New Physics in semi-leptonic 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 semi-leptonic τ decays?

They are used to extract various SM parameters: α_s, V_{us}, f_π, QCD vacuum condensates, ...

Tension between different determinations of V_{us}. $\longrightarrow$ BSM physics in the light quark sector

Anomalies in $B \to D^{(*)}\tau\nu$ $\longrightarrow$ Hints NP in the τ sector.

Motivates BSM physics in hadronic τ decays

Theoretical Framework

Effective Field Theory→Model independent bounds.

In particular,

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

$\epsilon_X^{D\ell}$ → BSM effects

↑ No BSM below ~ 2 GeV

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

↑ Experiment

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

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

Non-Perturbative effects contained in f_P

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

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

$$\delta_{\rm BSM}^{(P)} = \epsilon_L^{D\tau} - \epsilon_L^{De} - \epsilon_R^{D\tau} - \epsilon_R^{De} - \frac{B_0^D}{m_\tau}\epsilon_P^{D\tau} = \frac{\Gamma(\tau\to P\nu_\tau)_{\rm exp} - \widehat{\Gamma}(\tau\to P\nu_\tau)_{\rm SM}}{2\widehat{\Gamma}(\tau\to P\nu_\tau)_{\rm SM}}$$

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

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

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

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

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

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

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

Hadronic τ Decays: constraints

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

$\epsilon_S^{d\tau}$ contribution enhanced $\to$ keep quadratic contribution

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

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

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

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

$$\mathrm{BR}_{\mathrm{exp}} < 9.9 \times 10^{-5} \text{ at } 95\% \text{ CL}$$

$$\epsilon_S^{d\tau} \in (-0.021, 0.0010), \quad |\mathrm{Im}(\epsilon_S^{d\tau})| < 0.014$$

(if we let $\epsilon_S^{d\tau}$ to be complex)

Non-strange Inclusive

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

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

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

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

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

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

Hadronic τ Decays: constraints

Strange Inclusive

No $\rho_{exp}(s)$ avalaible $\rightarrow$ 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

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

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

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

→ 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 $\epsilon_X^{s\tau}$

Other probes

nuclear+ π decays

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

K decay + Hyperon β decay

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

Global fit

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

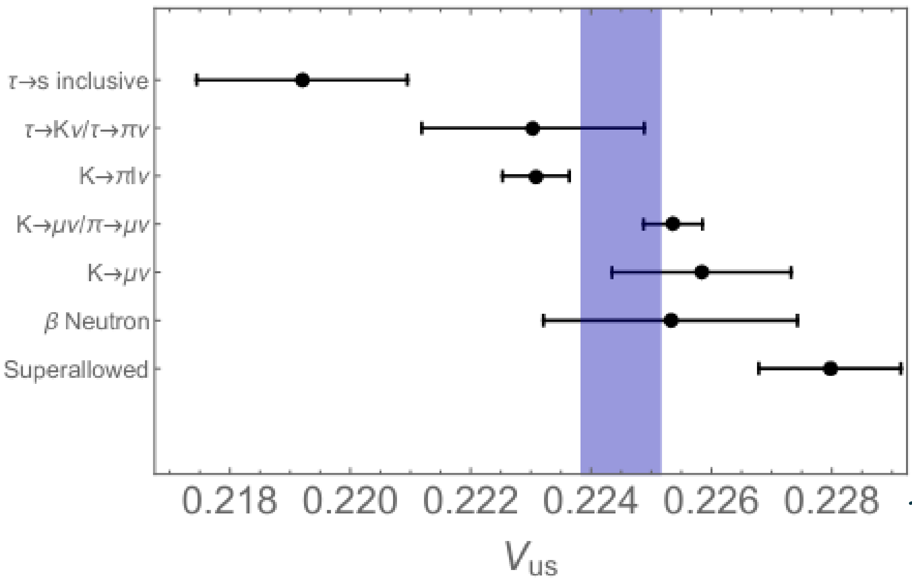
Model independent bounds for the light quark sector involving all three lepton families.

