The Cabibbo Angle Anomaly – the bigger picture

Matthew Kirk

Beyond the Flavour Anomalies V – 11 April 2024

CKM Matrix

- 3x3 unitary matrix, by construction
- Implies many relationships between elements
  - 9 complex elements, but only 4 parameters
- Including:
  - $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$

First row unitarity

- $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$
- $|V_{ub}|^2$ is very small, less than current uncertainties
- So we can approximate: $|V_{ud}|^2 + |V_{us}|^2 = 1$

Cabibbo approximation

- For a 2x2 unitary matrix, there is a very simple form: $$\begin{pmatrix} \cos\theta_C & \sin\theta_C \\ -\sin\theta_C & \cos\theta_C \end{pmatrix}$$

- With only one parameter – the Cabibbo angle!

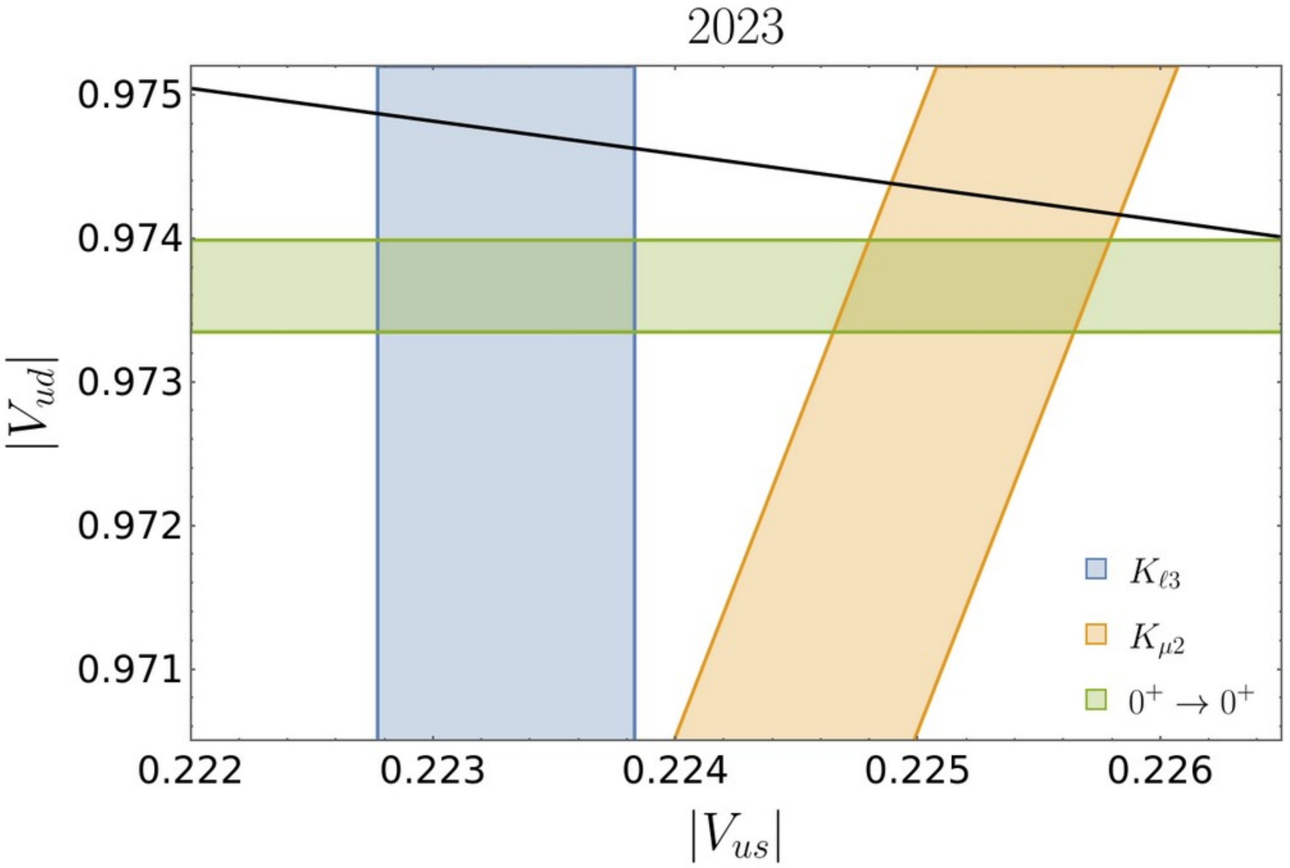
Cabibbo Angle

- SM makes a clear prediction:

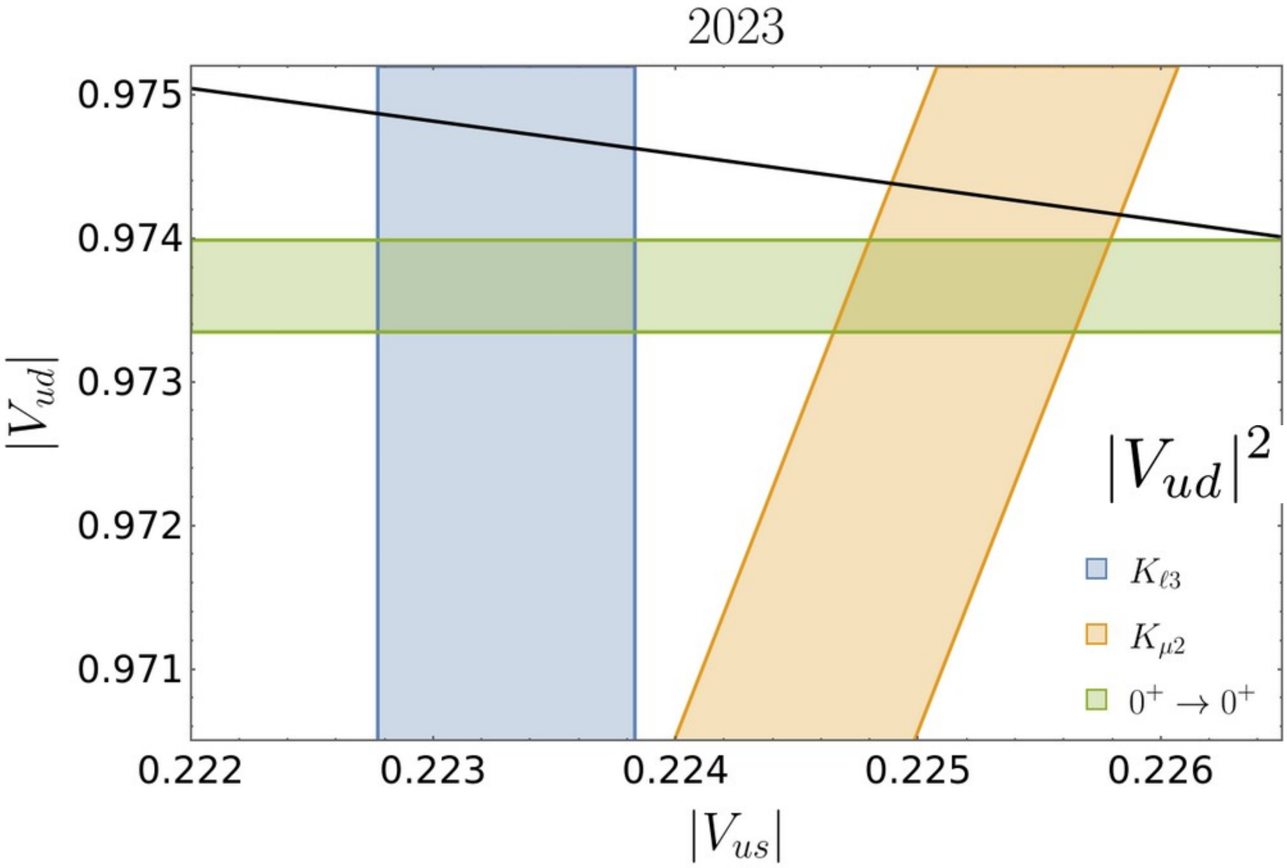
$$\theta_C = \arccos V_{ud} = \arcsin V_{us} = \arctan V_{us}/V_{ud}$$

