Cabibbo Angle Anomaly

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Anomalies & Precision in the Belle II Era - 7th Sep 2021

CKM matrix (V)

- 3x3 unitary matrix by construction
- We can talk about "unitary conditions", which are SM predictions like any other
- One prediction is "first row unitarity"
  - $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$

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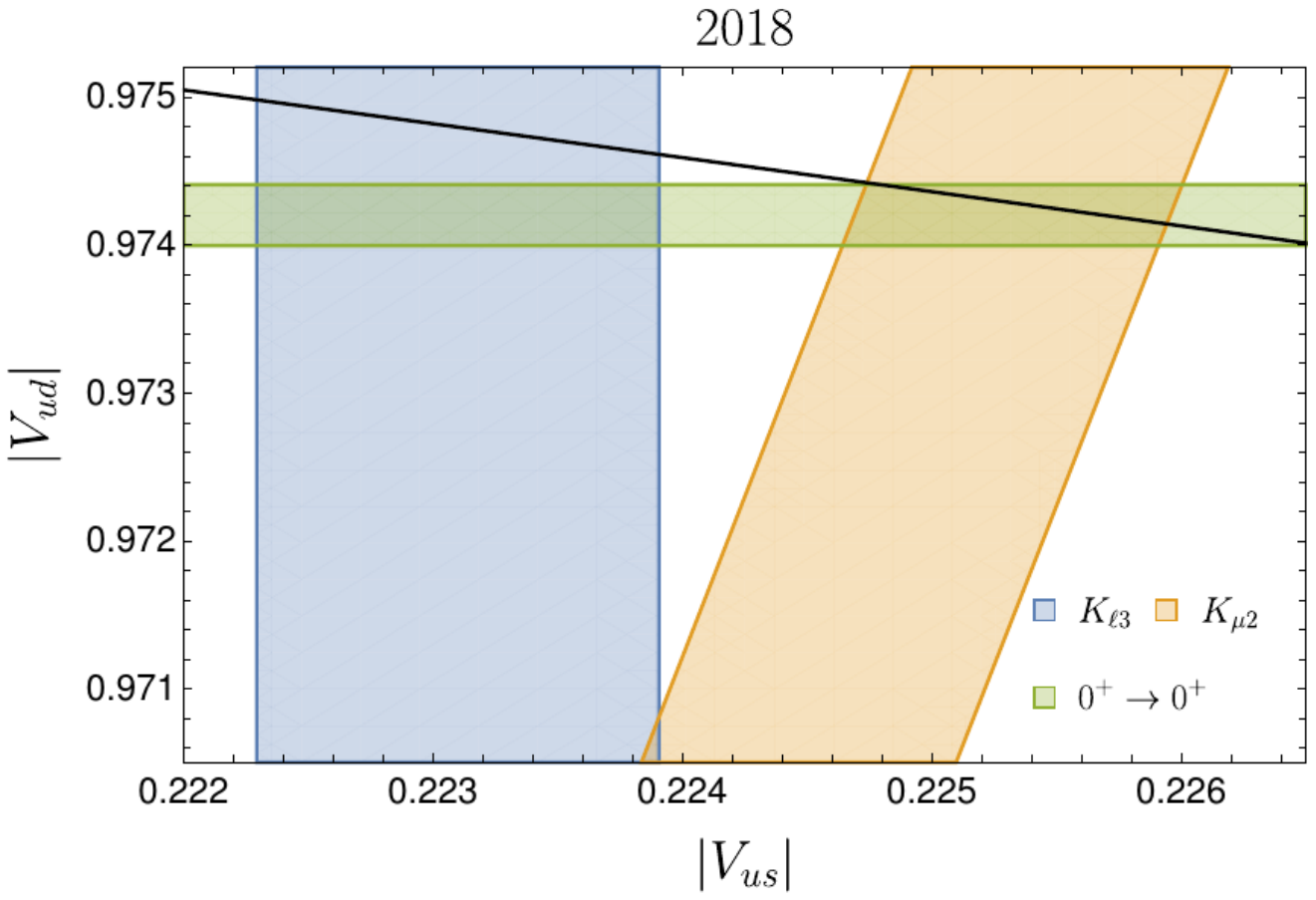
- As recently as 2018 (1807.01146)
  - $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9994 \pm 0.0005$
- Good agreement with SM prediction

