The Cabibbo Angle Anomaly and a global fit to vector-like quarks

Matthew Kirk
ICCUB, Barcelona

ICCUB
Institut de Ciències del Cosmos

Universitat de Barcelona

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

FPCP 2023 – 30 May 2023

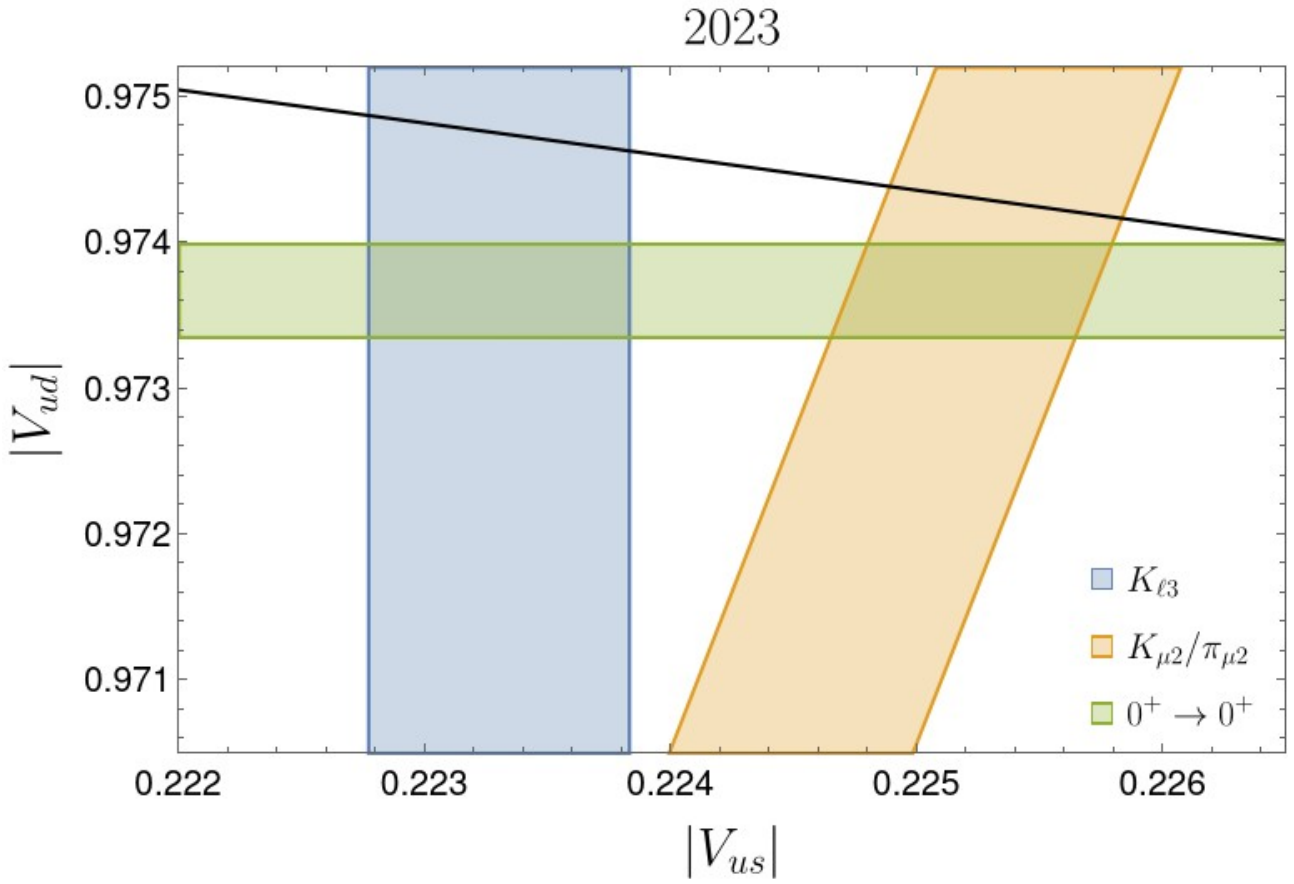
CKM Matrix

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

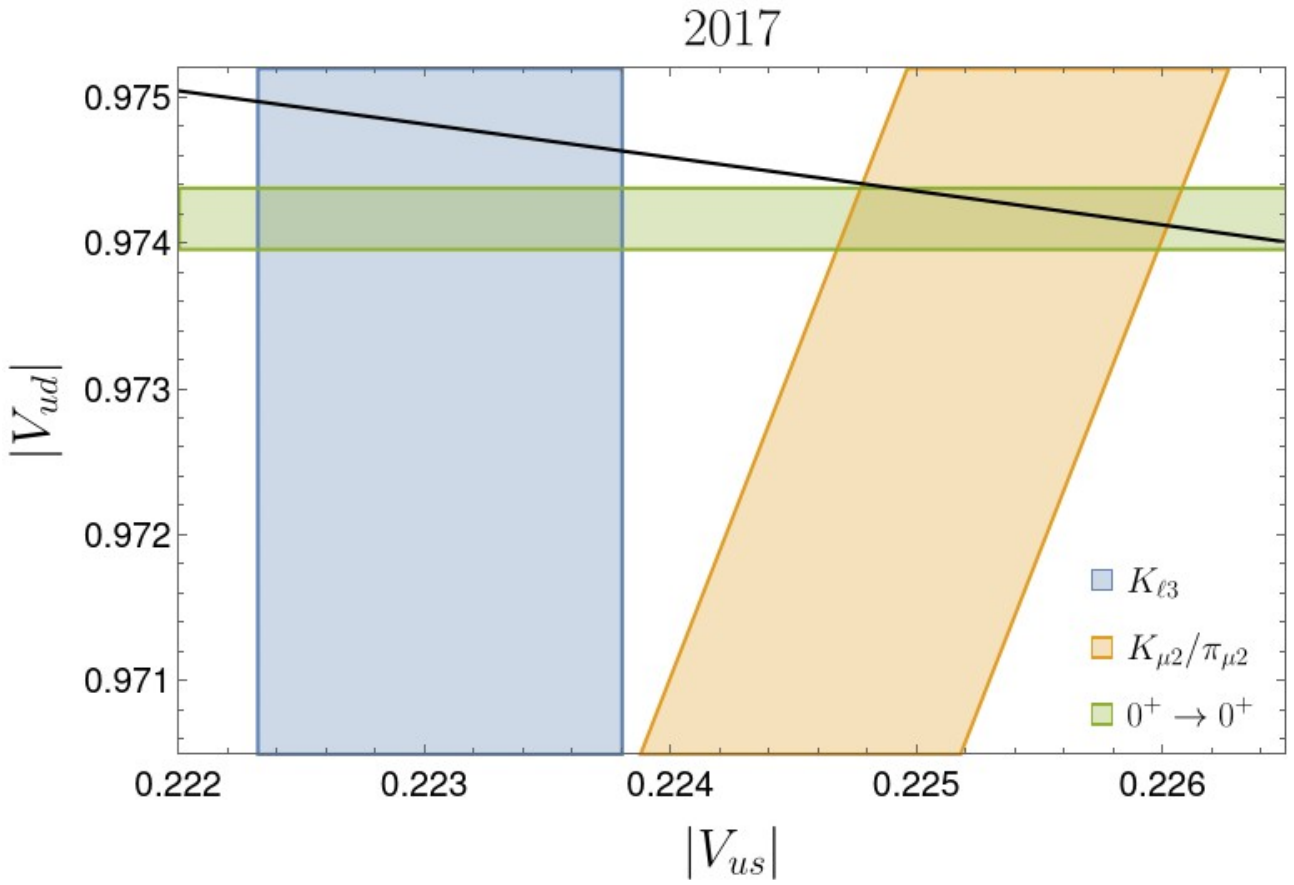
First row unitarity

- $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$
- $|V_{ub}|^2$ is very small, less than current uncertainties
- So we can approximate: $|V_{ud}|^2 + |V_{us}|^2 = 1$
- SM predicts this relation, but not the values