  - But doesn’t predict the value

Cabibbo Angle Anomaly

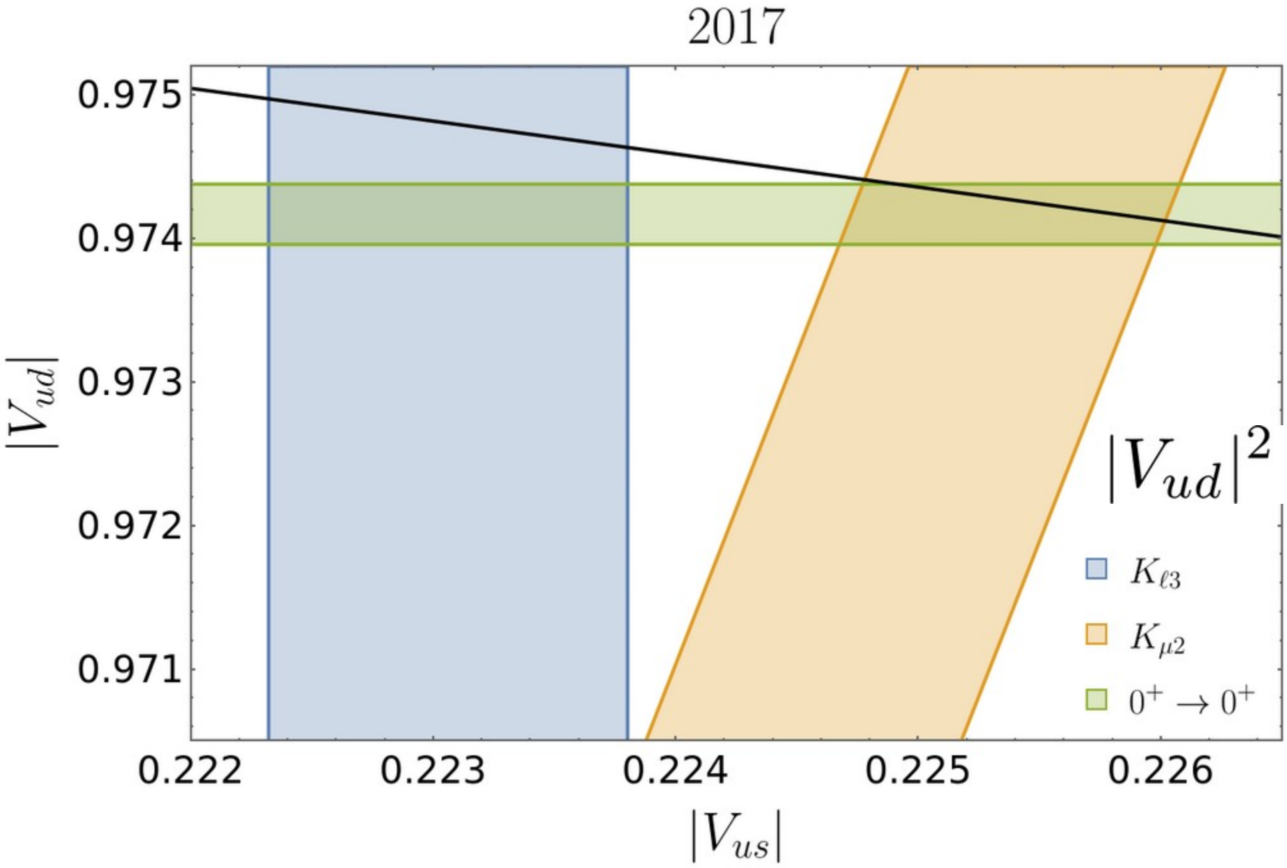


Cabibbo Angle Anomaly



$$|V_{ud}|^2 + |V_{us}|^2 = 0.9985 \pm 0.0005$$

Cabibbo Angle Anomaly



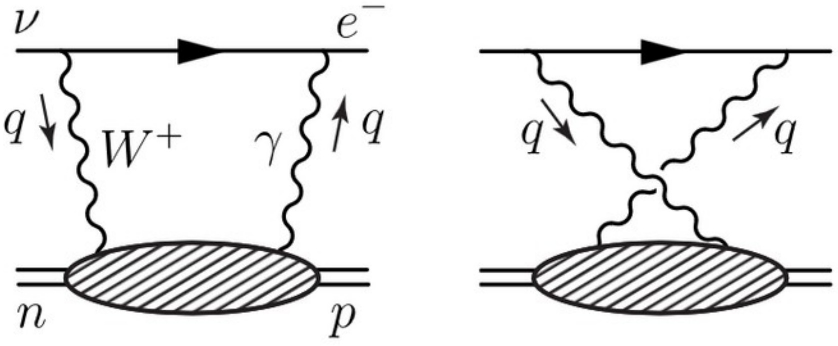
$$|V_{ud}|^2 + |V_{us}|^2 = 0.9993 \pm 0.0005$$

What changed?

