Tests of lepton flavor universality and CKM unitarity

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Developing New Directions in Fundamental Physics 2020

TRIUMF virtual meeting

- Precision-frontier tests of SM
- **Unitarity** of CKM matrix

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

- **Lepton flavor universality**: $\ell = \{e, \mu, \tau\}$ only differ in masses, e.g., in charged current

$$\mathcal{L} = -i\frac{g_2}{\sqrt{2}}\bar{\ell}_i\gamma^\mu P_L\nu_j W_\mu\big(\delta_{ij} + \varepsilon_{ij}\big)$$

$\hookrightarrow \varepsilon_{ij} = 0$ in SM

- This talk: review of current status and future prospects

Determination of V_{ud} from superallowed β decays

- Master formula Hardy, Towner 2018

$$|V_{ud}|^2 = \frac{2984.432(3)\,\text{s}}{\mathcal{F}t(1+\Delta_R^V)}$$

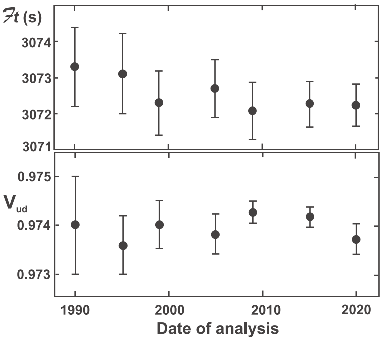
with (universal) radiative corrections Δ_R^V

- Value of V_{ud} crucially depends on Δ_R^V:

Ref.	Δ_R^V
Marciano, Sirlin 2006	0.02361(38)
Seng, Gorchtein, Patel, Ramsey-Musolf 2018	0.02467(22)
Czarnecki, Marciano, Sirlin 2019	0.02426(32)
Seng, Feng, Gorchtein, Jin 2020	0.02477(24)
Hayen 2020	0.02474(31)

- Possibly further nuclear corrections

Miller, Schwenk 2008, 2009, Seng, Gorchtein, Ramsey-Musolf 2018, Gorchtein 2018



Hardy, Towner 2020

Determination of V_{ud} from neutron decay

- Master formula Czarnecki, Marciano, Sirlin 2018

$$|V_{ud}|^2\tau_n(1+3g_A^2)(1+\Delta_{\text{RC}}) = 5100.1(7)\,\text{s}$$

with radiative corrections Δ_{RC}

$\hookrightarrow$ need lifetime τ_n and asymmetry $\lambda = g_A/g_V$

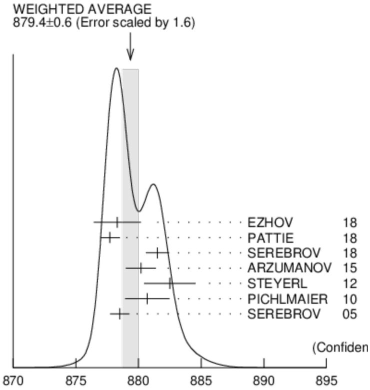
- PDG average only considers bottle experiments, latest Pattie et al. 2018

$$\tau_n = 877.7(7)(^{+0.4}_{-0.2})\,\text{s}$$

- Latest asymmetry measurement Märkisch et al. 2019

$$\lambda = g_A/g_V = -1.27641(56)$$

- Consistent with, but less precise than V_{ud} from superallowed β decays



PDG 2020

Determination of V_{ud} from pion β decay

- Master formula Cirigliano, Knecht, Neufeld, Pichl 2003
  Czarnecki, Marciano, Sirlin 2020, Feng et al. 2020

$$\Gamma(\pi^+ \to \pi^0 e^+ \nu_e(\gamma)) = \frac{G_F^2 |V_{ud}|^2 M_\pi^5 |f_+^\pi(0)|^2}{64\pi^3} \times (1 + \Delta_{RC}^{\pi\ell}) I_{\pi\ell}$$

