Adam Falkowski

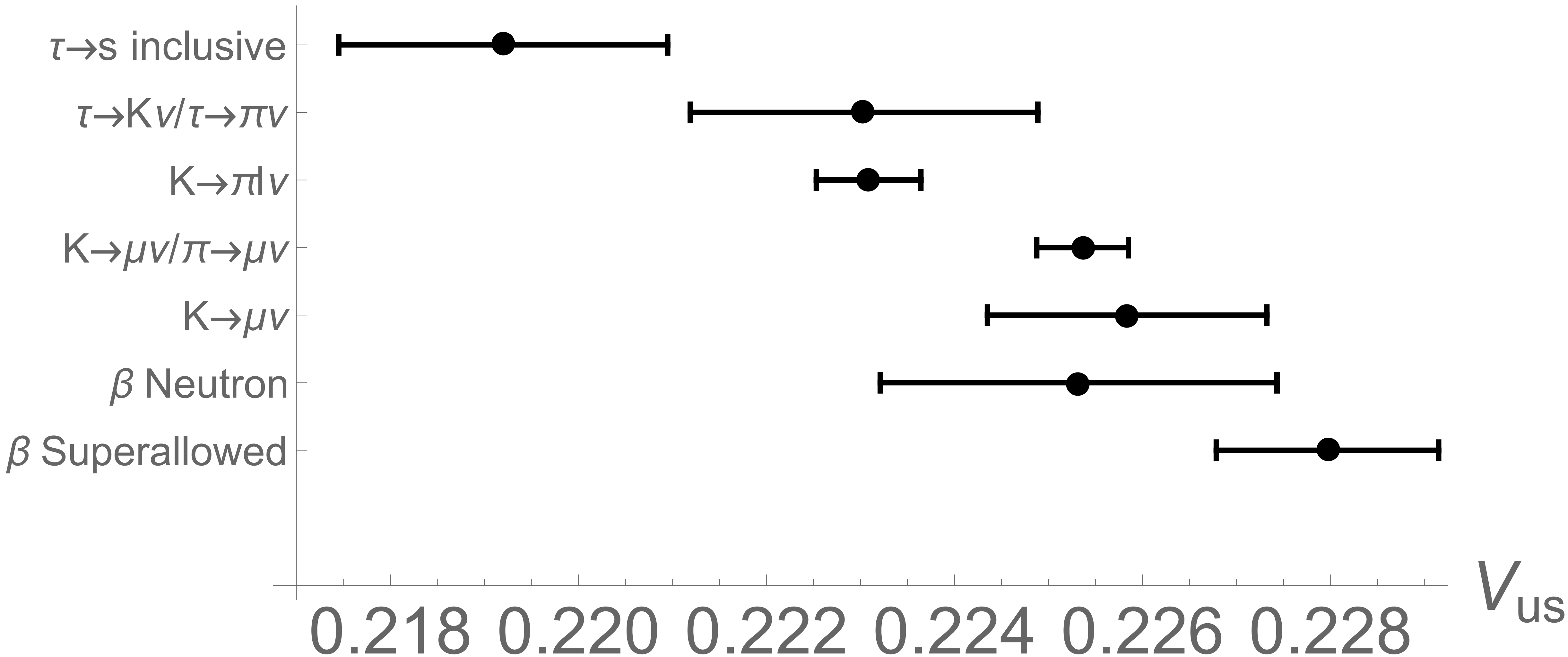
New physics in $d(s) \to u \ell \nu$

CKM 2021, 23 November ± 1 day

numerical results in this talk are based on work to appear with
Vincenzo Cirigliano, David Diaz, Martin Gonzalez-Alonso, and Antonio Rodriguez-Sanchez
all results are preliminary and may slightly change before the submission

Cabibbo anomaly

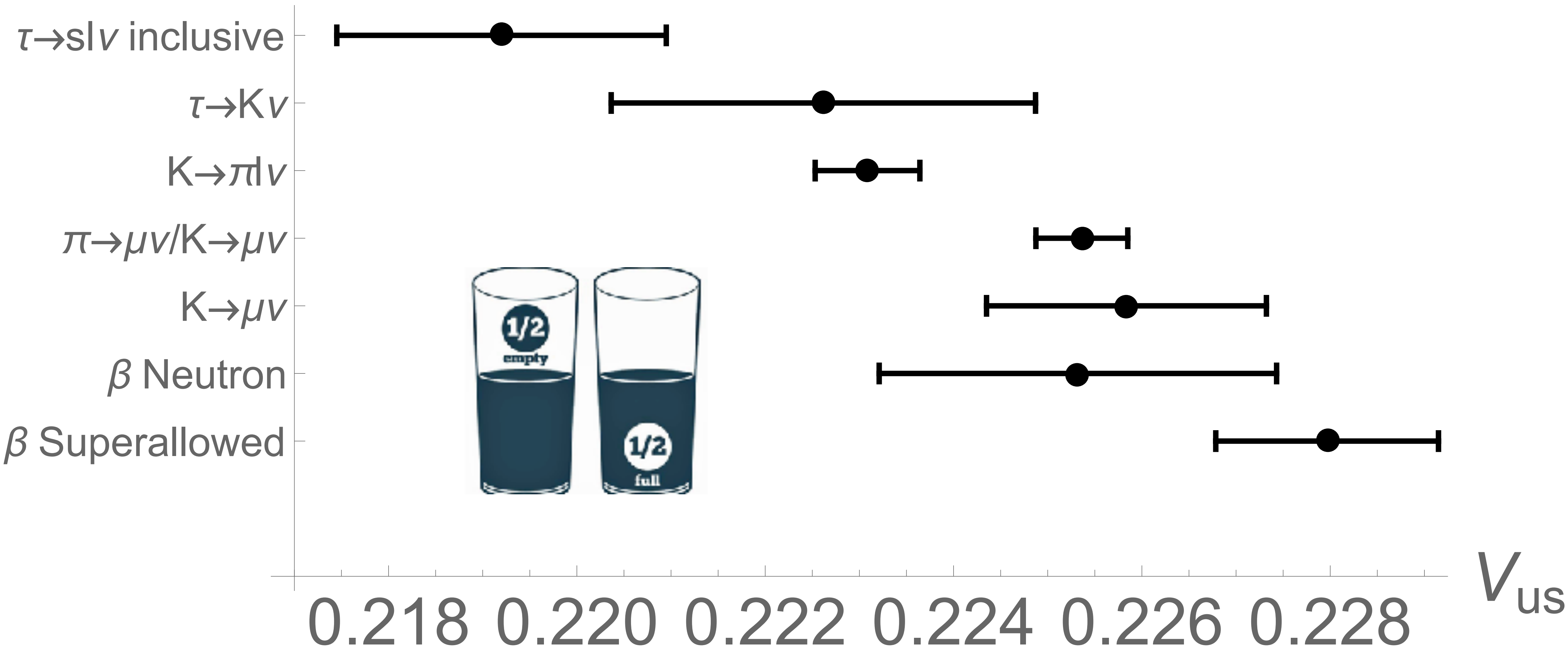
Seng et al 1807.10197
Grossman et al 1911.07821
Coutinho et al 1912.08823



