V_{ud}, V_{us}, V_{cd}, V_{cs} and semileptonic/leptonic D decays

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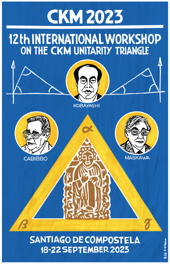
WG1

September 22nd, 2023

CKM 2023
Santiago de Compostela, Spain



Outline

CKM unitarity

Benchmarks numbers for CKM tests from PDG "12. CKM Quark-Mixing Matrix"

first row:	$\lvert V_{ud}\rvert^2 + \lvert V_{us}\rvert^2 + \lvert V_{ub}\rvert^2 = 0.9985(7)$
second row:	$\lvert V_{cd}\rvert^2 + \lvert V_{cs}\rvert^2 + \lvert V_{cb}\rvert^2 = 1.001(12)$
first column:	$\lvert V_{ud}\rvert^2 + \lvert V_{cd}\rvert^2 + \lvert V_{td}\rvert^2 = 0.9972(20)$
second column:	$\lvert V_{us}\rvert^2 + \lvert V_{cs}\rvert^2 + \lvert V_{ts}\rvert^2 = 1.004(12)$

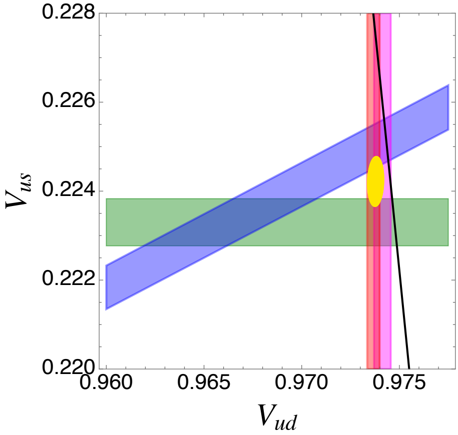
- International Workshop on the **CKM Unitarity Triangle** (CKM 2023)
- WG1 also studies CKM unitarity tests involving only $|V_{ij}|$
  $\hookrightarrow$ **CKM Unitarity Circles**

Outline

V_{ud}, V_{us}, and First-Row Unitarity

V_{cd}, V_{cs}, and (semi)-leptonic D decays

Tension in first-row unitarity



Cirigliano, Crivellin, Hoferichter, Moulson 2023

- Three bands from
  - $K_{\ell 3} = K \to \pi \ell \nu_\ell$
  - $\pi_{\ell 2}/K_{\ell 2}$
  - β decays (superallowed, neutron)
- Tensions

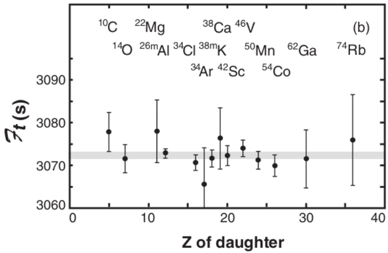
$$\Delta_{\text{CKM}} = |V_{ud}|^2 + |V_{us}|^2 - 1$$
$$\Delta_{\text{CKM}}^{K_{\ell 2}-K_{\ell 3}} = -0.016(6)\,[2.6\sigma]$$
$$\Delta_{\text{CKM}}^{K_{\ell 2}-\beta} = -0.0010(6)\,[1.7\sigma]$$
$$\Delta_{\text{CKM}}^{K_{\ell 3}-\beta} = -0.0018(6)\,[3.1\sigma]$$
$$\Delta_{\text{CKM}}^{\text{global}} = -0.0018(6)\,[2.8\sigma]$$

- Need to improve V_{ud}, V_{us}!