Graphical view



Beta decay

- Currently, best determination of V_{ud} is from super-allowed beta decays
- 2018 value: $V_{ud} = 0.97420 \pm 0.00021$
  - Dominant contribution to uncertainty is "nucleus independent radiative corrections": Δ_R^V
  - $V_{ud} = 0.97420 \pm 0.00010(\mathrm{exp}) \pm 0.00018(\Delta_R^V)$

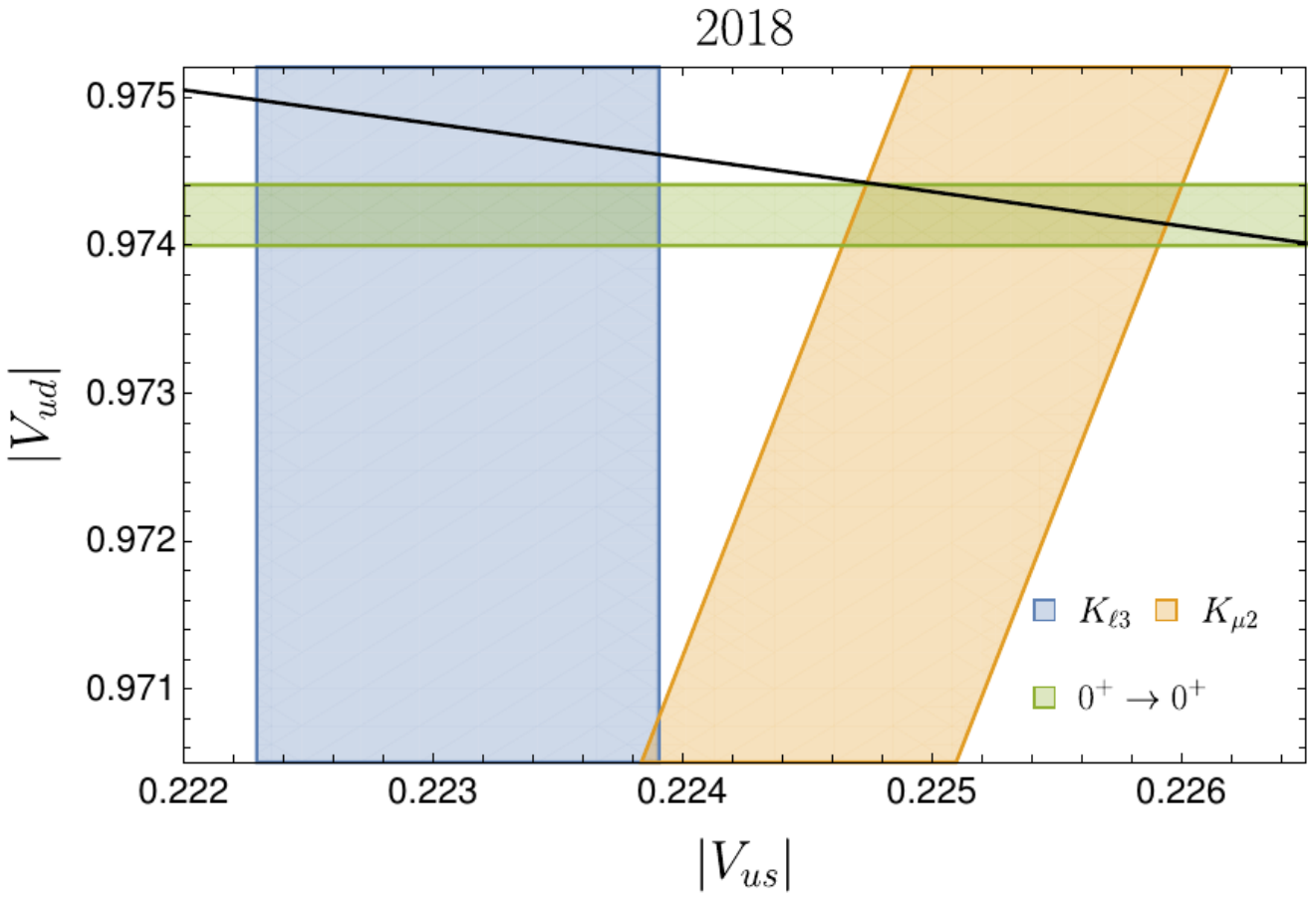
Beta decay

- 2018 value of V_{ud} uses Δ_R^V from 2006 (hep-ph/0510099)
- At end of 2018, new value of Δ_R^V (1807.10197)
- Gives $V_{ud} = 0.97370 \pm 0.00014$
- $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9985 \pm 0.0005$
  - Using 2020 PDG for V_{us}

