The Cabibbo Angle Anomaly and potential BSM explanations

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(mostly based on 2212.06862 with Crivellin, Kitahara, Mescia)

Beyond the Flavour Anomalies IV – 20 April 2023

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!

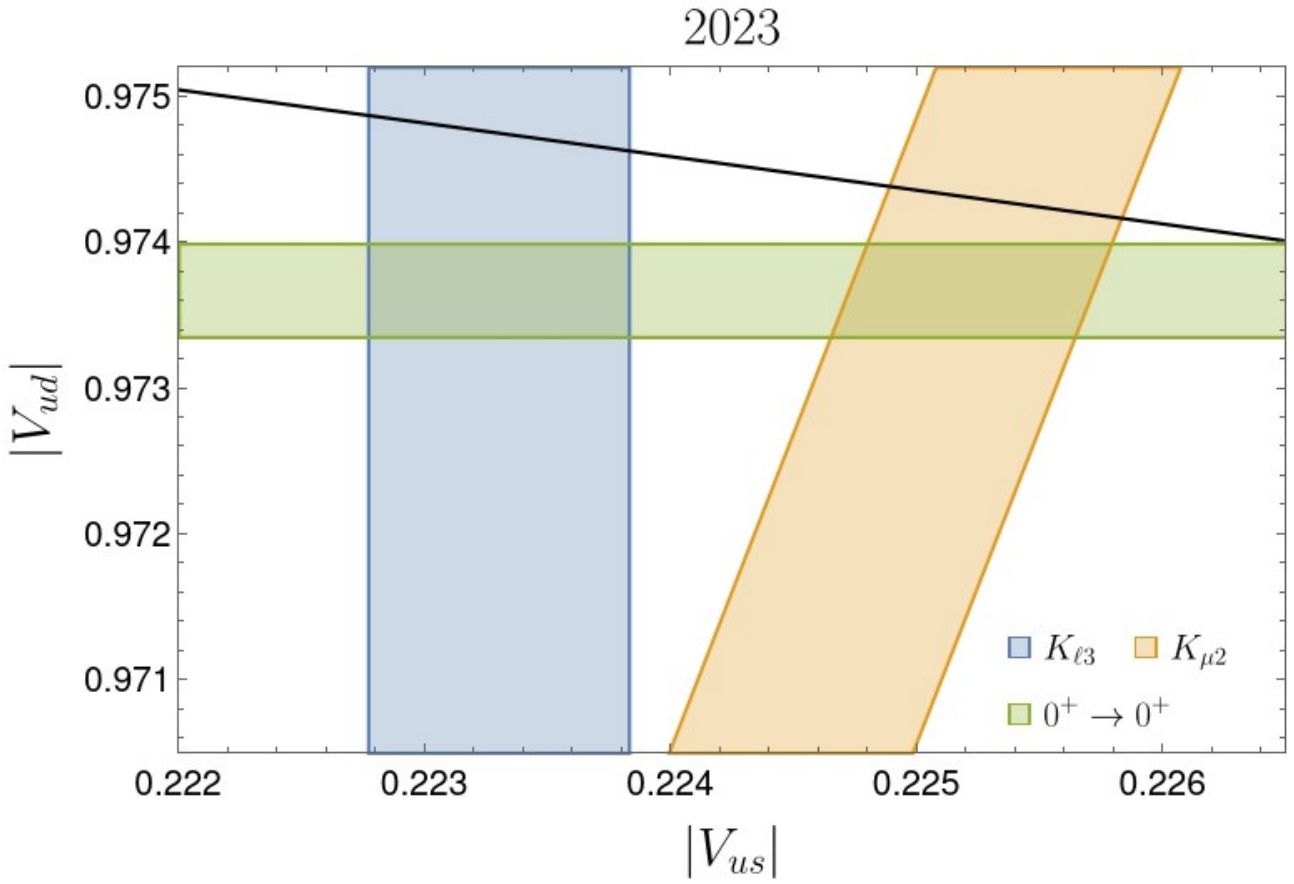
Cabibbo Angle

- SM makes a clear prediction:

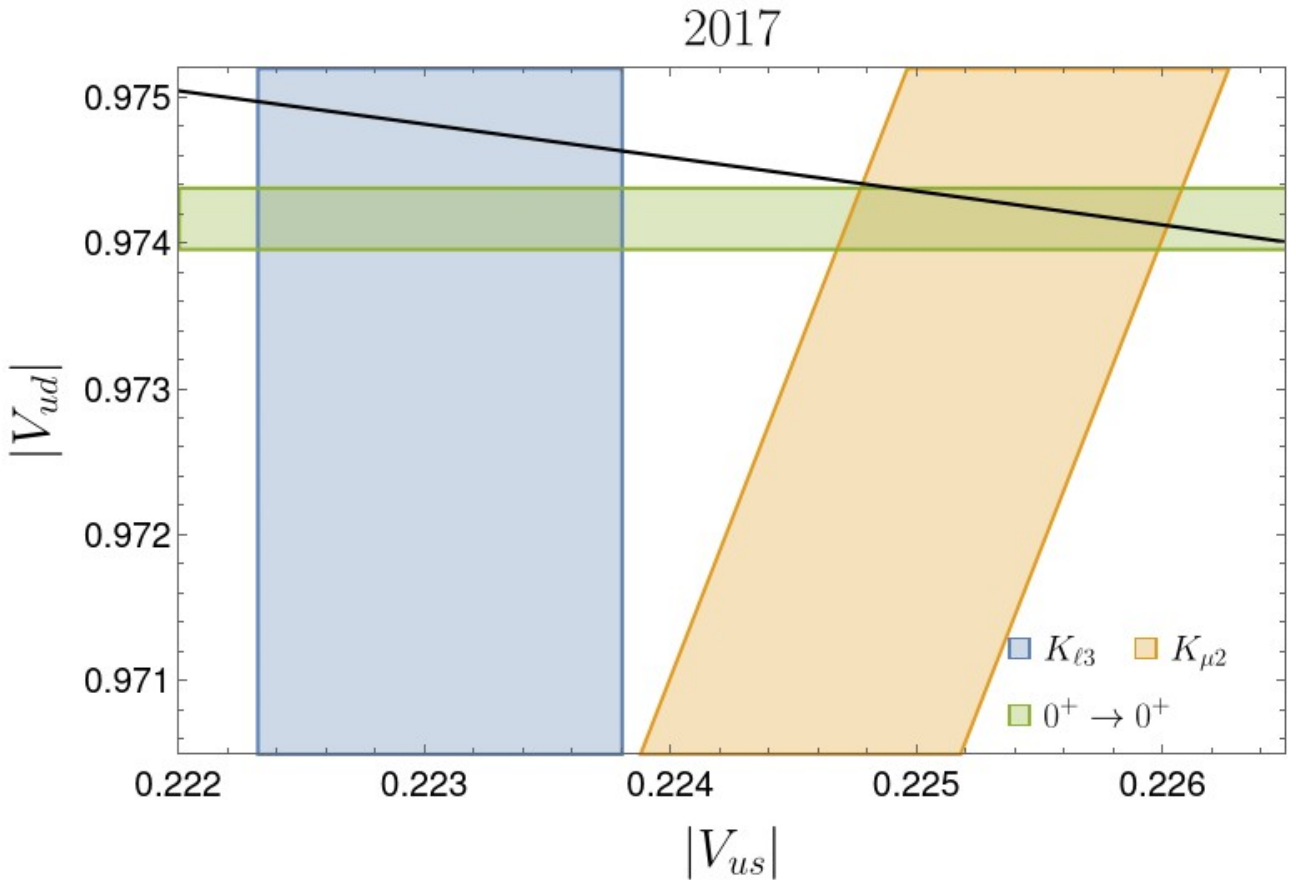
  $$\theta_C = \arccos V_{ud} = \arcsin V_{us} = \arctan V_{us}/V_{ud}$$