Cabibbo Angle Anomaly



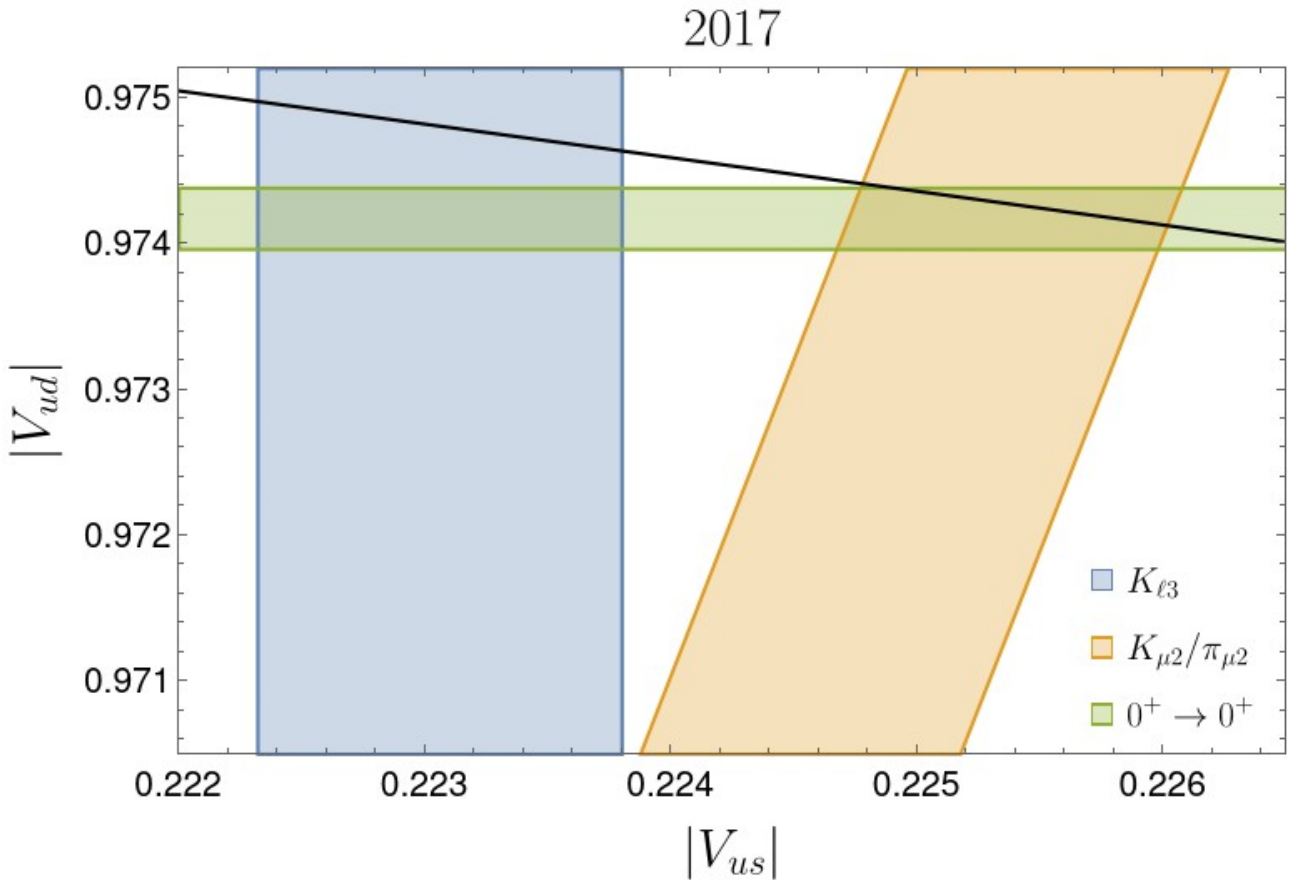
Cabibbo Angle Anomaly



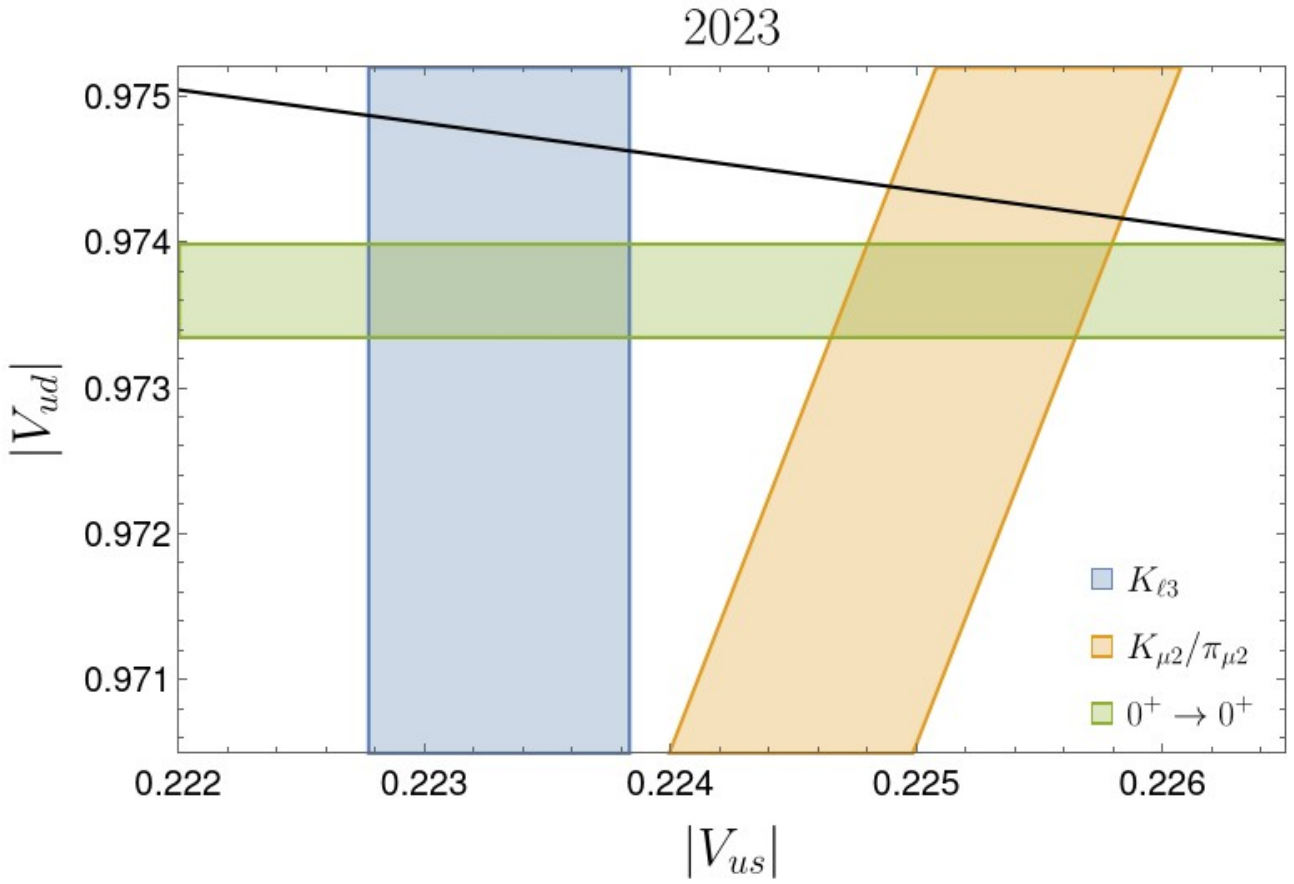
What changed?

- Lattice QCD improvements
  - $f_K/f_\pi : 1.193 \pm 0.003 \rightarrow 1.193 \pm 0.002\,(N_f = 2+1+1)$
  - $f_+(0) : 0.971 \pm 0.003 \rightarrow 0.970 \pm 0.002\,(N_f = 2+1+1)$
- Nuclear beta decay theory
  - New calculations of $\gamma - W$ EW corrections
  - Reanalysis of other nuclear uncertainties

Cabibbo Angle Anomaly



Cabibbo Angle Anomaly



Roughly $\sim 3\,\sigma$ tension

What's behind this?

- BSM models
  - Leptoquarks, W', vector-like leptons, vector-like quarks
- Vector-like quarks are the best option!

What's behind this?

- BSM models
  - Leptoquarks, W', vector-like leptons, vector-like quarks
- Vector-like quarks are the best option!
  - Why?
  - RH currents affect 3-body vs 2-body decays differently!

Vector-like quarks

- New heavy fermions, but L and R have the same charge under the gauge groups
- 7 representations that couple to SM at tree level