Nominal error of the combined V_{us} is 0.0003

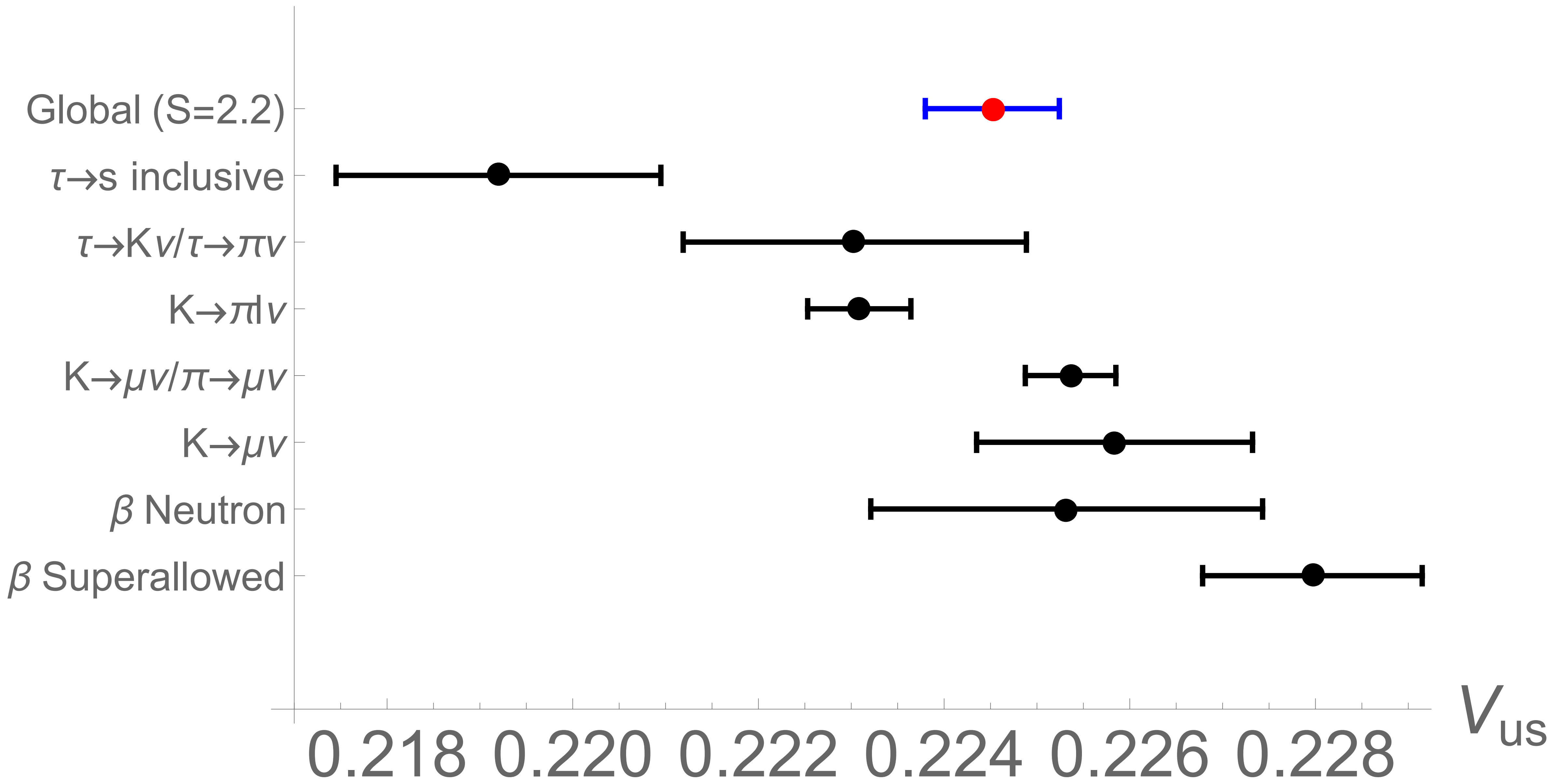
But the spread between central values is $O(0.01)$

Cabibbo anomaly



Embarrassment or opportunity ?

Cabibbo angle in the SM

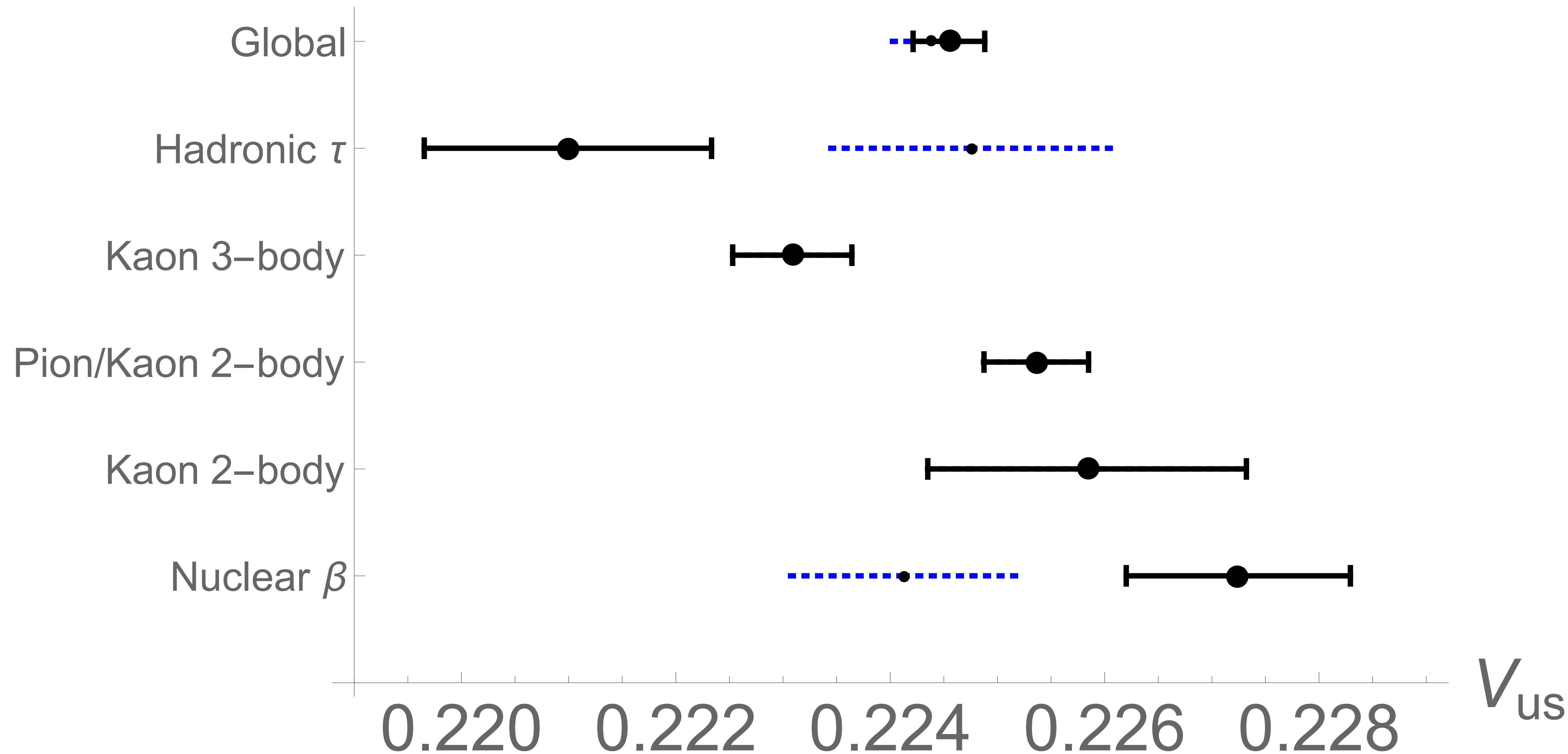


Within the SM paradigm, the Cabibbo anomaly signifies that some unresolved systematics is plaguing a subset of the measurements.

In this case, a naive combination of the different inputs does not describe the uncertainty about the real value of the Cabibbo angle.

An ad hoc but practical approach is then to combine the inputs a-la PDG with errors inflated by a scale factor, such that the overall goodness of fit becomes acceptable (1 unit of χ^2/dof)

Cabibbo angle beyond the SM



Beyond the SM, the observables never measure the Cabibbo angle, but instead they probe a combination of the Cabibbo angle and new physics parameters. Moreover, different observables measure in general different combinations.

The Cabibbo anomaly can then be interpreted as new physics contributions to a subset of the measurements.