  - But doesn't predict the value

Cabibbo Angle Anomaly



Cabibbo Angle Anomaly



What changed?

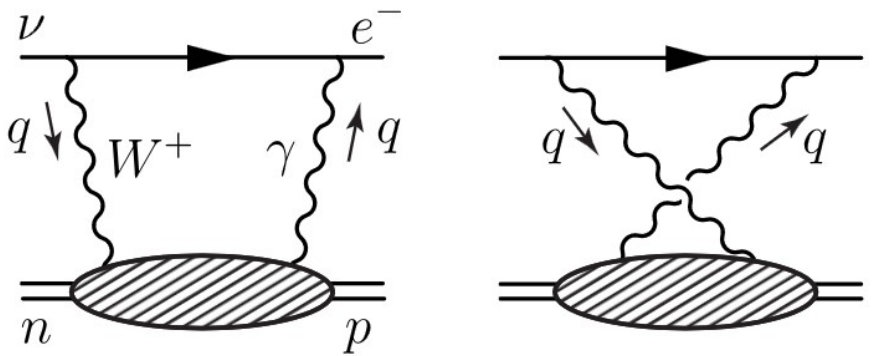
- Improvements to lattice QCD
  - f_K/f_π
    - FLAG 2017 update = $1.1930 \pm 0.0030\,(N_f = 2+1+1)$
    - FLAG 2023 update = $1.1934 \pm 0.0019\,(N_f = 2+1+1)$
  - $f_+(0)$
    - FLAG 2017 update = $0.9706 \pm 0.0027\,(N_f = 2+1+1)$
    - FLAG 2023 update = $0.9698 \pm 0.0017\,(N_f = 2+1+1)$

What changed?

- Nuclear corrections to beta decay
  - Experimentally, superallowed ($0^+ \to 0^+$) are known very precisely (around one part per 10 000)
  - But the theoretical corrections from pure beta decay ($d \to u\ell\nu$) to nuclear beta decay are complicated

Nuclear corrections

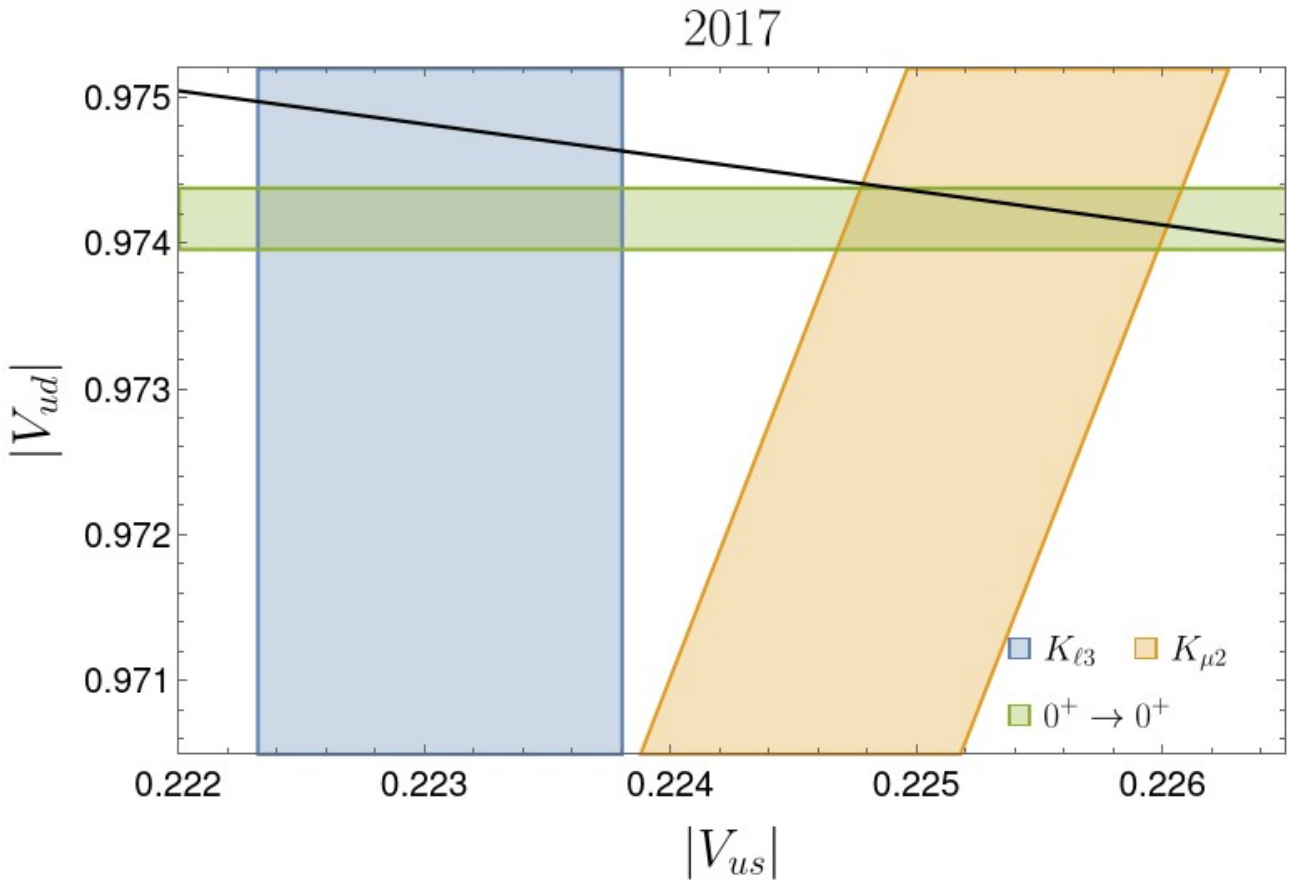
- But the theoretical corrections from pure beta decay ($d \to u\ell\nu$) to nuclear beta decay are complicated
- Lots of recent progress in the $\gamma - W$ box EW radiative correction