- Improvements to lattice QCD
- Nuclear corrections to beta decay
  - Δ_R^V: Nucleus independent radiative corrections / inner correction (d → u vs neutron → proton)
  - δ_{NS}: nuclear structure uncertainties (neutron → proton vs ^{14}O → ^{14}N vs ^{34}Ar → ^{34}Cl vs ^{74}Rb → ^{74}Kr vs …)

Nuclear corrections

- Lots of recent progress in the $\gamma - W$ box EW radiative correction using various methods



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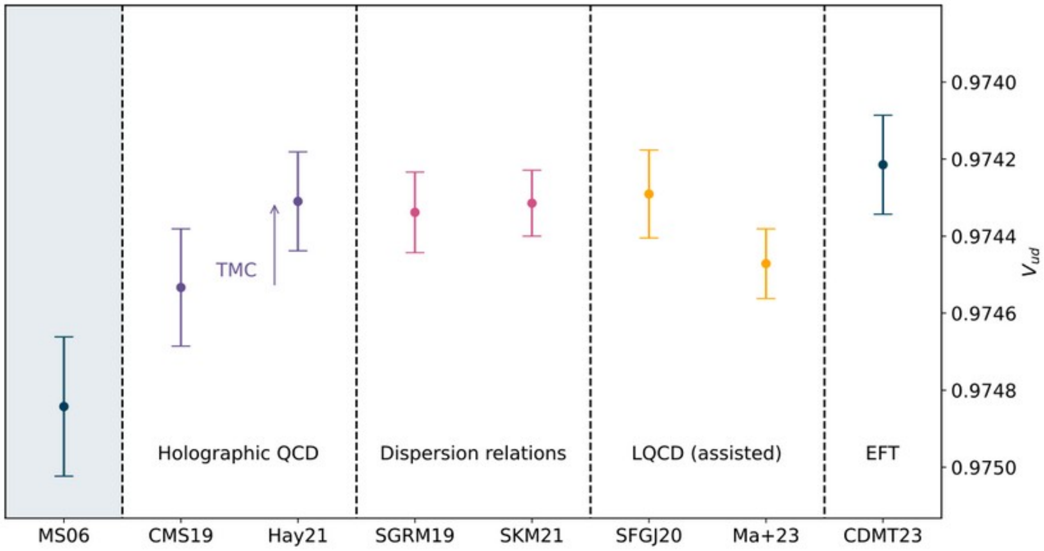
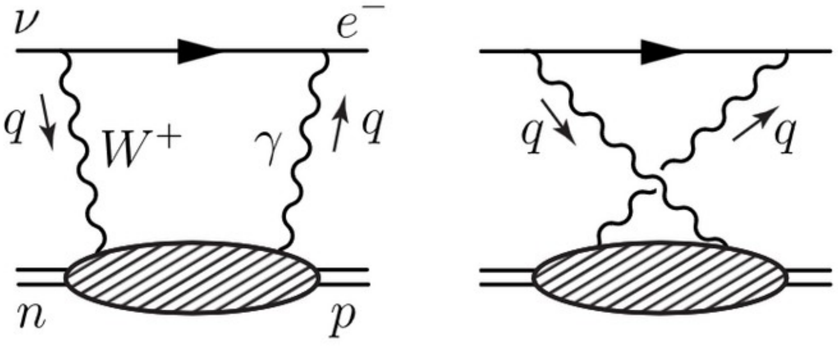


2403.08485

Nuclear corrections

- Lots of recent progress in the $\gamma - W$ box EW radiative correction using various methods
- Reassessment of nuclear structure uncertainties in progress



Aside on beta decay

- Opportunities and open questions in modern beta decay
  - arXiv: 2403.08485
- "As is well known, beta decay is full of surprises and subtleties. Its apparent perversities have threatened us not once but twice with the abandonment of some of our cherished conservation laws"
  - C.S. Wu

What's behind this?

- Low energy EFT
- EW scale modifications
- BSM models

Low energy EFT

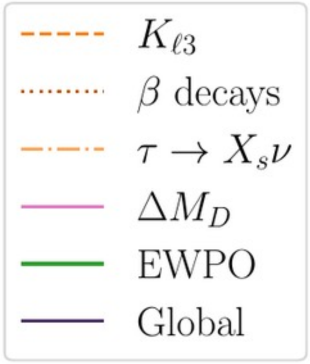
- Modifications of $2q2\ell$ decays
  - Checks from LFU tests of π, K decays
  - Good fit to BSM in $(\bar{u}\gamma^\mu P_L d)(\bar{e}\gamma_\mu P_L \nu_e)$ 2101.07811 (Crivellin, Müller, Schnell)
- Modifications of 4ℓ decays – affects G_F
  - Since G_F is a normalisation for semileptonic decays
  - Reduces tensions but doesn't solve it

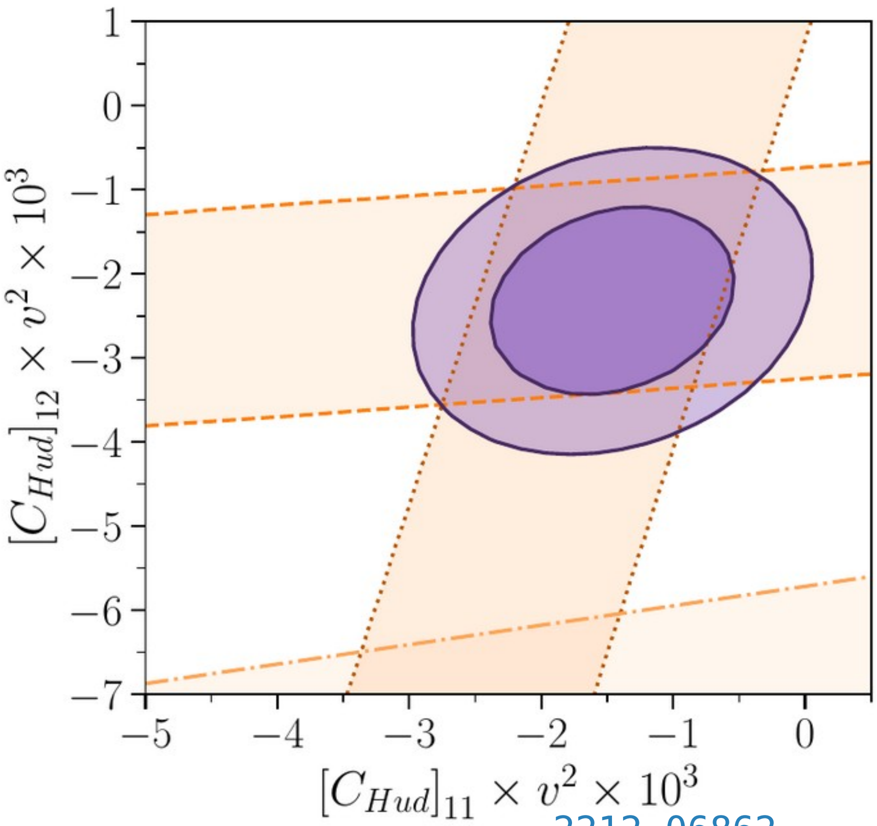
EW scale modifications

- Modifications of $W - q - q'$ or $W - \ell - \nu$
- For both: $SU(2)$ invariance demands changes to $Z - q - q$ or $Z - \ell - \ell$
  - Other constraints from EWPO, low energy parity violation or $\Delta F = 2$