Vector-like quarks

- New heavy fermions, but L and R have the same charge under the gauge groups
-

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

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

Vector-like quarks

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

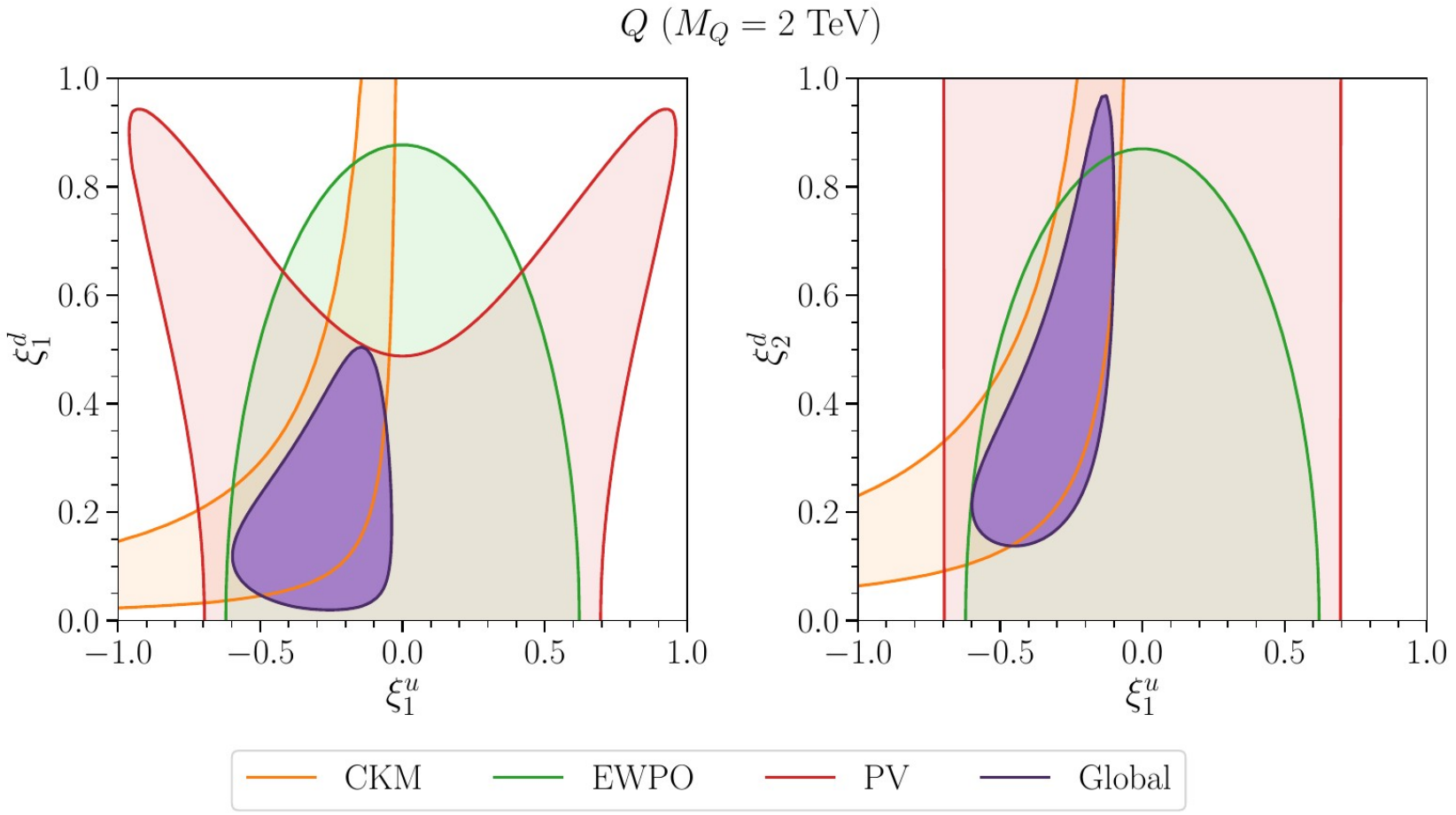
Vector-like quarks

- $SU(2)$ 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
- EWPO less strong, meson mixing almost absent
- Low energy PV important

Vector-like quarks

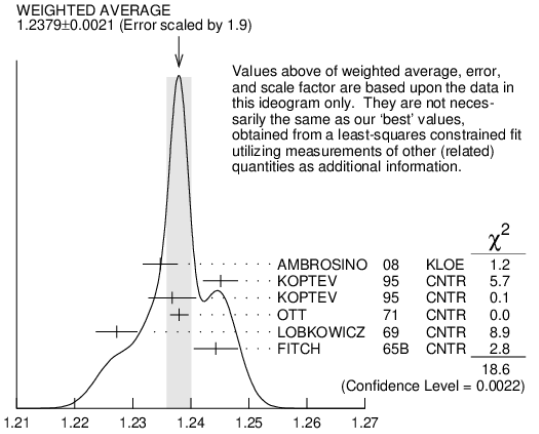


Future experiments?

- 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, also talk by Toshiyuki Iwamoto on Thursday)
  - 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)