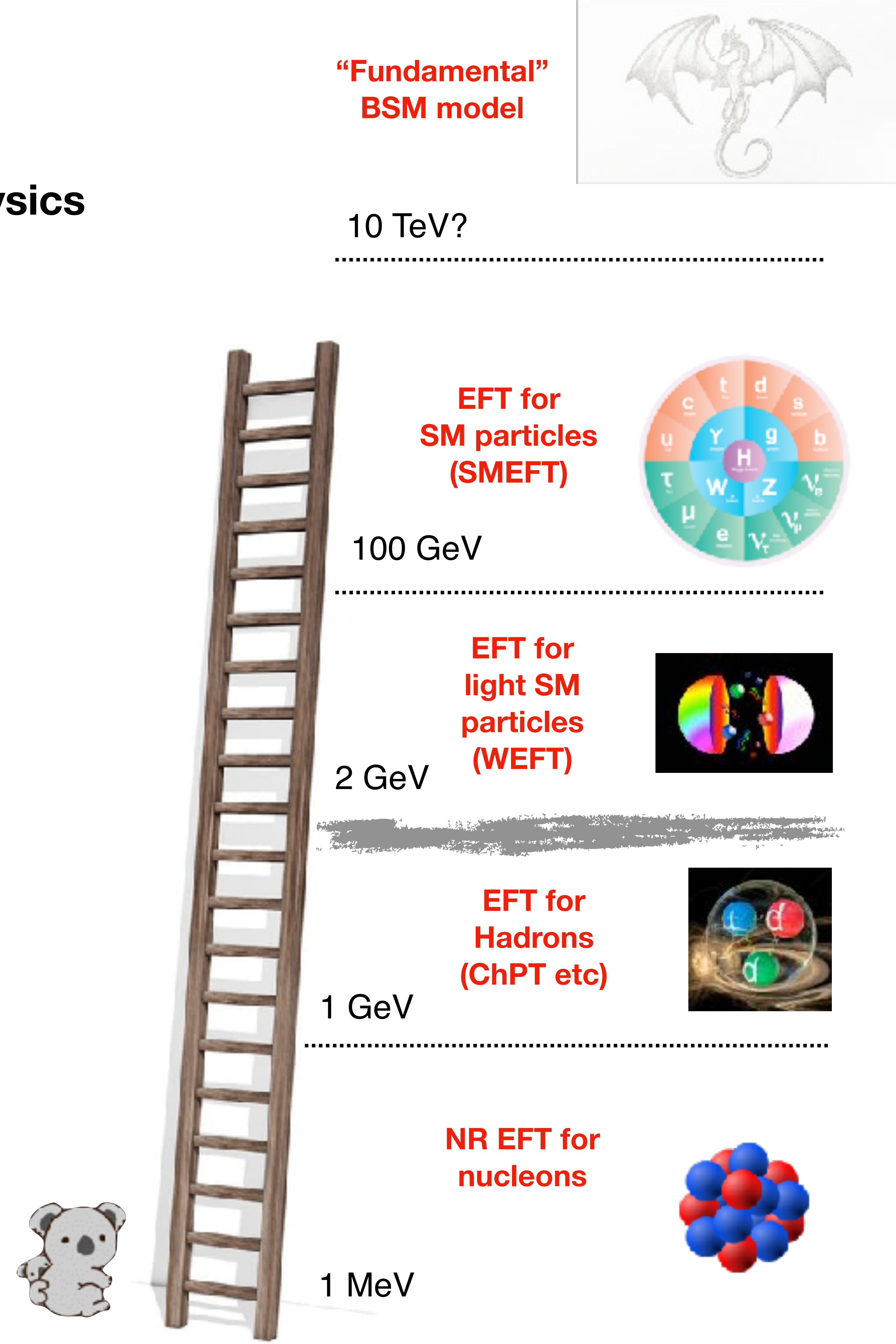
Disentangling these non-standard pieces, various measurements of the Cabibbo angle become consistent with each other

Plan of the talk

Language of EFT

EFT Ladder

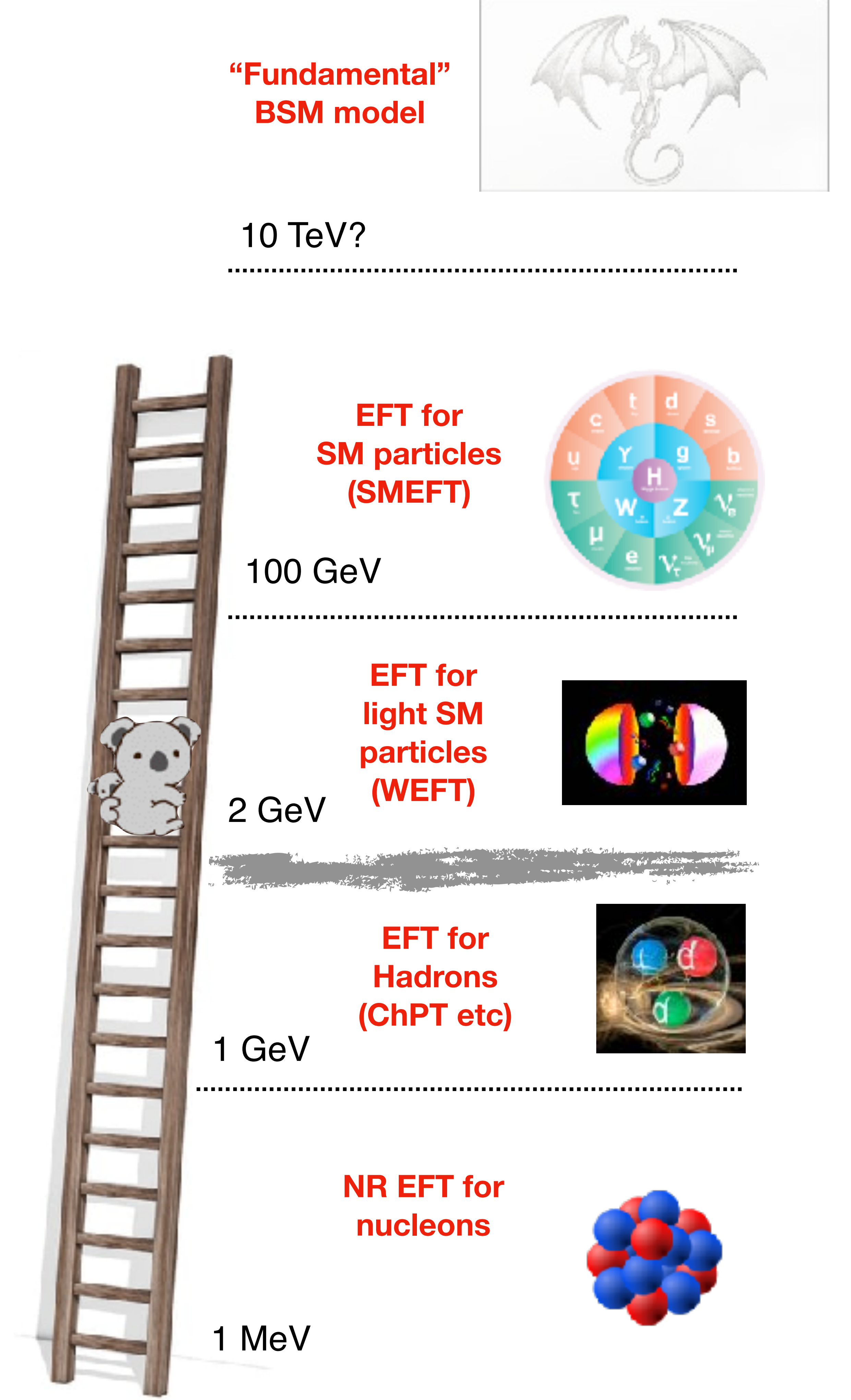
Connecting high- and low-energy physics via a series of effective theories