EW scale modifications

- Modifications of RH $W-u-d$ and $W-u-s$
- Pull of $3.2\,\sigma$ relative to SM





2212.06862
(Crivellin, MK, Kitahara, Mescia)

BSM models

- Leptoquarks
- W′
- Vector-like leptons
- Vector-like quarks

BSM models

- Leptoquarks
- W′
- Vector-like leptons
- **Vector-like quarks**

- Can generate RH currents
- Only one of two tree level BSM options

Vector-like quarks

- 7 representations that couple to SM at tree level

Vector-like quarks

-

Name	U	D	Q_1	Q_5	Q_7	T_1	T_2
Irrep	$(3,1)_{\frac{2}{3}}$	$(3,1)_{-\frac{1}{3}}$	$(3,2)_{\frac{1}{6}}$	$(3,2)_{-\frac{5}{6}}$	$(3,2)_{\frac{7}{6}}$	$(3,3)_{-\frac{1}{3}}$	$(3,3)_{\frac{2}{3}}$

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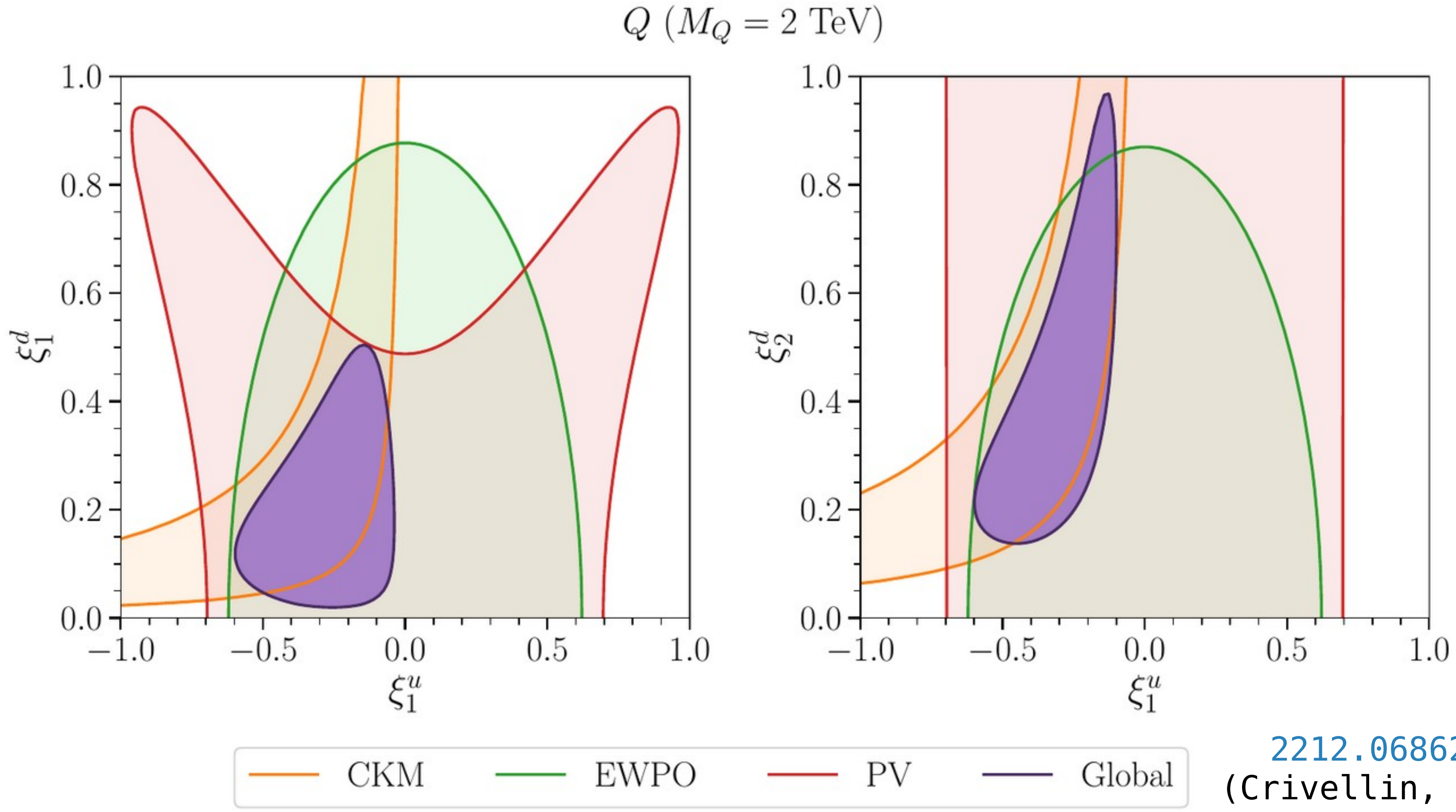
- $SU(2)$ singlets/triplets modify LH W coupling
- (Only one) $SU(2)$ doublet generates RH W couplings

Vector-like quarks

- Only Q_1 $SU(2)$ doublet generates RH W couplings
  - $\mathcal{L} \supset -\xi_i^u \overline{Q_1} \tilde{H} u_i - \xi_i^d \overline{Q_1} H d_i$
  - Q_1 with u and d couplings alters V_{ud}
  - Q_1 with u and s couplings alters V_{us}
- EWPO less strong, meson mixing almost absent, low energy PV important

Vector-like quarks



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Links to other BSM – sterile neutrinos

MeV Sterile Neutrino in light of the Cabibbo-Angle Anomaly

Teppei Kitahara[1,2,*] and Kohsaku Tobioka[3,4,†] 2308.13003

- O(1–10) MeV neutrino, 5% mixing with electron neutrino
- But need ~30 TeV BSM to avoid LFUV in leptonic pion/kaon decay ($M \to e\nu / M \to \mu\nu$)

Links to other BSM - M_W

Beta-decay implications for the W-boson mass anomaly
(Cirigliano, Dekens, de Vries, Mereghetti, Tong) 2204.08440

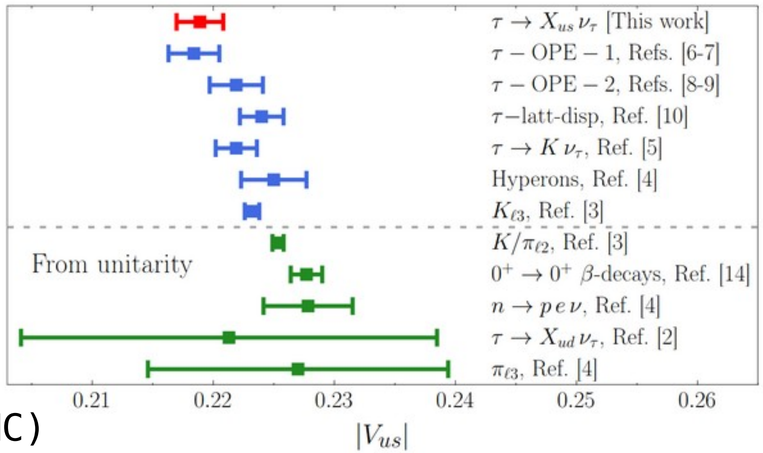
- In SMEFT, M_W modified by $O_{HD}, O_{HWB}, O_{H\ell}^{(3)}, O_{\ell\ell}$
- Latter two via G_F, and as mentioned changes to G_F affect CKM determinations
- Best fit to EW only data => % CKM unitarity violation
- Reduce by including $C_{\ell q}$, but then violates bounds from Drell-Yan tails