Nuclear corrections

- $\gamma - W$ box increased by about $3\,\sigma$, but now has half the error
  - See appendix of 2208.11707 for discussion
    (Cirigliano, Crivellin, Hoferichter, Moulson)
- However, new analysis of isospin-breaking corrections and other nuclear uncertainties has lead to larger error estimates

Cabibbo Angle Anomaly



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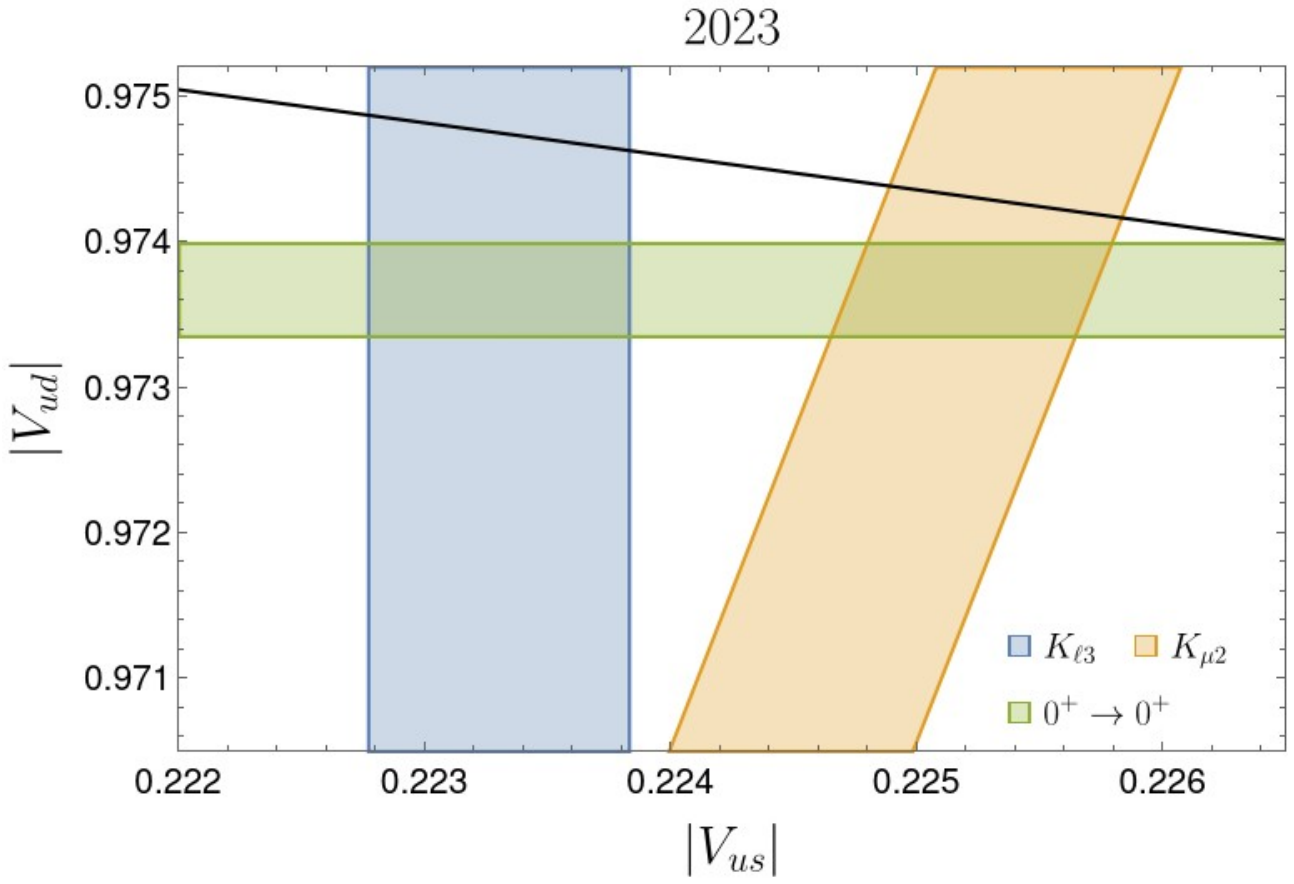


What's behind this?

