EFT analysis of light-quark semileptonic transitions and the Cabibbo anomaly

[Based on: V. Cirigliano, D. Díaz-Calderón, A. Falkowski, M. González-Alonso, & A. Rodríguez-Sánchez, JHEP 04 (2022) 152]

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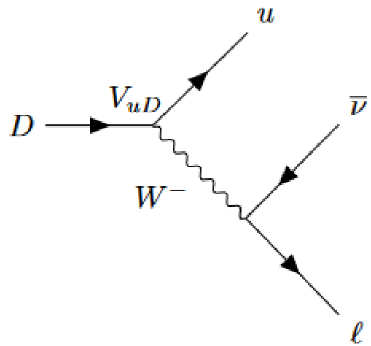
Motivation

Our goal is to explore BSM physics in $d(s) \to u\ell\bar{\nu}$ transitions in a model independent way

What motivates this?

V_{us} can be extracted from different decay channels:

- Kaon decays
- Pion decays
- Tau decays
- Nuclear β decays



Motivation

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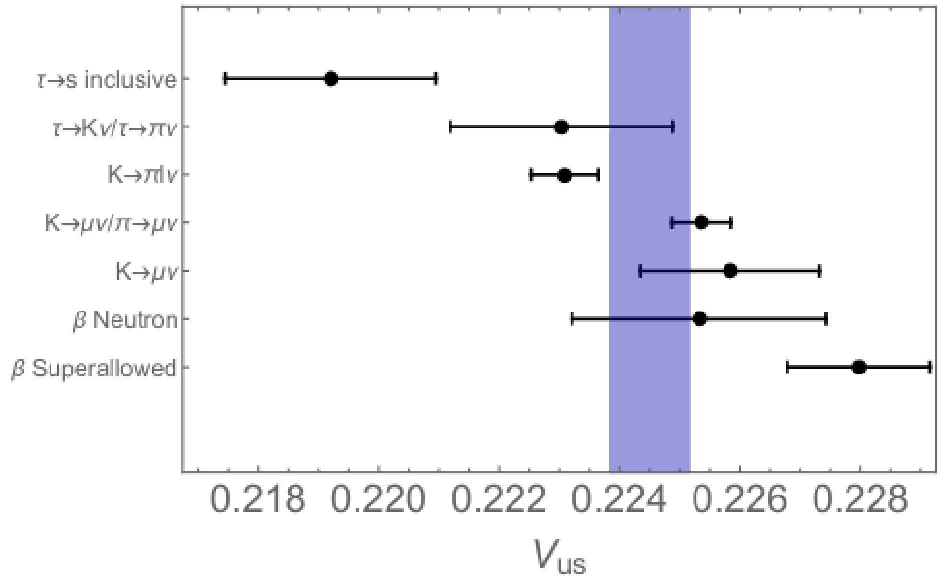


Cabibbo anomalies → Inconsistencies in V_{us} determinations

↓

New physics for light quarks?

Theoretical Framework

To explore BSM → EFT w/ u, d, s and ℓ, ν_ℓ ($\ell = e$, $\mu\,\tau$) as d.o.f.

Low energy processes → EFT below EW scale. In particular,

$$\mathcal{L}_{\rm WEFT} \supset -\frac{G_\mu V_{uD}}{\sqrt{2}} \Bigg[\left(1 + \epsilon_L^{D\ell}\right) \bar{\ell}\gamma_\mu (1-\gamma_5)\nu_\ell \cdot \bar{u}\gamma^\mu (1-\gamma_5) D + \epsilon_R^{D\ell}\; \bar{\ell}\gamma_\mu (1-\gamma_5)\nu_\ell \cdot \bar{u}\gamma^\mu (1+\gamma_5) D + \; \bar{\ell}(1-\gamma_5)\nu_\ell \cdot \bar{u}\left[\epsilon_S^{D\ell} - \epsilon_P^{D\ell}\gamma_5\right] D + \frac{1}{4}\hat{\epsilon}_T^{D\ell}\, \bar{\ell}\sigma_{\mu\nu}(1-\gamma_5)\nu_\ell \cdot \bar{u}\sigma^{\mu\nu}(1-\gamma_5) D \Bigg] + \mathrm{h.c.}$$