Summary

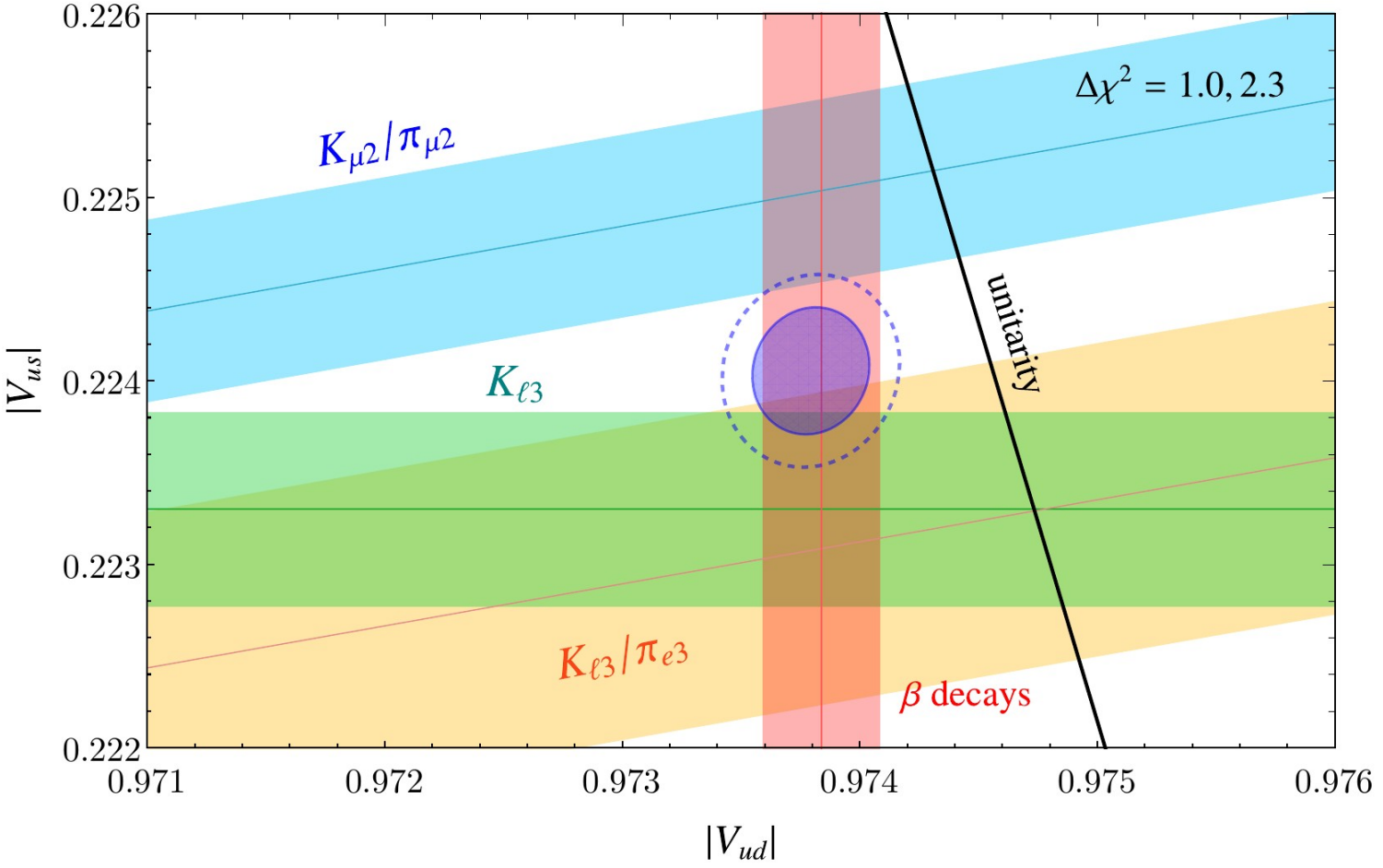
- Improvements in lattice and interesting new developments in beta decay have lead to ~ $3\,\sigma$ anomaly
- VLQs seem a good BSM candidate
- $SU(2)$ doublet Q_1 in particular
- Hopefully new data will sharpen the tension

Backup

Low energy parity violation

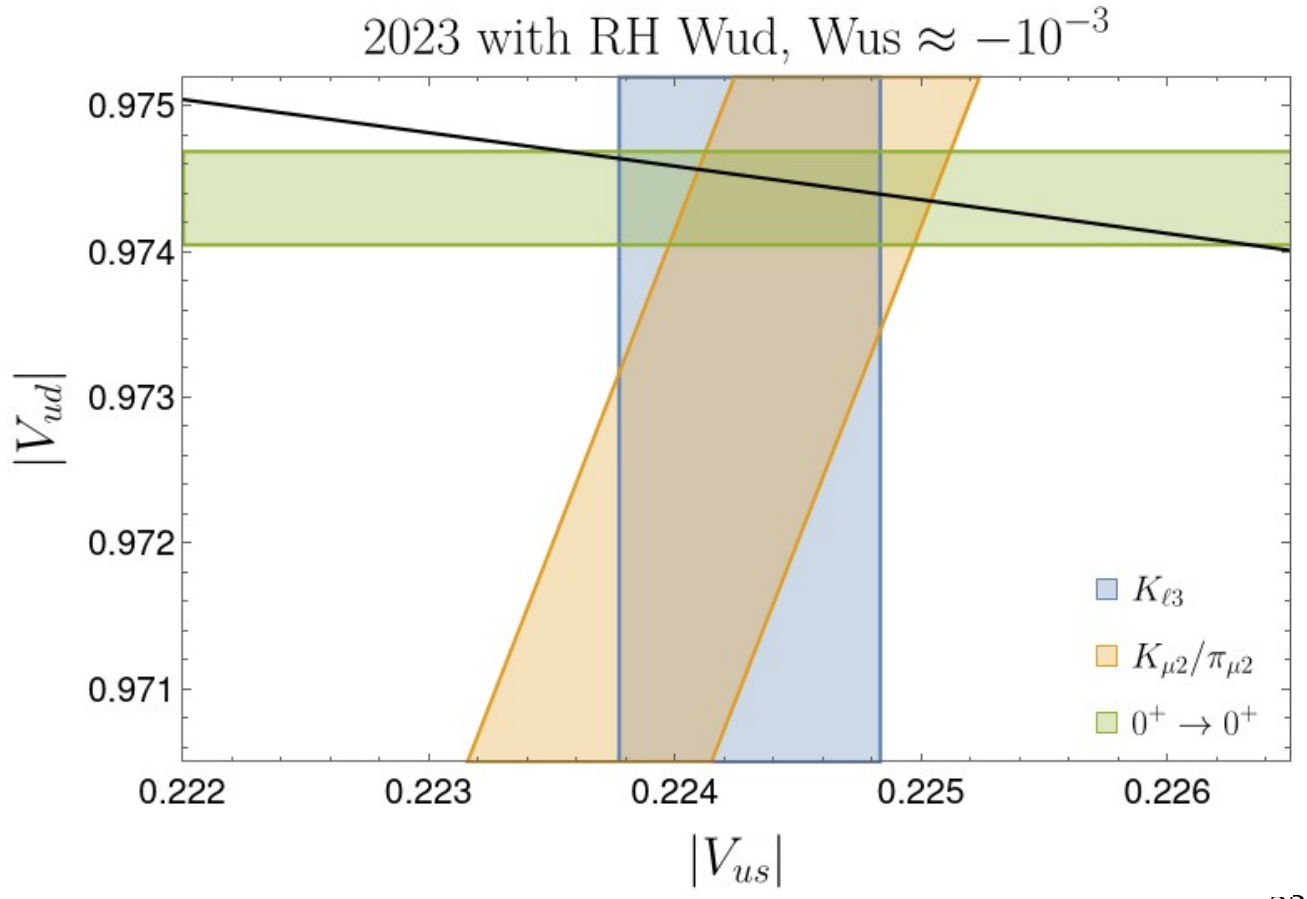
- $(\bar{e}\gamma_\mu\gamma_5 e)(\bar{q}\gamma^\mu q)$ or $(\bar{e}\gamma_\mu e)(\bar{q}\gamma^\mu\gamma_5 q)$
- Weak charge of the proton, more generally parity violating electron scattering or parity violating atomic transitions