- Low energy EFT
- EW scale modifications
- BSM models

Low energy EFT

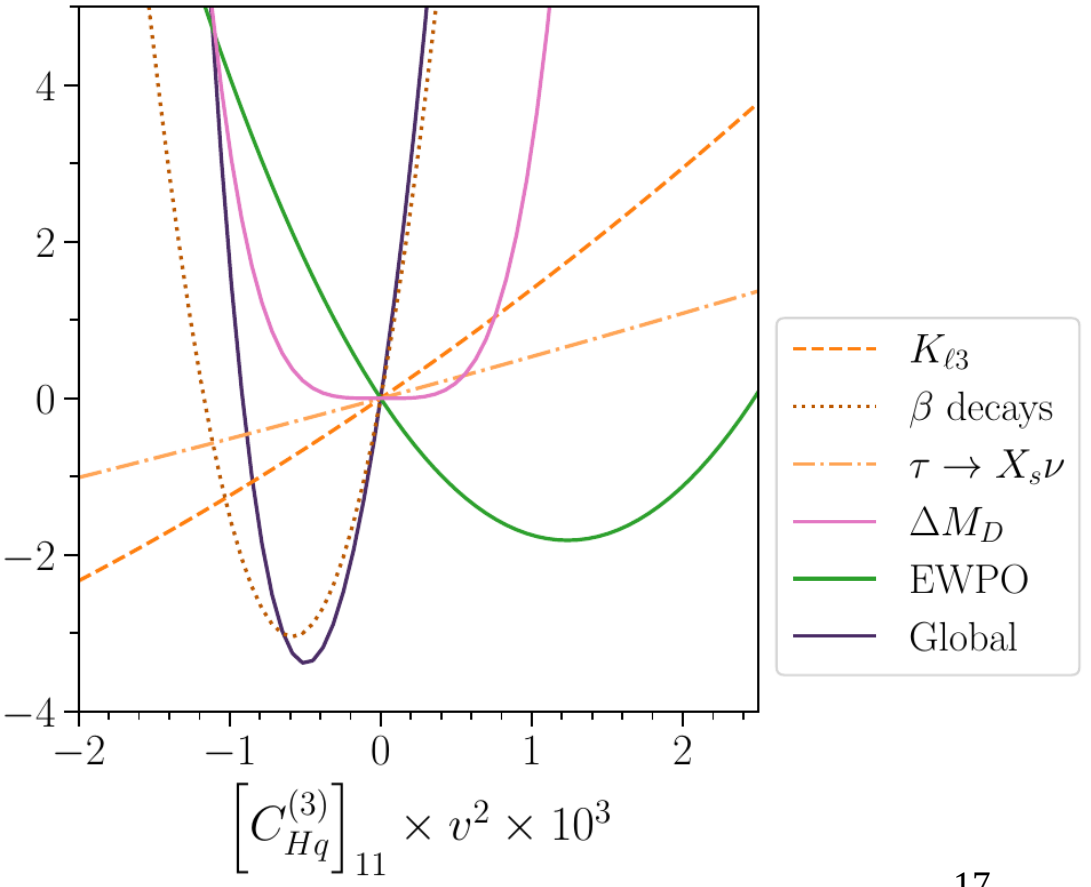
- Modifications of $2q2\ell$ decays
  - Checks from LFU tests of π, K decays
  - Good fit to BSM in $(\bar{u}\gamma^\mu P_L d)(\bar{e}\gamma_\mu P_L \nu_e)$ 2101.07811 (Crivellin, Müller, Schnell)
- Modifications of 4ℓ decays – affects G_F
  - Since G_F is a normalisation for semileptonic decays
  - 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 $\Delta F = 2$

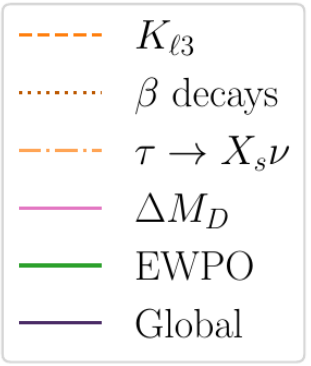
EW scale modifications

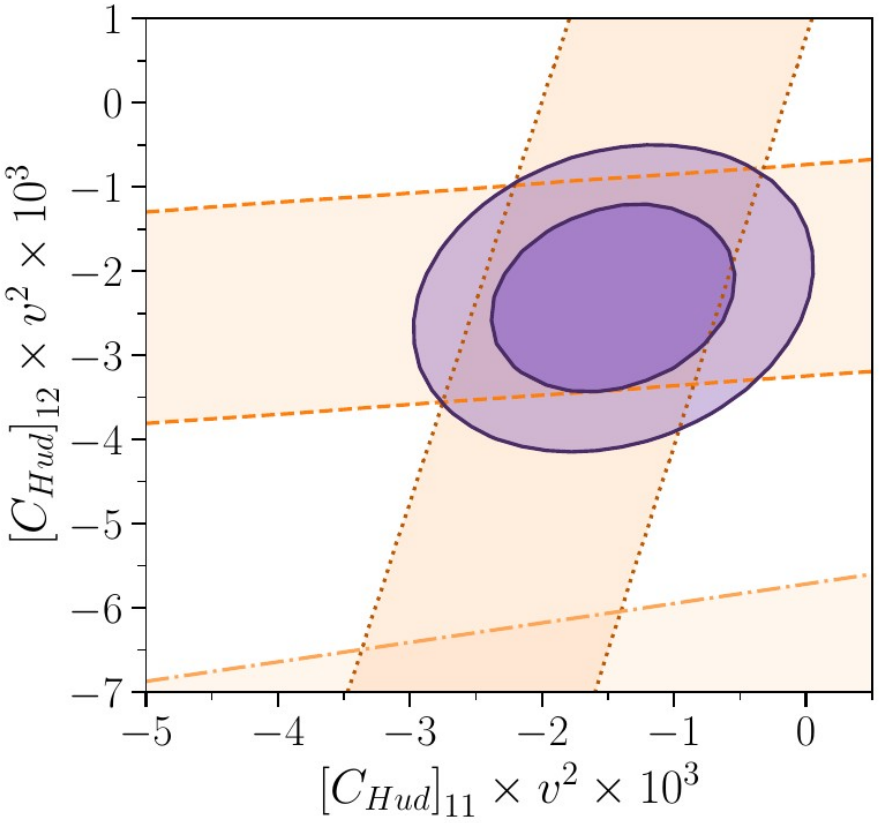
- Modifications of LH $W-u-d$
- Pull of $2\,\sigma$ relative to SM



EW scale modifications

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





BSM models

- LQs
- W′
- VLLs
- VLQs

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)