$\epsilon_X^{D\ell}$ → BSM effects

↑ No BSM below ~ 2 GeV. I.e., UV-completed by the SMEFT

V_{uD} → $\hat{V}_{uD} \equiv V_{uD}(1 + \epsilon_L^{De} + \epsilon_R^{De})$

↑ Experiment

Matching to SMEFT → $\epsilon_R^D \equiv \epsilon_R^{De} = \epsilon_R^{D\mu} = \epsilon_R^{D\tau}$

Low Energy Probes

Low energy probes considered:

Nuclear β-decays + π decays $\longrightarrow$ Probe $\widehat{V}_{ud}$, ϵ_X^{de} and $\epsilon_X^{d\mu}$

K decays + Hyperon β-decays $\longrightarrow$ Probe $\widehat{V}_{us}$, ϵ_X^{se} and $\epsilon_X^{s\mu}$

Semi-leptonic τ decays $\longrightarrow$ Probe $\widehat{V}_{ud}$, $\widehat{V}_{us}$, $\epsilon_X^{d\tau}$ and $\epsilon_X^{s\tau}$

Strategy to follow

1) Compute observables using $\mathcal{L}_{\text{eff}}$

2) Compare w/ exp. value to get bounds on L.C. of ϵ_X

3) Combine all the bounds to individually constrain ϵ_X

Nuclear β-decays

Superallowed $0^+ \to 0^+$

$\hat{V}_{ud}$ and ϵ_S^{de}

Neutron Decay

$\hat{V}_{ud}$, ϵ_S^{de}, ϵ_R^{d}, $\widehat{\epsilon}_T^{de}$

Mirror Transitions

$\hat{V}_{ud}$, ϵ_S^{de}, ϵ_R^{d}, $\widehat{\epsilon}_T^{de}$

Pure F and GT

F: $\hat{V}_{ud}$, ϵ_S^{de}

GT: $\hat{V}_{ud}$, ϵ_R^{d}, $\widehat{\epsilon}_T^{de}$

$$\begin{pmatrix} \hat{V}_{ud} \\ \epsilon_R^{d} \\ \epsilon_S^{de} \\ \widehat{\epsilon}_T^{de} \end{pmatrix} = \begin{pmatrix} 0.97382(43) \\ -0.012(12) \\ 0.0002(11) \\ -0.0006(13) \end{pmatrix}$$

→ Per-mille level constraints on $\epsilon_{S,T}^{de}$, ϵ_R^{d} only at % level.

→ Superallowed decays ⇒ $\hat{V}_{ud}$ constrained at sub-permille level.

→ No sensitivity to ϵ_P^{de} (appears at first order in recoil level, arxiv:2112.07688)

Pion Decays

$\pi \to e\bar{\nu}$ ⟶ ϵ_R^d and ϵ_P^{de}.

$\pi \to \mu\bar{\nu}$ ⟶ $\epsilon_L^{d\mu} - \epsilon_L^{de}$, ϵ_R^d and $\epsilon_P^{d\mu}$.

$\pi^- \to \pi^0 e\bar{\nu}$ ⟶ both $\hat{\epsilon}_T^{de}$ and ϵ_S^{de} suppressed$\to$ $\widehat{V}_{ud}$

$$\begin{pmatrix} \hat{V}_{ud} \\ \epsilon_R^d \\ \epsilon_S^{de} \\ \hat{\epsilon}_T^{de} \\ \epsilon_P^{de} \\ \epsilon_L^{d\mu} - \epsilon_L^{de} - \epsilon_P^{d\mu}\frac{m_\pi^2}{m_\mu(m_u+m_d)} \end{pmatrix} = \begin{pmatrix} 0.97386(40) \\ -0.012(12) \\ 0.00032(99) \\ -0.0004(11) \\ 3.9(4.3)\times 10^{-6} \\ -0.021(24) \end{pmatrix}$$

nuclear+ π decays

$\to$ Strong constraints for the *de* sector.

$\to$ Adding π decays strongly constrains ϵ_P^{de} since it is enhanced.

$\to$ Only a L.C. of $\epsilon_X^{d\mu}$ is constrained because we lack observables.

