New Physics in Hadronic τ decays

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

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Motivation

Why hadronic τ decays?

$\longrightarrow$ They are the only processes that probe the $D\tau$ sector

$\longrightarrow$ They are used to extract some fundamental SM parameters. There are inconsistencies with other determinations $\rightarrow V_{us}$

$\longrightarrow$ Anomalies in $B \rightarrow D^{(*)}\tau\bar{\nu}_\tau$ $\longrightarrow$ some BSM models predict new particles coupled to both τ leptons and light quarks

Theoretical Framework

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

$\epsilon_X^{D\ell}$ ⟶ BSM

Assuming UV-completion by the SMEFT, $\epsilon_R^{D\ell}=\epsilon_R^{D}$

$G_F,\ V_{uD}$ ⟶ SM

↑ ~~PDG~~

G_F from $\mu\to e\bar{\nu}_e\nu_\mu$ ⟶ $G_\mu = G_F(1+\delta G_\mu)$ ⟶ To use G_μ we rescale as $\epsilon_X^{D\ell}\to\frac{\epsilon_X^{D\ell}}{1+\delta G_\mu}$

V_{uD} ⟶ $\hat{V}_{uD}\equiv V_{uD}(1+\epsilon_L^{De}+\epsilon_R^{De})$ ($\hat{V}_{ud}$ and $\hat{V}_{us}$ can be extracted from Superallowed β-decays and $Ke3$ decays.)

Hadronic τ decays as New Physics Probes

Sensitivities of the different channels:

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

Strategy: compute $\epsilon_X^{D\ell}$ dependence of observables $\to$ compare with experiment to get a bounds on L.C. of $\epsilon_X^{D\ell}$s $\to$ minimize a χ^2 function to get bounds on individual $\epsilon_X^{D\ell}$

Hadronic τ Decays: constraints

$\tau \to \pi\nu$, $\tau \to K\nu$

$\uparrow$

Non-pert. QCD dynamics contained in f_P

$$\Gamma(\tau \to P\nu_\tau) = \widehat{\Gamma}(\tau \to P\nu_\tau)|_{SM}\left(1 + 2\delta^{(P)}_{\rm BSM}\right)$$

$$\widehat{\Gamma}(\tau \to P\nu_\tau)|_{SM} = \frac{m_\tau^3 f_P^2 G_\mu^2 |\widehat{V}_{uD}|^2}{16\pi}\left(1 - \frac{m_P^2}{m_\tau^2}\right)^2\left(1 + \delta^{(P)}_{\rm RC}\right)$$

New physics is contained in $\delta^{(P)}_{\rm BSM} \equiv \epsilon_L^{D\tau} - \epsilon_L^{De} - \epsilon_R^{D\tau} - \epsilon_R^{De} - \frac{B_0^D}{m_\tau}\epsilon_P^{D\tau}$

$\downarrow$

$$\delta^{(P)}_{\rm BSM} = \frac{\Gamma(\tau\to P\nu_\tau)_{\rm exp} - \widehat{\Gamma}(\tau\to P\nu_\tau)_{\rm SM}}{2\widehat{\Gamma}(\tau\to P\nu_\tau)_{\rm SM}}$$

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

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

Hadronic τ Decays: constraints

$\tau \to \pi\pi\nu$

$a_s(s) \sim \Delta^2_{PP'}/(m_u - m_d) \to 0$ for $\pi\pi$ channel

$$\frac{d\Gamma}{ds} = \left[\frac{d\hat{\Gamma}}{ds}\right]_{SM} \left(1 + 2(\epsilon_L^{D\tau} + \epsilon_R^{D\tau} - \epsilon_L^{De} - \epsilon_R^{De}) + a_S(s)\epsilon_S^{D\tau} + a_T(s)\hat{\epsilon}_T^{D\tau}\right)$$

$$\left[\frac{d\widehat{\Gamma}}{ds}\right]_{\rm SM} = \frac{G_\mu^2 |\widehat{V}_{uD}|^2 m_\tau^3}{768\pi^3} S_{EW}^{\rm had} C_{PP'}^2 \left(1 - \frac{s}{m_\tau^2}\right)^2 \left[\left(1 + 2\frac{s}{m_\tau^2}\right) \lambda_{PP'}^{3/2} |F_V^{PP'}(s)|^2 + 3\frac{\Delta_{PP'}^2}{s^2} \lambda_{PP'}^{1/2} |F_S^{PP'}(s)|^2\right]$$

