The quest for explaining the top-row CKM unitarity deficit

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The quest for explaining the top-row CKM unitarity deficit

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Motivation:

Recent improvements in theory/experiment of the extraction of V_{ud} and V_{us} have led to an **apparent violation of the top-row CKM unitarity at 3σ level**:

$$|V_{ud}|^2 + |V_{us}|^2 + \cancel{|V_{ub}|^2} = 0.9985(3)_{V_{ud}}(4)_{V_{us}}$$ (PDG 2020)

Needs **further reduction of SM uncertainties** to reach a level sufficient to claim a discovery.

★ : proposed research

V_{ud} from nuclear/neutron beta decay

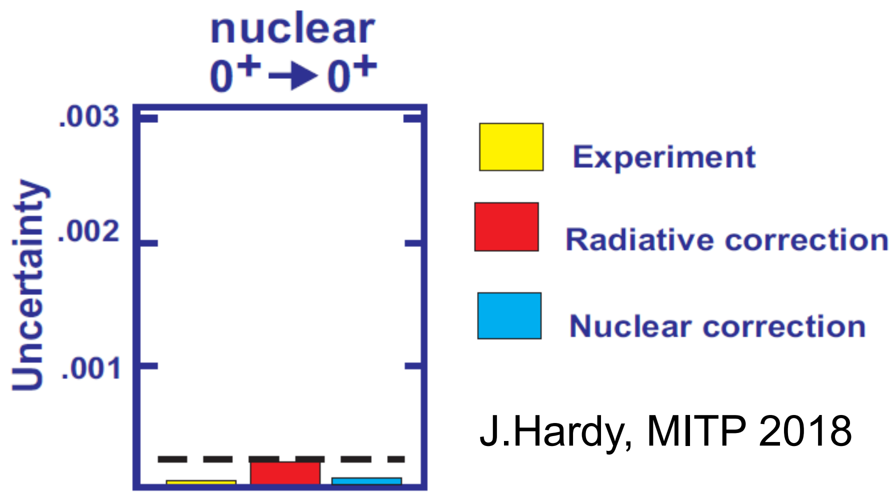
Superallowed $0^+ \to 0^+$:

$$|V_{ud}|^2 = \frac{2984.43\, s}{\mathcal{F}t\,(1+\Delta_R^V)}.$$

Experiment + nuclear corrections

Single-nucleon radiative correction (RC)

Error budget in early 2018:



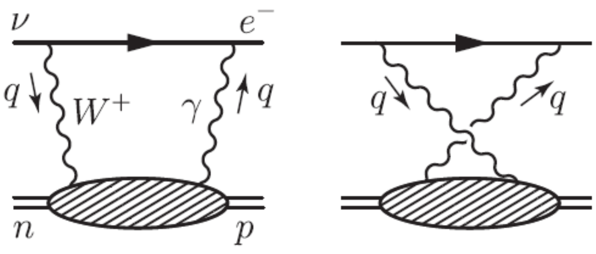
J.Hardy, MITP 2018

Recent **dispersion relation (DR) analysis** reduced the uncertainty in the single-nucleon RC.

$$\begin{aligned} |V_{ud}|_{0^+\to 0^+} &= 0.97420(10)_{\mathcal{F}t}(18)_{\mathrm{RC}} && \text{PDG 2018} \\ &\to 0.97370(10)_{\mathcal{F}t}(10)_{\mathrm{RC}} && \text{PDG 2020} \end{aligned}$$