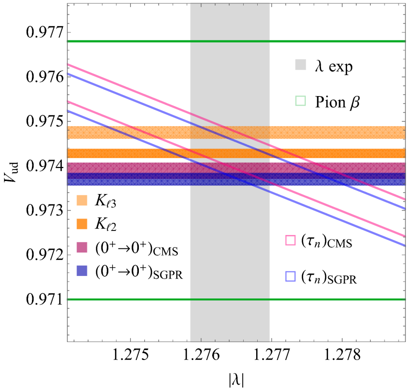
  with radiative corrections $\Delta_{RC}^{\pi\ell}$

  $\hookrightarrow$ need branching fraction and pion life time

- Resulting V_{ud} extracted from PIBETA 2004 still with relatively large error compared to other β decays

$$V_{ud} = 0.9739(29)$$

- Good consistency among all β-decay constraints, including mirror decays Hayen 2020



Crivellin, MH 2020

Indirect determination of V_{ud} from kaon decays: $K_{\ell 2}$

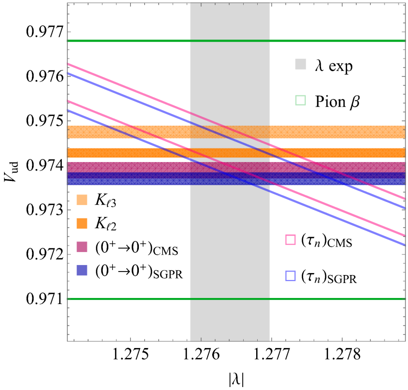
- Kaon-decay constraints derived **assuming CKM unitarity**
- ***$K_{\ell 2}$* decays**: $K \to \ell\nu_\ell$

$$\frac{V_{us}}{V_{ud}}\frac{F_K}{F_\pi} = \left(\frac{\Gamma(K^+\to\mu^+\nu_\mu(\gamma))M_\pi}{\Gamma(\pi^+\to\mu^+\nu_\mu(\gamma))M_K}\right)^{1/2} \times \frac{1-\frac{m_\mu^2}{M_\pi^2}}{1-\frac{m_\mu^2}{M_K^2}}\left(1-\frac{\Delta_{RC}^K-\Delta_{RC}^\pi}{2}\right)$$

$\hookrightarrow$ typically consider the ratio over $\pi_{\ell 2}$

- Need input for:
  - F_K/F_π
  - Isospin-breaking corrections

$\hookrightarrow$ lattice QCD, ChPT



Crivellin, MH 2020

- **$K_{\ell 3}$ decays**: $K \to \pi \ell \nu_\ell$

$$\Gamma(K \to \pi \ell \nu_\ell(\gamma)) = \frac{C_K^2 G_F^2 |V_{us}|^2 M_K^5 |f_+^{K\pi}(0)|^2}{192\pi^3} \times (1 + \Delta_{\rm RC}^{K\ell}) I_{K\ell}$$

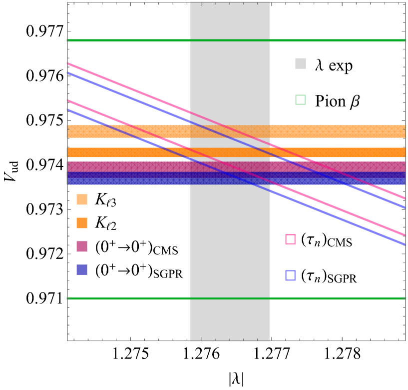
$\hookrightarrow$ $\ell = \mu$, e and two charge channels

- Need input for:
  - $K\pi$ form factor $f_+^{K\pi}(0)$
  - Radiative corrections

$\hookrightarrow$ lattice QCD, ChPT

- Tensions between
  - $K_{\ell 2}$ and $K_{\ell 3}$ decays
  - Kaon decays and β decays

$\hookrightarrow$ apparent violation of CKM unitarity



Crivellin, MH 2020

V_{ud} tension as a sign for the violation of lepton flavor universality?

