What’s the Matter with $V_{ud}$?

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Based on 3 papers:

arXiv: 1807.10197
arXiv: 1812.03352
arXiv: 1812.04229
Precision measurements of $V_{ud}$

Charged current interaction - $\beta$-decay ($\mu$, $\pi^{\pm}$, n)

$\mu^{-} \rightarrow e^{-} \nu_{e}$

$\pi^{\pm} \rightarrow \mu^{\pm} \nu_{\mu}$

$\nu$ (anti-$\nu$)

$W$ coupling to leptons and hadrons very close but not exactly the same:
quark mixing - Cabbibo-Kabayashi-Maskawa matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} = V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

CKM - Determines the relative strength of the weak CC interaction of quarks vs. that of leptons

CKM unitarity - measure of completeness of the SM: $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$
\[ |V_{ud}|^2 = 0.97420 \pm 0.00021 \]

From neutron decay
\[ |V_{ud}|^2 = \frac{5099.34 s}{\tau_n(1 + 3g_A^2)(1 + \Delta_R)} \]

From superallowed decays
\[ |V_{ud}|^2 = \frac{2984.43 s}{\mathcal{F} t(1 + \Delta_{VR}^V)} \]

\[
|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9994 \pm 0.0005
\]

CKM unitarity: \( V_{ud} \) the main contributor to the sum and to the uncertainty

\begin{align*}
0^{+}-0^{+} \text{ nuclear decays} & & |V_{ud}|^2 = 0.94906 \pm 0.00041 \\
\text{KI3 and KI2 average} & & |V_{us}|^2 = 0.05031 \pm 0.00022 \\
\text{B decays} & & |V_{ub}|^2 = 0.00002
\end{align*}
Why are superallowed decays special?

Superallowed 0\(^+\)-0\(^+\) nuclear decays:
- only conserved vector current (unlike the neutron decay and other mirror decays)
- many decays (unlike pion decay)
- all decay rates should be the same modulo phase space

Experiment: \( f \) - phase space (Q value) and \( t \) - partial half-life (\( t_{1/2} \), branching ratio)

- 8 cases with \( ft \)-values measured to <0.05% precision; 6 more cases with 0.05-0.3% precision.
- ~220 individual measurements with compatible precision

\( ft \) values: same within \( \sim 2\% \) but not exactly!
Reason: SU(2) slightly broken
a. RC (e.m. interaction does not conserve isospin)
   b. Nuclear WF are not SU(2) symmetric
      (proton and neutron distribution not the same)
Why are superallowed decays special?

\[ |V_{ud}|^2 = \frac{2984.432(3)}{\mathcal{F}t(1 + \Delta V_R)} \]

Modified \( ft \)-values to include these effects

\[ \mathcal{F}t = ft(1 + \delta'_R)[1 - (\delta_C - \delta_{NS})] \]

\( \delta'_R \) - "outer" correction (depends on e-energy) - QED

\( \delta_C \) - SU(2) breaking in the nuclear matrix elements
- mismatch of radial WF in parent-daughter
- mixing of different isospin states

\( \delta_{NS} \) - RC depending on the nuclear structure
\( \delta_C, \delta_{NS} \) - energy independent

Average

\[ \overline{\mathcal{F}t} = 3072.1 \pm 0.7 \]
Radiative corrections - “inner” and “outer”

Splitting inner-outer possible due to scales hierarchy: $m_e \leq E_e \ll \Lambda \sim m_\pi \ll M_n$

Outer: soft photon exchange and emission (QED + magnetic moment + charge radius)

Inner: everything else

$W,Z$-exchange: UV-sensitive, pQCD; model-independent

When $\gamma$ involved - sensitivity to long range physics $\rightarrow$ model-dependent

$V \times V$ correlator protected by CVC - no hadronic uncertainty

Axial vector not conserved $\rightarrow$ $A \times V$ correlator from $\gamma W$ box sensitive to hadron structure