EFT Ladder

Connecting high- and low-energy physics via a series of effective theories

Reference scale in this talk



EFT Ladder

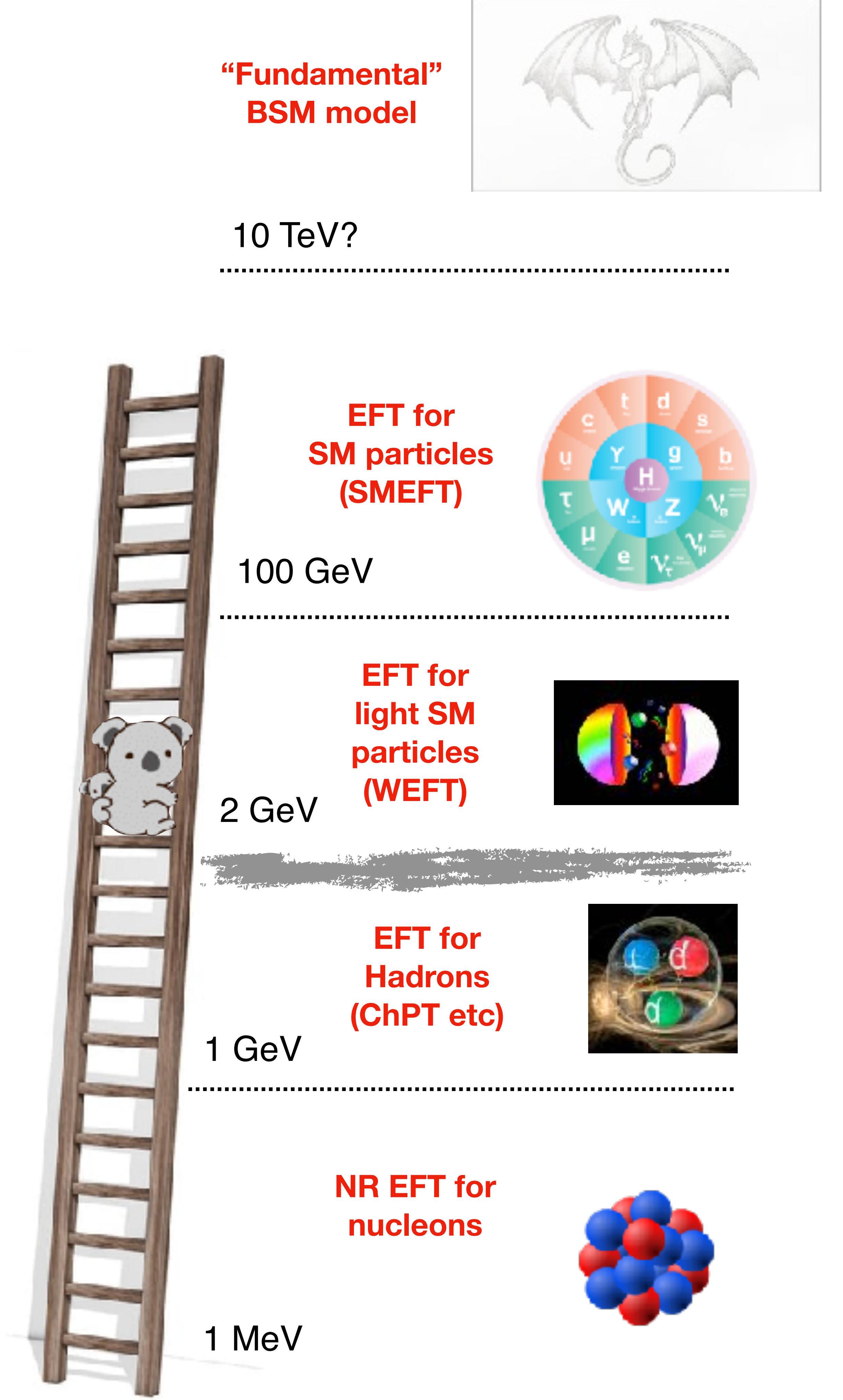
Assumption: lack of non-SM degrees of freedom lighter than ~2 GeV

Relevant EFT interactions for this talk

$$\mathscr{L}_{\mathrm{WEFT}} \supset -\sum_{D=d,s}\sum_{\ell=e,\mu,\tau}\frac{V_{uD}}{\mathrm{v}^2}\Big\{$$

V-A	$\left(1+\epsilon_L^{D\ell}\right)\ \bar{\ell}\gamma_\mu P_L \nu_\ell \cdot \bar{u}\gamma^\mu(1-\gamma_5)D$
V+A	$+\epsilon_R^{D\ell}\ \bar{\ell}\gamma_\mu P_L \nu_\ell \cdot \bar{u}\gamma^\mu(1+\gamma_5)D$
Tensor	$+\epsilon_T^{D\ell}\frac{1}{4}\bar{\ell}\sigma_{\mu\nu}P_L\nu_\ell \cdot \bar{u}\sigma^{\mu\nu}(1-\gamma_5)D$
Scalar	$+\epsilon_S^{D\ell}\ \bar{\ell}P_L\nu_\ell \cdot \bar{u}D$
Pseudoscalar	$-\epsilon_P^{D\ell}\ \bar{\ell}P_L\nu_\ell \cdot \bar{u}\gamma_5 D\Big\} + \mathrm{hc}$

Physics beyond the SM characterised by 30 parameters $\epsilon_X^{D\ell}$ describing effects of heavier non-standard particles (W', W_R, leptoquarks) coupled to light quarks and leptons



EFT Lagrangian

$$\mathscr{L}_{\text{WEFT}} \supset -\sum_{D=d,s}\sum_{\ell=e,\mu,\tau}\frac{V_{uD}}{\text{v}^2}\Bigg\{$$

$$\left(1+\epsilon_L^{D\ell}\right)\ \bar{\ell}\gamma_\mu P_L \nu_\ell \cdot \bar{u}\gamma^\mu(1-\gamma_5)D$$

$$+\epsilon_R^{D\ell}\ \bar{\ell}\gamma_\mu P_L \nu_\ell \cdot \bar{u}\gamma^\mu(1+\gamma_5)D$$

$$+\epsilon_T^{D\ell}\frac{1}{4}\bar{\ell}\sigma_{\mu\nu}P_L \nu_\ell \cdot \bar{u}\sigma^{\mu\nu}(1-\gamma_5)D$$

$$+\epsilon_S^{D\ell}\ \bar{\ell}P_L \nu_\ell \cdot \bar{u}D$$

$$-\epsilon_P^{D\ell}\ \bar{\ell}P_L \nu_\ell \cdot \bar{u}\gamma_5 D\Bigg\} + \text{hc}$$

SM parameters are the Fermi scale v = 246.22 GeV (determined from muon decay) and the Cabibbo angle V_{us} (V_{ud} is not independent, but instead connected to the Cabibbo angle by the unitarity relation $V_{ud}^2 \approx \sqrt{1-V_{us}^2}$)

The main goal will be to determine simultaneously the SM parameter Cabibbo angle and as many as possible new physics parameters $\epsilon_X^{D\ell}$ in the most general way without assuming any of them vanishes, or assuming any underlying flavor structure

EFT Lagrangian

$$\mathscr{L}_{\mathrm{WEFT}} \supset -\sum_{D=d,s}\sum_{\ell=e,\mu,\tau}\frac{V_{uD}}{\mathrm{v}^2}\Big\{$$

V-A $\quad \left(1+\epsilon_L^{D\ell}\right)\ \bar{\ell}\gamma_\mu P_L \nu_\ell \cdot \bar{u}\gamma^\mu(1-\gamma_5)D$

V+A $\quad +\epsilon_R^{D\ell}\ \bar{\ell}\gamma_\mu P_L \nu_\ell \cdot \bar{u}\gamma^\mu(1+\gamma_5)D$

Tensor $\quad +\epsilon_T^{D\ell}\frac{1}{4}\bar{\ell}\sigma_{\mu\nu}P_L\nu_\ell \cdot \bar{u}\sigma^{\mu\nu}(1-\gamma_5)D$

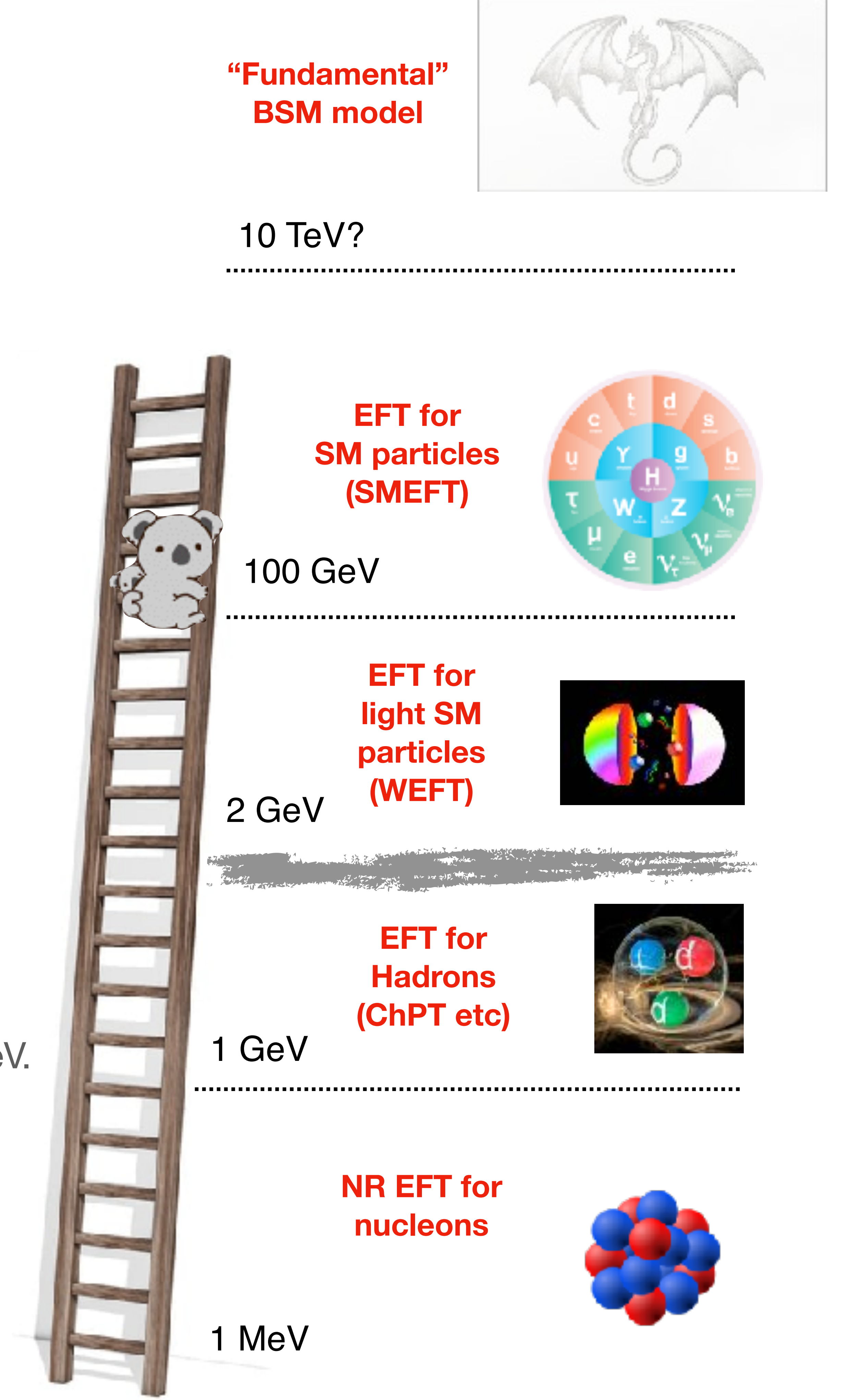
Scalar $\quad +\epsilon_S^{D\ell}\ \bar{\ell}P_L\nu_\ell \cdot \bar{u}D$