V_{ud} determinations

1. **Superallowed β decays** ($0^+ \to 0^+$ nuclear transitions) Talk by M. Gorchtein
   - $+$: many isotopes to average
   - $-$: nuclear uncertainties
2. **Neutron decay** ($n \to p e^+ \bar{\nu}_e$) Talks by W. Dekens, B. Märkisch, U. Schmidt
   - $+$: no nuclear uncertainties
   - $-$: need neutron lifetime τ_n and decay asymmetry $\lambda = g_A/g_V$
3. **Pion β decay** ($\pi^+ \to \pi^0 e^+ \bar{\nu}_e$) Talk by M. Hoferichter
   - $+$: theoretically pristine
   - $-$: experimentally challenging

Superallowed β decays Talk by M. Gorchtein



Once all corrections are included:
CVC —> Ft constant

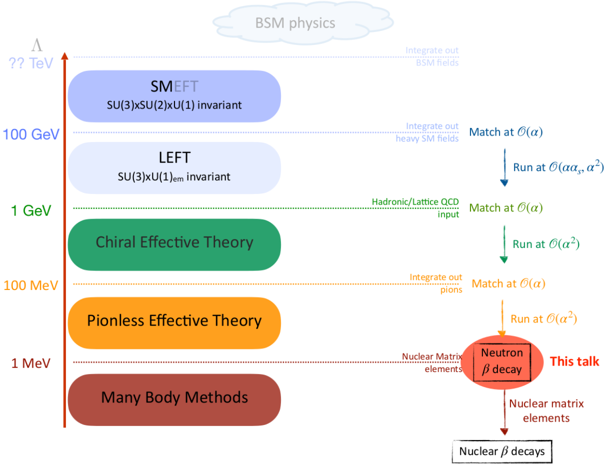
δ_C particularly important for alignment!

Fit to 14 transitions:
Ft constant within 0.02%

Hardy, Towner 2020

- New method to compute nuclear-structure corrections using **dispersion relations**
- **Modern ab-initio nuclear-structure** methods being applied to selected transitions
- **Nuclear charge radii** to help constrain nuclear-structure calculations
  $\hookrightarrow$ experimental program at PSI, FRIB, ISOLDE, ...

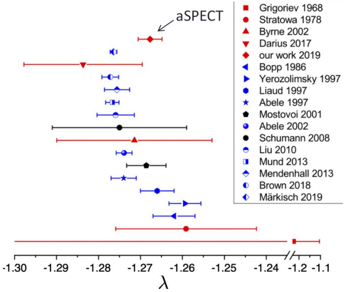
EFT for neutron decay Talk by W. Dekens



EFT framework

- Explicit separation of scales
- **Resum large logarithms**
- Systematically improvable

Neutron decay asymmetry Talks by B. Märkisch, U. Schmidt



PERKEO III Leading beta asymmetry and Fierz term results. Analysis of proton asymmetry and beta spectrum campaigns ongoing, Establishes *pulsed cold beam* technique.
$\frac{\Delta\lambda}{\lambda} = 4.4 \times 10^{-4}$

PERC Aims at improved measurements of Parameters A, (B), C, a, b. Commissioning!
$\frac{\Delta\lambda}{\lambda} \leq 1 \times 10^{-4}$

ANNI at ESS Proposed beam line at the ESS. Statistics gain factor for a PERC-like system: ×15 !

- Uncertainty in **decay asymmetry $\boldsymbol{\lambda}$** dominant

$$|V_{ud}^{\text{n, best}}| = 0.97402(2)_{\Delta_f}(13)_{\Delta_R}(35)_{\lambda}(20)_{\tau_n}[42]_{\text{total}}$$

↪ already close to superallowed β decays

- But: assumes PERKEO III vs. aSPECT to be resolved!

