

# Semi-leptonic $\tau$ decays BSM

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

David Díaz Calderón

IFIC (CSIC-UV)



VNIVERSITAT  
DE VALÈNCIA

**IFIC**  
INSTITUT DE FÍSICA  
CORPUSCULAR

 **CSIC**  
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

 GENERALITAT  
VALENCIANA

**Gen-T**

## Motivation

Great experimental and theoretical precision in hadronic tau decays.



Determination of SM parameters such as  $\alpha_s$ ,  $V_{us}$ ,  $f_\pi$ , QCD vacuum condensates, ...

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

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

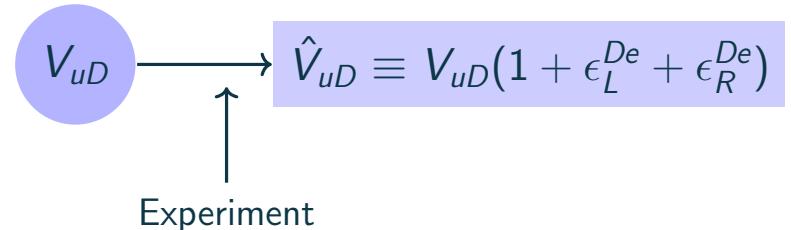
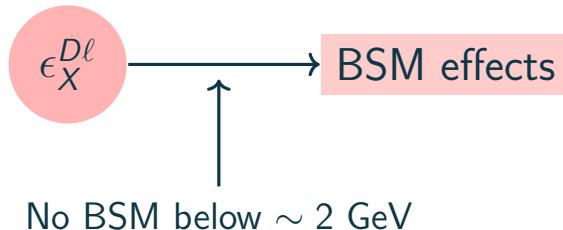
Motivates BSM physics in hadronic  $\tau$  decays

## Theoretical Framework

Effective Field Theory → Model independent bounds.

In particular,

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



## Hadronic $\tau$ Decays

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

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

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

Non-strange inclusive  $\longrightarrow$  Isospin Symmetry  $\rightarrow \epsilon_L^{d\tau} - \epsilon_L^{de}, \epsilon_R^{d\tau}$  and  $\epsilon_T^{d\tau}$ .

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

## Hadronic $\tau$ Decays: constraints

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

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

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

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

## Hadronic $\tau$ Decays: constraints

$$\left. \begin{array}{l}
 \epsilon_{L+R}^{d\tau} - \epsilon_{L+R}^{de} - 0.76 \epsilon_R^{d\tau} + 0.49(16) \hat{\epsilon}_T^{d\tau} = (4 \pm 10) \times 10^{-3} \\
 \epsilon_{L+R}^{d\tau} - \epsilon_{L+R}^{de} - 0.88 \epsilon_R^{d\tau} + 0.27(9) \hat{\epsilon}_T^{d\tau} = (9.1 \pm 8.8) \times 10^{-3} \\
 \epsilon_{L+R}^{d\tau} - \epsilon_{L+R}^{de} + 3.05 \epsilon_R^{d\tau} + 1.9(1.2) \hat{\epsilon}_T^{d\tau} = (5 \pm 51) \times 10^{-3} \\
 \epsilon_{L+R}^{d\tau} - \epsilon_{L+R}^{de} + 1.93 \epsilon_R^{d\tau} + 1.6(1.5) \hat{\epsilon}_T^{d\tau} = (7.0 \pm 9.5) \times 10^{-3}
 \end{array} \right\} \rho_{V+A} \quad \left. \begin{array}{l}
 \text{Non-strange Inclusive} \\
 \uparrow \\
 \int_{s_{th}}^{s_0} \frac{ds}{s_0} \omega(s) \rho_{exp}(s).
 \end{array} \right\}$$

$$\left. \begin{array}{l}
 1.00 (\epsilon_{L+R}^{s\tau} - \epsilon_{L+R}^{se}) - 1.03 \epsilon_R^{s\tau} - 0.38 \epsilon_P^{s\tau} + 0.40(13) \hat{\epsilon}_T^{s\tau} + 0.08(1) \epsilon_S^{s\tau} \\
 - 1.07 (\epsilon_{L+R}^{d\tau} - \epsilon_{L+R}^{de}) + 1.04 \epsilon_R^{d\tau} + 0.30 \epsilon_P^{d\tau} - 0.43(14) \hat{\epsilon}_T^{d\tau} \\
 = -(0.0171 \pm 0.0085)
 \end{array} \right\} \rho_{V-A} \quad \left. \begin{array}{l}
 \text{Strange Inclusive} \\
 \uparrow \\
 |\widehat{V}_{us}|^{\text{inc}} = \left( \frac{\hat{R}_\tau^s}{\hat{R}_\tau^d / |\hat{V}_{ud}|^2 - \delta R_{\text{th}}^{\text{SM}}} \right)^{1/2}
 \end{array} \right\}$$

