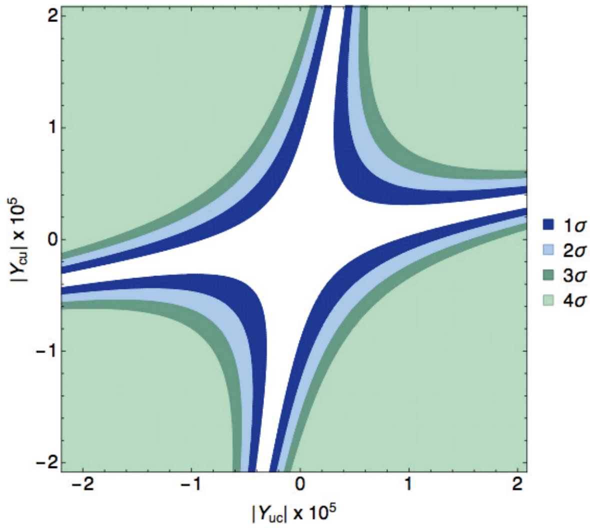

Fig. 1. Bounds on a specific model of new physics in which the Higgs has flavor-violating couplings,[2)] using recent experimental results on the complex D-mixing parameter x_{12}[3)] and our new lattice QCD results for the D-mixing matrix elements. Colored regions are excluded at the indicated statistical significance. Complex phases of the Yukawa couplings Y_{uc} and Y_{cu} are marginalized over.

References
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*1 RIKEN Nishina Center
*2 Department of Physics, University of Colorado, Boulder