Semi-leptonic τ decays BSM

[Based on: V. Cirigliano, D. Díaz-Calderón, A. Falkowski, M. González-Alonso, & A. Rodríguez-Sánchez, arxiv:2112.02087]

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Overview

- Motivation
- Theoretical framework
- Hadronic tau decays
- Combination of bounds
- Other probes
  - π decays
  - K + Hyperon decays
  - Nuclear β decays
- Global fit
- What can be improved with data?
- Recap

Motivation

Great experimental and theoretical precision in hadronic tau decays.

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Motivation

Great experimental and theoretical precision in hadronic tau decays.

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Determination of SM parameters such as α_s, V_{us}, f_π, QCD vacuum condensates, ...

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

Anomalies in $B \to D^{(*)}\tau\nu$ and LFUV in $b \to s\mu\mu(ee)$ ⟶ May have counterpart in the τ sector

Motivates BSM physics in hadronic τ decays

Theoretical Framework

Effective Field Theory→Model independent bounds.

In particular,

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

$\epsilon_X^{D\ell}$ ⟶ BSM effects

↑ No BSM below ~ 2 GeV

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

↑ Experiment

Hadronic τ Decays

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

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

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

Non-strange inclusive

Strange inclusive

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 $\epsilon_T^{d\tau}$.

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

Hadronic τ Decays: constraints

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

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

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

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

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

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

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: constraints

	$\epsilon_L^{d\tau} \times 10^3$	$\epsilon_L^{de} \times 10^3$	$\epsilon_R^{d} \times 10^3$	$\epsilon_P^{d\tau} \times 10^3$	$\epsilon_T^{d\tau} \times 10^3$	$\epsilon_S^{d\tau} \times 10^3$
$\tau \to \pi\nu$	-0.9(7.3)	0.9(7.3)	0.9(7.3)	0.6(5.0)	x	x
$\tau \to \pi\pi\nu$	10(4.9)	-10(4.9)	x	x	23(12)	x
$\tau \to \pi\eta\nu$	x	x	x	x	x	$(-21, 10)$
$V + A$	6.9(7.0)	-6.9(7.0)	-8.6(8.4)	x	15(19)	x
$V - A$	7.0(9.5)	-7.0(9.5)	3.6(4.9)	x	15(17)	x

	$\epsilon_L^{s\tau} \times 10^3$	$\epsilon_L^{se} \times 10^3$	$\epsilon_R^{s} \times 10^3$	$\epsilon_P^{s\tau} \times 10^3$	$\epsilon_T^{s\tau} \times 10^3$	$\epsilon_S^{s\tau} \times 10^3$
$\tau \to K\nu$	-2(10)	2(10)	2(10)	1.2(6.1)	x	x
S. Inclusive	-17(16)	17(16)	23(22)	340(327)	-34(35)	-170(161)

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.

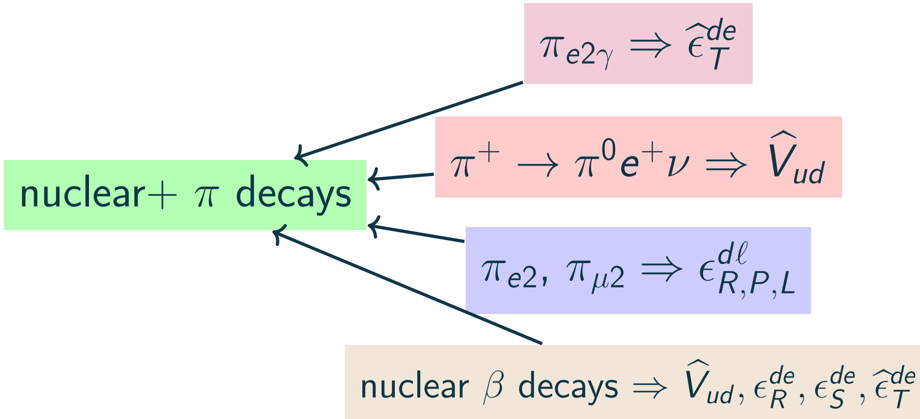
↑ We cannot resolve $\epsilon_X^{s\tau}$

Other probes

nuclear+ π decays

K decay + Hyperon β decay

Other probes



K decay + Hyperon β decay

Other probes

nuclear+ π decays

- $\pi_{e2\gamma} \Rightarrow \widehat{\epsilon}_T^{de}$
- $\pi^+ \to \pi^0 e^+ \nu \Rightarrow \widehat{V}_{ud}$
- $\pi_{e2},\ \pi_{\mu 2} \Rightarrow \epsilon_{R,P,L}^{d\ell}$
- nuclear β decays $\Rightarrow \widehat{V}_{ud}, \epsilon_R^{de}, \epsilon_S^{de}, \widehat{\epsilon}_T^{de}$