$F_{V,T}(s)$ need to be BSM free → We use $a_\mu^{\rm had,LO}[\pi\pi]$ as observable

$$\frac{a_\mu^\tau - a_\mu^{ee}}{2a_\mu^{ee}} = \epsilon_L^{d\tau} + \epsilon_R^{d\tau} - \epsilon_L^{de} - \epsilon_R^{d\tau} + 0.43(8)\hat{\epsilon}_T^{d\tau} = 10.0(4.9) \times 10^{-3}$$

$\tau \to \eta\pi\nu$

$a_s(s) \sim (m^2_{\pi^\pm} - m^2_\eta)/(m_u - m_d)$ ⟶ Enhanced scalar contribution

↓ the scalar terms dominate the NP contribution

$$\mathrm{BR}_{\mathrm{exp}}(\tau \to \eta\pi\nu_\tau) = \widehat{\mathrm{BR}}_{\mathrm{SM}}(\tau \to \eta\pi\nu_\tau)(1 + \alpha\epsilon_S^{d\tau} + \gamma(\epsilon_S^{d\tau})^2)$$

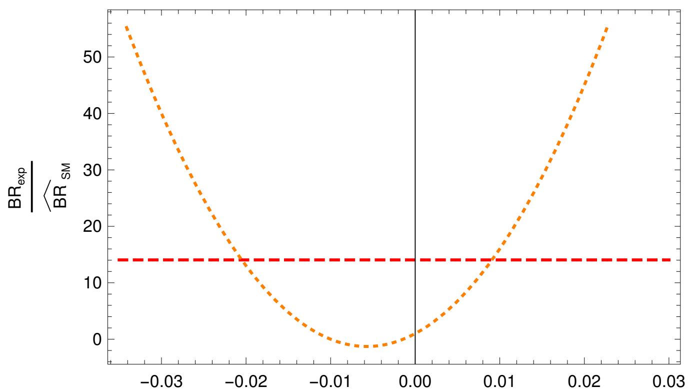
$\tau \to \eta\pi\nu$ violates isospin ⟶ $\mathrm{BR}_{\mathrm{exp}} < 9.9 \times 10^{-5}$ at 95% CL

$\alpha \in [3, 8] \times 10^2$

$\gamma \in [0.7, 1.75] \times 10^5$

$\widehat{\mathrm{BR}}_{\mathrm{SM}} \in [0.3, 2.1] \times 10^{-5}$

Theoretical estimations (*JHEP* **12** (2017) 027)



$\epsilon_S^{d\tau} \in (-0.021, 0.010)$ $\quad |\mathrm{Im}\,\epsilon_S^{d\tau}| < 0.014$

Hadronic τ Decays: constraints

Non-strange Inclusive

$$I^{\rm exp}_{V\pm A} - I^{\rm SM}_{V\pm A} = 2\left(\epsilon^{d\tau}_{L+R} - \epsilon^{de}_{L+R}\right)\, I^{\rm SM}_{V\pm A} \mp\, 4\epsilon^{d\tau}_{R}\, I^{\rm SM}_{A} + 6\,\hat{\epsilon}^{d\tau}_{T}\, I_{VT}$$

$$I^{\rm exp}_{J}(s_0;n) \equiv \int_{s_{th}}^{s_0} \frac{ds}{s_0}\left(\frac{s}{s_0}\right)^n \rho^{\rm exp}_J(s)$$