PIONEER Talk by M. Hoferichter

A next-generation rare PION dEcay ExpeRiment

- Physics goals
  - (Phase I) **Lepton flavor universality** at 10^{-4} in

$$R_{e/\mu} = \frac{\Gamma[\pi^+ \to e^+ \nu_e(\gamma)]}{\Gamma[\pi^+ \to \mu^+ \nu_\mu(\gamma)]}$$

  - (Phase II+III) **CKM unitarity** V_{ud} at 3×10^{-4} from $\pi^+ \to \pi^0 e^+ \bar{\nu}_e$
  - In both cases: factor 10 improvement to match theory errors
  - Searches for **exotics** (heavy neutrinos, ...)
- Status
  - Approved to run at PSI 2203.01981
  - R&D ongoing, Phase I to start in 2029

Determination of V_{us} from kaon decays

Talk by M. Moulson:

$$\Gamma(K_{\ell 3(\gamma)}) = \frac{C_K^2 G_F^2 m_K^5}{192\pi^3} S_{\rm EW} |V_{us}|^2 |f_+^{K^0\pi^-}(0)|^2 \times I_{K\ell}(\lambda_{K\ell}) \left(1 + 2\Delta_K^{SU(2)} + 2\Delta_{K\ell}^{\rm EM}\right)$$

with $K \in \{K^+, K^0\}$; $\ell \in \{e, \mu\}$, and:

C_K^2	1/2 for K^+, 1 for K^0
$S_{\rm EW}$	Universal SD EW correction (1.0232)

Inputs from experiment:

$\Gamma(K_{\ell 3(\gamma)})$ Rates with well-determined treatment of radiative decays:

- Branching ratios: K_S, K_L, $K^\pm$
- Kaon lifetimes

$I_{K\ell}(\{\lambda\}_{K\ell})$ Integral of form factor over phase space: λs parameterize evolution in t

- K_{e3}: Only λ_+ (or λ_+', λ_+'')
- $K_{\mu 3}$: Need λ_+ and λ_0

Inputs from theory:

$f_+^{K^0\pi^-}(0)$ Hadronic matrix element (form factor) at zero momentum transfer ($t = 0$)

$\Delta_K^{SU(2)}$ Form-factor correction for $SU(2)$ breaking

$\Delta_{K\ell}^{\rm EM}$ Form-factor correction for long-distance EM effects

New KLOE measurement of $K_S \to \pi\ell\nu$

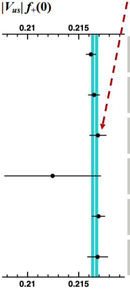
Talk by A. Passeri:

JHEP 02 (2023) 098

KLOE: analysis of the data sample (1.63 fb^{-1}) collected in 2004-05, measured ratio:

$$\mathcal{R} = \frac{\Gamma(K_S \to \pi e\nu)}{\Gamma(K_S \to \pi^+\pi^-)} = \frac{N_{\pi e\nu}}{\epsilon_{\pi e\nu}} \times \frac{\epsilon_{\pi\pi}}{N_{\pi\pi}} \times R_\epsilon = (1.0338 \pm 0.0054_{\rm stat} \pm 0.0064_{\rm syst}) \times 10^{-3}$$

$$\mathcal{B}(K_S \to \pi e\nu) = (7.153 \pm 0.037_{\rm stat} \pm 0.044_{\rm syst}) \times 10^{-4} = (7.153 \pm 0.058) \times 10^{-4}$$



		% err	Approx. contrib. to % err from: BR	τ	Δ	Int
K_Le3	0.2162(5)	0.23	0.09	0.20	0.02	0.05
$K_L\mu3$	0.2165(6)	0.26	0.15	0.18	0.02	0.07
K_Se3	0.2169(8)	0.39	0.38	0.02	0.02	0.05
$K_S\mu3$	0.2125(47)	2.2	2.2	0.02	0.02	0.08
$K^\pm e3$	0.2169(6)	0.30	0.27	0.06	0.11	0.05
$K^\pm\mu3$	0.2168(10)	0.47	0.45	0.06	0.11	0.08

Average (M. Moulson):

$$|V_{us}|f_+(0) = \mathbf{0.21656(35)}$$

V_{us}/V_{ud} and $K_{\ell 2}$ decays

Talk by M. Moulson:

$$\frac{|V_{us}|}{|V_{ud}|}\frac{f_K}{f_\pi} = \left(\frac{\Gamma_{K_{\mu 2(\gamma)}} m_{\pi^\pm}}{\Gamma_{\pi_{\mu 2(\gamma)}} m_{K^\pm}}\right)^{1/2} \frac{1 - m_\mu^2/m_{\pi^\pm}^2}{1 - m_\mu^2/m_{K^\pm}^2} \left(1 - \frac{1}{2}\delta_{EM} - \frac{1}{2}\delta_{SU(2)}\right)$$