Links to other BSM – tau decays

- Belle II data on tau decay to strange hadrons will give better sensitivity to different BSM operators involving strange

2112.02087 (Cirigliano, Díaz-Calderón, Falkowski, González-Alonso, Rodríguez-Sánchez)

- Recent new determination of V_{us} from inclusive tau decays using lattice

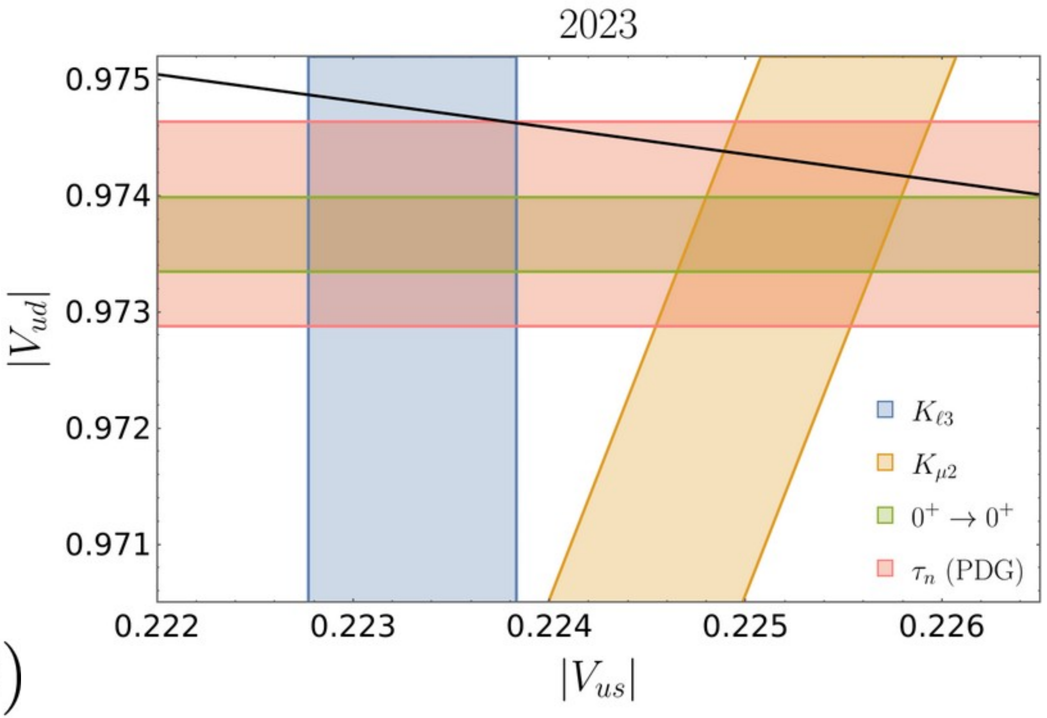


2403.05404 (ETMC)

Where next?

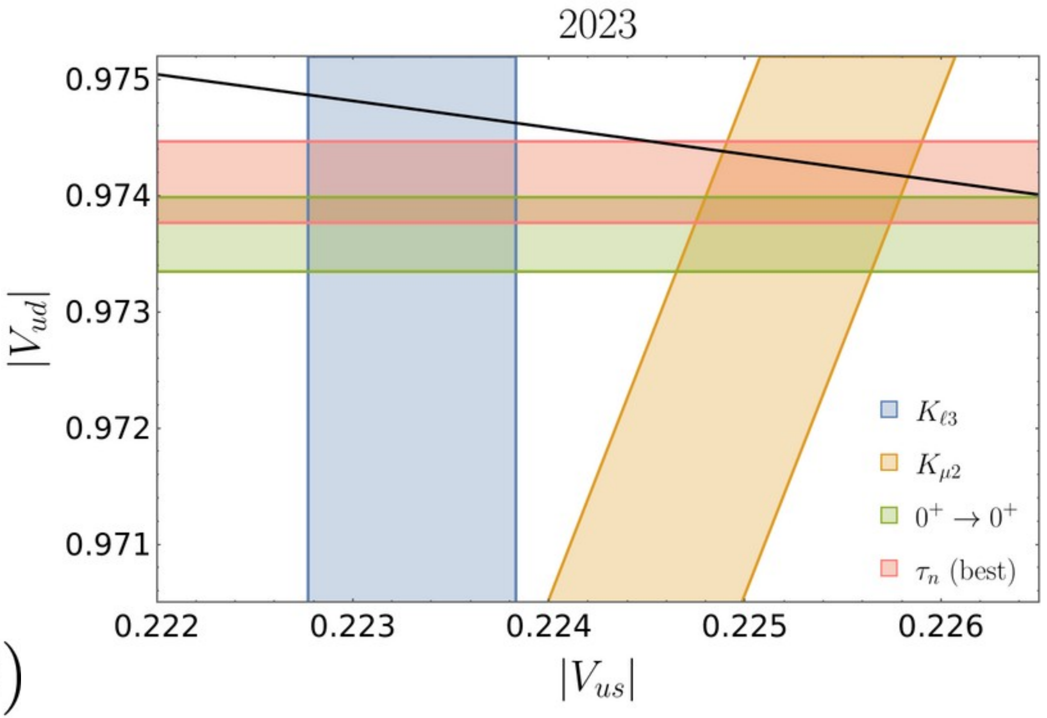
- Neutron lifetime
  - Current PDG average for lifetime and g_A not competitive with super-allowed beta decays

$$\frac{1}{\tau_n} \propto G_F^2 V_{ud}^2 (1 + 3g_A^2)(1 + \text{RC})$$



Where next?

- Neutron lifetime
  - World best lifetime (bottle, $\mathrm{UCN}\tau$)+g_A (PERKEO III) gives comparable precision to super-allowed beta decays



$$\frac{1}{\tau_n} \propto G_F^2 V_{ud}^2 (1 + 3g_A^2)(1 + \mathrm{RC})$$

Where next?

- PIONEER (v. long term)
  - Pion beta decay, currently known at ~0.6%, need order of magnitude improvement to be competitive with super-allowed beta decay
  - Factor of 3 in phase II, factor 10 in phase III hopefully

Where next?