Cabibbo Angle Anomaly

- $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9985 \pm 0.0005$
- 3 sigma tension with SM!
- This is the CAA

Graphical view



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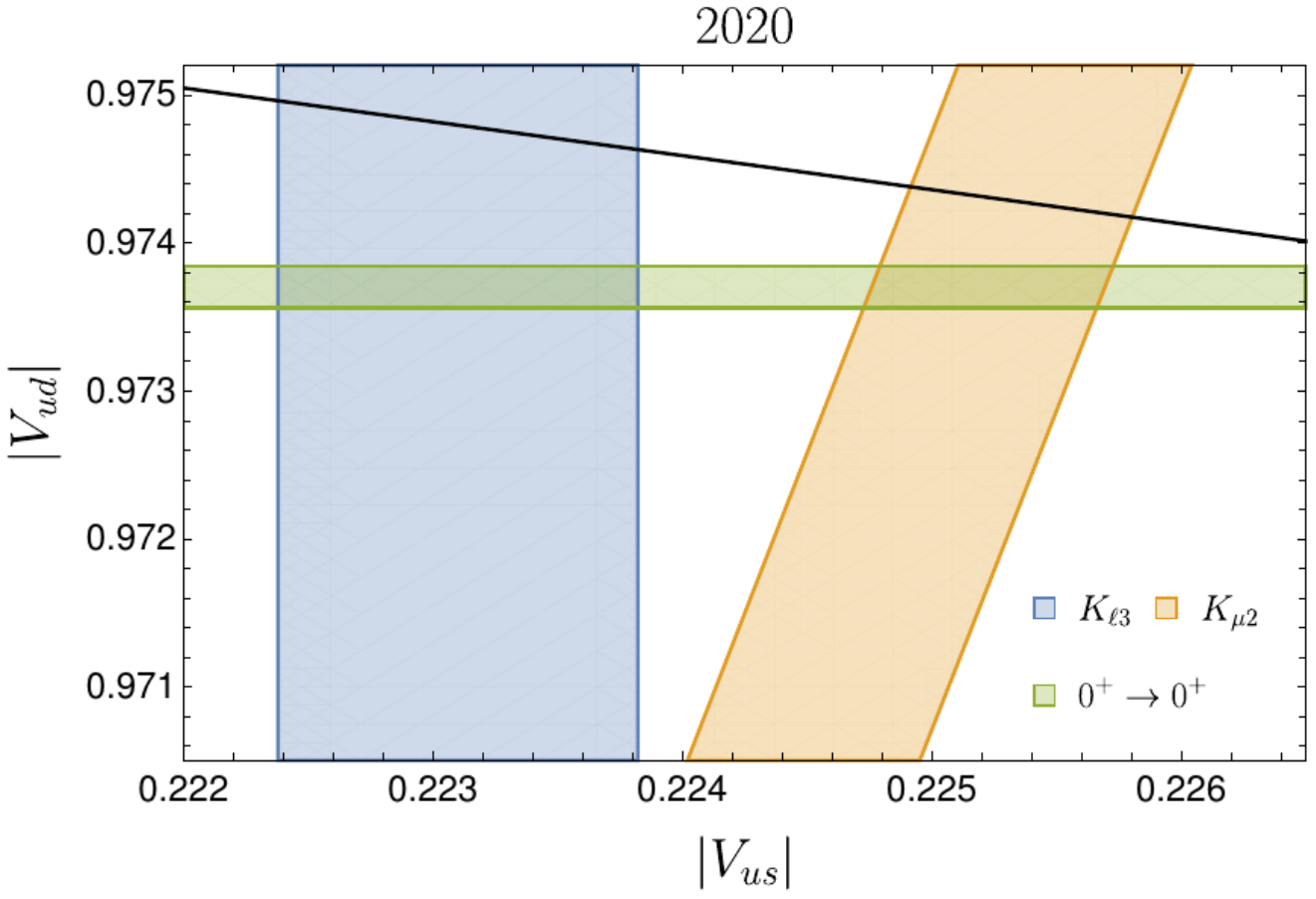


What's wrong?