$$I^{\rm SM}_{J}(s_0;n) \equiv \int_{s_{th}}^{s_0} \frac{ds}{s_0}\left(\frac{s}{s_0}\right)^n \frac{1}{\pi}\,{\rm Im}\,\Pi^{(1+0)}_J$$

$$I_{VT}(s_0;n;\mu) \equiv \int_{s_{th}}^{s_0} \frac{ds}{s_0}\left(\frac{s}{s_0}\right)^n \left(1+2\frac{s}{m_\tau^2}\right)^{-1} \frac{{\rm Im}\,\Pi_{VT}}{\pi\, m_\tau}(s)$$

$$\left.\begin{aligned} \epsilon^{d\tau}_{L+R} - \epsilon^{de}_{L+R} - 0.76\epsilon^{d\tau}_{R} + 0.49(16)\hat{\epsilon}^{d\tau}_{T} &= (4\pm 10)\times 10^{-3} \\ \epsilon^{d\tau}_{L+R} - \epsilon^{de}_{L+R} - 0.88\epsilon^{d\tau}_{R} + 0.27(9)\,\hat{\epsilon}^{d\tau}_{T} &= (9.1\pm 8.8)\times 10^{-3} \end{aligned}\right\} \rho_{\rm V+A}\!:\ \omega_\tau(s) = \left(1-\frac{s}{m_\tau^2}\right)^2\left(1+2\frac{s}{m_\tau^2}\right),\ \omega_0(s)=1\,,$$

$$\left.\begin{aligned} \epsilon^{d\tau}_{L+R} - \epsilon^{de}_{L+R} + 3.05\epsilon^{d\tau}_{R} + 1.9(1.2)\hat{\epsilon}^{d\tau}_{T} &= (5\pm 51)\times 10^{-3} \\ \epsilon^{d\tau}_{L+R} - \epsilon^{de}_{L+R} + 1.93\epsilon^{d\tau}_{R} + 1.6(1.5)\hat{\epsilon}^{d\tau}_{T} &= (7.0\pm 9.5)\times 10^{-3} \end{aligned}\right\} \rho_{\rm V-A}\!:\ \omega_1(s) \equiv 1-\frac{s}{s_0},\ \omega_2(s) \equiv \left(1-\frac{s}{s_0}\right)^2$$

Strange Inclusive

No $\rho_{exp}(s)$ available $\rightarrow$ we use V_{us} as observable.

$$\frac{R_\tau^d}{|V_{ud}|^2} = \frac{R_\tau^s}{|V_{us}|^2} + \delta R_{\rm th}^{\rm SM}$$

$$\downarrow$$

$$|\widehat{V}_{us}|^{\rm inc} = \left(\frac{\hat{R}_\tau^s}{\frac{\hat{R}_\tau^d}{|\hat{V}_{ud}|^2} - \delta R_{\rm th}^{\rm SM}}\right)^{1/2} = |\hat{V}_{us}|\left(1 + \delta_{{\rm BSM},\,s}^{\rm inc} - (1+\eta)\delta_{{\rm BSM},\,d}^{\rm inc}\right)$$

$$1.00\,(\epsilon_{L+R}^{s\tau} - \epsilon_{L+R}^{se}) - 1.03\,\epsilon_R^{s\tau} - 0.38\,\epsilon_P^{s\tau} + 0.40(13)\,\hat{\epsilon}_T^{s\tau} + 0.08(1)\,\epsilon_S^{s\tau}$$
$$- 1.07\,(\epsilon_{L+R}^{d\tau} - \epsilon_{L+R}^{de}) + 1.04\,\epsilon_R^{d\tau} + 0.30\,\epsilon_P^{d\tau} - 0.43(14)\,\hat{\epsilon}_T^{d\tau}$$
$$= -(0.0171 \pm 0.0085)$$

Hadronic τ Decays: fit

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

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

$$\rho = \begin{pmatrix} 1 & 0.87 & -0.18 & -0.98 & -0.03 & -0.45 \\ & 1 & -0.59 & -0.86 & 0.06 & -0.59 \\ & & 1 & 0.18 & -0.36 & 0.38 \\ & & & 1 & 0.04 & 0.49 \\ & & & & 1 & 0.16 \\ & & & & & 1 \end{pmatrix} .$$

$\longrightarrow$ Percent level marginalized constrains.