- Let us parameterize the ***W*** **couplings** as $\mathcal{L} = -i\frac{g_2}{\sqrt{2}}\bar{\ell}_i\gamma^\mu P_L\nu_j W_\mu\big(\delta_{ij} + \varepsilon_{ij}\big)$
- Modifies Fermi constant in **muon decay**

$$\frac{1}{\tau_\mu} = \frac{(G_F^{\mathcal{L}})^2 m_\mu^5}{192\pi^3}(1+\Delta q)(1+\varepsilon_{ee}+\varepsilon_{\mu\mu})^2$$

$\hookrightarrow$ measured Fermi constant $G_F = G_F^{\mathcal{L}}(1+\varepsilon_{ee}+\varepsilon_{\mu\mu})$

V_{ud} tension as a sign for the violation of lepton flavor universality?

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- All β-decay observables affected according to

$$V_{ud} \to V_{ud}^\beta = V_{ud}^{\mathcal{L}}(1-\varepsilon_{\mu\mu})$$

where $V_{ij}^{\mathcal{L}}$ fulfill CKM unitarity

- Construct ratio Crivellin, MH 2020

$$R(V_{us}) \equiv \frac{V_{us}^{K_{\mu 2}}}{V_{us}^\beta} \equiv \frac{V_{us}^{K_{\mu 2}}}{\sqrt{1-(V_{ud}^\beta)^2 - |V_{ub}|^2}} = 1 - \bigg(\frac{V_{ud}}{V_{us}}\bigg)^2 \varepsilon_{\mu\mu} + \mathcal{O}(\varepsilon^2)$$

$\hookrightarrow$ LFUV effect enhanced by $(V_{ud}/V_{us})^2 \sim 20$!

V_{ud} tension as a sign for the violation of lepton flavor universality?

Observable	Measurement	Constraint $\times 10^3$
$\frac{K\to\pi\mu\bar\nu}{K\to\pi e\bar\nu} \simeq 1 + \varepsilon_{\mu\mu} - \varepsilon_{ee}$	1.0010(25)	1.0(2.5)
$\frac{K\to\mu\nu}{K\to e\nu} \simeq 1 + \varepsilon_{\mu\mu} - \varepsilon_{ee}$	0.9978(18)	$-2.2(1.8)$
$\frac{\pi\to\mu\nu}{\pi\to e\nu} \simeq 1 + \varepsilon_{\mu\mu} - \varepsilon_{ee}$	1.0010(9)	1.0(9)
$\frac{\tau\to\mu\nu\bar\nu}{\tau\to e\nu\bar\nu} \simeq 1 + \varepsilon_{\mu\mu} - \varepsilon_{ee}$	1.0018(14)	1.8(1.4)
$\frac{W\to\mu\bar\nu}{W\to e\bar\nu} \simeq 1 + \varepsilon_{\mu\mu} - \varepsilon_{ee}$	0.9960(100)	$-4(10)$
$\frac{B\to D^{(*)}\mu\nu}{B\to D^{(*)}e\nu} \simeq 1 + \varepsilon_{\mu\mu} - \varepsilon_{ee}$	0.9890(120)	$-11(12)$
$R(V_{us}) \simeq 1 - \left(\frac{V_{ud}}{V_{us}}\right)^2 \varepsilon_{\mu\mu}$	0.9891(33) (SGPR)	0.58(17)
	0.9927(39) (CMS)	0.39(21)

- Most stringent constraint on $\varepsilon_{\mu\mu}$ thanks to **CKM enhancement**
- Could explain tension between β decays and kaon decays, but not between $K_{\ell 2}$ and $K_{\ell 3}$ (right-handed currents?)
- Best constraint on $\varepsilon_{\mu\mu} - \varepsilon_{ee}$ from

$$R^{\pi}_{e/\mu} = \frac{\Gamma(\pi \to e\nu_e(\gamma))}{\Gamma(\pi \to \mu\nu_\mu(\gamma))}$$