- PIONEER (not quite so long term)
  - In Phase I, measure $\pi^+ \to \mu\nu / \pi^+ \to e\nu$
  - Check LFUV, useful for VLL models

Summary

- Still appears to be a $\sim 3\,\sigma$ anomaly in CKM unitarity
- Q_1 VLQ seem a good BSM candidate
- Interesting links between CAA to neutrino sector, MW, tau decays, general EW and collider physics

Discussion points

- Can neutron lifetime measurements converge?
- What progress will be made in V_{us} from tau?
- RH currents from g_A (exp vs lattice)?
- Discovering a VLQ or VLL at Belle II?
- Are there other low energy precision observables we should be including in global fits?

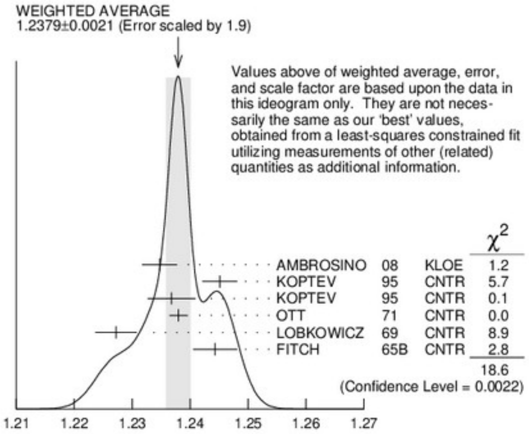
Backup

Future experiments?

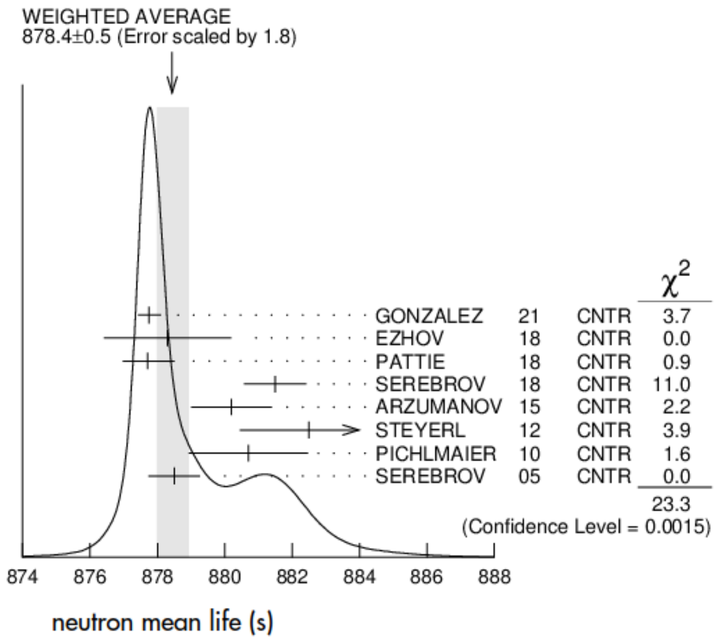
- NA62 could measure $K_{\ell 3}/K_{\mu 2}$
- Two weeks of data could increase tension to $4\,\sigma$
  - See 2208.11707

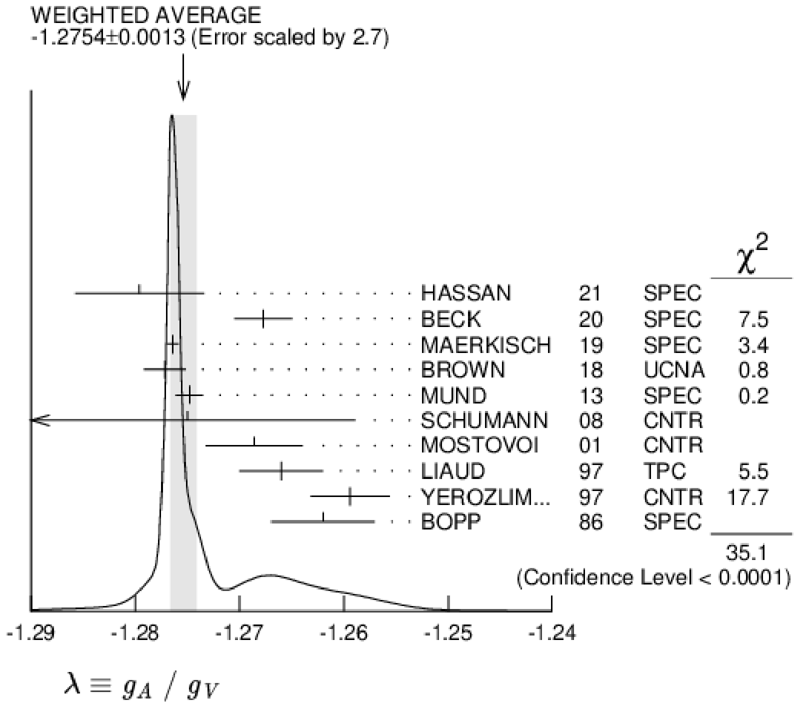
(Cirigliano, Crivellin, Hoferichter, Moulson)

- Also new data in $K_{\mu 2}$ would be good
  - Only recent data from KLOE in 2008



Neutron lifetime, gA

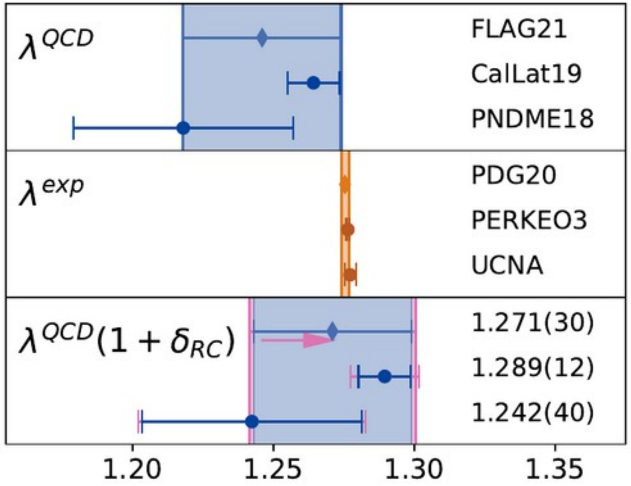




RH currents from axial coupling

- If neutron lifetime precision confirms CAA, useful to look at axial coupling more carefully for signs of RH currents
- $g_A^{\text{exp}} = g_A^{\text{LQCD}}(1 + 2\delta^{\text{RC}} - 2\epsilon_R)$