Pseudoscalar $\quad -\epsilon_P^{D\ell}\ \bar{\ell}P_L\nu_\ell \cdot \bar{u}\gamma_5 D\Big\} + \mathrm{hc}$

Additional assumption: lack of non-SM degrees of freedom lighter than ~100 GeV

Then WEFT can be matched to SMEFT at the scale of 100 GeV. One can then show that new physics corrections to the V+A currents are lepton-flavor universal up to corrections from dimension-8 operators. This leads to the relation:

$$\epsilon_R^{qe} = \epsilon_R^{q\mu} = \epsilon_R^{q\tau} \equiv \epsilon_R^{q}$$



EFT Lagrangian

$$\mathscr{L}_{\mathrm{WEFT}} \supset -\sum_{D=d,s}\sum_{\ell=e,\mu,\tau}\frac{V_{uD}}{\mathrm{v}^2}\Bigg\{$$

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$$+\epsilon_T^{D\ell}\frac{1}{4}\bar{\ell}\sigma_{\mu\nu} P_L \nu_\ell \cdot \bar{u}\sigma^{\mu\nu}(1-\gamma_5)D$$

$$+\epsilon_S^{D\ell}\,\bar{\ell} P_L \nu_\ell \cdot \bar{u}D$$

$$-\epsilon_P^{D\ell}\,\bar{\ell} P_L \nu_\ell \cdot \bar{u}\gamma_5 D\Bigg\} + \mathrm{hc}$$

Observables never probe directly the CKM elements V_{ud} or V_{us} . Instead, they always probe certain combination of CKM elements and new physics parameters $\epsilon_X^{D\ell}$. It is therefore convenient to define the "polluted" CKM elements:

$$\hat{V}_{uD} = \left(1 + \epsilon_L^{De} + \epsilon_R^{D}\right)\ V_{uD}$$

The point is that vector currents depend only on $\hat{V}_{uD}$ and not on other parameters, therefore it is more straightforward to extract this particular combination from the data

Note that $\hat{V}_{ud}^2 + \hat{V}_{us}^2 \neq 1$ in the presence of general new physics

Data

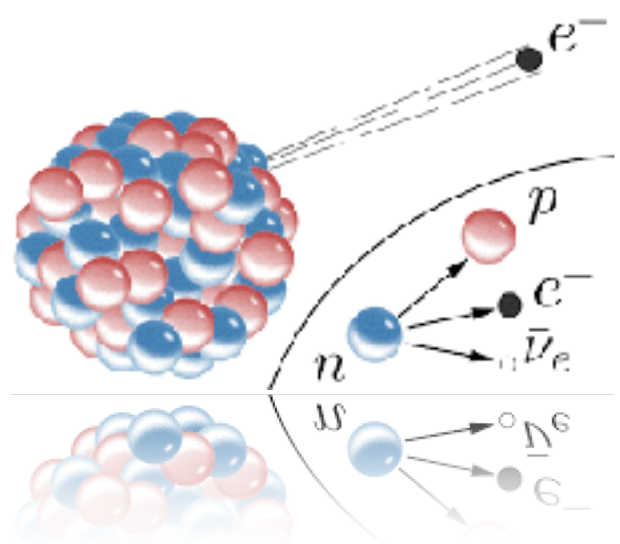
Beta decays

Superallowed 0+ → 0+ beta transitions

Parent	$\mathcal{F}t$ [s]	$\langle m_e/E_e \rangle$
^{10}C	3075.7 ± 4.4	0.619
^{14}O	3070.2 ± 1.9	0.438
^{22}Mg	3076.2 ± 7.0	0.308
^{26m}Al	3072.4 ± 1.1	0.300
^{26}Si	3075.4 ± 5.7	0.264
^{34}Cl	3071.6 ± 1.8	0.234
^{34}Ar	3075.1 ± 3.1	0.212
^{38m}K	3072.9 ± 2.0	0.213
^{38}Ca	3077.8 ± 6.2	0.195
^{42}Sc	3071.7 ± 2.0	0.201
^{46}V	3074.3 ± 2.0	0.183
^{50}Mn	3071.1 ± 1.6	0.169
^{54}Co	3070.4 ± 2.5	0.157
^{62}Ga	3072.4 ± 6.7	0.142
^{74}Rb	3077 ± 11	0.125

For recent compilations see

Gonzalez-Alonso et al
1803.08732
2010.13797



Neutron decay

Observable	Value
τ_n (s)	**878.64(59)**
$\tilde{A}_n$	$-0.11958(18)$
$\tilde{B}_n$	$0.9805(30)$
λ_{AB}	$-1.2686(47)$
a_n	$-0.10426(82)$
$\tilde{a}_n$	**-0.1078(20)**

Mirror decays

Parent	Spin	Δ [MeV]	$\langle m_e/E_e \rangle$	f_A/f_V	$\mathcal{F}t$ [s]	Correlation
^{17}F	5/2	2.24947(25)	0.447	1.0007(1)	2292.4(2.7) [47]	$\tilde{A} = 0.960(82)$ [12, 48]
^{19}Ne	1/2	2.72849(16)	0.386	1.0012(2)	1721.44(92) [44]	$\tilde{A}_0 = -0.0391(14)$ [49]
						$\tilde{A}_0 = -0.03871(91)$ [42]
^{21}Na	3/2	3.035920(18)	0.355	1.0019(4)	4071(4) [45]	$\tilde{a} = 0.5502(60)$ [39]
^{29}P	1/2	4.4312(4)	0.258	0.9992(1)	4764.6(7.9) [50]	$\tilde{A} = 0.681(86)$ [51]
^{35}Ar	3/2	5.4552(7)	0.215	0.9930(14)	5688.6(7.2) [13]	$\tilde{A} = 0.430(22)$ [14, 52, 53]
^{37}K	3/2	5.63647(23)	0.209	0.9957(9)	4605.4(8.2) [43]	$\tilde{A} = -0.5707(19)$ [38]
						$\tilde{B} = -0.755(24)$ [41]

Various asymmetries

Parent	J_i	J_f	Type	Observable	Value
^{6}He	0	1	GT/β^-	a	$-0.3308(30)$
^{32}Ar	0	0	F/β^+	$\tilde{a}$	0.9989(65)
^{38m}K	0	0	F/β^+	$\tilde{a}$	0.9981(48)
^{60}Co	5	4	GT/β^-	$\tilde{A}$	$-1.014(20)$
^{67}Cu	3/2	5/2	GT/β^-	$\tilde{A}$	0.587(14)
^{114}In	1	0	GT/β^-	$\tilde{A}$	$-0.994(14)$
^{14}O/^{10}C			F-GT/β^+	P_F/P_{GT}	0.9996(37)
^{26}Al/^{30}P			F-GT/β^+	P_F/P_{GT}	1.0030 (40)