BSM models

- LQs
- W′
- VLLs
- **VLQs**

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

Vector-like quarks

- $SU(2)$ triplets modify LH W coupling
- But with wrong sign

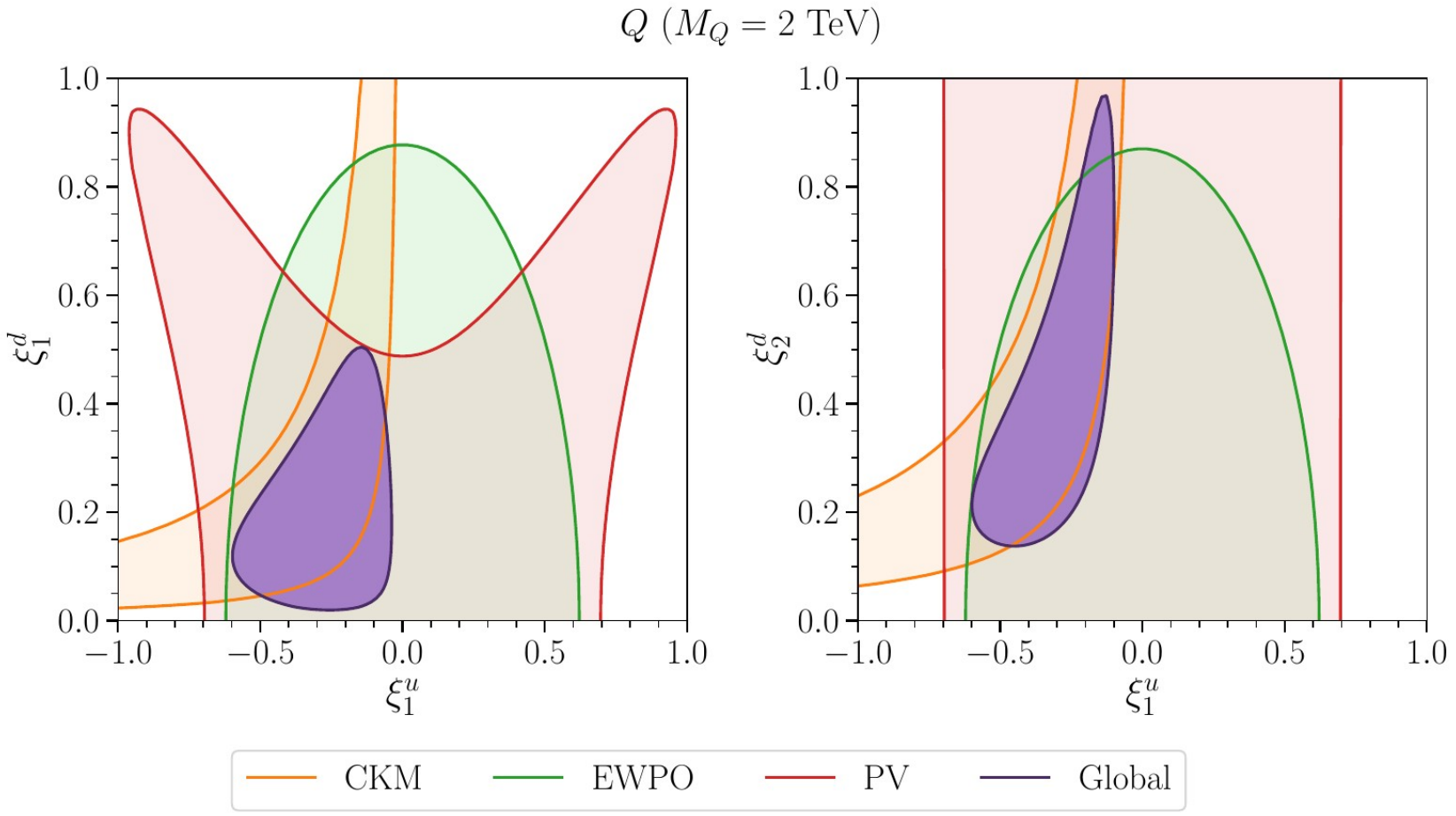
Vector-like quarks

- $SU(2)$ singlets modify LH W coupling
  - With right sign!
- But strong constraints from K/D mixing, as well as EWPO and low energy parity violation
- Overall $2\,\sigma$ pull vs SM

Vector-like quarks

- Only Q_1 $SU(2)$ doublet generates RH W couplings
  - 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