V_{ud} from nuclear/neutron beta decay

Closing the chapter for single-nucleon RC

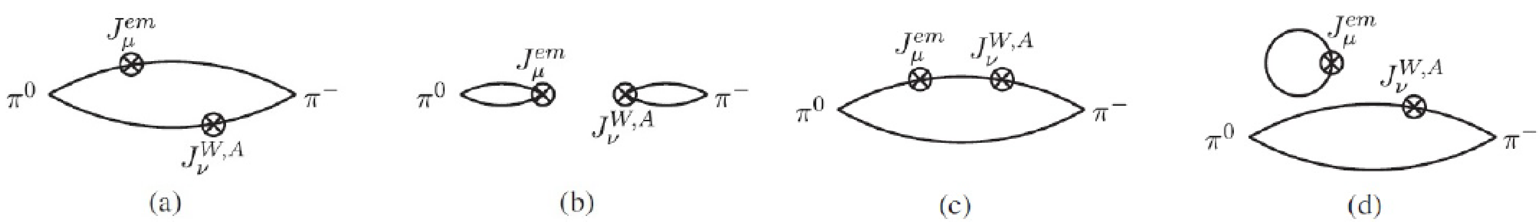


$$\Delta_R^V = 0.02361(38)$$ 2006

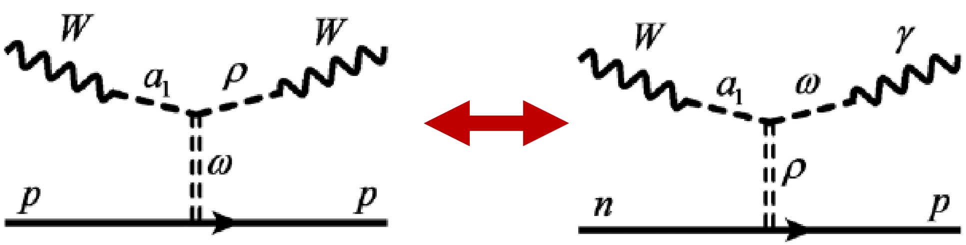
$$\rightarrow 0.02467(22)$$ 2018, DR + experiment

$$\rightarrow 0.02477(24)$$ 2020, DR + indirect lattice

★ **Direct lattice QCD calculation** of the **neutron γW box diagram**, (calculating four-point functions in analogy to pion, or using Feynman-Hellmann theorem)



★ More precise data on **neutrino-nucleus scattering**, as input to DR. e.g. from DUNE (Fermilab)



V_{ud} from nuclear/neutron beta decay

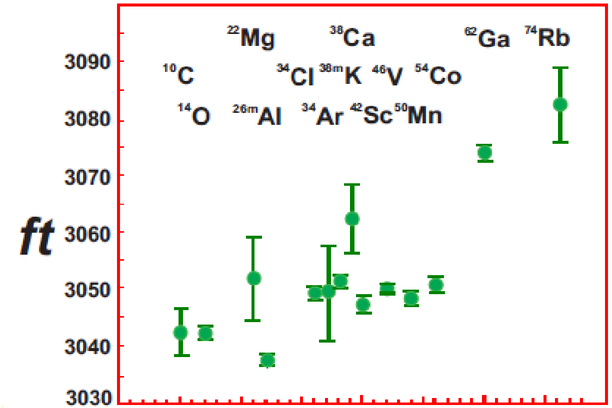
A closer look at the nuclear corrections

"outer correction"

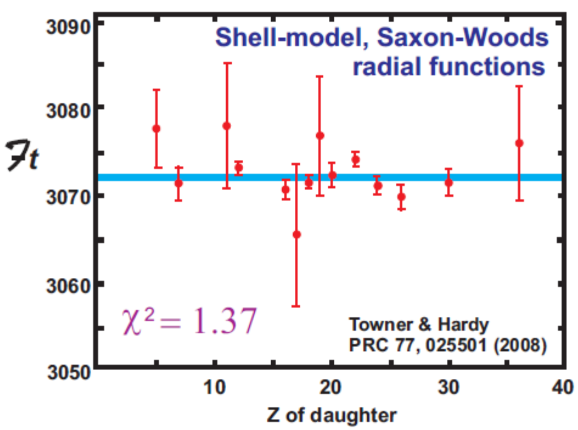
Isospin breaking (ISB) effects in nuclear states

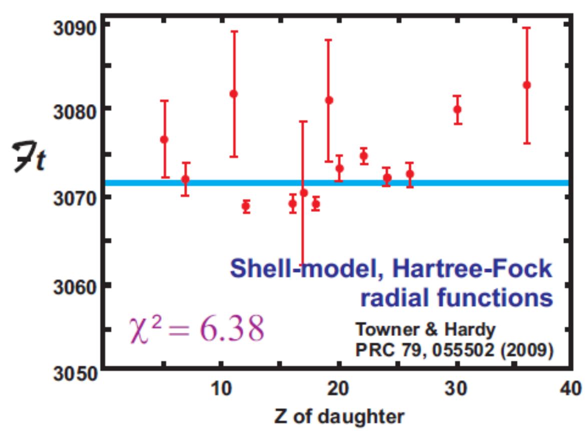
$$\mathcal{F}t = ft\,(1+\delta'_{\rm R})\,(1+\delta_{\rm NS}-\delta_{\rm C})$$