$\gamma W$ box - the main source of the uncertainty

$$\Delta^V_R = 2 \square^A_{\gamma W} + \text{model independent}$$
\[
\Delta V^W_R = \frac{\alpha}{2\pi} \left[ \ln \frac{M_W}{\Lambda} + A_g + C^{Int} + 2C_B \right] 
\]

Marciano & Sirlin 2006

\[
\square V^A_{\gamma W} = \frac{\alpha_s}{8\pi} \int_0^\infty \frac{dQ^2 M_W^2}{M_W^2 + Q^2} F(Q^2)
\]

GLS and Bjorken SR to N3LO

Larin, Vermaseren 1997

Short distance: OPE

\[
F^{DIS}(Q^2) = \frac{1}{Q^2} \left[ 1 - \frac{\bar{\alpha}_s}{\pi} - C_2 \left( \frac{\bar{\alpha}_s}{\pi} \right)^2 - C_3 \left( \frac{\bar{\alpha}_s}{\pi} \right)^3 \right]
\]

Interpolate: VDM Ansatz

\[
F^{INT}(Q^2) = -\frac{1.490}{Q^2 + m_\rho^2} + \frac{6.855}{Q^2 + m_A^2} - \frac{4.414}{Q^2 + m_{\rho'}^2}
\]

Long distance: Born (axial and magnetic form factors)
V_{ud} and CKM unitarity in early 2018

\[ |V_{ud}|^2 = \frac{5099.34 s}{\tau_n (1 + 3 g_A^2)(1 + \Delta_R)} \]

\[ |V_{ud}|^2 = \frac{2984.43 s}{\mathcal{F} t (1 + \Delta_V^R)} \]

|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9994 \pm 0.0005

0^{+}-0^{+} nuclear decays

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KI3 and KI2 average

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B decays

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CKM unitarity: V_{ud} the main contributor to the sum and to the uncertainty
$V_{ud}$ and CKM unitarity in Fall 2018

Seng et al., 1807.10197

$V_{ud} = 0.97366 \pm 0.00015$

0$^+ \rightarrow 0^+$ nuclear decays
$|V_{ud}|^2 = 0.94801 \pm 0.00029$

$|V_{us}|^2 + |V_{us}|^2 + V_{ub}|^2 = 0.9979 \pm 0.0004$

$0^+ - 0^+$ nuclear mirrors
$|V_{us}|^2 = 0.04987 \pm 0.00027$

CKM unitarity: $V_{ud}$ und $V_{us}$ contribute equally to the uncertainty

Bazavov et al. (FNAL/MILC), 1809.02827
$V_{ud}$ and CKM unitarity in December 2018

Major improvement in exp. determination of $g_A$

**PDG2018**

**PERKEO-III**

Märkisch et al., 1812.04666

$g_A = -1.2723(23)$

$g_A = -1.2764(6)$

$V_{ud}$ from free neutron decay

$V_{ud} = 0.9763(5)\tau_n(15)g_A(2)_{RC} \quad \rightarrow \quad V_{ud} = 0.9735(5)\tau_n(3)g_A(1)_{RC}$

Revision of nuclear corrections to $0^+ - 0^+\text{-beta decay}$

Seng et al., 1812.03352; MG 1812.04229

$V_{ud} = 0.97366(10)\tau_n(3)g_A(1)_{RC} \quad \rightarrow \quad V_{ud} = 0.97366(32)\tau_n(3)g_A(1)_{RC}$

Free neutron decay becomes competitive;
Limitation: the lifetime (also, beam vs. bottle)

Scrutiny of nuclear corrections with new methods

Top-row unitarity: 2,5-3,5σ deficit

$\Delta_u = -(0.0016 - 0.0021) \pm 0.0006$

(depending on $V_{us}$)
\(\gamma W\)-box from Dispersion Relations

Box at zero momentum transfer* (but with energy dependence)

\[
T_{\gamma W} = \sqrt{2}e^2 G_F V_{ud} \int \frac{d^4q}{(2\pi)^4} \frac{\bar{u}_e \gamma^\mu (k - \not{q} + m_e) \gamma^\nu (1 - \gamma_5) u_\nu}{q^2[(k - q)^2 - m_e^2]} \frac{M_W^2}{q^2 - M_W^2} T_{\gamma W}^{\mu \nu}
\]