Pion beta decay



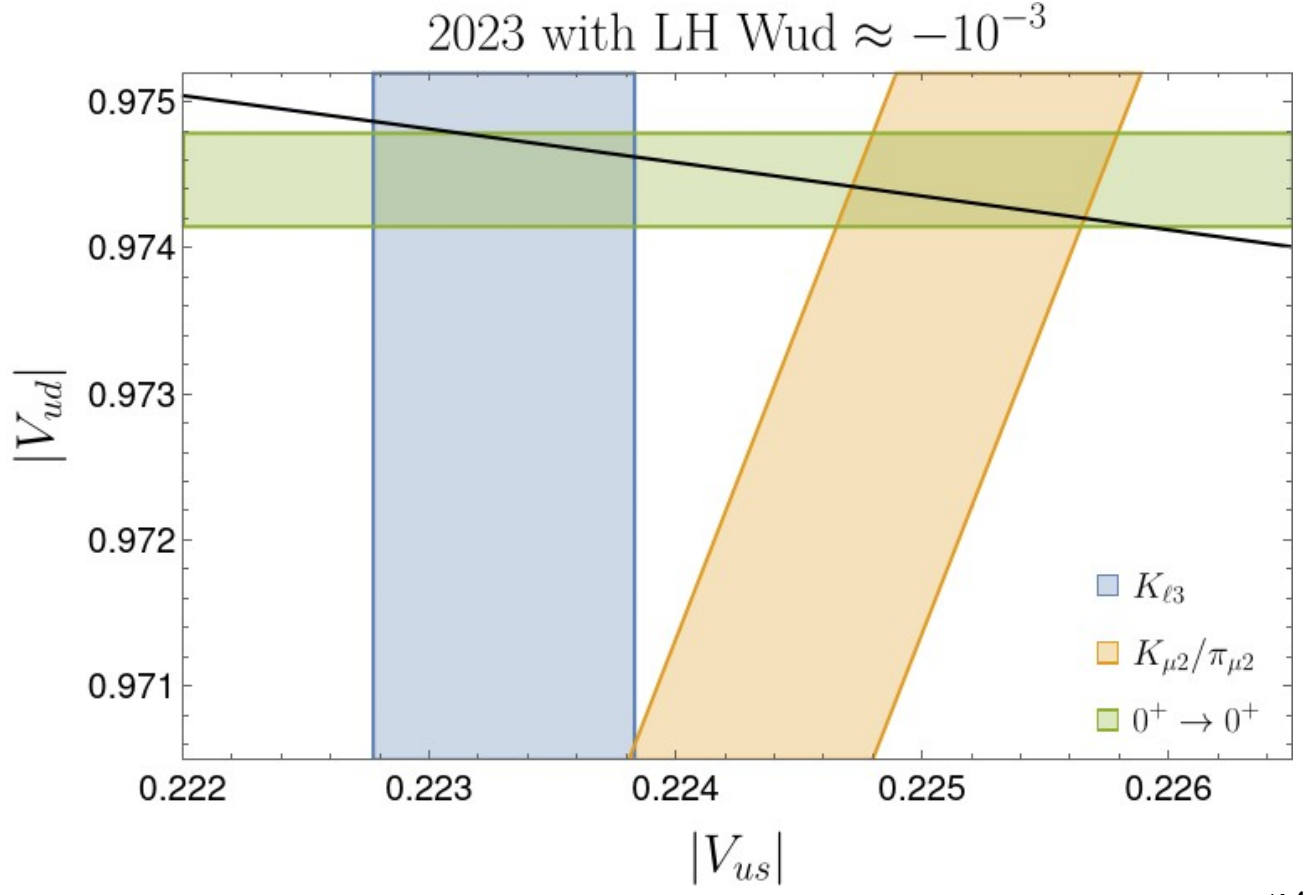
EW modifications

- Modifications of RH current

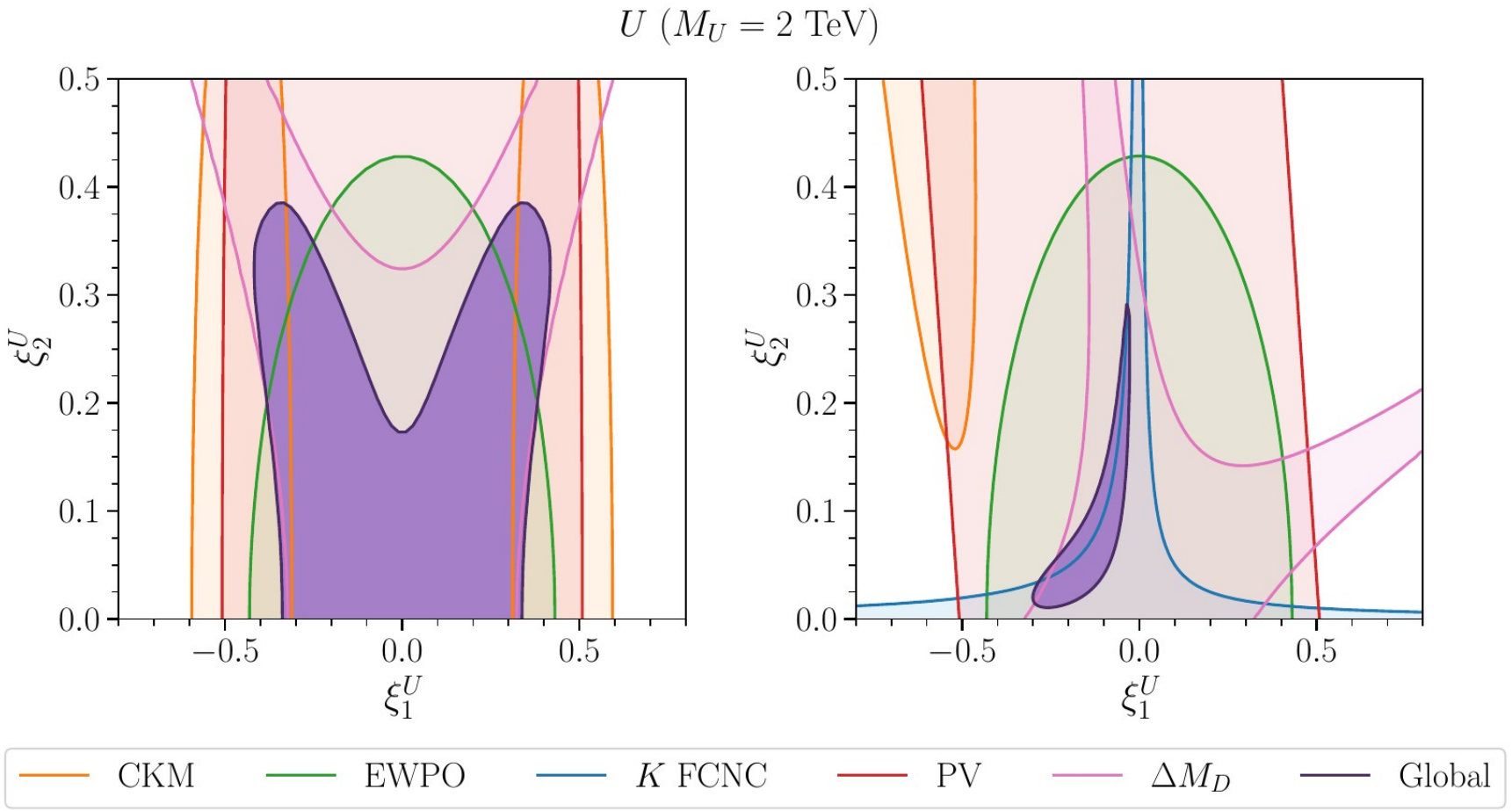


EW modifications

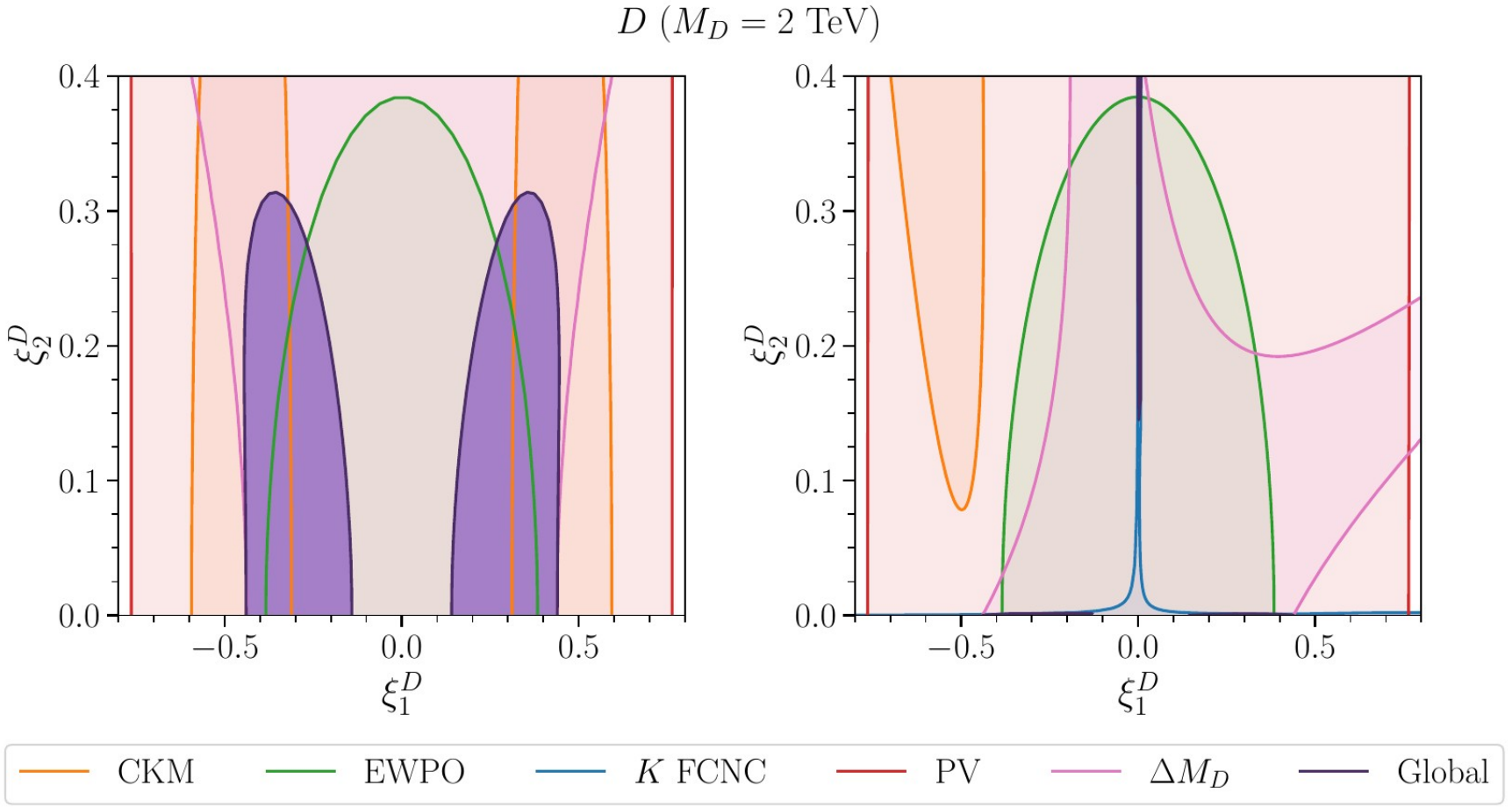