↑

more precision observablessuch as low energy μ scattering or μ-capture on nuclei are needed

K Decays and Hyperon β-decays

$K \to e\bar{\nu}$ → ϵ_R^s and ϵ_P^{se}.

$K \to \mu\bar{\nu}$ → $\epsilon_L^{s\mu} - \epsilon_L^{se}$, ϵ_R^s and $\epsilon_P^{s\mu}$.

$K_{\ell 3}$ → K_{e3} → $\hat{\epsilon}_T^{se}$ and $f_0(q^2)$ suppressed $\to \widehat{V}_{us}$.

$K_{\ell 3}$ → $K_{\mu 3}$ → fit to distribution ([hep-ex/0312004]) $\to \hat{\epsilon}_T^{s\mu}$

$K_{\mu 3}$ → $\epsilon_L^{s\mu} - \epsilon_L^{se}$, $\widehat{V}_{us}$ and $\hat{\epsilon}_T^{s\mu}$.

$K_{\ell 3}$ → $\epsilon_S^{s\ell}$ can be absorbed in $f_0(q^2)$. → Constrains $\epsilon_S^{s\ell}$ using the Callan-Treiman theorem.

Hyperon β-decays → ϵ_R^s through its axial coupling g_1.

K Decays and Hyperon β-decays

$$\begin{pmatrix} \hat{V}_{us} \\ \epsilon_L^{s\mu} - \epsilon_L^{se} \\ \epsilon_R^{s} \\ \epsilon_S^{s\mu} \\ \epsilon_P^{se} \\ \epsilon_P^{s\mu} \\ \hat{\epsilon}_T^{s\mu} \end{pmatrix} = \begin{pmatrix} 0.22306(56) \\ 0.0008(22) \\ 0.001(50) \\ -0.00026(44) \\ -0.3(2.0) \times 10^{-5} \\ -0.0006(41) \\ 0.002(22) \end{pmatrix}$$

→ The whole $s\mu$ sector is resolved.

→ As in π decays, $\epsilon_P^{de,\mu}$ is strongly constrained because it is enhanced.

→ K_{e3} directly probes $\widehat{V}_{us}$ → sub-permille bound.

→ $\epsilon_{S,T}^{se}$ are not constrained because they are suppressed by m_e → leading contribution at $\mathcal{O}((\epsilon_X^{se})^2)$

Hadronic τ Decays

$\tau \to \pi\nu$, $\tau \to K\nu$ $\longrightarrow$ $\epsilon_L^{D\tau} - \epsilon_L^{De}$, ϵ_R^{D} and $\epsilon_P^{D\tau}$.

$\tau \to \pi\pi\nu$ $\longrightarrow$ $\epsilon_L^{d\tau} - \epsilon_L^{de}$ and $\epsilon_T^{d\tau}$. $\epsilon_S^{d\tau}$ is suppressed.

$\tau \to \eta\pi\nu$ $\longrightarrow$ $\epsilon_S^{d\tau}$ enhanced $\to$ only constrains $\epsilon_S^{d\tau}$.

Non-strange inclusive $\longrightarrow$ Isospin Symmetry $\to$ $\epsilon_L^{d\tau} - \epsilon_L^{de}$, $\epsilon_R^{d\tau}$ and $\hat{\epsilon}_T^{d\tau}$.

Strange inclusive $\longrightarrow$ SU(3) $\to$ $\epsilon_L^{s\tau} - \epsilon_L^{se}$, $\epsilon_R^{s\tau}$, $\hat{\epsilon}_T^{s\tau}$, $\epsilon_S^{s\tau}$ and $\epsilon_P^{s\tau}$.