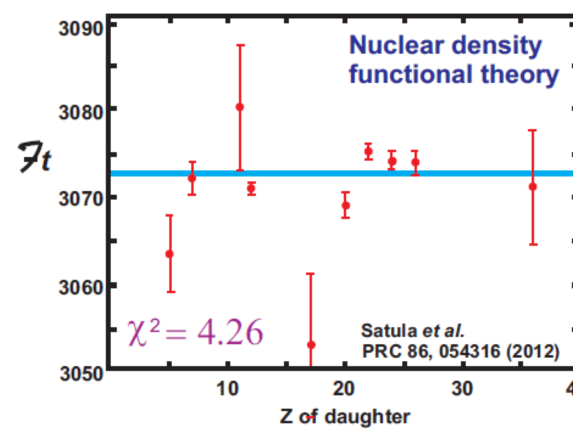
Nuclear modification of free-nucleon RC



CVC + absence of second-class current : **Ft = constant**







- Current estimations of nuclear effects are based entirely on **shell model + Woods-Saxon WF**. How reliable are they?
- Several **new nuclear corrections** are recently identified!

V_{ud} from nuclear/neutron beta decay

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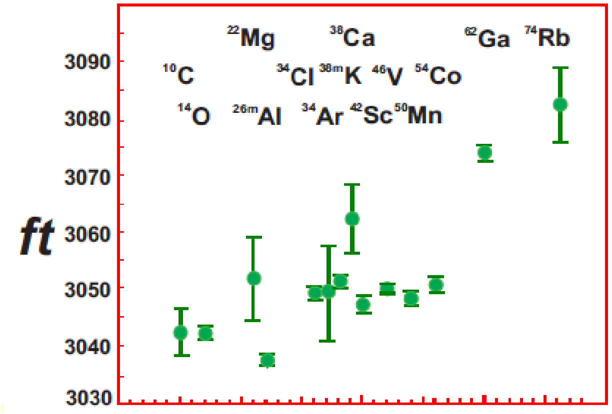


CVC + absence of second-class current : **Ft = constant**

- ★ **Ab-initio calculations** of nuclear corrections: e.g. Lorentz Integral Transform, Quantum Monte Carlo, Coupled Cluster...

see G. Hagen and S. Bacca, in the 2019 ECT workshop "Precise beta decay calculations for searches For new physics"*

- ★ Constraining the **ISB effects** from **experimental measurements** of charge radii and neutron skins

V_{ud} from nuclear/neutron beta decay

Decay of free neutron and nuclear mirrors

$$ft = \frac{K}{G_V^2 \langle \tau \rangle^2 + G_A^2 \langle \sigma\tau \rangle^2}$$

G_V, G_A: **vector** and **axial** coupling (after RC)

$<\sigma>$, $<\sigma\tau>$: **Fermi** and **Gamow-Teller** matrix element

RC to GT-matrix element: not relevant for V_{ud} extraction because axial coupling*GT-matrix element is directly measured.

However, it is **useful in comparison between experiment and first-principles QCD Predictions**. E.g. $\lambda=g_A/g_V$ from neutron decay asymmetry, and the pure-QCD g_A obtained from lattice. Could become a **future avenue for BSM searches**.

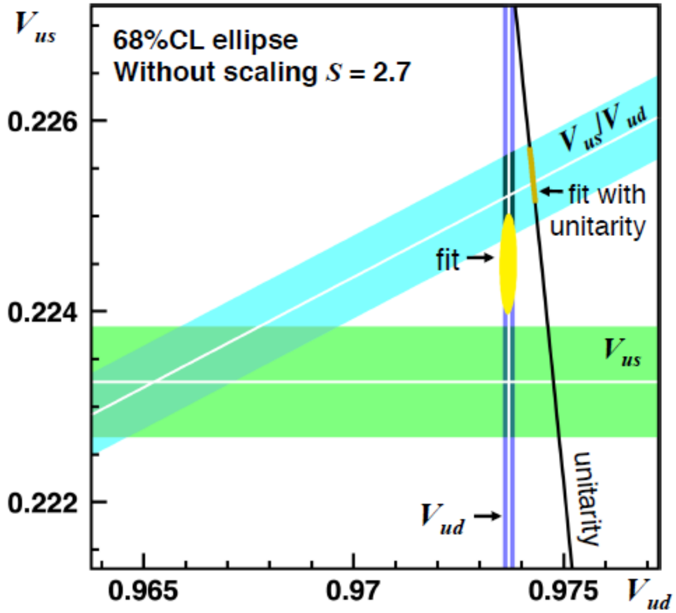
★ Systematic analysis of **RC to Gamow-Teller rates**.