Beta decays

$$\mathscr{L}_{\rm WEFT} \supset -\sum_{D=d,s}\sum_{\ell=e,\mu,\tau}\frac{V_{uD}}{v^2}\Big\{ \big(1+\epsilon_L^{D\ell}\big)\ \bar\ell\gamma_\mu P_L\nu_\ell\cdot\bar u\gamma^\mu(1-\gamma_5)D + \epsilon_R^D\,\bar\ell\gamma_\mu P_L\nu_\ell\cdot\bar u\gamma^\mu(1+\gamma_5)D + \epsilon_T^{D\ell}\frac{1}{4}\bar\ell\sigma_{\mu\nu}P_L\nu_\ell\cdot\bar u\sigma^{\mu\nu}(1-\gamma_5)D + \epsilon_S^{D\ell}\,\bar\ell P_L\nu_\ell\cdot\bar uD - \epsilon_P^{D\ell}\,\bar\ell P_L\nu_\ell\cdot\bar u\gamma_5 D\Big\} + \text{hc}$$

AA, Gonzalez-Alonso, Naviliat-Cuncic
2010.13797 + updates

$$\begin{pmatrix}\hat V_{ud}\\ \epsilon_R^d\\ \epsilon_S^{de}\\ \epsilon_T^{de}\end{pmatrix} = \begin{pmatrix}0.97382(42)\\ -0.012(12)\\ 0.0002(10)\\ -0.0006(12)\end{pmatrix} \qquad \rho = \begin{pmatrix}1 & 0.01 & 0.78 & 0.69\\ & 1 & 0.01 & 0.\\ & & 1 & 0.64\\ & & & 1\end{pmatrix}$$

- The underlying process is $u \to de\nu$, thus beta decay probe $\hat V_{ud}$ and new physics in the down-electron sector parametrized by ϵ_X^{de}
- Sub-permille constraints on the polluted matrix element $\hat V_{ud}$
- Permille level constraints on scalar and tensor interactions
- Percent level constraint on V+A down sector currents (weaker, because they rely on the lattice determination of the axial nucleon coupling g_A)
- Effects of pseudoscalar interactions are very suppressed in beta decay (they enter in the subleading order in the non-relativistic EFT expansion), and we do not display here the resulting bounds

Pion decays

Process	Observable	Value
$\pi \to \mu\nu$	$\Gamma(\pi \to \mu\nu)$	$2.52806(49) \times 10^{-17}$ GeV
$\pi \to e^{\pm}\nu$	$\frac{\Gamma(\pi\to e\nu)}{\Gamma(\pi\to\mu\nu)}$	$1.2327(23) \times 10^{-4}$
$\pi \to e\nu\gamma$	$f_T\epsilon_T^{de}$	$1.2(5.6) \times 10^{-4}$
$\pi^+ \to \pi^0 e^+\nu$	$\hat{V}_{ud}$	$0.9729(30)$

Probes one linear combination of $\epsilon_X^{d\mu}$

Gives access to pseudoscalar coupling ϵ_P^{de}

Probe same parameters as β decay but with less precision

Updating the analysis of

Camalich, Gonzalez-Alonso 1605.07114

Pion decays

Beta decay + pion constraints together

$$\begin{pmatrix} \hat{V}_{ud} \\ \epsilon_R^d \\ \epsilon_S^{de} \\ \epsilon_T^{de} \\ \epsilon_P^{de} \\ \epsilon_L^{d\mu} - \epsilon_L^{de} - \epsilon_P^{d\mu} \frac{m_\pi^2}{m_\mu(m_u+m_d)} \end{pmatrix} = \begin{pmatrix} 0.97386(40) \\ -0.012(12) \\ 0.00032(99) \\ -0.0003(11) \\ 3.9(4.3) \times 10^{-6} \\ -0.021(24) \end{pmatrix} \qquad \begin{pmatrix} 1 & 0.01 & 0.75 & 0.64 & 0.01 & -0.01 \\ & 1 & 0.01 & 0. & -0.96 & 0.96 \\ & & 1 & 0.6 & 0.01 & -0.01 \\ & & & 1 & 0.01 & -0.01 \\ & & & & 1 & -0.999 \\ & & & & & 1 \end{pmatrix}$$

Cirigliano, Diaz, AA, Gonzalez-Alonso, Rodriguez-Sanchez
to appear

- Very strong constraints on pseudoscalar interactions, thanks to chiral enhancement: by $\frac{m_\pi^2}{m_e(m_u+m_d)}$ for ϵ_P^{de} and by $\frac{m_\pi^2}{m_\mu(m_u+m_d)}$ for $\epsilon_P^{d\mu}$
  As a result, for some BSM models, pion decays can probe new particles with masses well above the LHC reach
- Currently impossible to resolve all coupling in the down-muon sector, $\epsilon_X^{d\mu}$. We need more precision observables probing that sector, e.g. low-energy muon scattering or muon capture on nuclei
- No hint of new physics here

Kaon decays

Kaon decays give us access to $\hat{V}_{us}$ and strange Wilson coefficients ϵ_X^{se} and $\epsilon_X^{s\mu}$

Process	Observable	Value
$K \to \mu\nu$	$\Gamma(K \to \mu\nu)$	$3.3793(79) \times 10^{-17}$ GeV
$K \to e\nu$	$\frac{\Gamma(K\to e\nu)}{\Gamma(K\to\mu\nu)}$	$2.488(9) \times 10^{-5}$
$K^- \to \pi^0\mu^-\nu$	$f_T/f_+(0)$	-0.0007(74)
$K \to \pi\mu\nu$	$\log C$	0.1985(70)
hyperon decay	g_1/f_1	0.72(7)

Leptonic kaon decays mostly probe pseudoscalar couplings ϵ_P^{se} and $\epsilon_P^{s\mu}$

Spectrum shape in semileptonic kaon decay allows one to constrain $\epsilon_T^{s\mu}$

Comparison of phenomenological and theoretical scalar form factor in semileptonic kaon decay gives access to $\epsilon_S^{s\mu}$

Comparison of measured and lattice hyperon axial coupling gives access to ϵ_R^s

Updating the analysis of
Camalich, Gonzalez-Alonso
1605.07114

Width of electronic semileptonic kaon decays directly probes polluted CKM element $\hat{V}_{us}$

Width of muonic semileptonic kaon decays probes combination of $\hat{V}_{us}$, ϵ_R^s, $\epsilon_S^{s\mu}$, $\epsilon_T^{s\mu}$ and $\epsilon_L^{s\mu} - \epsilon_L^{se}$ which allows us to disentangle $\epsilon_L^{s\mu} - \epsilon_L^{se}$

	$\lvert V_{us} f_+^K(0)\rvert$	Correlation Matrix					
$K_L e$	$0.21617(46)_{\text{exp}}(10)_{I_K}(3)_{\delta_{\text{EM}}}$	1	0.021	0.025	0.510	0.003	0.012
$K_S e$	$0.21530(122)_{\text{exp}}(10)_{I_K}(3)_{\delta_{\text{EM}}}$		1	0.009	0.009	0.000	0.005
$K^+ e$	$0.21714(88)_{\text{exp}}(10)_{I_K}(21)_{\delta_{\text{SU(2)}}}(5)_{\delta_{\text{EM}}}$			1	0.012	0.001	0.869
$K_L \mu$	$0.21664(50)_{\text{exp}}(16)_{I_K}(24)_{\delta_{\text{EM}}}$				1	0.029	0.047
$K_S \mu$	$0.21265(466)_{\text{exp}}(16)_{I_K}(23)_{\delta_{\text{EM}}}$					1	0.006
$K^+ \mu$	$0.21703(108)_{\text{exp}}(16)_{I_K}(21)_{\delta_{\text{SU(2)}}}(26)_{\delta_{\text{EM}}}$						1
Average	$0.21635(38)_K(3)_{\text{HO}}$						