Hadronic τ Decays: constraints

$\tau \to \pi\nu$ $\xrightarrow{\Gamma(\tau \to \pi\nu)}$ $\epsilon_L^{d\tau} - \epsilon_L^{de} - \epsilon_R^{d\tau} - \epsilon_R^{de} - \frac{B_0^d}{m_\tau}\epsilon_P^{d\tau} = -(0.9 \pm 7.3) \times 10^{-3}$

$\tau \to K\nu$ $\xrightarrow{\Gamma(\tau \to K\nu)}$ $\epsilon_L^{s\tau} - \epsilon_L^{se} - \epsilon_R^{s\tau} - \epsilon_R^{se} - \frac{B_0^s}{m_\tau}\epsilon_P^{s\tau} = -(2 \pm 10) \times 10^{-3}$

$\tau \to \pi\pi\nu$ $\xrightarrow{a_\mu^{\mathrm{had,\,LO}}}$ $\epsilon_L^{d\tau} - \epsilon_L^{de} + \epsilon_R^{d\tau} - \epsilon_R^{de} + 0.43(8)\,\hat{\epsilon}_T^{d\tau} = (10.0 \pm 4.9) \times 10^{-3}$

$\tau \to \eta\pi\nu$ $\xrightarrow{\mathrm{BR}(\tau \to \eta\pi\nu)}$ $\epsilon_S^{d\tau} \in (-0.021, 0.0010), \quad |\mathrm{Im}(\epsilon_S^{d\tau})| < 0.014$

Hadronic τ Decays: constraints

$$\left.\begin{aligned}
\epsilon^{d\tau}_{L+R} - \epsilon^{de}_{L+R} - 0.76\epsilon^{d\tau}_{R} + 0.49(16)\hat{\epsilon}^{d\tau}_{T} &= (4 \pm 10) \times 10^{-3} \\
\epsilon^{d\tau}_{L+R} - \epsilon^{de}_{L+R} - 0.88\epsilon^{d\tau}_{R} + 0.27(9)\,\hat{\epsilon}^{d\tau}_{T} &= (9.1 \pm 8.8) \times 10^{-3}
\end{aligned}\right\} \rho_{\mathrm{V+A}}$$

$$\left.\begin{aligned}
\epsilon^{d\tau}_{L+R} - \epsilon^{de}_{L+R} + 3.05\epsilon^{d\tau}_{R} + 1.9(1.2)\hat{\epsilon}^{d\tau}_{T} &= (5 \pm 51) \times 10^{-3} \\
\epsilon^{d\tau}_{L+R} - \epsilon^{de}_{L+R} + 1.93\epsilon^{d\tau}_{R} + 1.6(1.5)\hat{\epsilon}^{d\tau}_{T} &= (7.0 \pm 9.5) \times 10^{-3}
\end{aligned}\right\} \rho_{\mathrm{V-A}}$$

Non-strange Inclusive

↑

$\int_{s_{th}}^{s_0} \frac{ds}{s_0}\, \omega(s)\, \rho_{exp}(s).$

$$\begin{aligned}
&1.00\,(\epsilon^{s\tau}_{L+R} - \epsilon^{se}_{L+R}) - 1.03\,\epsilon^{s\tau}_{R} - 0.38\,\epsilon^{s\tau}_{P} + 0.40(13)\,\hat{\epsilon}^{s\tau}_{T} + 0.08(1)\,\epsilon^{s\tau}_{S} \\
&- 1.07\,(\epsilon^{d\tau}_{L+R} - \epsilon^{de}_{L+R}) + 1.04\,\epsilon^{d\tau}_{R} + 0.30\,\epsilon^{d\tau}_{P} - 0.43(14)\,\hat{\epsilon}^{d\tau}_{T} \\
&= -(0.0171 \pm 0.0085)
\end{aligned}$$

Strange Inclusive

↑

$|\widehat{V_{us}}|^{\mathrm{inc}} = \left(\frac{\hat{R}^s_\tau}{\hat{R}^d_\tau/|\hat{V}_{ud}|^2 - \delta R^{\mathrm{SM}}_{\mathrm{th}}}\right)^{1/2}$

Hadronic τ Decays: fit

$$\begin{pmatrix} \epsilon_L^{d\tau/e} + \epsilon_R^{d\tau} - \epsilon_R^{de} \\ \epsilon_R^{d\tau} \\ \epsilon_P^{d\tau} \\ \hat{\epsilon}_T^{d\tau} \\ \epsilon_L^{s\tau/e} - \epsilon_R^{s\tau} - \epsilon_R^{se} - \frac{m_{K^\pm}^2}{m_\tau(m_u+m_s)}\epsilon_P^{s\tau} \\ \epsilon_L^{s\tau/e} - 0.03\epsilon_R^{s\tau} - \epsilon_R^{se} + 0.08(1)\epsilon_S^{s\tau} - 0.38\epsilon_P^{s\tau} + 0.40(13)\hat{\epsilon}_T^{s\tau} \end{pmatrix} = \begin{pmatrix} 2.4 \pm 2.6 \\ 0.7 \pm 1.4 \\ 0.4 \pm 1.0 \\ -3.3 \pm 6.0 \\ -0.2 \pm 1.0 \\ -1.3 \pm 1.2 \end{pmatrix} \times 10^{-2} \, ,$$