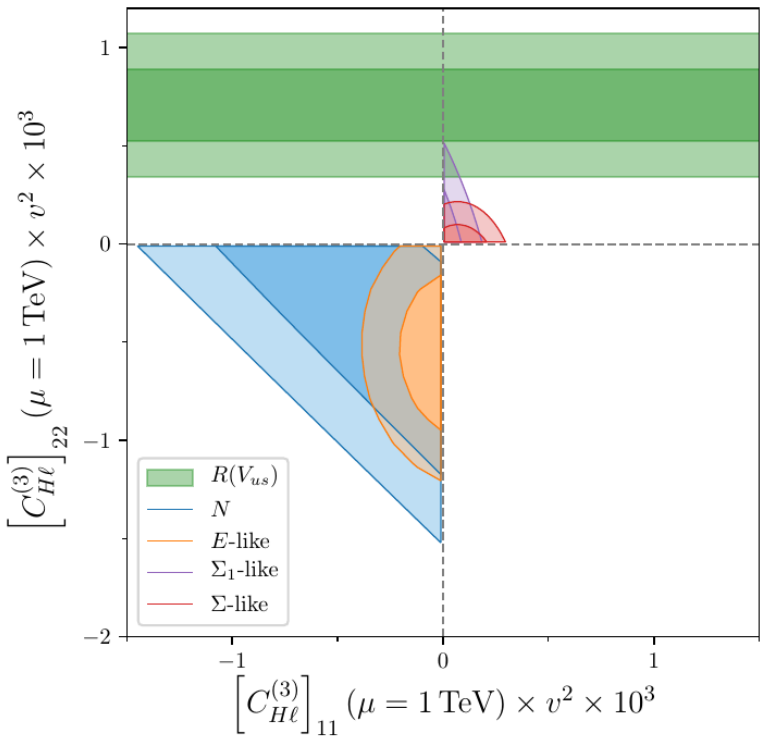
- "Boring" answers:
  - Problem with lattice form factors
    - $f_+(q^2 = 0)$ used to get V_{us} from semi-leptonic kaon decays, f_{K^+}/f_{π^+} to get V_{us}/V_{ud} from leptonic decays
  - Problem with radiative corrections in beta decay
    - Maybe old 2006 value is closer to truth

What's wrong?

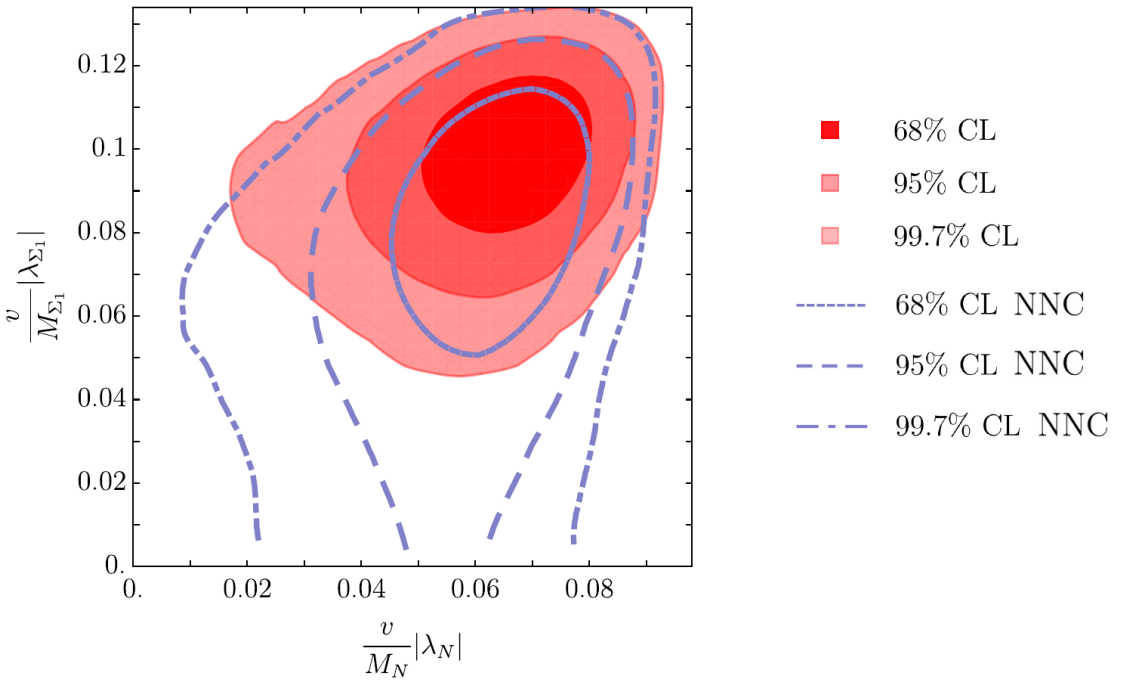
- More fun answer: BSM!
  - Modifying W decays ($qq' \to W \to \ell\nu$)
    - Changes to $W - q - q'$
    - Changes to $W - \ell - \nu$
  - Modifying $2q2\ell$ contact operators ($qq\ell\nu$)
  - Modifying muon decay (4ℓ) => G_F changes => affects normalisation of V_{ud}, V_{us}