- Modifications of LH current



VLQs – U & D singlets

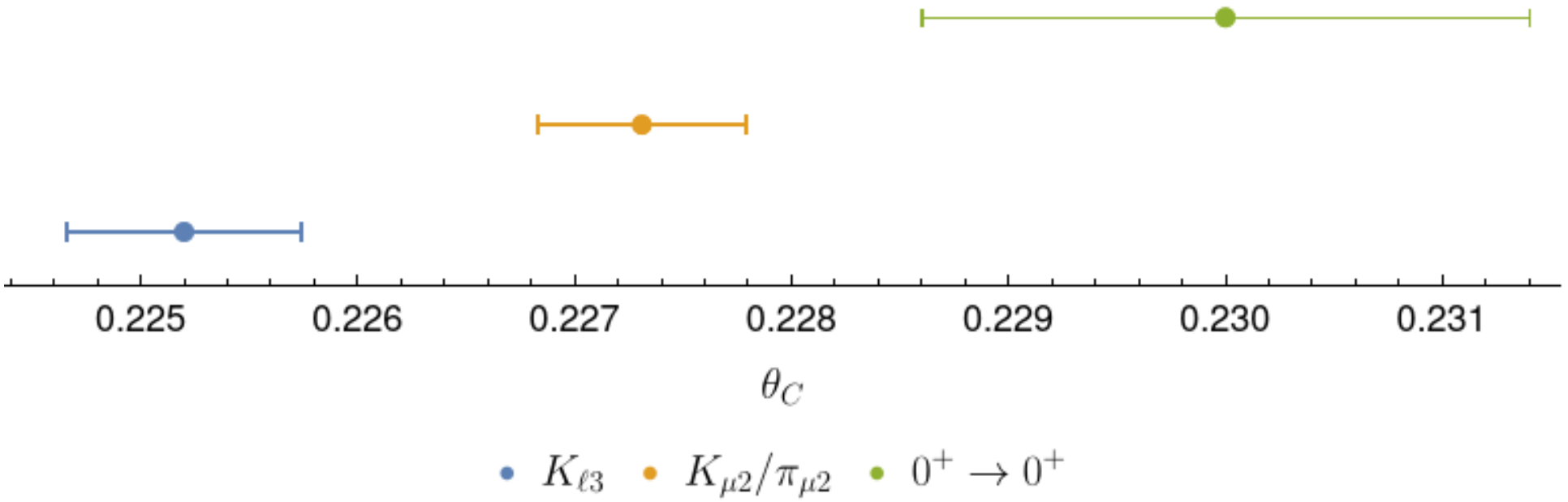


VLQs – U & D singlets



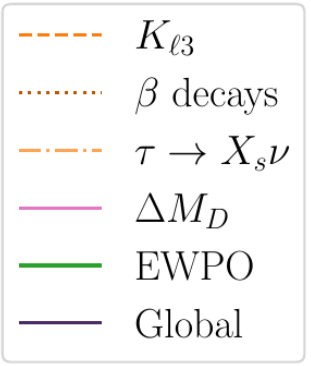
Cabibbo Angle

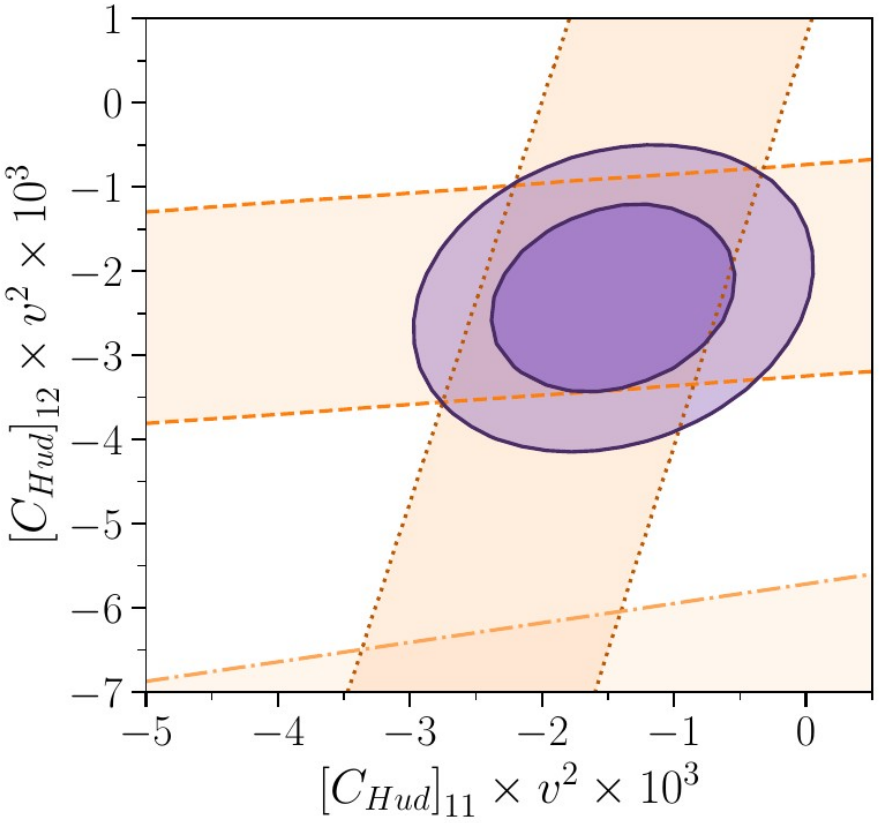
$$\theta_C = \arccos V_{ud} = \arcsin V_{us} = \arctan V_{us}/V_{ud}$$



EW scale modifications

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





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