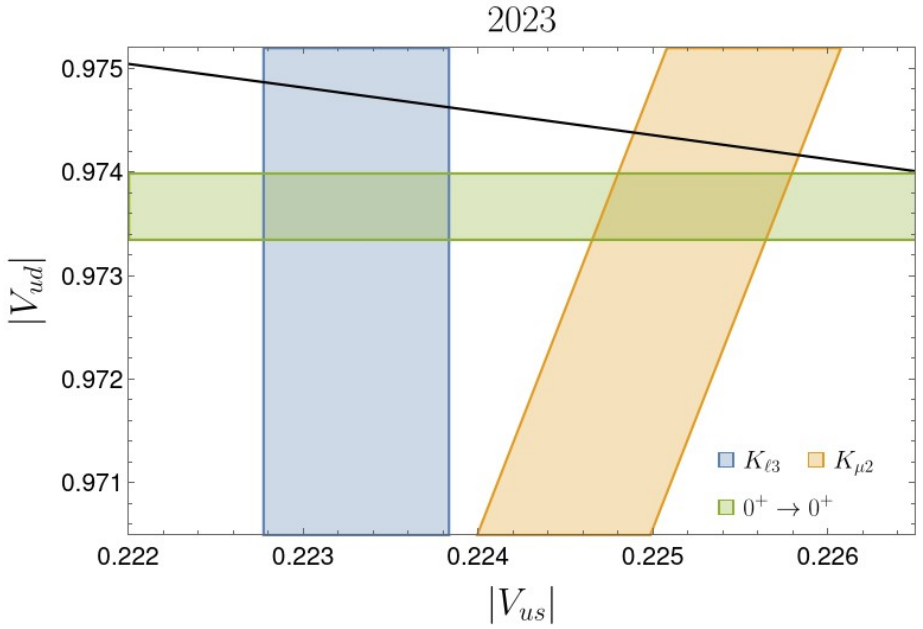
Summary

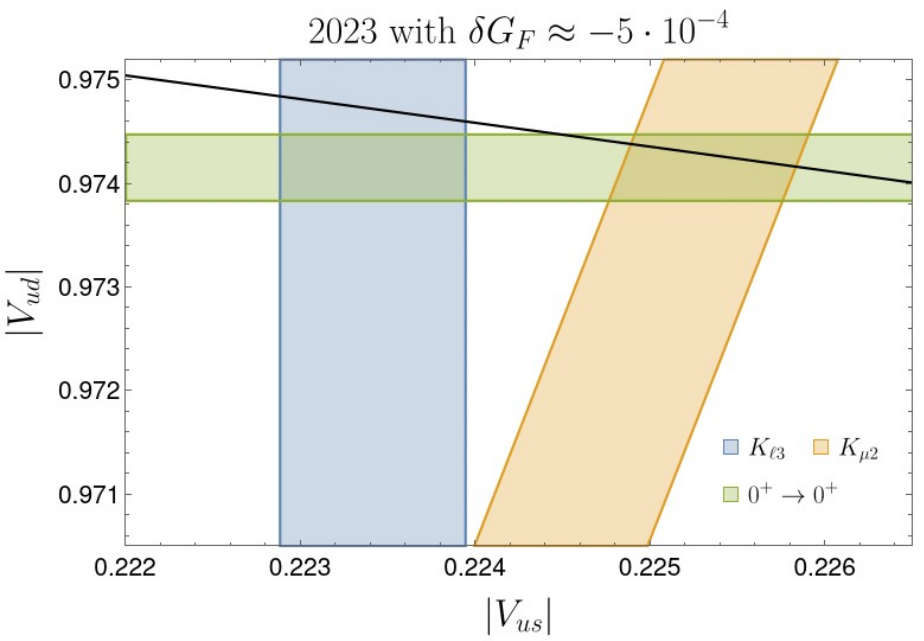
- Improvements in lattice and interesting new developments in beta decay have lead to ~ $3\,\sigma$ anomaly
- VLQs seem a good BSM candidate
- $SU(2)$ doublet Q_1 in particular

Backup

Low energy EFT ideas

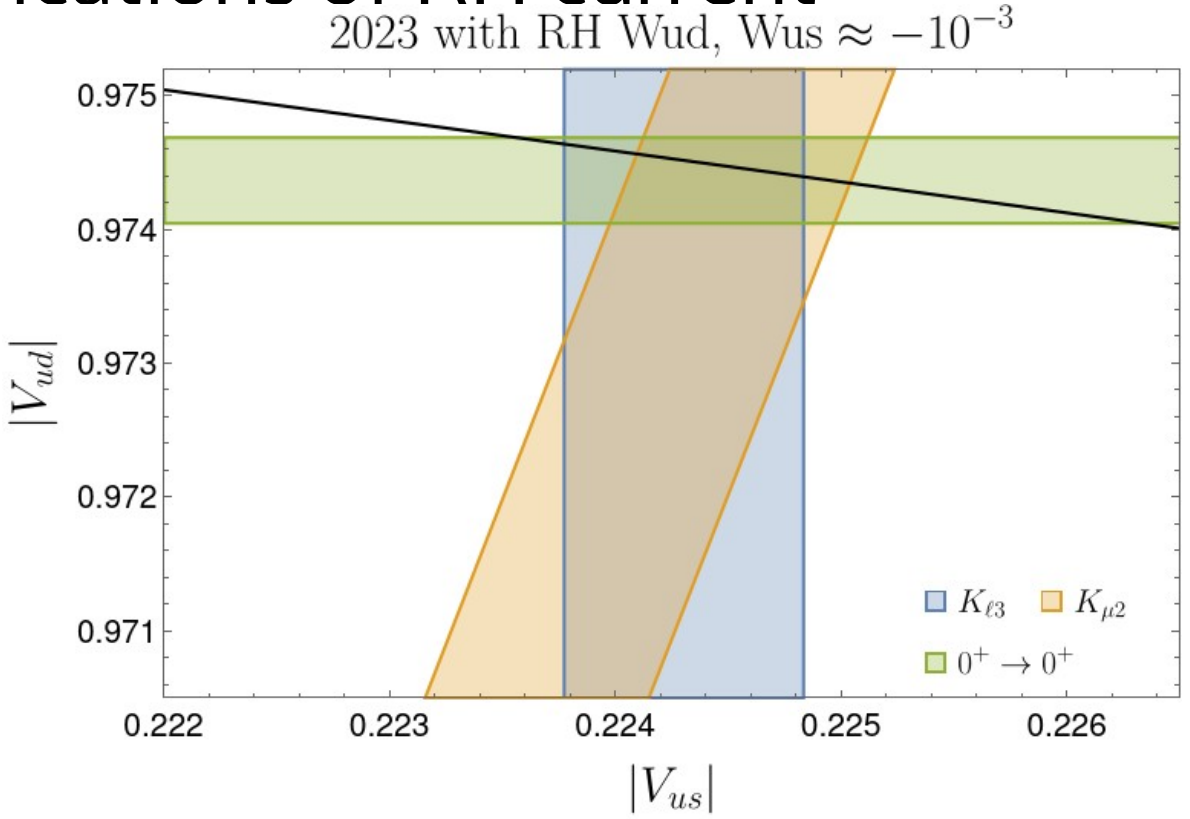
- Modifications of GF / muon decay
- Reduces tensions but doesn't solve it