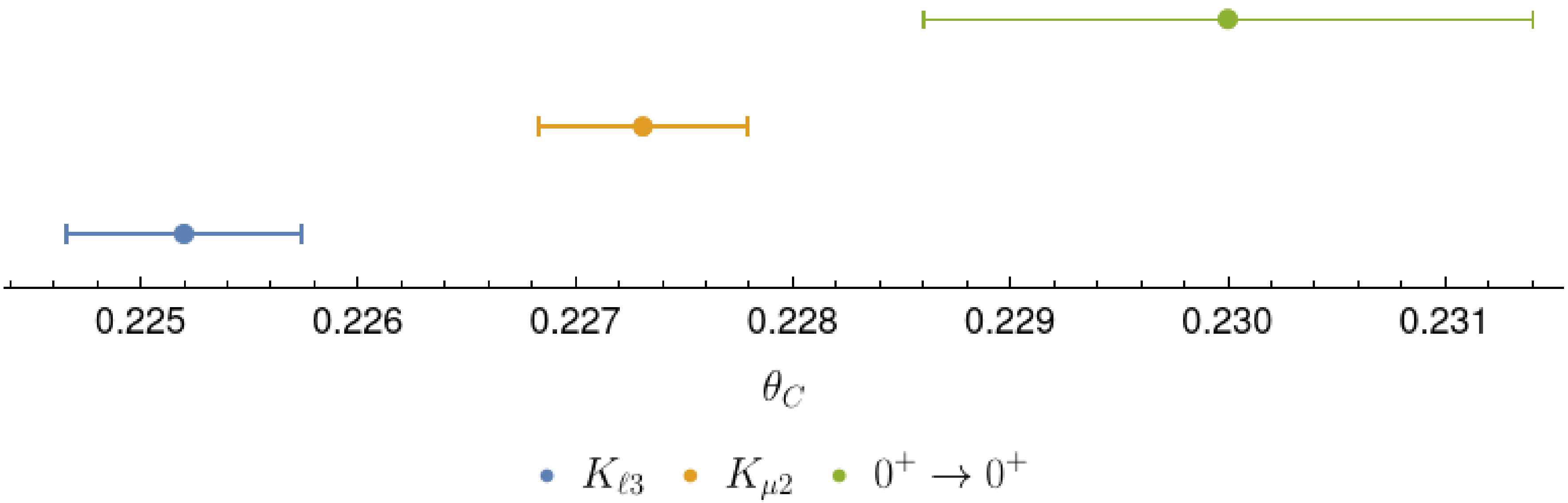
2202.10439 Cirigliano, de Vries, Hayen, Mereghetti, Walker-Loud



"I believe LQCD can reach 0.1 - 0.2% for isospin symmetric gA in the ~5-year time-scale" – A. Walker-Loud (MITP October 2022)

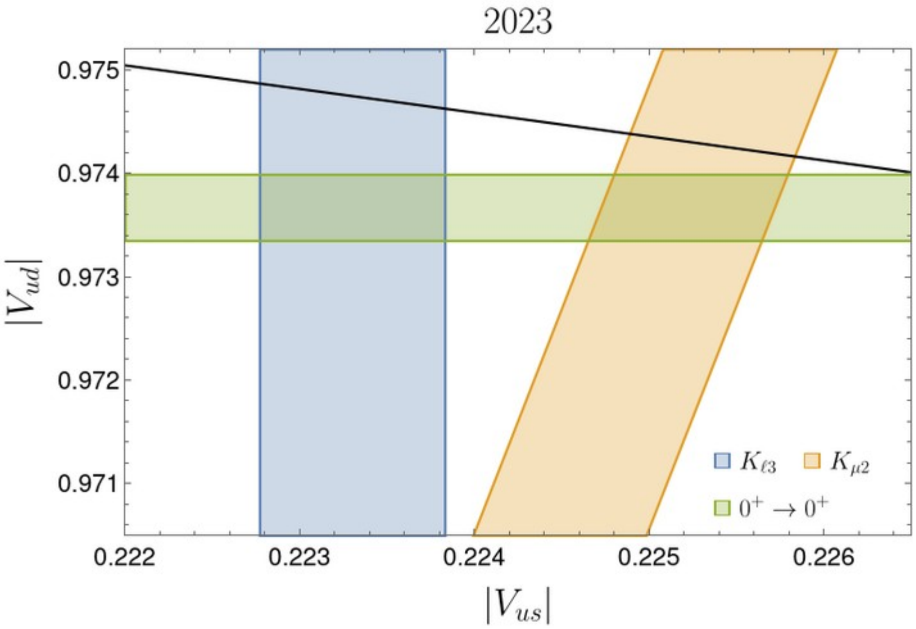
Cabibbo Angle

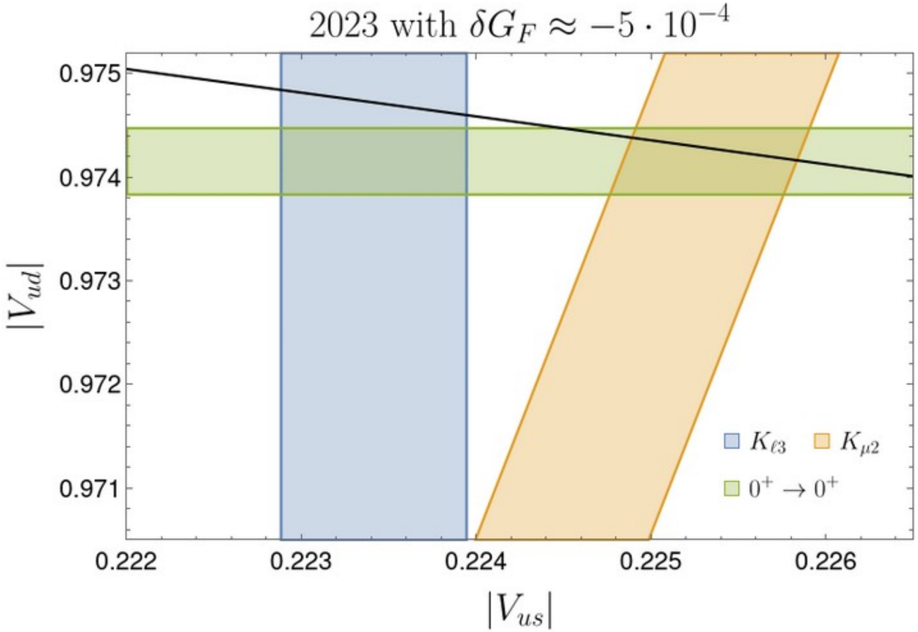
$$\theta_C = \arccos V_{ud} = \arcsin V_{us} = \arctan V_{us}/V_{ud}$$