Searching for the violation of lepton flavor universality in $R^{\pi,K}_{e/\mu}$

- SM prediction at two loops Cirigliano, Rosell 2007

$$R^{\pi}_{e/\mu} = 1.2352(1) \times 10^{-4}$$
$$R^{K}_{e/\mu} = 2.477(1) \times 10^{-5}$$

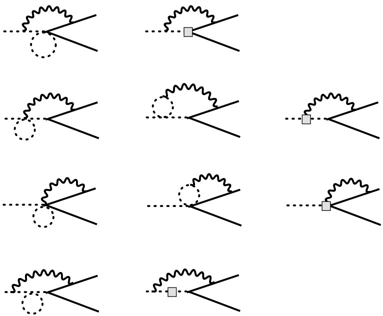
$\hookrightarrow$ see talk by Vincenzo Cirigliano

- Experimental status PDG 2020

$$R^{\pi}_{e/\mu} = 1.2327(23) \times 10^{-4}$$
$$R^{K}_{e/\mu} = 2.488(9) \times 10^{-5}$$

$\hookrightarrow$ in both cases theory far ahead!

- Future improvements from PEN, PiENu ($R^{\pi}_{e/\mu}$) and J-PARC E36 ($R^{K}_{e/\mu}$)



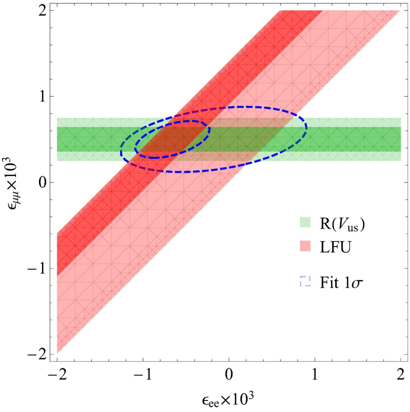
Cirigliano, Rosell 2007

Projections in ε_{ee}–$\varepsilon_{\mu\mu}$ plane

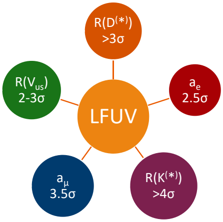
- Potential improvements for $R(V_{us})$
  - Radiative corrections for β decays
  - Improved measurements of τ_n and g_A
  - New data on $K_{\ell 3}$ decays

  $\hookrightarrow$ assumed $\sqrt{2}$ due to neutron decay
- Potential improvements for $\varepsilon_{\mu\mu} - \varepsilon_{ee}$
  - **Factor 3 from PEN/PiENu**
  - Factor 3 for τ decays from Belle II

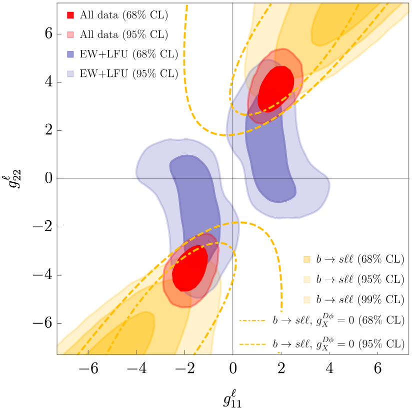
  $\hookrightarrow$ would probe ε_{ee} below $\mathcal{O}(10^{-3})$



Crivellin, MH 2020



- Modified W couplings $\Rightarrow$ expect **modified Z couplings** from $SU(2)_L$ invariance
- Example: heavy W', Z' ("**vector triplet**")
- W' for β decay tension
- Z' can explain $b \to s\ell\ell$ anomalies
- Via $SU(2)_L$: constraints from electroweak precision observables