*Precision goal: \(10^{-4}\); RC \(\sim \alpha/2\pi \sim 10^{-3}\); recoil on top - negligible

Hadronic tensor: two-current correlator

\[
T_{\gamma W}^{\mu \nu} = \int dx e^{iqx} \langle f \mid T[J_{em}^\mu(x)J_{\gamma W}^{\nu,\pm}(0)] \mid i \rangle
\]

General gauge-invariant decomposition of a spin-independent tensor

\[
T_{\gamma W}^{\mu \nu} = \left( -g^{\mu \nu} + \frac{q^\mu q^\nu}{q^2} \right) T_1 + \frac{1}{(p \cdot q)} \left( p - \frac{(p \cdot q)}{q^2} q \right)^\mu \left( p - \frac{(p \cdot q)}{q^2} q \right)^\nu T_2 + \frac{i\epsilon^{\mu \nu \alpha \beta} p_\alpha q_\beta}{2(p \cdot q)} T_3
\]

Loop integral with generally unknown forward amplitudes

\[
T_{\gamma W} = -\frac{\alpha}{2\pi} G_F V_{ud} \int \frac{d^4q M_W^2}{q^2(M_W^2 - q^2)} \bar{u}_e \gamma_\beta(1 - \gamma_5) u_\nu \sum_i C_i^\beta(E, \nu, q^2) T_i^{\gamma W}(\nu, q^2)
\]

Known algebraic functions of external energy \(E\) and loop variables \(\nu, q^2\)

\[
p^\mu = (M, \vec{0}) \quad E = (pk)/M \quad \nu = (pq)/M
\]
**γW-box from Dispersion Relations**

T\(_{1,2,3}\) - analytic functions inside the contour C in the complex \(\nu\)-plane determined by their singularities on the real axis - poles + cuts

\[
T_i^{\gamma W}(\nu, Q^2) = \frac{1}{2\pi i} \int dz \frac{T_i^{\gamma W}(z, Q^2)}{z - \nu}, \quad \nu \in C
\]

Forward amplitudes \(T_i\) - unknown;
Their absorptive parts can be related to production of on-shell intermediate states —> a \(γW\)-analog of structure functions \(F_{1,2,3}\)

Structure functions \(F_i^{γW}\) are NOT data
But they can be related to data

\[
\text{Im} T_i^{\gamma W}(\nu, Q^2) = 2\pi F_i^{\gamma W}(\nu, Q^2)
\]
Mixed box from Dispersion Relations

Crossing behavior: relate the left and right hand cut
Mismatch between the initial and final states - asymmetric;
Symmetrize - \( \gamma \) is a mix of \( I=0 \) and \( I=1 \)

\[
T^{W,a}_i = T^{(0)}_i \tau^a + T^{(-)}_i \frac{1}{2} [\tau^3, \tau^a]
\]

\[
T^{(I)}_i(-\nu, Q^2) = \xi^{(I)}_i T^{(I)}_i(\nu, Q^2)
\]

\[
\xi^{(0)}_1 = +1, \quad \xi^{(0)}_{2,3} = -1; \quad \xi^{(-)} = -\xi^{(0)}
\]

Two types of dispersion relations for scalar amplitudes

\[
T^{(I)}_i(\nu, Q^2) = 2 \int_0^{\infty} d\nu' \left[ \frac{1}{\nu' - \nu - i\epsilon} + \frac{\xi^{(I)}_i}{\nu' - \nu - i\epsilon} \right] F^{(I)}_i(\nu', Q^2)
\]