Inputs from experiment:

From $K^\pm$ BR fit:

$BR(K^\pm_{\mu 2(\gamma)}) = 0.6358(11)$
$\tau_{K\pm} = 12.384(15)$ ns

From PDG:

$BR(\pi^\pm_{\mu 2(\gamma)}) = 0.9999$
$\tau_{\pi\pm} = 26.033(5)$ ns

Inputs from theory:

δ_{EM} Long-distance EM corrections

$\delta_{SU(2)}$ Strong isospin breaking
$f_K/f_\pi \rightarrow f_{K\pm}/f_{\pi\pm}$

f_K/f_π Ratio of decay constants

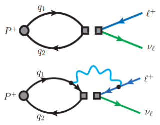
Cancellation of lattice-scale uncertainties from ratio

NB: Most lattice results already corrected for $SU(2)$-breaking: $f_{K\pm}/f_{\pi\pm}$

V_{us}/V_{ud} from lattice

Talk by F. Erben:

- Experiment very accurately determines $|V_{us}/V_{ud}|f_{K^+}/f_{\pi^+}$ [PDG, Prog. Theor. Exp. Phys. 2022, 083C01]
- Ratio of decay constants f_{K^+}/f_{π^+} can also be accuratley determined from lattice QCD
- sub-percent precision: **isospin-breaking** and **QED effects** need to be controlled!



Final result:

$$\frac{|V_{us}|}{|V_{ud}|} = \left[\frac{\Gamma(K \to \mu\nu)}{\Gamma(\pi \to \mu\nu)} \frac{m_K}{m_\pi} \frac{(m_\pi^2 - m_\mu^2)}{(m_K^2 - m_\mu^2)}\right]^{1/2} \frac{f_\pi}{f_K} \left(1 - \frac{1}{2}\delta R_{K\pi}\right)$$

with values from experiment, FLAG lattice average, and this calculation:

$$\delta R_{K\pi} = -0.0086(3)_{\text{stat.}}(^{+11}_{-4})_{\text{fit}}(5)_{\text{disc.}}(5)_{\text{quench.}}(39)_{\text{vol.}}$$

leading to

$$\frac{|V_{us}|}{|V_{ud}|} = 0.23154(28)_{\text{exp.}}(15)_{\delta R_{K\pi}}(45)_{\delta R_{K\pi},\text{vol.}}(65)_{f_\pi/f_K}$$

- our uncertainty is dominated by finite-volume error due to single lattice spacing - this will improve drastically in the near future! [Matteo Di Carlo, plenary at Lattice23]
- result in agreement with only other lattice calculation [Di Carlo et al., Phys.Rev.D 100 (2019) 3, 034514]
- $|V_{us}|/|V_{ud}|$ uncertainty dominated by f_π/f_K lattice average

New work: Prospects for a lattice calculation of the rare decay $\Sigma^+ \to p\,\ell^+\ell^-$, [F. Erben et al., JHEP 04 (2023) 108]

V_{us} and V_{us}/V_{ud} from kaons, first-row fit

Summary for V_{us} from kaon decays and first-row global fit (M. Moulson)

$K_{\ell 3}$ $f_+(0) = 0.9698(17)$ $N_f = 2+1+1$	$V_{us} = 0.22330(35)_{exp}(39)_{lat}(8)_{IB}$ $(53)_{tot} = 0.24\%$
$K_{\mu 2}$ $f_K/f_\pi = 1.1978(22)$ $N_f = 2+1+1$	$V_{us}/V_{ud} = 0.23108(23)_{exp}(42)_{lat}(16)_{IB}$ $(51)_{tot} = 0.22\%$

Fit results:

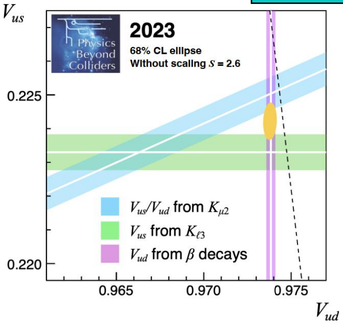
$V_{ud} = \mathbf{0.97378(26)}$

$V_{us} = \mathbf{0.22422(36)}$

$\chi^2/\mathrm{ndf} = 6.4/2\ (4.1\%)$

$\Delta_{CKM} = \mathbf{-0.0018(6)}$

-2.8σ



Prospects for V_{us} from kaon decays :

- New measurement of $K_{\mu 3}/K_{\mu 2}$ at NA62
- Precision measurements at proposed HIKE High Intensity Kaon Experiments:
  - Phase I, K^+ beam
  - Phase II, K_L beam

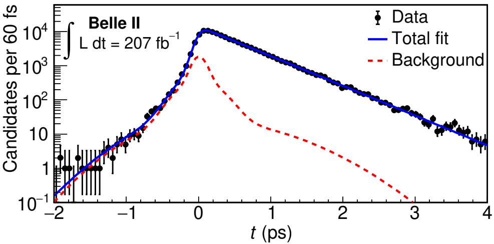
Outline

V_{ud}, V_{us}, and First-Row Unitarity

V_{cd}, V_{cs}, and (semi)-leptonic D decays

Charmed Hadron Lifetimes from BelleII (A. Schwartz)

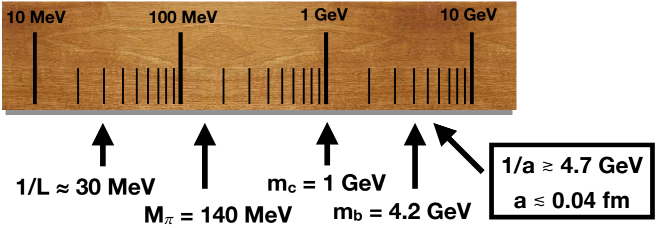
τ_{D_s}



	BelleII	PDG2020
D^0	$410.5 \pm 1.1 \pm 0.8$	410.3 ± 1.0
D^+	$1030.4 \pm 4.7 \pm 3.1$	1033 ± 5
D_s^+	$499.5 \pm 1.7 \pm 0.9$	504 ± 4
Λ_c^+	$203.20 \pm 0.89 \pm 0.77$	210.5 ± 2.7
	BelleII	LHCb 2022
Ω_c^0	$243 \pm 48 \pm 11$	$276.5 \pm 13.4 \pm 4.4 \pm 0.7$

- D_s^+, Λ_c^+ precision improved by $\sim 2x$ over world average
- Long Ω_c^0 lifetime confirmed by BelleII

New D Form Factors from the Lattice (W. Jay)



Heavy quarks are hard: lattice artifacts grow like powers $(am_h)^n$ — especially tricky for masses near or above the cutoff

$$\frac{1}{L} \ll M_\pi \ll m_h \ll \frac{1}{a}$$

W.I. Jay — MIT

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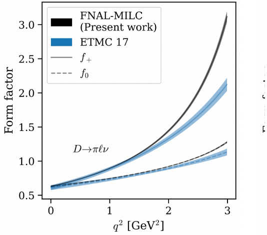
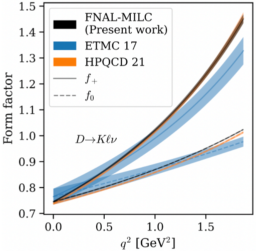
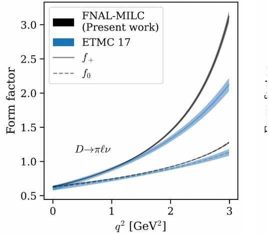
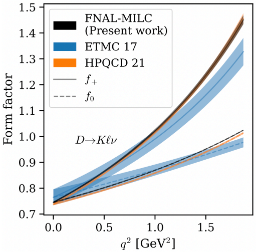
New D Form Factors from the Lattice (W. Jay)