L. Hayen, available soon on arXiv

V_{us} from kaon decays

~**3σ discrepancy** exists between V_{us} extracted from **leptonic kaon decay ($K_{\mu 2}$)** and **semileptonic kaon decay (K_{l3})**:

$$|V_{us}^{K_{\mu 2}}| = 0.2252(5), \quad |V_{us}^{K_{l3}}| = 0.2231(4)_{\text{exp+RC}}(6)_{\text{lattice}}.$$ (PDG 2020)



E.Passemar, INT-19-75W

Signal of BSM physics or unidentified SM systematic errors? Needs further theory improvement to tell.

$K_{\mu 2}$ result comes from the ratio $R_A = \Gamma_{K\mu 2}/\Gamma_{\pi\mu 2}$, which is more robust due to the partial cancellation of uncertainties. We shall **focus mainly on K_{l3}**.

V_{us} from kaon decays

K_{l3} decay rate formula:

(known) Short-distance RC

t-dependence of form factor: DR

$$\Gamma_{K_{l3}} = \frac{C_K^2 G_F^2 M_K^5}{128\pi^3} S_{\mathrm{EW}} |V_{us}|^2 |f_+^{\pi^- K^0}(0)|^2 I_{Kl}^{(0)}(\lambda_i)(1 + \delta_{\mathrm{em}}^{Kl} + \delta_{\mathrm{SU(2)}}^{K\pi})$$

Form factor at t=0: lattice input

Long-distance EM correction and
strong isospin breaking: ChPT input

Possible culprit: **$f_+(0)$=0.9706(27)** (FLAG-averaged, 2020).
Discrepancies exists between different lattice results:

$$|f_+^{\pi^- K^0}(0)| = \begin{cases} 0.9696(15)(12) & \text{FNAL/MILC} \\ 0.9603(16)(^{+14}_{-4})(44)(19) & \text{PACS} \end{cases}$$

★ Reconcile the conflicting numbers!

V_{us} from kaon decays

Remaining theory input with significant model dependence:
the **long-range EM corrections**

	$\delta_{\rm em}^{Kl}(\%)$
K_{e3}^{0}	$0.99 \pm 0.19_{e^2p^4} \pm 0.11_{\rm LEC}$
$K_{e3}^{\pm}$	$0.10 \pm 0.19_{e^2p^4} \pm 0.16_{\rm LEC}$
$K_{\mu 3}^{0}$	$1.40 \pm 0.19_{e^2p^4} \pm 0.11_{\rm LEC}$
$K_{\mu 3}^{\pm}$	$0.016 \pm 0.19_{e^2p^4} \pm 0.16_{\rm LEC}$

Limitations from fixed-order ChPT

LECs calculated within resonance model

- **Lattice QCD calculations** of the LECs
- Including **higher-order effects**: by multi-loop ChPT calculation, or by new theory framework

They will also improve the theory prediction of the ratio $R_V=\Gamma_{Kl3}/\Gamma_{\pi l3}$, which serves an another important avenue to extract V_{us}/V_{ud}.

Synergies with other LOIs

Neutron/pion beta decay experiments

- "Neutron beta decay in the test of the Unitarity of the CKM matrix", SNOWMASS21-RF0_RF3-102
- "Testing lepton flavor universality and CKM unitarity with rare pion decays", SNOWMASS21-RF2_RF3-048

Lattice QCD

- "Precise Lattice QCD calculations of kaon and pion decay parameters and first-row CKM unitarity tests", SNOWMASS21-RF2_RF0-EF5_EF0-TF5_TF0-CompF2_CompF0_El-Khadra-094
- "High-precision determination of Vus and Vud from lattice QCD", SNOWMASS21-RF2_RF0-TF5_TF0-CompF2_CompF0-054

Neutrino scattering experiments

- "Neutrino Scattering Measurements on Hydrogen and Deuterium", SNOWMASS21-NF6_NF3-TF11_TF5_LauraFields_RichardHill_TomJunk-165