Modifying $W - \ell - \nu$

- Affects determination of V_{us}, V_{ud} but not V_{us}/V_{ud}
- Possible BSM explanations: vector-like leptons, W′
- Minimal explanations in tension with EWPO (2008.03261)
- But more complex scenarios can agree with all data (2008.01113)



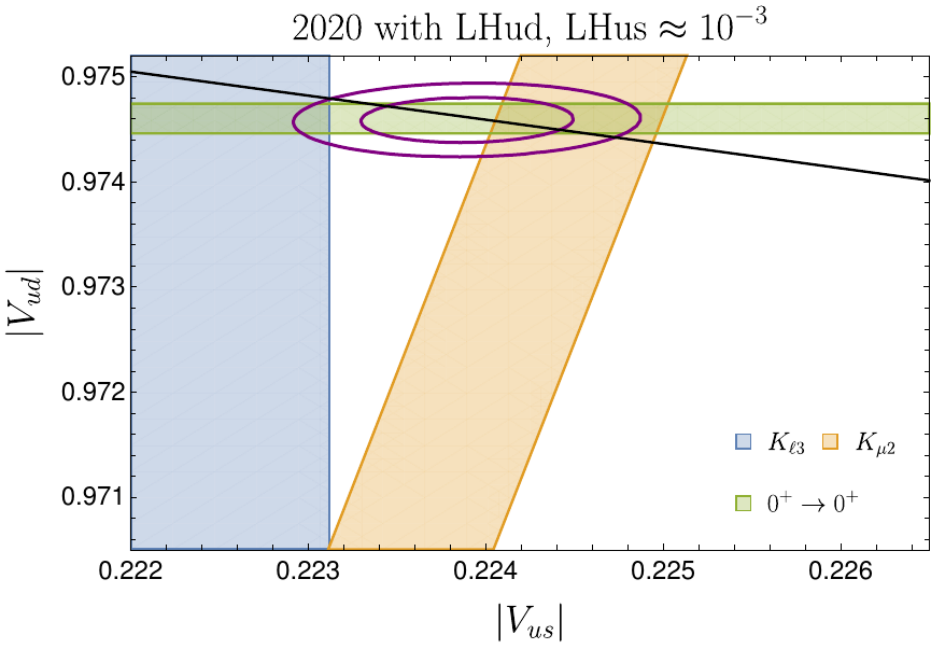
2008.03261

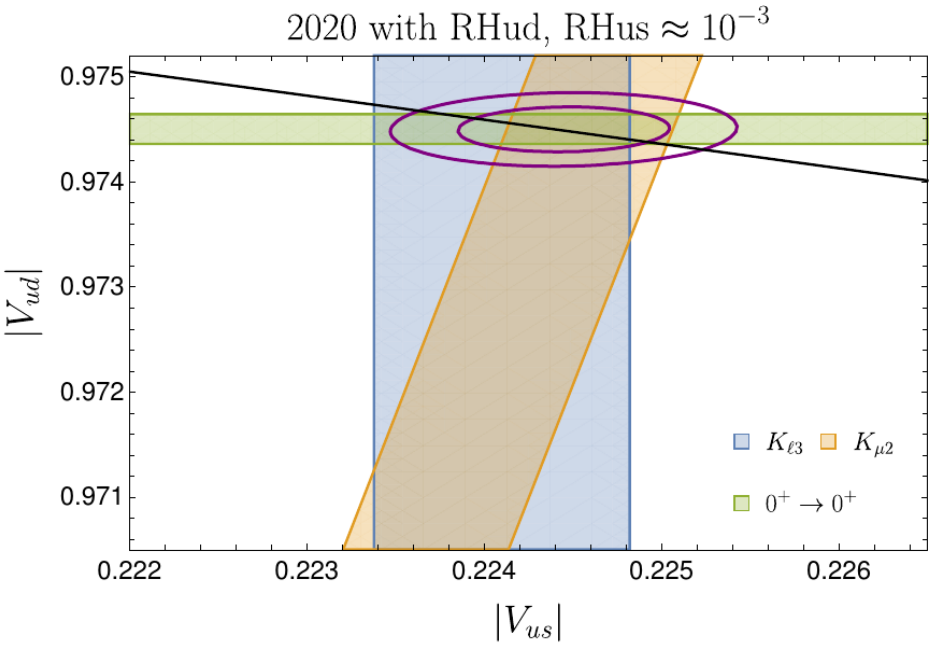


2008.01113

Modifying $W - q - q'$

- Adding a RH coupling in ud and us can resolve the tension between V_{us} determinations (1911.07821, 2103.05549)
  - But SU(2) invariance means RH quark couplings can affect other observables, e.g. ϵ_K
- Altering LH does not
- Possible BSM explanations: vector-like quarks, W′


2020 with LHud, LHus ≈ 10^{-3}
0.975
0.974
0.973
0.972
0.971
$|V_{ud}|$