Substitute into the loop and calculate leading energy dependence

\[
\text{Re} \Box^{even}_{\gamma W} = \frac{\alpha}{\pi N} \int_0^{\nu_{thr}} dQ^2 \int_0^{\infty} d\nu \frac{F^{(0)}_3(M\nu)}{(\nu + q)^2} + O(E^2)
\]

\[
\text{Re} \Box^{odd}_{\gamma W}(E) = \frac{8\alpha E}{3\pi NM} \int_0^{\nu_{thr}} dQ^2 \int_{\nu_{thr}}^{\infty} d\nu \left[ +F^{(0)}_1 + \left( \frac{3\nu(\nu + q)}{2Q^2} + 1 \right) \frac{M}{\nu} F^{(0)}_2 + \frac{\nu + 3q}{4\nu} F^{(-)}_3 \right] + O(E^3)
\]
Input into dispersion integral

Dispersion in energy: \( W^2 = M^2 + 2M\nu - Q^2 \)
scanning hadronic intermediate states

Dispersion in \( Q^2 \):
scanning dominant physics pictures

\[ Q^2 \]
\[ \sim 2 \text{GeV}^2 \]
\[ \text{Born} \]
\[ \text{Parton + pQCD} \]
\[ N\pi \]
\[ \text{Res. + B.G} \]
\[ \text{Regge + VMD} \]
\[ M^2 \quad (M + m_\pi)^2 \]
\[ \sim 5 \text{GeV}^2 \]
\[ W^2 \]

Boundaries between regions - approximate

Input in DR related (directly or indirectly) to experimentally accessible data
Input into dispersion integral

Our parametrization of the needed SF follows from this diagram

\[ F_3^{(0)} = F_{\text{Born}} + \begin{cases} F_{\text{pQCD}}, & Q^2 \gtrsim 2 \text{ GeV}^2 \\ F_{\pi N} + F_{\text{res}} + F_{\text{IR}}, & Q^2 \lesssim 2 \text{ GeV}^2 \end{cases} \]

Born: elastic FF from e⁻, ν scattering data

πN: relativistic ChPT calculation plus nucleon FF

Resonances: axial excitation from PCAC (Lalakulich et al, 2006) - neutrino scattering; electron and γ inelastic scattering

Above resonance region: multiparticle continuum described by Regge exchanges

**Inelastic contributions quantify how strongly the decay electron polarizes the proton**
Universal RC from DR

\[ \gamma W\text{-box at zero energy} \]

\[
\text{Re} \Box_{\gamma W}^{\text{even}} = \frac{\alpha}{\pi M} \int_0^\infty \frac{dQ^2 M_W^2}{M_W^2 + Q^2} \int_0^\infty \frac{d\nu}{\nu} \frac{\nu + 2q}{(\nu + q)^2} F_3^{(0)}(\nu, Q^2)
\]

\[
\text{Re} \Box_{\gamma W}^{\text{odd}} (E = 0) = 0
\]

Connection to MS: rewrite in terms of the first Nachtmann moment of \( F_3 \)

\[
M_3^{(0)}(1, Q^2) = \frac{4}{3} \int_0^1 dx \frac{1 + 2\sqrt{1 + 4M^2x^2/Q^2}}{(1 + \sqrt{1 + 4M^2x^2/Q^2})^2} F_3^{(0)}(x, Q^2)
\]

\[
x = \frac{Q^2}{2M\nu}
\]

\[
\text{Re} \Box_{\gamma W}^{\text{even}} = \frac{3\alpha}{2\pi} \int_0^\infty \frac{dQ^2 M_W^2}{Q^2(M_W^2 + Q^2)} M_3^{(0)}(1, Q^2) = \frac{\alpha}{8\pi} \int_0^\infty \frac{dQ^2 M_W^2}{M_W^2 + Q^2} F_{MS}(Q^2)
\]

MS loop fn. \( F(Q^2) \) directly related to \( M_3^{(0)} \)

\[
F_{MS}(Q^2) = \frac{12}{Q^2} M_3^{(0)}(1, Q^2)
\]

SF \( F_3 \) - commutator of em and weak currents - insert complete set of on-shell hadronic states

\[
F_3^{(0)} \propto \int dx e^{iqx} \langle p \left| [J_{em}^{\mu, (0)}(x), J_{W}^{\nu, +}(0)] \right| n \rangle \sim \int dx e^{iqx} \sum_X \langle p \left| J_{em}^{\mu, (0)}(x) \right| X \rangle \langle X \left| J_{W}^{\nu, +}(0) \right| n \rangle
\]
Unfortunately, no data can be obtained for \( F_3^{\gamma W (0)} \).

