Snowmass2021 - Letter of Interest

Unitarity of CKM Matrix, $|V_{ud}|$, Radiative Corrections and Semi-leptonic Form Factors

Topical Groups:

■ (EF04) EW Physics: EW Precision Physics and constraining new physics
■ (EF05) QCD and strong interactions:Precision QCD
■ (RF02) BSM: Weak decays of strange and light quarks
■ (RF03) Fundamental Physics in Small Experiments
■ (TF05) Lattice gauge theory
■ (CompF2) Theoretical Calculations and Simulation

Contact Information:
Rajan Gupta (Los Alamos National Laboratory) [rajan@lanl.gov]:
Vincenzo Cirigliano (Los Alamos National Laboratory) [cirigliano@lanl.gov]
Collaboration: Precision Neutron Decay Matrix Elements (PNDME) and Nucleon Matrix Elements (NME)

Authors:

Tanmoy Bhattacharya (Los Alamos National Laboratory) [tanmoy@lanl.gov]
Steven Clayton (Los Alamos National Laboratory) [sclayton@lanl.gov] Vincenzo Cirigliano (Los Alamos National Laboratory) [cirigliano@lanl.gov]
Rajan Gupta (Los Alamos National Laboratory) [rajan@lanl.gov]
Takeyasu Ito (Los Alamos National Laboratory) [ito@lanl.gov]
Yong-Chull Jang (Brookhaven National Laboratory) [ypj@bnl.gov]
Emanuele Mereghetti (Los Alamos National Laboratory) [emereghetti@lanl.gov]
Santanu Mondal (Los Alamos National Laboratory) [santanu@lanl.gov]
Sungwoo Park (Los Alamos National Laboratory) [sungwoo@lanl.gov]
Andrew Saunders (Los Alamos National Laboratory) [asaunders@lanl.gov]
Boram Yoon (Los Alamos National Laboratory) [boram@lanl.gov]
Albert Young (North Carolina State University) [aryoung@ncsu.edu]

Abstract: Exploring deviations from unitarity of the CKM matrix provides several probes of BSM physics. Many of these require calculating the matrix elements of the electroweak current between ground state mesons or nucleons, for which large scale simulations of lattice QCD provide the best systematically improvable method. This LOI focues on improvments in the precision with which the CKM element $|V_{ud}|$ can be extracted from neutron decay experiments coupled with lattice QCD calculations of the radiative corrections. The same lattice calculations will also provide results for semi-leptonic form factors and radiative corrections to kaon and D decays.

Motivation and Physics Goals The Standard Model (SM) synthesizes our knowledge of the workings of nature at its most fundamental level. Despite its many successes, the SM fails to account for dark energy, dark matter, and the observed matter-antimatter asymmetry in the Universe. This motivates the search for physics beyond the SM (BSM), both at high-energy colliders and through high-precision low-energy measurements that, through quantum corrections, probe new physics effects originating at energy scales far beyond the reach of present colliders. This LOI focuses on testing the unitarity of the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix by improving the precision of (i) the *up-down* quark mixing parameter $|V_{ud}|$ from neutron decay to $\delta V_{ud} \sim 2 \times 10^{-4}$ or better, and (ii) providing results for semi-leptonic form factors and radiative corrections for kaon and D decays.

SM predicts $\Delta_{\text{CKM}} \equiv |V_{ud}|^2+|V_{us}|^2+|V_{ub}|^2-1$ to be zero. $|V_{ud}|^2$ can be extracted from β decays of the pion, neutron, or nuclei. Currently, the most precise value of $|V_{ud}|^2 = 0.94907(43)$ comes from $0^+\to 0^+$ nuclear β decays[1], while $|V_{us}|^2 = 0.05031(22)$ is obtained from kaon decays ($K \to \pi e \bar{\nu}_e$, $K \to \mu \bar{\nu}_\mu$) and $|V_{ub}|^2 \approx (2 \pm 0.4) \times 10^{-5}$ has no impact on the unitarity test. The 2019 Particle Data Group (PDG) lists $\Delta_{\text{CKM}} = -(6 \pm 5) \times 10^{-4}$[1], an impressive check of the SM. A recent reanalysis of the *nuclear-structure-independent* radiative corrections (RC)[2;3], however, gives $\Delta_{\text{CKM}} = -(16 \pm 4) \times 10^{-4}$, a $4\,\sigma$ deviation from unitarity. Another work, using RC from Ref.[4] gives only a $2.8\,\sigma$ discrepancy, highlighting the strong model dependence of the theoretical uncertainties.