0.222
0.223
0.224
0.225
0.226
$|V_{us}|$
$K_{\ell 3}$
$K_{\mu 2}$
$0^+ \to 0^+$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Relation to other anomalies

- Solving CAA plus:
  - CMS $pp \to e^+e^-$ (2107.13569, talk by Claudio Andrea Manzari)
  - Flavour anomalies (2005.13542)
  - $(g-2)_\mu$ (2005.03933)
  - A^b_{FB} (2001.02853)
  - ...

Future prospects

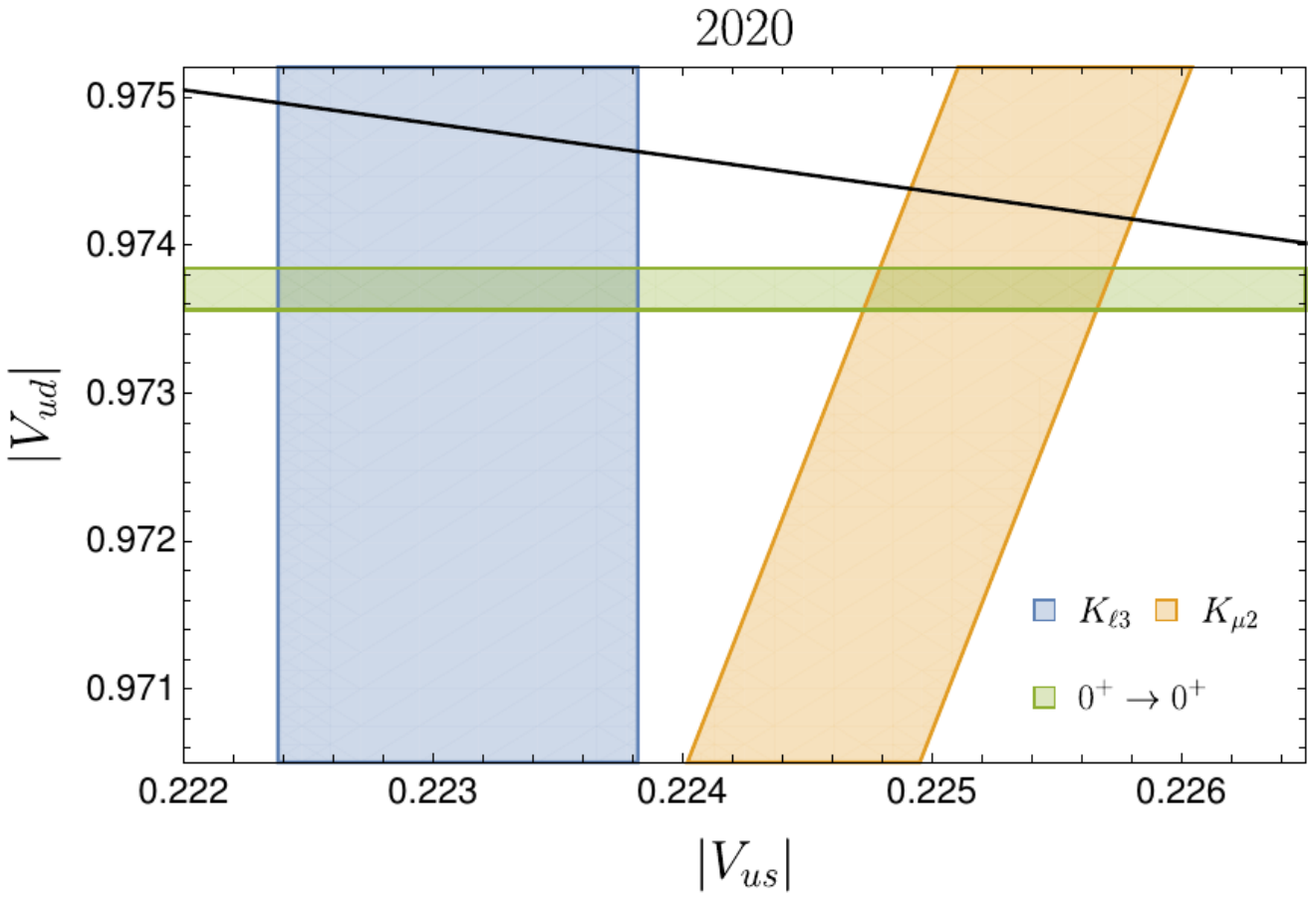
- Improved V_{ud} ? Seems unlikely anytime soon
  - Agreement from community on value of Δ_R^V from different methods – naive weighted average gives $4\,\sigma$ deviation
- Future V_{us}/V_{ud} ?
  - $R(K_{e3}/\pi_{e3})$ (1911.04685, 2107.14708) is now theoretically cleaner than $R(K_{\mu 2}/\pi_{\mu 2})$
  - More realistic, but unknown timeline