Data exist for the pure CC processes

\[
\frac{d^2 \sigma^{\nu}\nu}{dx dy} = \frac{G_F^2 ME}{\pi} \left[ xy^2 F_1 + \left( 1 - y - \frac{Mxy}{2E} \right) F_2 \pm x \left( y - \frac{y^2}{2} \right) F_3 \right]
\]

\[
\sigma^{\nu p} - \sigma^{\bar{\nu} p} \sim F_3^{\nu p} + F_3^{\bar{\nu} p} = u^p_v(x) + d^p_v(x)
\]

Gross-Llewellyn-Smith sum rule

\[
\int_0^1 dx (u^p_v(x) + d^p_v(x)) = 3
\]

Validate the model for CC process; apply an isospin rotation to obtain \( \gamma W \)

\[
F_{3, \text{low-}Q^2}^{\nu p + \bar{\nu} p} = F_{3, \text{el.}}^{\nu p + \bar{\nu} p} + F_{3, \pi N}^{\nu p + \bar{\nu} p} + F_{3, R}^{\nu p + \bar{\nu} p} + F_{3, \text{Regge}}^{\nu p + \bar{\nu} p}
\]

Low-\( W \) part of spectrum:

- neutrino data from MiniBooNE, Minerva, …
- axial FF, resonance contributions, pi-N continuum

High-\( W \): Regge behavior \( F_3 \sim q^\nu \sim x^{-\alpha} \), \( \alpha \sim 0.5-0.7 \)
Use of neutrino data via isospin rotation

Low $Q^2 < 0.1 \text{ GeV}^2$: Born + $\Delta(1232)$ dominate
Not fitted: modern data more precise but
cover only limited energy range
Fit driven by 4 data points between 0.2 and 2 GeV$^2$

Model & Uncertainty fully specified
- compare M&S vs This work

\[ M_{3\gamma\gamma} (1, Q^2) \]

\[ M_{3\gamma\gamma} (1, Q^2) \]

M&S: integrand discontinuous at $Q^2 = 2.25 \text{ GeV}^2$

Log scale for x-axis: integral = surface under the curve

\[ \text{MS Total: } [0]_W^{(0)} = 0.00324 \pm 0.00018 \]
\[ \text{New Total: } [0]_W^{(0)} = 0.00379 \pm 0.00010 \]

Uncertainty reduced by almost factor 2;
~ 3 sigma shift from the old value
Consequences for the $V_{ud}$ extraction

Marciano, Sirlin 2006: $\Delta^V_R = 0.02361(38) \rightarrow |V_{ud}| = 0.97420(10)_{Ft}(18)_{RC}$

DR (Seng et al. 2018): $\Delta^V_R = 0.02467(22) \rightarrow |V_{ud}| = 0.97370(10)_{Ft}(10)_{RC}$

In July 2019 Czarnecki, Marciano and Sirlin published an update in which they largely agreed that the RC was underestimated:

*Czarnecki, Marciano, Sirlin, 1907.06737*

C-M-S 2019: $\Delta^V_R = 0.02421(32) \rightarrow |V_{ud}| = 0.97391(10)_{Ft}(15)_{RC}$

*Seng, Meissner, 1903.07969:

$\gamma$W-box can be calculated on the lattice via Feynman-Hellman Theorem*
Nuclear Structure Modification

Long-range RC: the decay electron polarizes the proton
Nuclear polarizabilities are much different from nucleon - need to account for that

General structure of RC for nuclear decay

\[ ft(1 + RC') = Ft(1 + \delta'_R)(1 - \delta_C + \delta_{NS})(1 + \Delta^V_R) \]

NS correction reflects this extraction of the free box

\[ \frac{\Delta^W_{VA, Nucl.}}{\Delta^W_{VA, free n}} = \frac{\Delta^W_{VA, Nucl.} - \Delta^W_{VA, free n}}{\Delta^W_{VA, free n}} \]