## Hadronic $\tau$ Decays: constraints

	$\epsilon_L^{d\tau} \times 10^3$	$\epsilon_L^{de} \times 10^3$	$\epsilon_R^d \times 10^3$	$\epsilon_P^{d\tau} \times 10^3$	$\epsilon_T^{d\tau} \times 10^3$	$\epsilon_S^{d\tau} \times 10^3$
$\tau \rightarrow \pi\nu$	-0.9(7.3)	0.9(7.3)	0.9(7.3)	0.6(5.0)	x	x
$\tau \rightarrow \pi\pi\nu$	10(4.9)	-10(4.9)	x	x	23(12)	x
$\tau \rightarrow \pi\eta\nu$	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
	$\epsilon_L^{s\tau} \times 10^3$	$\epsilon_L^{se} \times 10^3$	$\epsilon_R^s \times 10^3$	$\epsilon_P^{s\tau} \times 10^3$	$\epsilon_T^{s\tau} \times 10^3$	$\epsilon_S^{s\tau} \times 10^3$
$\tau \rightarrow K\nu$	-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 $\tau$ 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.



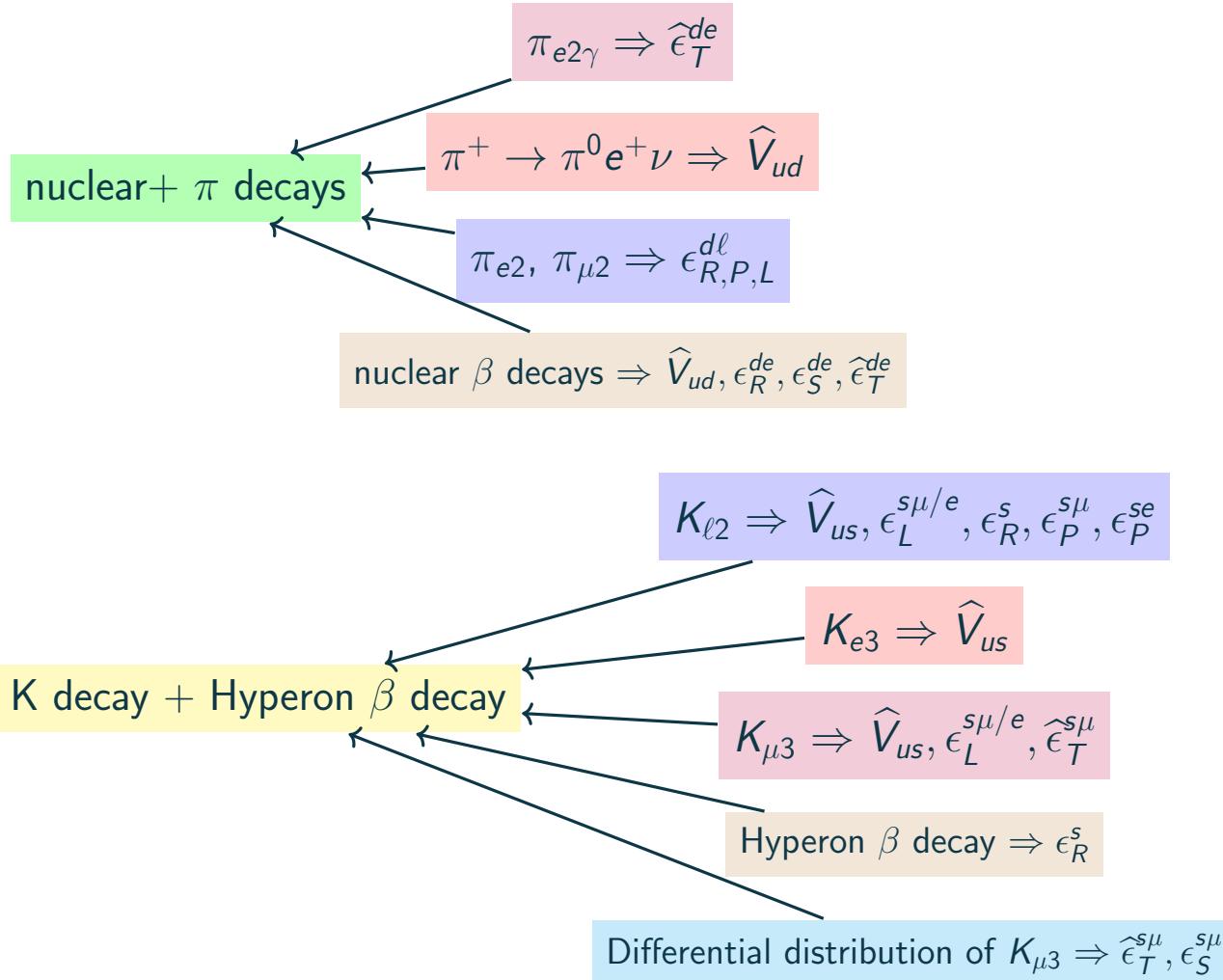
We cannot resolve  $\epsilon_X^{s\tau}$

## Other probes

nuclear+  $\pi$  decays

K decay + Hyperon  $\beta$  decay

## Other probes



## Other probes

nuclear+  $\pi$  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  $\beta$  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

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

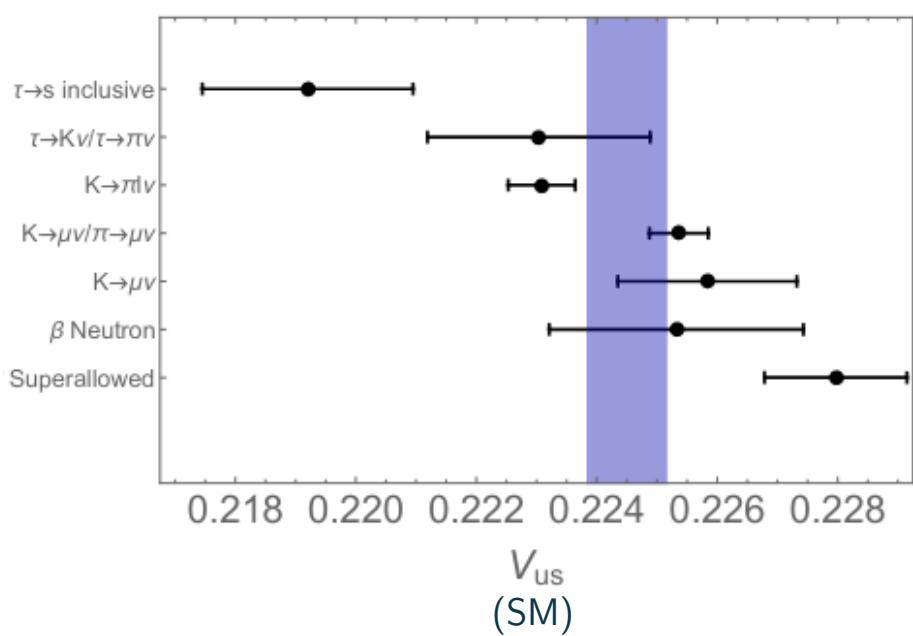
Model independent bounds for the light quark sector involving all three lepton families.