Thanks! Questions?

Backups

Modifying G_F

- Brings best fit closer to unitarity
- But cannot fully resolve the discrepancy between $K_{\ell 3}$ and $K_{\mu 2}$ for V_{us}
- Possible BSM explanation: colour and weak singlet with charge 1 (ϕ^+), can only couple to leptons (2012.09845)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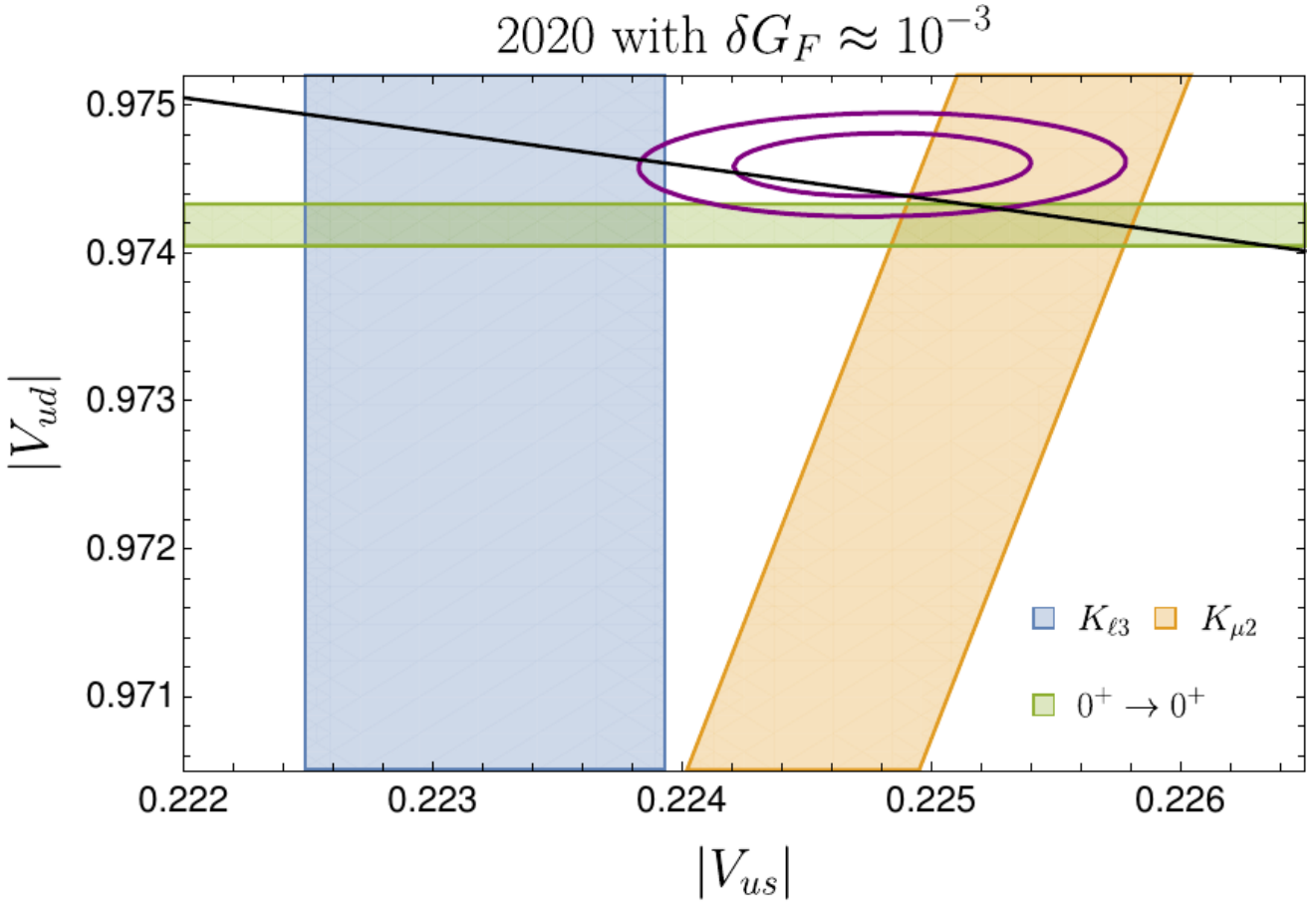
2020 with $\delta G_F \approx 10^{-3}$
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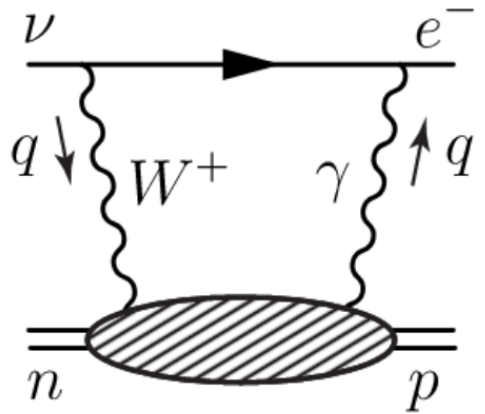
Δ_R^V