Nuclear modification in the lower part of the spectrum

Input in the DR for the universal RC

Input in the DR for the RC on a nucleus
\( \delta_{NS} \) from DR with energy dependence averaged over the spectrum

\[
\delta_{NS} = \frac{2\alpha}{\pi NM} \int_0^{1\text{GeV}^2} dQ^2 \int_{\nu_{thr}}^{\nu} d\nu \left[ \frac{\nu + 2q}{(\nu + q)^2} \left( F_3^{(0)\text{Nucl.}} - F_3^{(0),B} \right) + \frac{2\langle E \rangle}{3} \frac{\nu + 3q}{(\nu + q)^3} F_3^{(-)\text{Nucl.}} \right]
\]

Hardy & Towner 1994 on: ad hoc description by nuclear quenching of spin operators

Compare the effect on the average \( \mathcal{F}t \) value:

- HT value 2018: \( \mathcal{F}t = 3072.1(7)s \)
- Old estimate: \( \delta \mathcal{F}t = -(1.8 \pm 0.4)s \) + (0 \pm 0)s
- New estimate: \( \delta \mathcal{F}t = -(3.5 \pm 1.0)s \) + (1.6\pm0.5)s

Two 2\sigma corrections that cancel each other;

The cancellation is delicate: the two terms are highly correlated

- Larger E-dep. term will correspond to a smaller negative E-indep. term and vv.

Conservative uncertainty estimate: 100%

\( \mathcal{F}t = (3072 \pm 2)s \)
$V_{ud}$ and CKM unitarity in December 2018

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Revision of nuclear corrections to 0+$\rightarrow$ 0+-$\beta$ decay

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Limitation: the lifetime (also, beam vs. bottle)

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(depending on $V_{us}$)
Discrepancy - BSM?

BSM explanation: non-standard CC interactions —> new V,A,S(PS),T(PT) terms

\[ H_{S+V} = (\overline{\psi}_p \psi_n) (C_S \overline{\phi}_e \phi_{\gamma e} + C'_{S} \overline{\phi}_e \gamma_5 \phi_{\gamma e}) + (\overline{\psi}_p \gamma_{\mu} \psi_n) [C_V \overline{\phi}_e \gamma_{\mu} (1 + \gamma_5) \phi_{\gamma e}] \]

Scalar and Tensor interactions: distort the beta decay spectra

Complementarity to LHC searches

Exp. high precision measurement of $^6\text{He}$ spectrum (O. Naviliat-Cuncic, A. Garcia, …)

\[ N(E)dE = p_eE(E_m - E)^2 \left[ 1 + C_1 E + b \frac{m_e}{E} \right] \]

$C_1 = 0.00650(7)$ MeV$^{-1}$ - effect of weak magnetism - positive slope

$b \sim \pm 0.001$ - negative slope

Energy-dep. polarizability correction —> $C'_{1} \sim 0.00020(20)$ MeV$^{-1}$ — at the level 3σ of $C_1$
Conclusions & Outlook

- The γW-box in the forward dispersion relation framework
- Hadronic and nuclear corrections in a unified framework
- Nuclear structure leaks in the outer correction, distorts the beta decay spectrum
- Nuclear uncertainties shift the emphasis on free neutron decay
- Tensions with CKM unitarity: \[ \sum_{i=d,s,b} |V_{ui}|^2 - 1 = -0.0016(4-6) \]

**Nuclear correction δ_{NS}**

DR allow to address hadronic and nuclear parts of the calculation on the same footing. The full nuclear correction should be calculated (not just QE) - further test of H&T δ_{NS}

**Decay spectra and nuclear polarizabilities**

Can contaminate the extraction of Fierz interference from precise spectra!

**Further applications**

γW box correction to GT rate (nuclear; nucleon - comparison of g_A w. lattice)
γW box correction to Kl3 decays and V_{us} - potential to reconcile Kl3 and Kl2?
γW box on the lattice - both for n and πl3 possible!