$|V_{ud}|$ from neutron decay is given by the master formula[4;5]

$$|V_{ud}|^2 = \left(\frac{G_\mu^2 m_e^5}{2\pi^3} f\right)^{-1} \frac{1}{\tau_n(1+3g_A^2)(1+\text{RC})} = \frac{5099.3(4)\text{s}}{\tau_n(1+3g_A^2)(1+\text{RC})} \tag{1}$$

where τ_n is free neutron lifetime, g_A is the axial coupling which can be obtained from the neutron β decay asymmetry parameter A, G_μ is the Fermi constant extracted from muon decays, and $f = 1.6887(1)$ is a phase space factor. To extract $|V_{ud}|$ from neutron decays at the precision level of $\delta V_{ud} \sim 2 \times 10^{-4}$ requires $\delta\tau_n \sim$ 0.05–0.1 sec and $\delta A/A \sim 0.1$ %, and the theoretical uncertainty in the nonperturbative component of radiative correction (RC) to $\leq 10\%$. This improved V_{ud} from neutron decay will have precision equal to that from nuclear β decays and be more reliable—free from uncontrolled nuclear theory systematic uncertainties.

To reach these milestones and go beyond, improvements are needed in each of the three components: (i) neutron lifetime experiment (UCNτ[6–8]) with uncertainty below the 0.1 s level[9]. (ii) UCN measurement of the β asymmetry A with a goal of $\delta A/A < 0.1\%$. Current experiments include polarized neutron decay (UCNA)[10] with the ultimate goal of $\delta A/A < 0.2\%$[11], Nab experiment[12], and the PERC experiment[13]. (iii) Calculation of RC to the neutron decay using lattice QCD to reduce the theoretical uncertainty.

Beta-decay experiments: A large component of the neutron fundamental symmetries research program worldwide involves beta decay measurements which can provide the value of $|V_{ud}|$ at the same precision level as the superallowed $0^+\to 0^+$ nuclear β decays, with the current status recently reviewed in Ref.[14]. This sensitivity level requires a precision of about 0.1% for angular correlation measurements and 0.25 s for the lifetime. There has been dramatic experimental progress over the past three years, with four new high precision measurements of the neutron lifetime[8;15–17] and three of the axial coupling constant[18–20]. The most precise neutron lifetime measurements (Serebrov[21] and UCNτ[22]) and g_A (PERKEO III[19]) are now within a factor of three of these goals. The value of V_{ud} extracted from neutron decay is $|V_{ud}| = 0.97374(68)$ using the PDG average for the lifetime, and including the measurement of Beck[20] in an average for g_A using PDG methodology. In the next five years, at least two angular correlations measurements, Nab[23] and PERC[13;24], and a number of lifetime experiments also target the desired level, with UCNτ poised to hit this precision with the current experimental data set. There are at least another four lifetime measurements using UCN storage experiments and one cold neutron beam experiment also targeting this precsion.

Radiative Corrections: The theoretical error in Eq. (1) is dominated by the uncertainty in the RC, which can be expressed as the sum of three terms[25]

$$\mathrm{RC} = \frac{\alpha_{\mathrm{em}}}{2\pi}\left\{\bar{g}(E_m) + 4\ln\frac{m_Z}{m_p} + \Delta_{\mathrm{np}}\right\}. \tag{2}$$

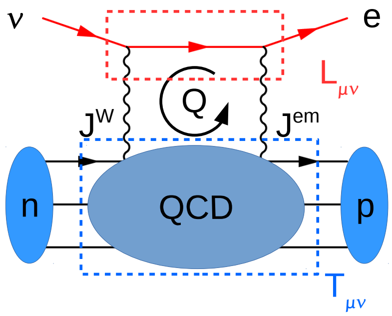

Figure 1: The γW box diagram of neutron decay mediated by J^W and radiative correction due to J^{em}. The "QCD" blob represents all possible corrections due to gluons and virtual quarks.