$\left(\epsilon_L^{D\tau/e} \equiv \epsilon_L^{D\tau} - \epsilon_L^{De}\right)$

→ Percent level marginalized constrains.

→ All Lorentz structures resolved in the $d\tau$ sector.

→ Only two combinations of $\epsilon_X^{s\tau}$ are constrained.

↑

We cannot resolve $\epsilon_X^{s\tau}$

Global fit

$$\begin{pmatrix} \hat{V}_{us} \equiv V_{us}\left(1+\epsilon_L^{se}+\epsilon_R^{s}\right) \\ \epsilon_L^{dse} \equiv \epsilon_L^{de} + \frac{\hat{V}_{us}^2}{1-\hat{V}_{us}^2}\epsilon_L^{se} \\ \epsilon_R^{d} \\ \epsilon_S^{de} \\ \epsilon_P^{de} \\ \hat{\epsilon}_T^{de} \\ \epsilon_L^{s\mu}-\epsilon_L^{se} \\ \epsilon_R^{s} \\ \epsilon_P^{se} \\ \epsilon_L^{d\mu}-\epsilon_L^{de}-\epsilon_P^{d\mu}\frac{m_{\pi^\pm}^2}{m_\mu(m_u+m_d)} \\ \epsilon_S^{s\mu} \\ \epsilon_P^{s\mu} \\ \hat{\epsilon}_T^{s\mu} \\ \epsilon_L^{d\tau}-\epsilon_L^{de} \\ \epsilon_P^{d\tau} \\ \hat{\epsilon}_T^{d\tau} \\ \epsilon_L^{s\tau}-\epsilon_L^{se}-\epsilon_P^{s\tau}\frac{m_{K^\pm}^2}{m_\tau(m_u+m_s)} \\ \epsilon_L^{s\tau}-\epsilon_L^{se}+0.08(1)\epsilon_S^{s\tau}-0.38\epsilon_P^{s\tau}+0.40(13)\hat{\epsilon}_T^{s\tau} \end{pmatrix} = \begin{pmatrix} 0.22306(56) \\ 2.2(8.6) \\ -3.3(8.2) \\ 3.0(9.9) \\ 1.3(3.4) \\ -0.4(1.1) \\ 0.8(2.2) \\ 0.2(5.0) \\ -0.3(2.0) \\ -0.5(1.8) \\ -2.6(4.4) \\ -0.6(4.1) \\ 0.2(2.2) \\ 0.1(1.9) \\ 9.2(8.6) \\ 1.9(4.5) \\ 0.0(1.0) \\ -0.7(5.2) \end{pmatrix} \times 10^\wedge \begin{pmatrix} 0 \\ -3 \\ -3 \\ -4 \\ -6 \\ -3 \\ -3 \\ -2 \\ -5 \\ -2 \\ -4 \\ -3 \\ -2 \\ -2 \\ -3 \\ -2 \\ -1 \\ -2 \end{pmatrix}$$