Table copied from
Seng et al 2107.14708

Kaon decays

$$\mathscr{L}_{\rm WEFT} \supset -\sum_{D=d,s}\sum_{\ell=e,\mu,\tau}\frac{V_{uD}}{v^2}\Big\{ \left(1+\epsilon_L^{D\ell}\right)\ \bar\ell\gamma_\mu P_L\nu_\ell\cdot\bar u\gamma^\mu(1-\gamma_5)D$$
$$+\epsilon_R^{D}\,\bar\ell\gamma_\mu P_L\nu_\ell\cdot\bar u\gamma^\mu(1+\gamma_5)D$$
$$+\epsilon_T^{D\ell}\frac{1}{4}\bar\ell\sigma_{\mu\nu}P_L\nu_\ell\cdot\bar u\sigma^{\mu\nu}(1-\gamma_5)D$$
$$+\epsilon_S^{D\ell}\,\bar\ell P_L\nu_\ell\cdot\bar u D$$
$$-\epsilon_P^{D\ell}\,\bar\ell P_L\nu_\ell\cdot\bar u\gamma_5 D\Big\} + \text{hc}$$

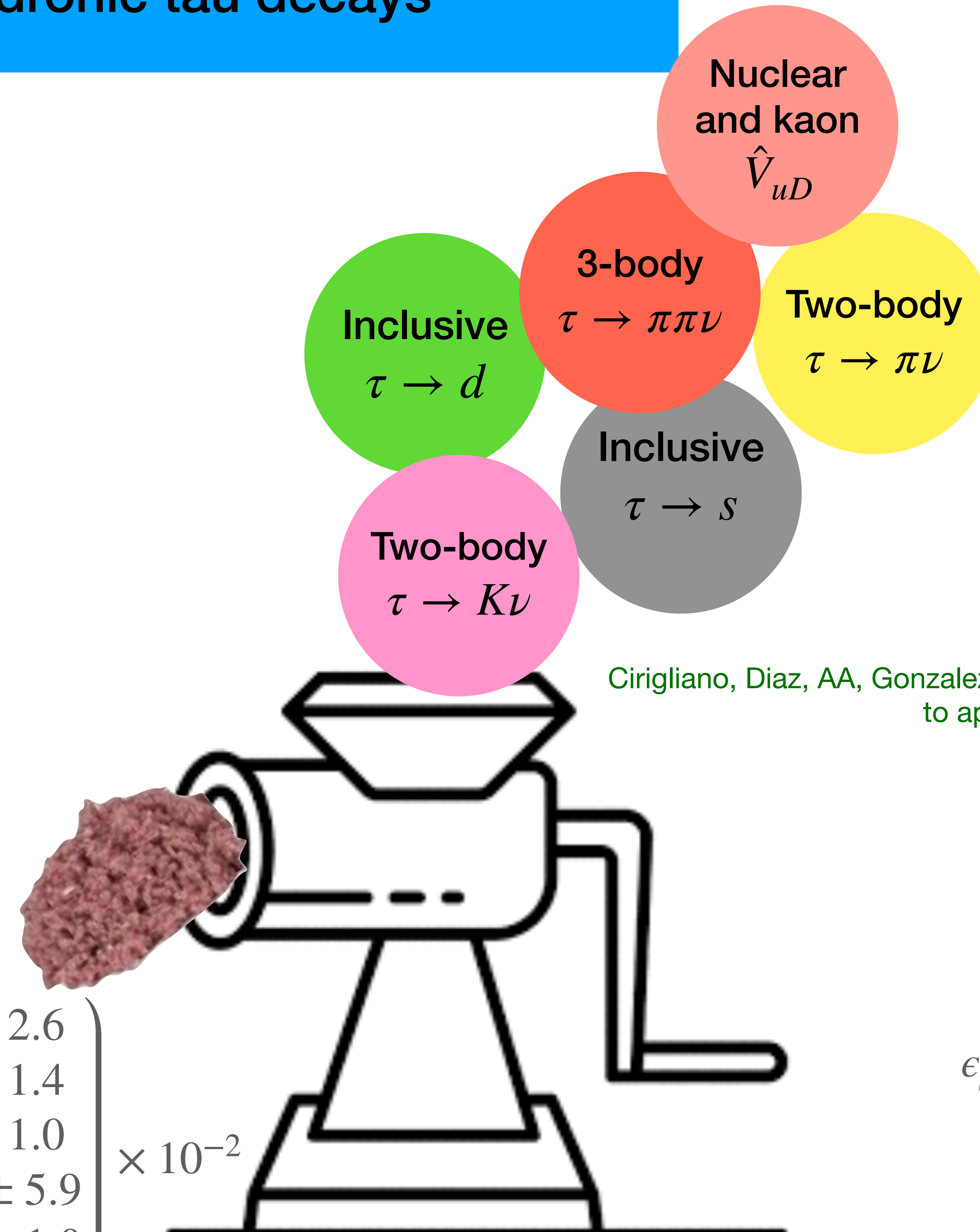
$$\begin{pmatrix}\hat V_{us}\\ \epsilon_L^{s\mu}-\epsilon_L^{se}\\ \epsilon_R^{s}\\ \epsilon_S^{s\mu}\\ \epsilon_P^{se}\\ \epsilon_P^{s\mu}\\ \epsilon_T^{s\mu}\end{pmatrix} = \begin{pmatrix}0.22306(56)\\ 0.0008(26)\\ 0.001(50)\\ -0.00026(44)\\ -0.3(2.0)\times10^{-5}\\ -0.0006(41)\\ 0.002(22)\end{pmatrix} \qquad \rho = \begin{pmatrix} 1 & -0.11 & 0. & -0.12 & 0.03 & 0.02 & 0.\\ & 1 & 0. & 0. & 0. & 0.02 & 0.55\\ & & 1 & 0. & -0.997 & -0.997 & 0.\\ & & & 1 & -0.01 & -0.01 & 0.\\ & & & & 1 & 0.9996 & 0.\\ & & & & & 1 & 0.01\\ & & & & & & 1\end{pmatrix}$$

Cirigliano, Diaz, AA, Gonzalez-Alonso, Rodriguez-Sanchez
to appear

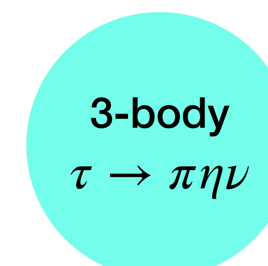
- One can resolve all Lorentz structures in the strange-muon sector, $\epsilon_X^{s\mu}$, because of interplay of width and differential distribution observables
- Less discriminating power in the strange-electron sector, because effects of ϵ_S^{se} and ϵ_T^{se} suppressed by the small electron mass
- Sub-permille constraints on the polluted matrix element $\hat V_{us}$
- Again very strong constraints on pseudoscalar interactions (completely resolved this time) thanks to chiral enhancement
- No hint of new physics here

Hadronic tau decays

$$\mathscr{L}_{\rm WEFT} \supset -\sum_{D=d,s}\sum_{\ell=e,\mu,\tau}\frac{V_{uD}}{v^2}\Big\{ \left(1+\epsilon_L^{D\ell}\right)\ \bar{\ell}\gamma_\mu P_L \nu_\ell \cdot \bar{u}\gamma^\mu(1-\gamma_5)D$$
$$+\epsilon_R^{D\ell}\ \bar{\ell}\gamma_\mu P_L \nu_\ell \cdot \bar{u}\gamma^\mu(1+\gamma_5)D$$
$$+\epsilon_T^{D\ell}\frac{1}{4}\bar{\ell}\sigma_{\mu\nu}P_L\nu_\ell \cdot \bar{u}\sigma^{\mu\nu}(1-\gamma_5)D$$
$$+\epsilon_S^{D\ell}\ \bar{\ell}P_L\nu_\ell \cdot \bar{u}D$$
$$-\epsilon_P^{D\ell}\ \bar{\ell}P_L\nu_\ell \cdot \bar{u}\gamma_5 D\Big\} + \text{hc}$$