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

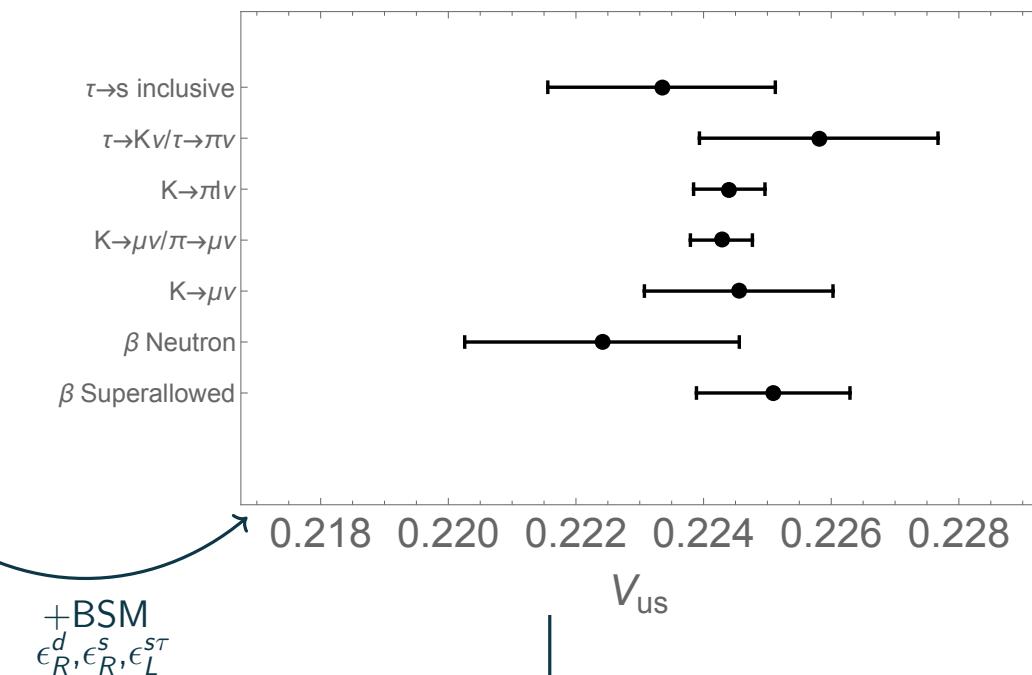
## Global fit

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

Why?



Cabibbo anomaly  $\rightarrow$  Inconsistency in  $V_{us}$  determinations



The anomaly disappears with a few BSM parameters

## Global fit

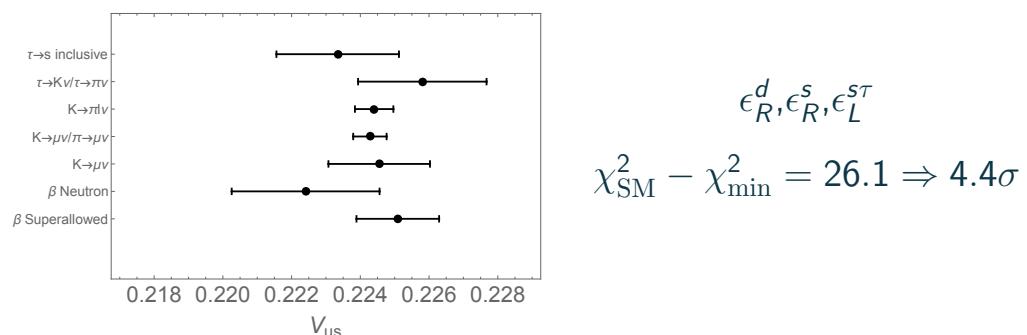
### One-at-a-time fit

	$\epsilon_X^{de} \times 10^3$	$\epsilon_X^{se} \times 10^3$	$\epsilon_X^{d\mu} \times 10^3$	$\epsilon_X^{s\mu} \times 10^3$	$\epsilon_X^{d\tau} \times 10^3$	$\epsilon_X^{s\tau} \times 10^3$
$L$	-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:  $3\sigma$  or more preference for BSM

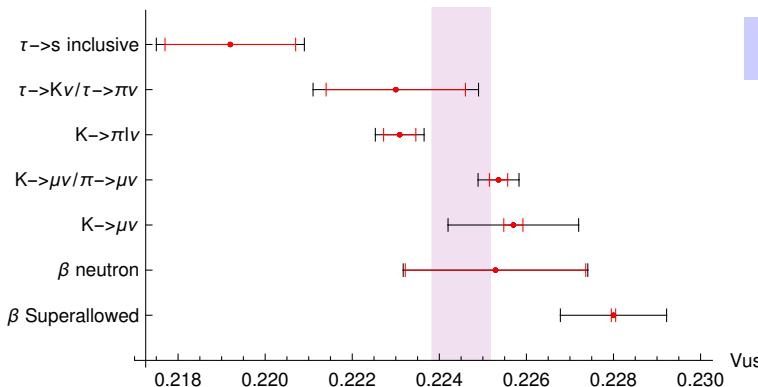
$\rightarrow \epsilon_R^s, \epsilon_L^{de}$  ease the tension between nuclear and kaon decays.

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

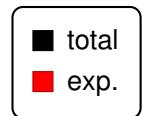


## What can we improve with better experimental data?

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 be improved by Belle II.

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

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

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

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