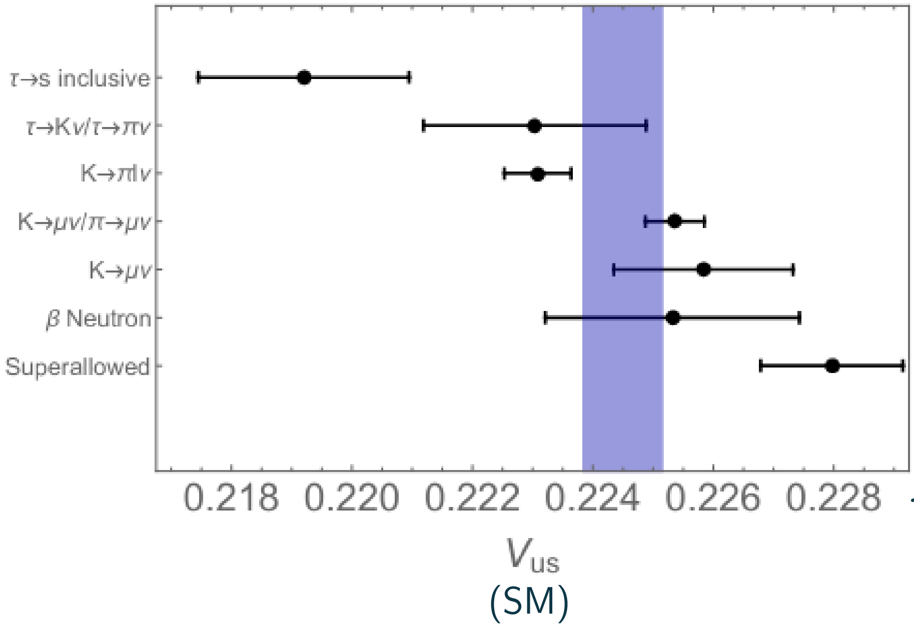
Model independent bounds for the light quark sector involving all three lepton families.

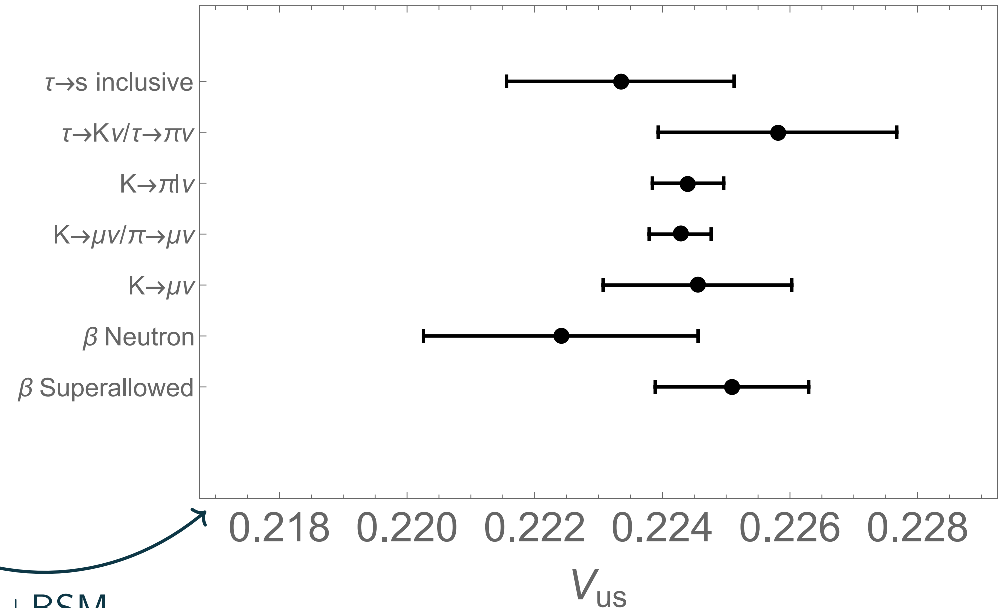
$$\chi^2_{SM}-\chi^2_{min}=37.4 \Rightarrow 3\sigma$$

Global fit

$$\chi^2_{SM} - \chi^2_{min} = 37.4 \Rightarrow 3\sigma$$

Why?