K decay + Hyperon β decay

- $K_{\ell 2} \Rightarrow \widehat{V}_{us}, \epsilon_L^{s\mu/e}, \epsilon_R^{s}, \epsilon_P^{s\mu}, \epsilon_P^{se}$
- $K_{e3} \Rightarrow \widehat{V}_{us}$
- $K_{\mu 3} \Rightarrow \widehat{V}_{us}, \epsilon_L^{s\mu/e}, \widehat{\epsilon}_T^{s\mu}$
- Hyperon β decay $\Rightarrow \epsilon_R^{s}$
- Differential distribution of $K_{\mu 3} \Rightarrow \widehat{\epsilon}_T^{s\mu}, \epsilon_S^{s\mu}$

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

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

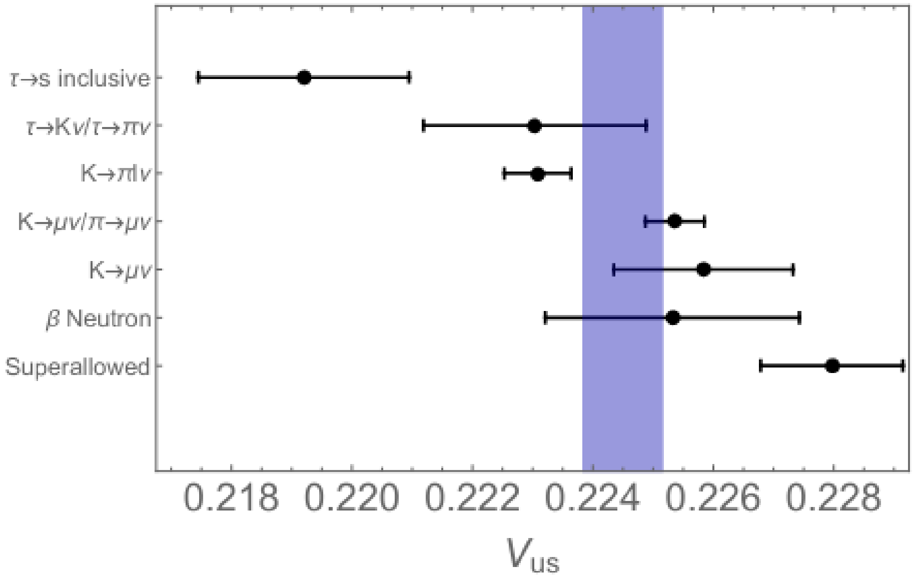
Model independent bounds for the light quark sector involving all three lepton families.

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

Global fit

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

Why?



(SM)

Cabibbo anomaly → Inconsistency in V_{us} determinations

Global fit

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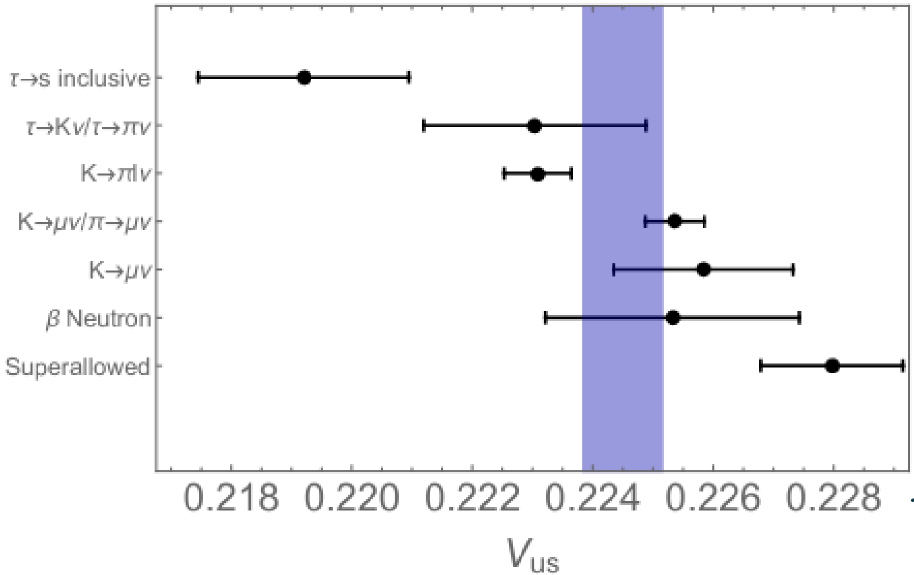
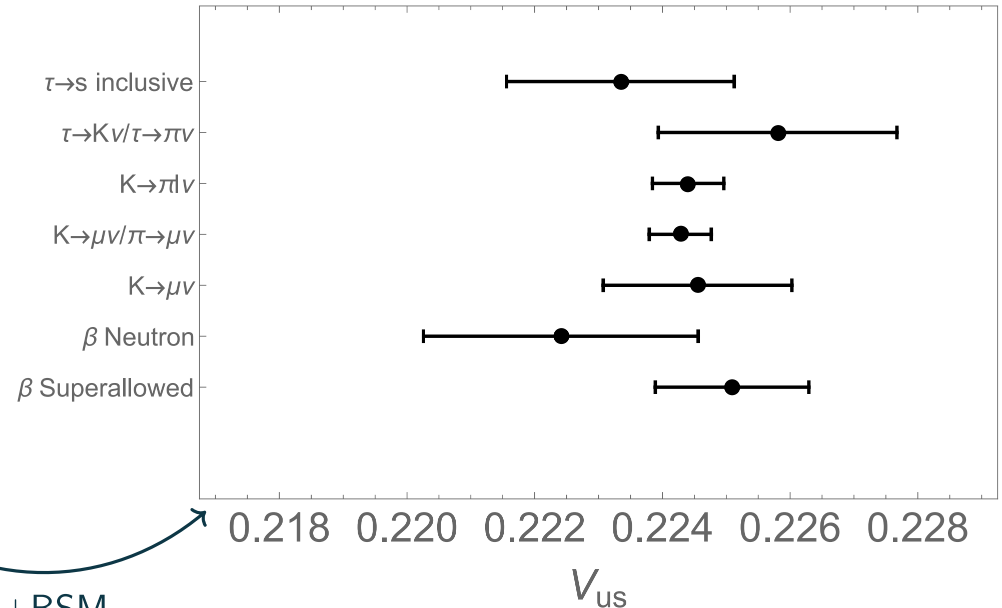
Why?