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

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

$\uparrow$

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

Other probes

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

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

Global fit

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

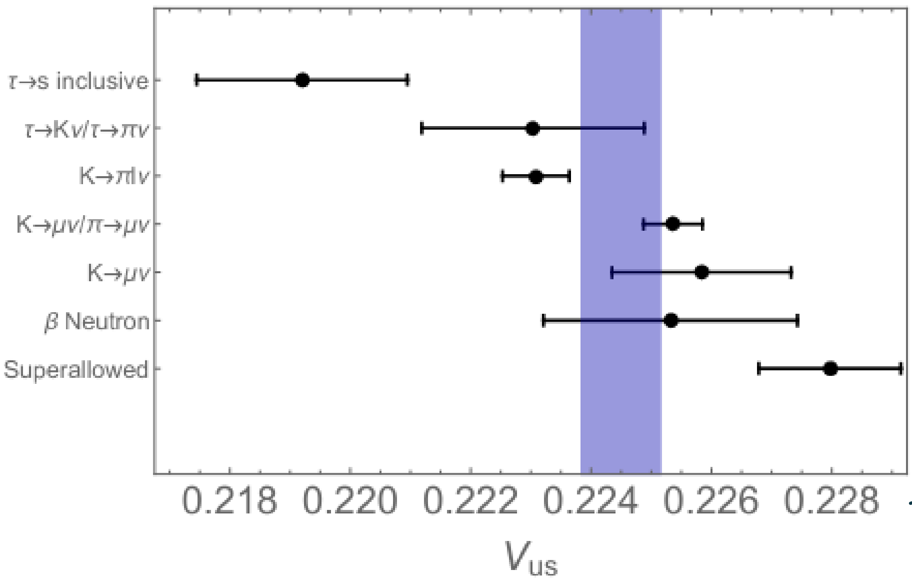
Model independent bounds for the light quark sector involving all three lepton families.

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

Global fit

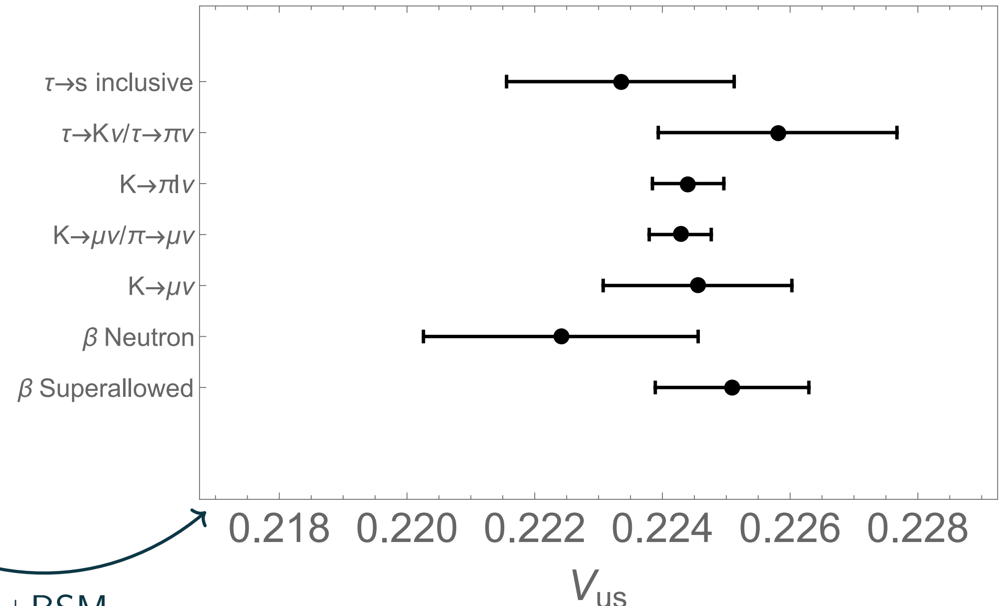
$$\chi^2_{SM} - \chi^2_{min} = 37.4 \Rightarrow 3\sigma$$

Why?