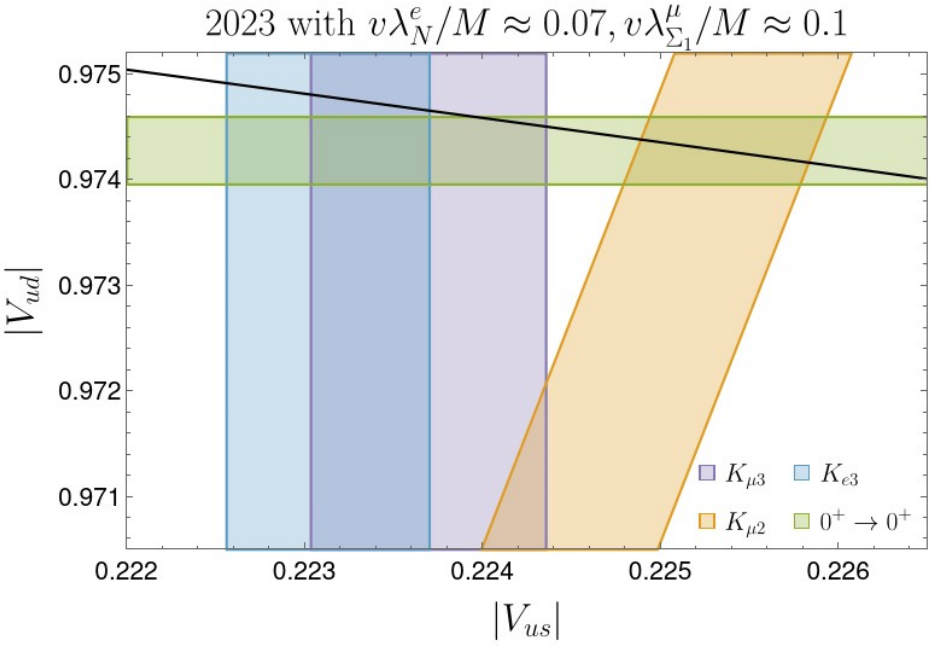
EW modifications

- Modifications of RH current

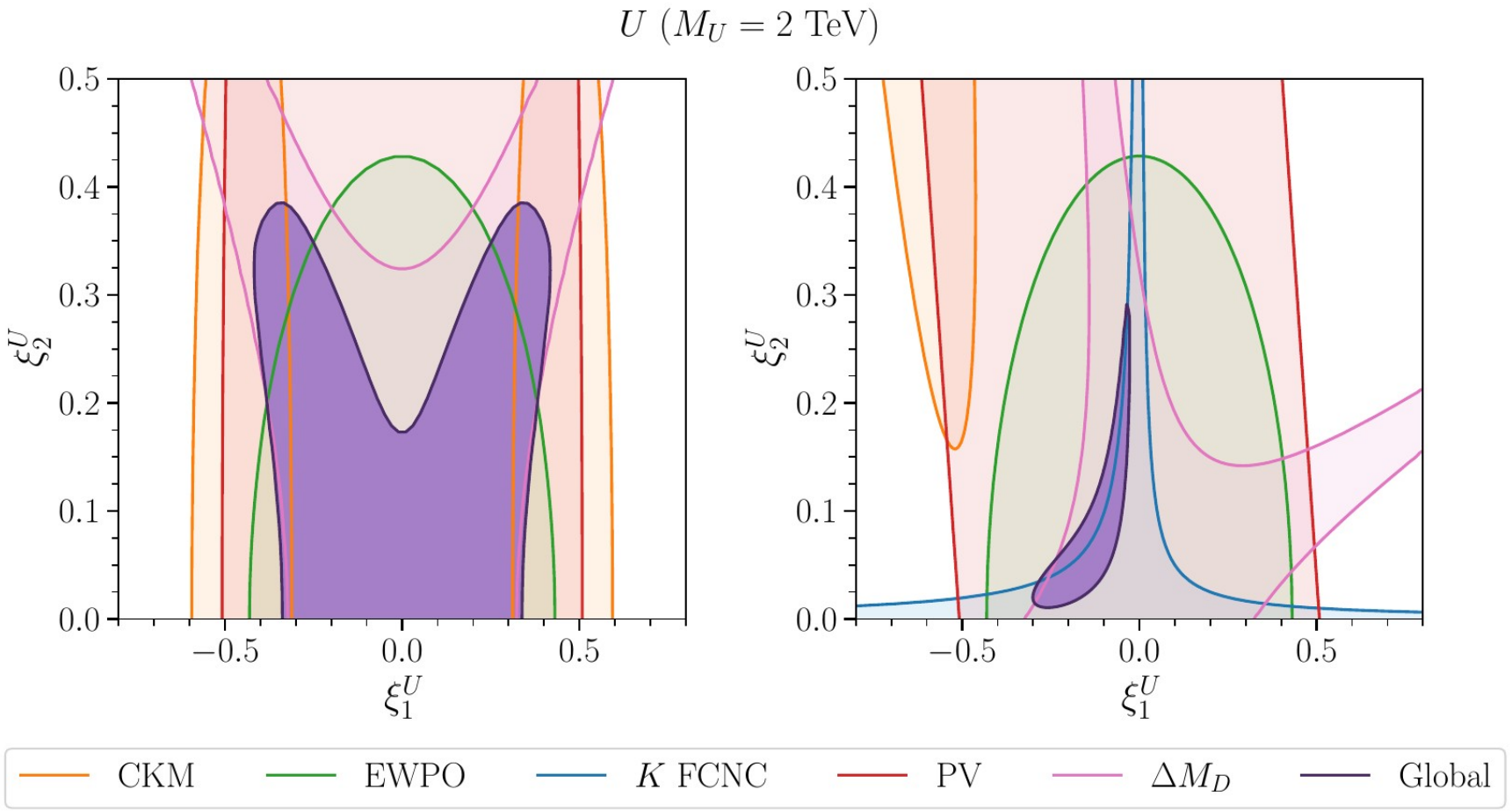


VLLs – singlet and triplet

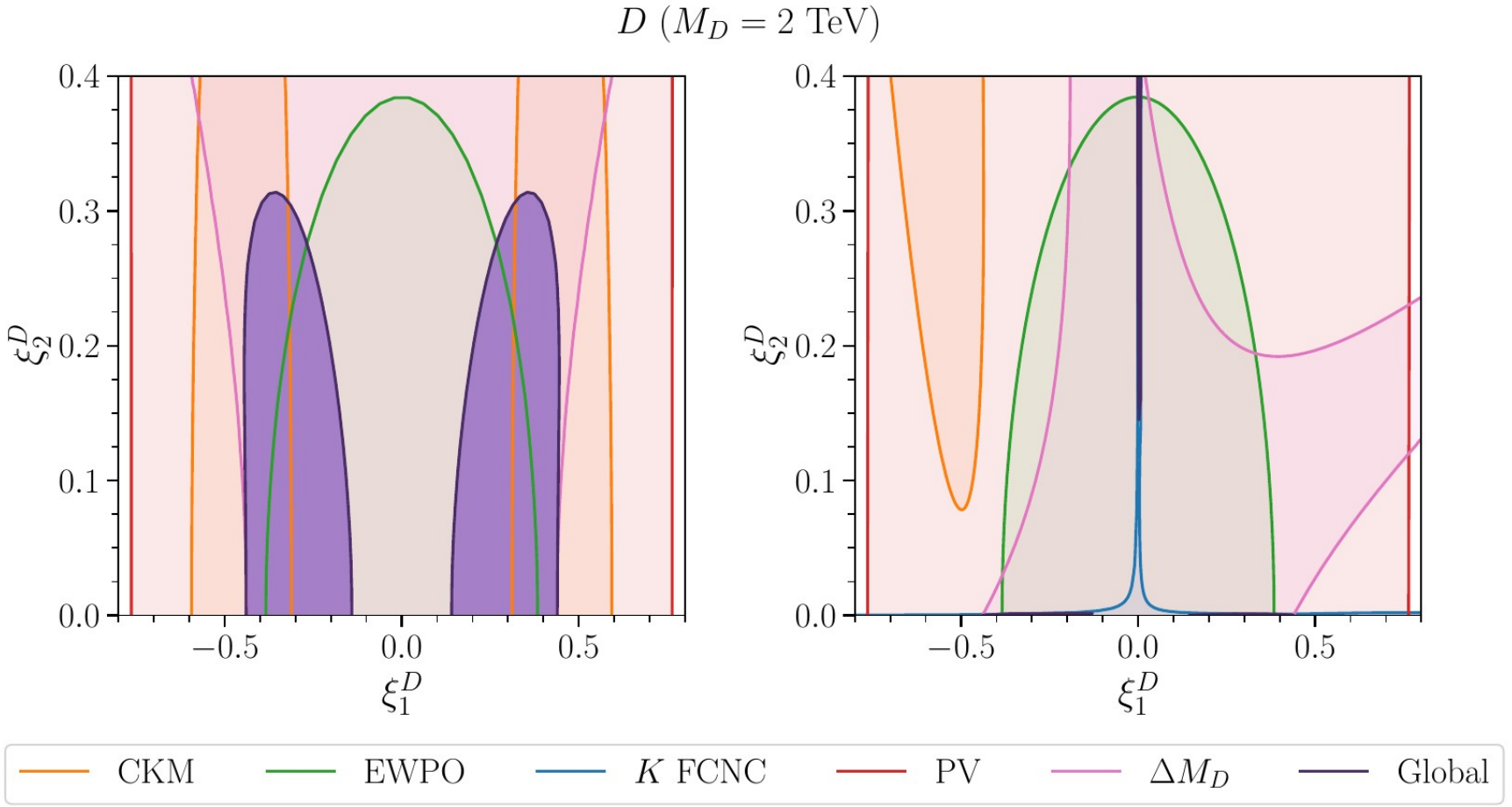
- VLLs coupled to muons and electrons
- Good improvement in CKM data
- And also slight improvement in EWPO
- See 2008.01113
  (Crivellin, Kirk, Manzari, Montull)



VLQs – U & D singlets



VLQs – U & D singlets

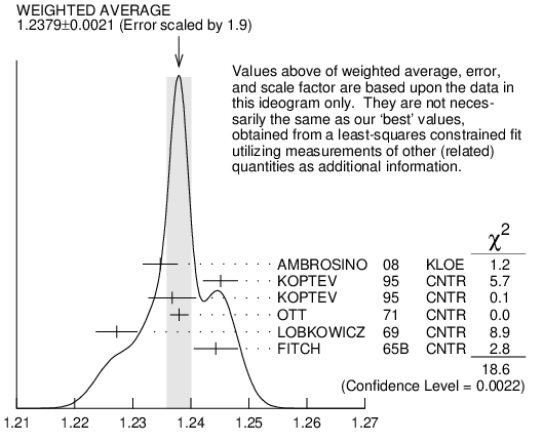


Future experiments?

- 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



Future experiments?