- Universal / nucleus independent / inner corrections
- $\gamma - W$ box



1) Dispersion relations
2) Perturbative QCD – four-loop Bjorken sum rule
3) Combined lattice + dispersion relations

Δ_R^V

$\Delta_R^V \times 10^2$	V_{ud}	Source	$\Delta_{\rm CKM} \times 10^3$	Significance
2.361 ± 0.038	$0.974\,20 \pm 0.000\,21$	MS [15, 16]	0.16 ± 0.52	$0.3\,\sigma$
2.467 ± 0.022	$0.973\,70 \pm 0.000\,14$	SGPR [3]	1.18 ± 0.35	$3.3\,\sigma$
2.426 ± 0.032	$0.973\,89 \pm 0.000\,18$	CMS [4]	0.81 ± 0.42	$1.9\,\sigma$
2.477 ± 0.024	$0.973\,65 \pm 0.000\,15$	SFGJ [5]	1.27 ± 0.37	$3.5\,\sigma$
2.462 ± 0.014	$0.973\,73 \pm 0.000\,09$		1.12 ± 0.28	$3.9\,\sigma$

1) Dispersion relations

2) Perturbative QCD – four-loop Bjorken sum rule

3) Combined lattice + dispersion relations

Also 2012.01580

$$\Delta_R^V = (2.472 \pm 0.018) \times 10^{-2} \Rightarrow 4\,\sigma$$

2q2l operators

- Many operators ruled out by leptonic pion decay
- Leptoquarks good candidates to generate this operator
- But also constrained by high energy $pp \to e^+e^-$ (see talk by Claudio)

Sub anomaly

- Not just unitarity that doesn't work
- Also Vus/Vud and Vus don't match up
  - Unless Vud very small (=> very far from unitarity)
- 3 body vs 2 body decays

Notes on modifying W-l-nu

- If we have LFUV NP, then we have to distinguish between lepton flavours in CKM determinations
- Specifically, the "Kl3" method is an average of "Kmu3" and "Ke3", which could be affected differently.