(SM)

+BSM
$\epsilon^d_R, \epsilon^s_R, \epsilon^{s\tau}_L$



Cabibbo anomaly → Inconsistency in V_{us} determinations

The anomaly disappears with a few BSM parameters

Global fit

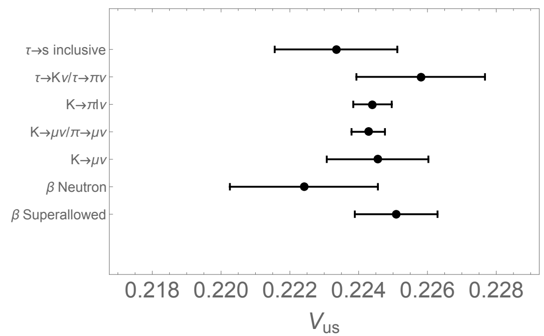
One-at-a-time fit

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

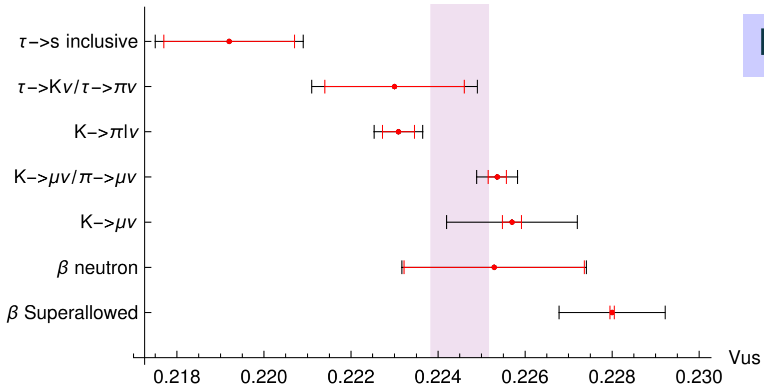


$\epsilon_R^d, \epsilon_R^s, \epsilon_L^{s\tau}$

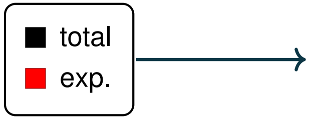
$$\chi^2_{\rm SM} - \chi^2_{\rm min} = 26.1 \Rightarrow 4.4\sigma$$

What can we improve with better experimental data?

SM



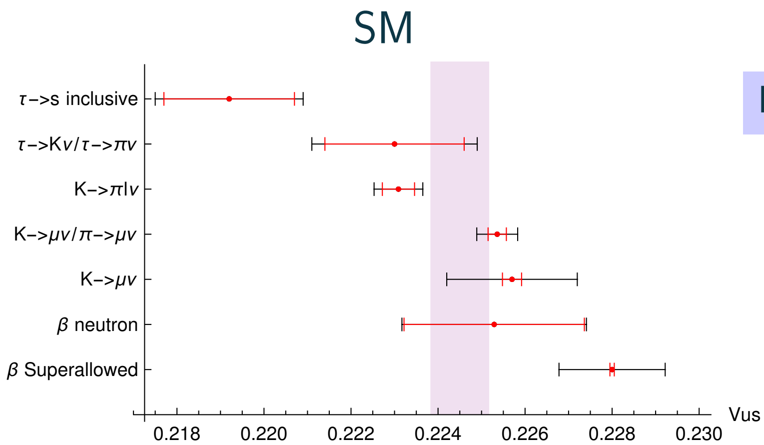
More precise branching ratios → improved bounds from exclusive decays.



Improvement of experimental data will improve several bounds

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

What can we improve with better experimental data?



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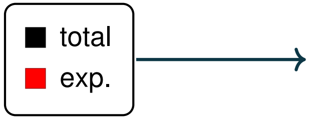

Improvement of experimental data will improve several bounds

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 $\epsilon_S^{s\tau}$.

Recap

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.

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