(SM)

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



Cabibbo anomaly → Inconsistency in V_{us} determinations

The anomaly disappears with a few BSM parameters

Global fit

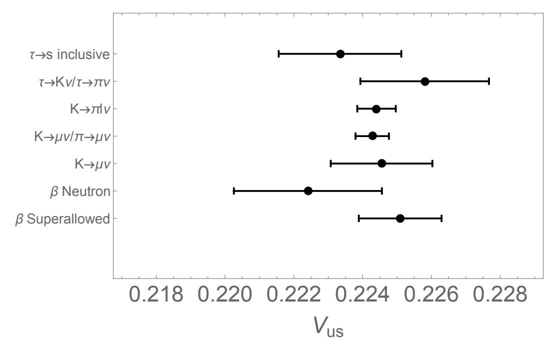
One-at-a-time fit

	$\epsilon_X^{de} \times 10^3$	$\epsilon_X^{se} \times 10^3$	$\epsilon_X^{d\mu} \times 10^3$	$\epsilon_X^{s\mu} \times 10^3$	$\epsilon_X^{d\tau} \times 10^3$	$\epsilon_X^{s\tau} \times 10^3$
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

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

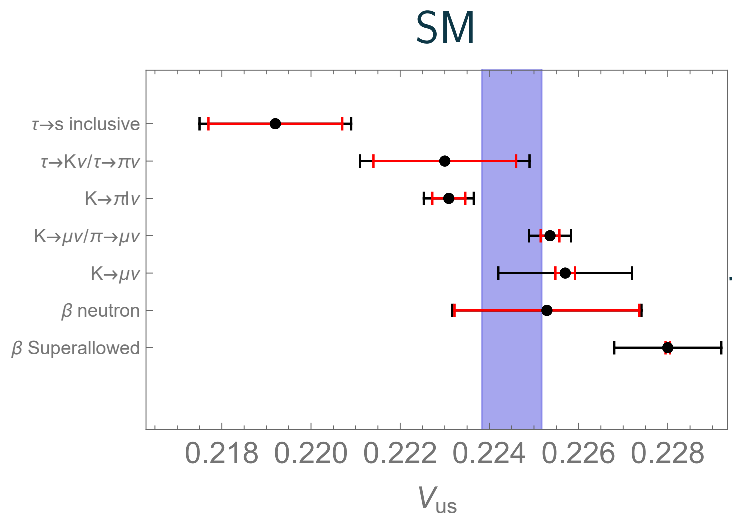
$\rightarrow$ $\epsilon_L^{s\tau}$ eases the tension between $\tau \rightarrow s$ inclusive and kaon decays.



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

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

What can we improve with better experimental data?



More precise branching ratios $\to$ improved bounds from exclusive decays.

Improvement of experimental data will improve several bounds

We use the old LEP measurements of the non-strange spectral functions $\to$ they should de improved by Belle II.

Concerning $\epsilon_X^{D\tau}$s

Strange inclusive spectral functions $\to$ resolving the $\epsilon_X^{s\tau}$ sector.

$\tau \to \pi\pi\nu$ distribution $\to$ resolving $\epsilon_L^{d\tau} - \epsilon_L^{de}$ and $\epsilon_T^{d\tau}$.

$\tau \to K\pi\nu$ distribution $\to$ resolving $\epsilon_L^{s\tau} - \epsilon_L^{se}$, $\epsilon_T^{s\tau}$ and $\epsilon_S^{s\tau}$.

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 anomaly. → It can be eradicated in scenarios with a few BSM parameters.

More precise experimental data. → Improvement of several bounds.

3 body decay distributions and S.I. spectral functions → bounds on individual $\epsilon_X^{D\ell}$, specially in the $s\tau$ sector.