- PIONEER @ PSI (2203.01981)
  - Can measure the LFU ratio $\pi^+ \to \mu\nu / \pi^+ \to e\nu$
  - And $\pi^+ \to \pi^0 e\nu$ (π_{e3})
- π_{e3} is theoretically clean, and can reduce uncertainty further by considering $K_{\ell 3}/\pi_{e3}$
  - See 1911.04685
    (Czarnecki, Marciano, Sirlin)

Cabibbo Angle

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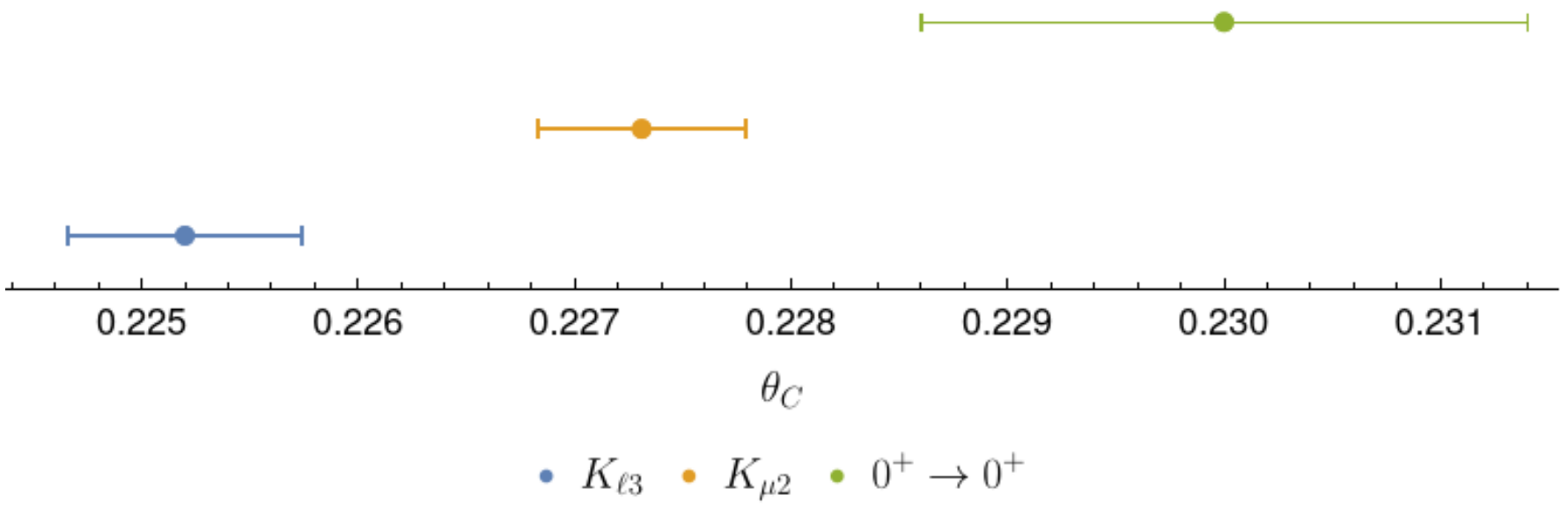

Cabibbo Angle Anomaly

- Roughly $3\,\sigma$ deviation
- Depends how you define it
  - See discussion in 1911.07821
    (Grossman, Passemar, Schacht)