Capdevila, Crivellin, Manzari, Montull 2020

$g^\ell_{11/22}$: electron/muon coupling

Back to pion β decay

- For $K_{\ell 2}$ and $\pi_{\ell 2}$ decays one uses the ratio

$$\frac{\Gamma(K^+ \to \mu^+ \nu_\mu(\gamma))}{\Gamma(\pi^+ \to \mu^+ \nu_\mu(\gamma))} = \left(\frac{V_{us}}{V_{ud}} \frac{F_K}{F_\pi}\right)^2 \frac{M_K}{M_\pi} \left(\frac{1 - \frac{m_\mu^2}{M_K^2}}{1 - \frac{m_\mu^2}{M_\pi^2}}\right)^2 \left(1 + \Delta_{\text{RC}}^K - \Delta_{\text{RC}}^\pi\right)$$

  to cancel uncertainties and extract V_{us}/V_{ud}

- Can do the same for $K_{\ell 3}$ and $\pi_{\ell 3}$! Czarnecki, Marciano, Sirlin 2020
- Pion β decay not competitive for V_{us}, but combined with $K_{\ell 3}$ decays improvement by a factor 2–3 would suffice to obtain a competitive value of V_{us}/V_{ud}

BSM searches with pion β decay

- Generalize master formula to include **effective operators** not present in SM

$$\Gamma(\pi^+ \to \pi^0 e^+ \nu_e(\gamma)) = \frac{G_F^2 |V_{ud}|^2}{192\pi^3 M_\pi^3}(1+\Delta_{\text{RC}}^{\pi\ell}) \int_{m_e^2}^{(M_\pi - M_{\pi^0})^2} ds\, \lambda^{3/2}(s)\left(1+\frac{m_e^2}{2s}\right)\left(1-\frac{m_e^2}{s}\right)^2$$
$$\times \left[|V(s)|^2 + |A(s)|^2 + \frac{4(s-m_e^2)^2}{9sm_e^2}|T(s)|^2 + \frac{3m_e^2(M_\pi^2 - M_{\pi^0}^2)^2}{(2s+m_e^2)\lambda(s)}\left(|S(s)|^2 + |P(s)|^2\right)\right]$$

with $V(s)$, $A(s)$, ... depending on Wilson coefficients c_V, c_A, ...

- **Tensor**: $T(s) = \frac{3s}{2s+m_e^2}\frac{m_e}{M_\pi} c_T B_T^\pi(s)$
  $\hookrightarrow$ suppressed by electron mass and tensor form factor
- **Scalar**: more competitive constraints, but still not at the same level as other β decays Falkowski, Gonzáles-Alonso, Naviliat-Cuncic 2020
- More on rare pion decays in talk by Vincenzo Cirigliano

Testing Lepton Flavor Universality and CKM Unitarity with Rare Pion Decays

LOI for Snowmass 2020 Discussion

August 27, 2020

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Abstract

We describe the physics motivation and concept of a next-generation experiment to measure the charged-pion branching ratio to electrons vs. muons, $R_{e/\mu}$, which is extremely sensitive to new physics at high mass scales. The proposed detector system will also measure pion beta decay, $\pi^+ \to \pi^0 e^+ \nu(\gamma)$, and other rare decays to high precision. Order of magnitude improvements in sensitivity to these reactions will probe lepton universality at an unprecedented level, determine V_{ud} in a theoretically pristine manner and test CKM unitarity at the quantum loop level.

Conclusions

- Tensions between β decays and kaon decays point to the **apparent violation of CKM unitarity**
- Could be interpreted as a hint for the **violation of lepton flavor universality**
  $\hookrightarrow$ relation to B anomalies and $(g-2)_{\mu,e}$?
- $R(V_{us})$ ideal probe of LFU due to **CKM enhancement**
- Interesting parameter space probed by forthcoming results on $R^{\pi}_{e/\mu}$
- Next-generation PiENu experiment could
  - bring experimental error for $R^{\pi}_{e/\mu}$ even closer to the theoretical uncertainty
  - improve pion β decay and extraction of V_{us}/V_{ud}