The first two terms dominate the RC but have very small uncertainties: $\bar{g}(E_m)$, where E_m is the electron endpoint energy, arises from the emission of soft photons, integrated over the allowed phase space, while $\ln(m_Z/m_p)$ encodes perturbative short-distance $\gamma - Z_{\mathrm{boson}}$ loop effects. Together they give 0.036, or about 95% of RC. Δ_{np}, the nonperturbative long distance effect, is comparatively small, $\alpha_{\mathrm{em}}\Delta_{\mathrm{np}}/(2\pi) \sim 0.002$, but its estimated uncertainty, $\sim 20\%$, dominates the theory error budget. Lattice QCD is the only known *controlled* method to determine Δ_{np} at the 10% level and to reach $\delta V_{ud} \leq 2\times 10^{-4}$. It is given by the product of the leptonic, $L^{\mu\nu}$, and the hadronic, $T_{\mu\nu}$, terms[2;26]

$$\Delta_{\mathrm{np}} = \int_0^{+\infty} dQ^2 \int_{-Q}^{Q} dQ_0 \frac{1}{Q^4}\frac{1}{Q^2+m_W^2} L^{\mu\nu}(Q,Q_0) T^{VA}_{\mu\nu}(Q,Q_0)\,, \tag{3}$$

integrated over the Euclidean four momentum Q in the γW-box shown in Fig. 1, with Q_0 the photon energy in the proton rest frame. The leptonic tensor $L^{\mu\nu}$ is a known function of the kinematic variables and weak couplings. The hadronic tensor $T^{\mu\nu}$ is the matrix element of the product of the axial current $J^{W,A}_\nu(0)$, responsible for the decay of the neutron, and the electromagnetic current $J^{em}_\mu(x)$ evaluated between the initial neutron and final proton states $N_{i/f}$

$$T^{VA}_{\mu\nu} = \frac{1}{2}\int d^4x\, e^{iQ\cdot x}\langle N_f(p)|T\left[J^{em}_\mu(0,0) J^{W,A}_\nu(\vec{x},t)\right]|N_i(p)\rangle\,. \tag{4}$$

The uncertainty in the integral over Q^2 in Eq. (3) is dominated by $T^{\mu\nu}$, especially at low Q^2, the regime in which QCD gives large corrections. The best estimates in the literature[2;4;27] combine robust theoretical information on the behavior of the integrand at $Q^2 \sim 0$, where it is determined by the nucleon elastic form factors, and at large $Q^2 \gtrsim (2\,\mathrm{GeV})^2$, where operator product expansion and perturbation theory are reliable. Proposed lattice QCD calculations will reduce the uncertainty in the problematic intermediate region, $0.1 < Q^2 < 2\,\mathrm{GeV}^2$, which is currently being *approximated*.

Lattice QCD calculations: To calculate the γW-box diagram in Fig. 1 requires evaluating the matrix element of the product of the weak axial and electromagnetic currents, $J^{W,A}_\nu$ and J^{em}_μ, separated in space and time by $(\vec{x},t)$, between nucleon states (see Eq. (4)). This is given by the sum of the four diagrams shown in Fig. 2. Current calculations of RC to kaon decays are promising[28] and extensions to neutron decays are underway. The calculation of semi-leptonic form factors for $|V_{cs}|$ and $|V_{us}|$ will be done synergistically.

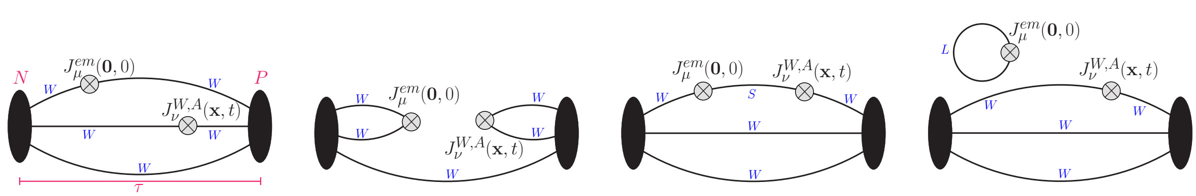

Figure 2: Four classes of connected (left three) and disconnected (rightmost) diagrams contribute to the γW-box diagram defined in Eq. (4). The figures illustrate only the weak process—quark lines (W, S and L type of quark propagators) connecting the neutron (N) and proton (P) states, separated by time τ, to the currents, J^{em} at locations $(0,0)$ and J^W at $(\vec{x},t)$. All possible gluons and virtual quark loops are implicit.

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