+BSM

$\epsilon_R^d, \epsilon_R^s, \epsilon_L^{s\tau}$

Cabibbo anomalies → Inconsistencies in V_{us} determinations

The anomalies disappear with a few BSM parameters

Global fit

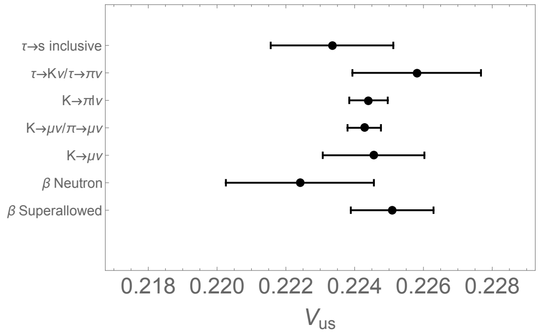
One-at-a-time fit

	$\epsilon_X^{de} \times 10^3$	$\epsilon_X^{se} \times 10^3$	$\epsilon_X^{d\mu} \times 10^3$	$\epsilon_X^{s\mu} \times 10^3$	$\epsilon_X^{d\tau} \times 10^3$	$\epsilon_X^{s\tau} \times 10^3$
L	-0.79(25)	-0.6(1.2)	0.40(87)	0.5(1.2)	5.0(2.5)	-18.2(6.2)
R	-0.62(25)	-5.2(1.7)	-0.62(25)	-5.2(1.7)	-0.62(25)	-5.2(1.7)
S	1.40(65)	-1.6(3.2)	x	-0.51(43)	-6(16)	-270(100)
P	0.00018(17)	-0.00044(36)	-0.015(32)	-0.032(64)	1.7(2.5)	10.4(5.5)
$\hat{T}$	0.29(82)	0.035(70)	x	2(18)	28(10)	-55(27)

In red: 3σ or more preference for BSM

→ ϵ_R^s, ϵ_L^{de} ease the tension between nuclear and kaon decays.

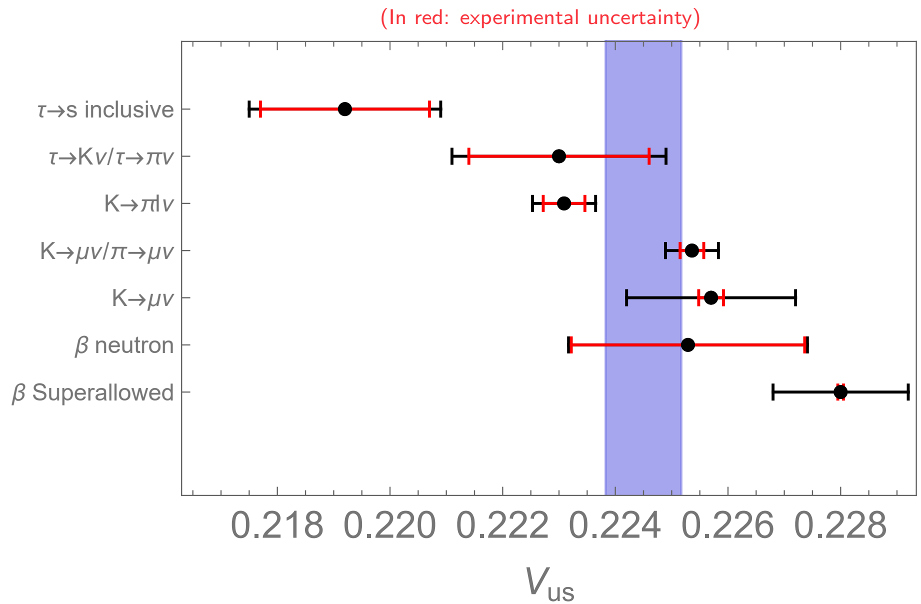
→ $\epsilon_L^{s\tau}$ eases the tension between $\tau \to s$ inclusive and kaon decays.



$\epsilon_R^d, \epsilon_R^s, \epsilon_L^{s\tau}$

$$\chi^2_{\rm SM} - \chi^2_{\rm min} = 26.1 \Rightarrow 4.4\sigma$$

What can be improved?



→ Determinations from τ data dominated by exp. → should be improved with Belle-II.

→ K decay data is fairly precise → need to improve theoretical inputs.

→ Superallowed decays dominated by theory uncertainties → radiative corrections

→ Neutron β decay dominated by experimental unc. ← neutron lifetime beam-bottle puzzle

Summary

Model independent bounds for the light quark sector involving all three lepton families. → Guidance for model building and unbiased tool to test implications of BSM models in this set of transitions.

Strong preference for BSM physics in the global fit. ← Cabibbo anomalies. → They can be eradicated in scenarios with a few BSM parameters.

More precise experimental data. → Improvement of some bounds, specially from τ decays and neutron decays.

Improvement of theoretical inputs → Improvement of K decays and β-superallowed bounds.