Low energy EFT ideas

- Modifications of GF / muon decay
- Reduces tensions but doesn't solve it





EW scale modifications

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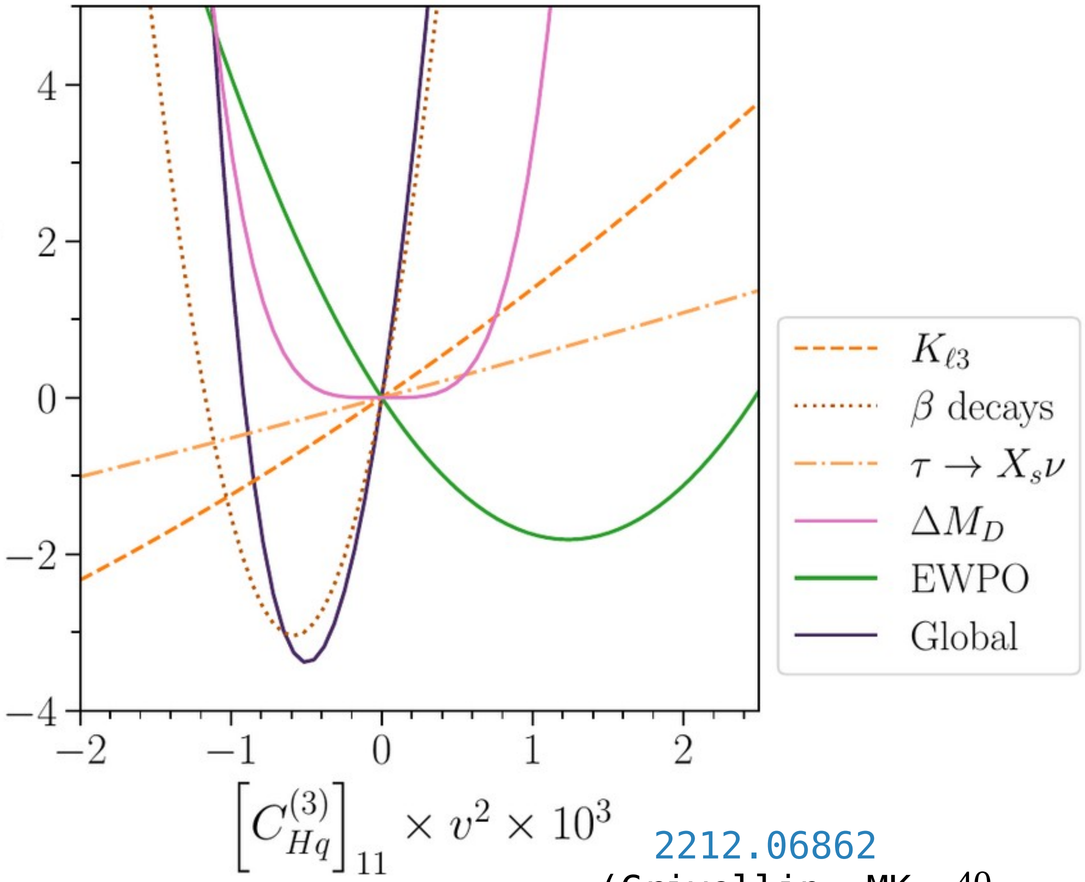
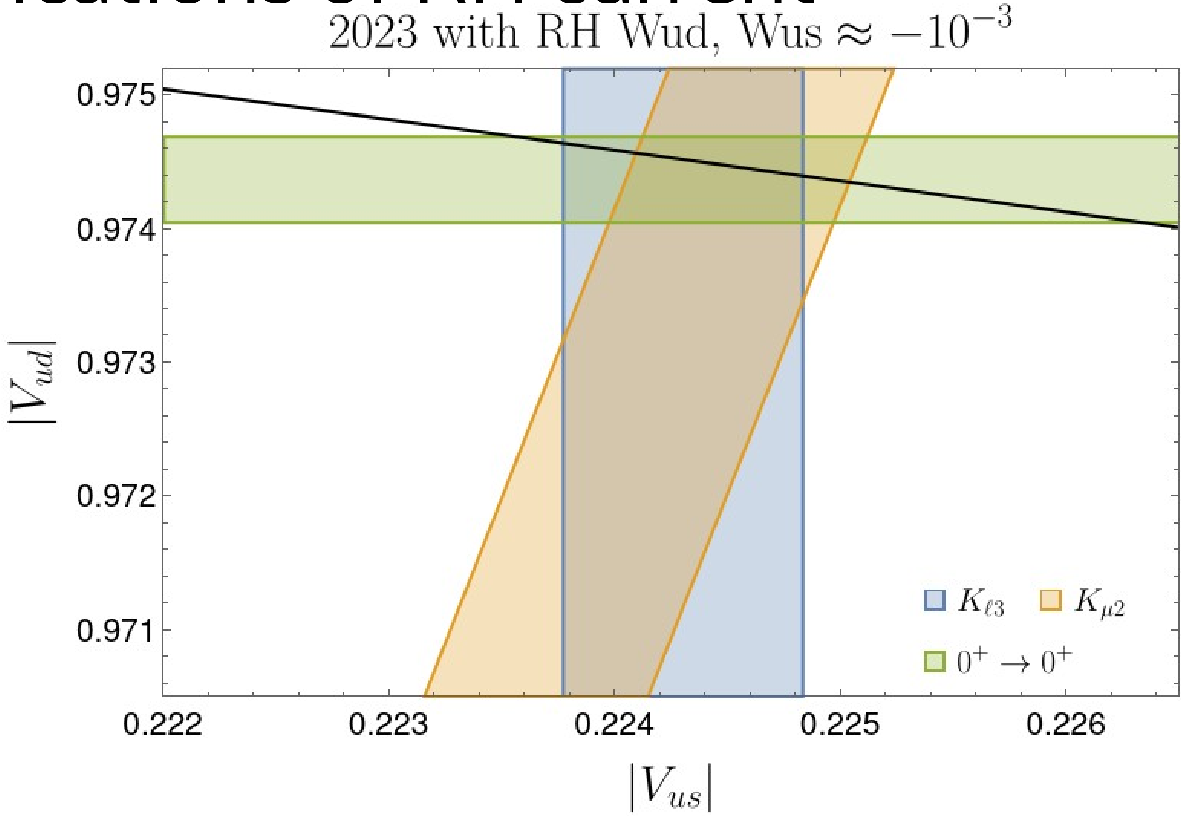
- Pull of $2\,\sigma$ relative to SM



2212.06862 (Crivellin, MK, Kitahara, Mescia)

EW modifications

- Modifications of RH current



BSM models

- **LQs**
- W′
- VLLs
- VLQs

- Lots of related flavour constraints
- PV, D/K mixing
- Also LHC Drell-Yan

BSM models

- LQs
- W′
- VLLs
- VLQs

- Often comes with a Z′
- That leads to Z mass change, $\Delta F = 2$, PV
- Again Drell-Yan

BSM models

- LQs
- W'
- **VLLs**
- VLQs

- Also alter EW fit through modifications of $Z - \ell - \ell$
- Decent fit with two VLLs (one with μ coupling, one with e)

2008.01113
(Crivellin, Kirk, Manzari, Montull)

VLLs – singlet and triplet

- VLLs coupled to muons and electrons
- Good improvement in CKM data
- And also slight improvement in EWPO
- See 2008.01113

  (Crivellin, Kirk, Manzari, Montull)