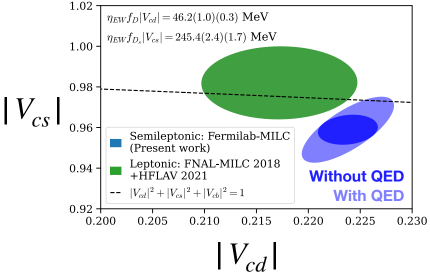


New D Form Factors from the Lattice (W. Jay)



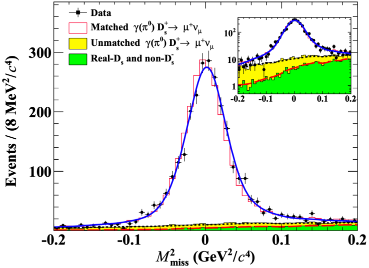


$\Rightarrow$



With BESIII $D \to K/\pi \ell \nu$

New $D_s^+ \to \ell\nu$ from BESIII (T.J. Wang)

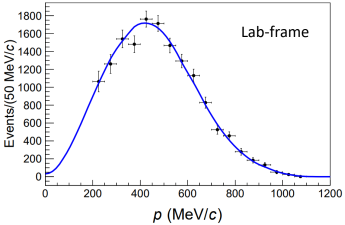


- $\sim 1.4\%$ precision on $|V_{cs}|$ from BESIII $D_s^+ \to \mu\nu$
- Many new measurements $D_s^+ \to \tau\nu$ in a variety of τ final states
- BESIII average determination of $|V_{cs}| = 0.9774 \pm 0.0056 \pm 0.0072$
- Sub-percent level precision, further reductions from improved D_s^+ lifetime measured at BelleII

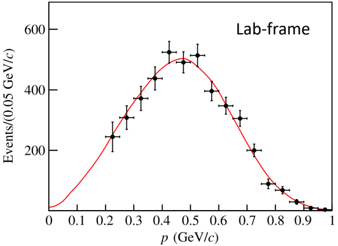
Inclusive $c \to X\ell\nu$ (from M. Prim)

Recent measurements from BESIII

$D_s^+ \to Xe\nu$



$\Lambda_c \to Xe\nu$



- Lepton momentum spectra extrapolated to zero-recoil based on sum-of-exclusive model
- In principle, access to HQE lepton energy moments

Inclusive $c \to X\ell\nu$ (from K. Vos)

HQE for charm revisited

$\rho = m_s^2/m_c^2$

Fael, Mannel, KKV, hep-ph/1910.05234

$$\frac{\Gamma(D \to X_s\ell\nu)}{\Gamma_0} = \left(1 - 8\rho - 10\rho^2\right)\mu_3 + (-2 - 8\rho)\frac{\mu_G^2}{m_c^2} + 6\frac{\tilde{\rho}_D^3}{m_c^3} + \frac{16}{9}\frac{r_G^4}{m_c^4} + \frac{32}{9}\frac{r_E^4}{m_c^4} - \frac{34}{3}\frac{s_B^4}{m_c^4} + \frac{74}{9}\frac{s_E^4}{m_c^4} + \frac{47}{36}\frac{s_{qB}^4}{m_c^4} + \frac{\tau_0}{m_c^3}$$

Key question: HQE indeed applicable to inclusive charm decays?

- My wish: Extract HQE and WA directly from q^2 moments at BESIII

Future Prospects on D leptonic/semileptonic decays

- 20 fb^{-1} of D^+ and D^0 data from BESIII by 2024 ($\sim 7x$ current data)
- Exciting prospects from BelleII in D leptonic/semileptonic
  - 10000 $D_s^+ \to \mu\nu$ decays from 20 ab^{-1}, compared to 2500 from current BESIII data
- Inclusive $c \to X\ell\nu$ has strong prospects for tests of HQE

Final Summary