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

Global fit

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

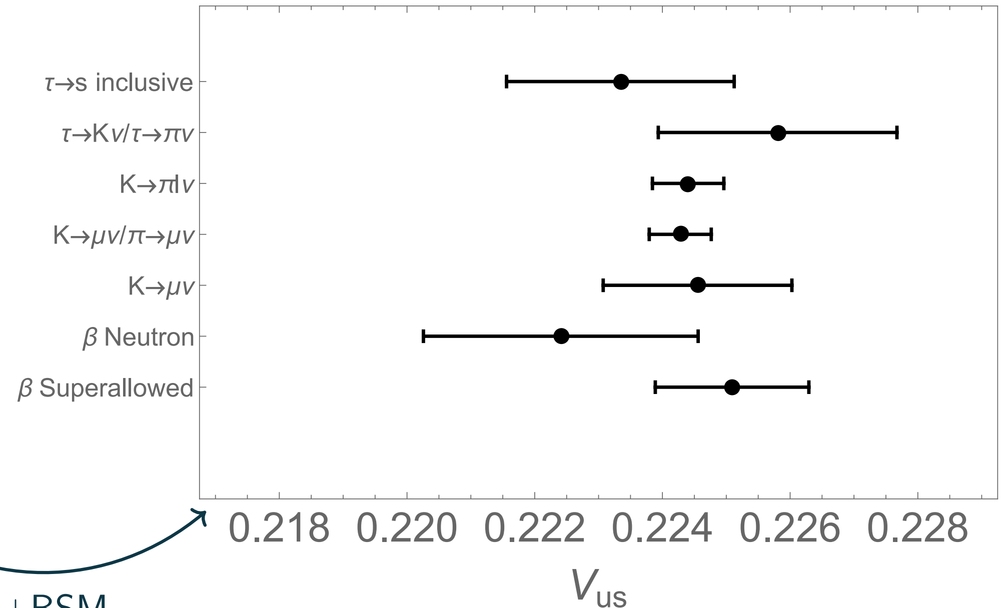
Why?



(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

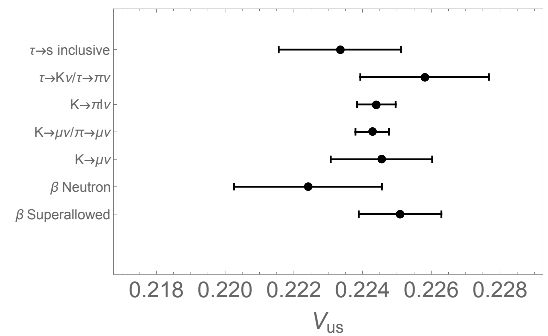
One-at-a-time fit

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

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

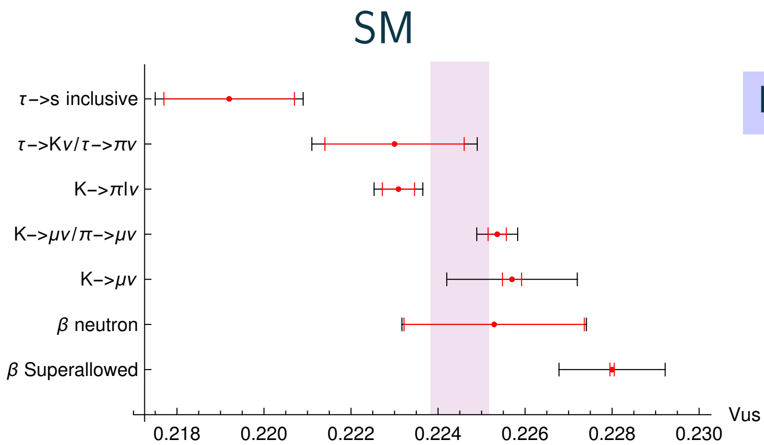
→ $\epsilon_L^{s\tau}$ eases the tension between $\tau \to s$ inclusive and kaon decays.



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

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

What can we improve with better experimental data?



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

■ total
■ exp.

$\longrightarrow$ Improvement of experimental data will improve several bounds

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

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

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

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

$\tau \rightarrow K\pi\nu$ distribution $\rightarrow$ 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.