Cirigliano, Diaz, AA, Gonzalez-Alonso, Rodriguez-Sanchez
to appear



$\epsilon_S^{d\tau} \in (-0.021, 0.010)$

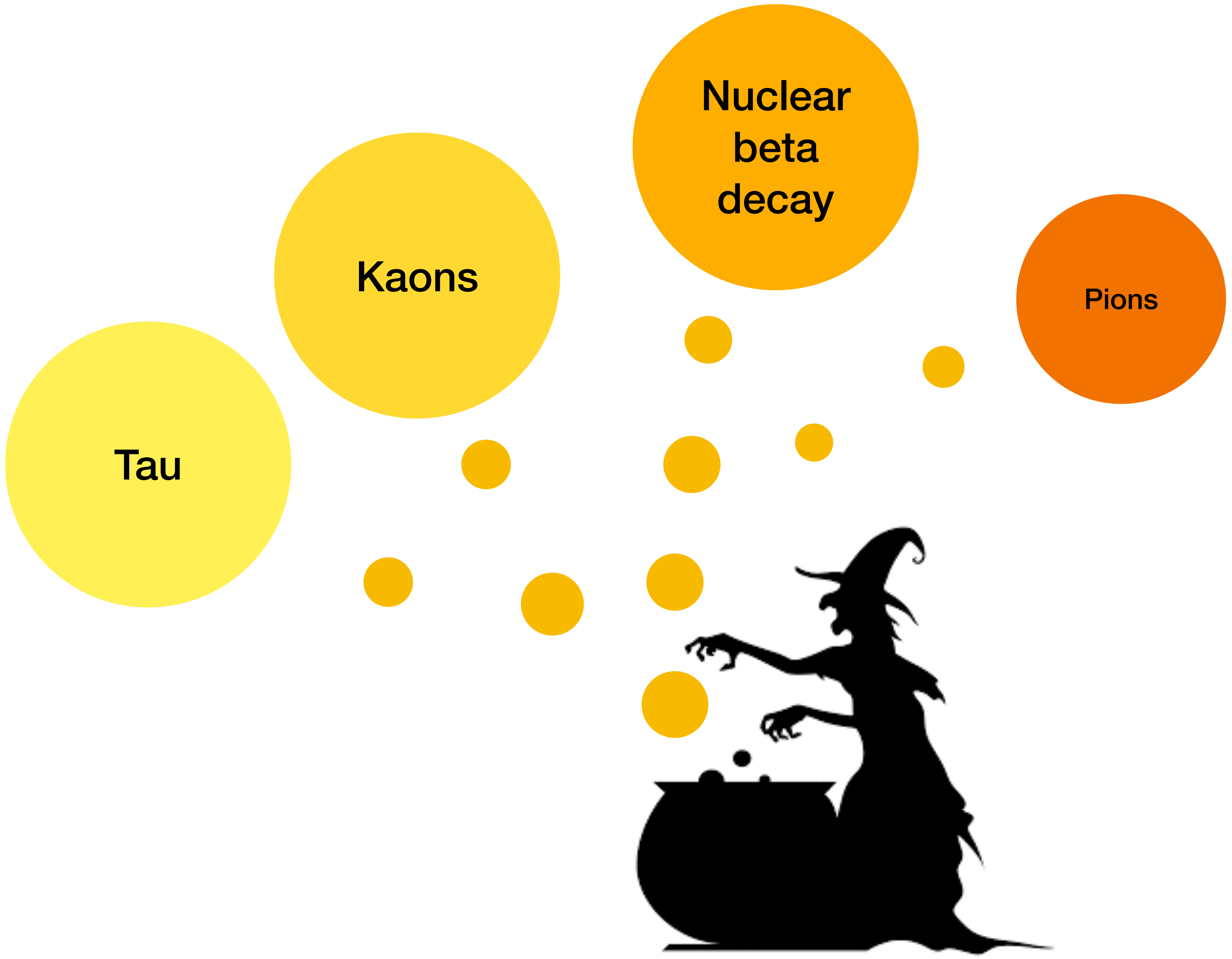
$$\begin{pmatrix} \epsilon_L^{d\tau}-\epsilon_L^{de} \\ \epsilon_R^{d\tau} \\ \epsilon_P^{d\tau} \\ \epsilon_T^{d\tau} \\ \epsilon_L^{s\tau}-\epsilon_L^{se}-2\epsilon_R^{s}-\frac{m_{K^\pm}^2}{m_\tau(m_u+m_s)}\epsilon_P^{s\tau} \\ \epsilon_L^{s\tau}-\epsilon_L^{se}+0.08(1)\epsilon_S^{s\tau}-0.39\epsilon_P^{s\tau}+0.4(1)\epsilon_T^{s\tau} \end{pmatrix} = \begin{pmatrix} 2.2 \pm 2.6 \\ 0.6 \pm 1.4 \\ 0.4 \pm 1.0 \\ -2.8 \pm 5.9 \\ -0.2 \pm 1.0 \\ -1.2 \pm 1.2 \end{pmatrix} \times 10^{-2}$$

$$\rho = \begin{pmatrix} 1 & 0.87 & -0.24 & -0.97 & -0.04 & -0.42 \\ & 1 & -0.63 & -0.86 & 0.06 & -0.57 \\ & & 1 & 0.24 & -0.36 & 0.39 \\ & & & 1 & 0.05 & 0.48 \\ & & & & 1 & 0.16 \\ & & & & & 1 \end{pmatrix}$$

- All Lorentz structures resolved in the down-tau sector, $\epsilon_X^{d\tau}$
- Only two linear combinations probed in the strange-tau sector, $\epsilon_X^{s\tau}$
  Progress on the theory side needed to improve the situation
- Percent level constraints on new physics Wilson coefficients
- No hint of new physics here

Global fit

Global fit



Global fit

$$
\begin{pmatrix}
\hat{V}_{us} \equiv V_{us}\left(1+\epsilon_L^{se}+\epsilon_R^{s}\right) \\
\epsilon_L^{dse} \equiv \epsilon_L^{de} + \frac{\hat{V}_{us}^2}{1-\hat{V}_{us}^2}\epsilon_L^{se} \\
\epsilon_R^{d} \\
\epsilon_S^{de} \\
\epsilon_P^{de} \\
\epsilon_T^{de} \\
\epsilon_L^{s\mu} - \epsilon_L^{se} \\
\epsilon_R^{s} \\
\epsilon_P^{se} \\
\epsilon_{LP}^{d\mu} \equiv \epsilon_L^{d\mu} - \epsilon_L^{de} - \epsilon_P^{d\mu}\frac{m_{\pi^\pm}^2}{m_\mu(m_u+m_d)} \\
\epsilon_S^{s\mu} \\
\epsilon_P^{s\mu} \\
\epsilon_T^{s\mu} \\
\epsilon_L^{d\tau} - \epsilon_L^{de} \\
\epsilon_P^{d\tau} \\
\epsilon_T^{d\tau} \\
\epsilon_{LP}^{s\tau} \equiv \epsilon_L^{s\tau} - \epsilon_L^{se} - \epsilon_P^{s\tau}\frac{m_{K^\pm}^2}{m_\tau(m_u+m_s)} \\
\epsilon_{LSPT}^{s\tau} \equiv \epsilon_L^{s\tau} - \epsilon_L^{se} + 0.08(1)\epsilon_S^{s\tau} - 0.39\epsilon_P^{s\tau} + 0.4(1)\epsilon_T^{s\tau}
\end{pmatrix}
=
\begin{pmatrix}
0.22306(56) \\ 1.1(9.6) \\ -2.1(9.2) \\ 3.1(9.9) \\ 0.6(3.6) \\ -0.4(1.1) \\ 0.8(2.2) \\ 0.1(5.0) \\ -0.3(2.0) \\ -0.2(2.0) \\ -2.6(4.4) \\ -0.6(4.1) \\ 0.2(2.2) \\ 0.5(2.0) \\ 8.1(8.8) \\ 0.9(4.6) \\ 0.0(1.0) \\ -0.7(5.2)
\end{pmatrix}
\times 10\wedge
\begin{pmatrix}
0 \\ -3 \\ -3 \\ -4 \\ -6 \\ -3 \\ -3 \\ -2 \\ -5 \\ -2 \\ -4 \\ -3 \\ -2 \\ -2 \\ -3 \\ -2 \\ -1 \\ -2
\end{pmatrix}
$$

$$
\rho = \begin{pmatrix}
1 & 0.02 & 0. & 0. & 0. & 0. & -0.11 & 0. & 0.03 & 0. & -0.12 & 0.02 & 0. & 0. & 0. & 0. & -0.02 & -0.05 \\
 & 1 & -0.95 & 0.01 & 0.89 & 0.01 & 0. & -0.3 & 0.3 & -0.89 & 0. & 0.3 & 0. & -0.76 & 0.53 & 0.79 & -0.3 & -0.22 \\
 & & 1 & 0.03 & -0.93 & 0.02 & 0. & 0. & 0. & 0.93 & 0. & 0. & 0. & 0.79 & -0.56 & -0.83 & 0. & -0.08 \\
 & & & 1 & -0.01 & 0.6 & 0. & 0. & 0. & 0.01 & 0. & 0. & 0. & 0.02 & 0. & -0.03 & 0. & 0. \\
 & & & & 1 & 0. & 0. & 0. & 0.03 & -0.999 & 0. & 0.03 & 0. & -0.66 & 0.73 & 0.68 & -0.02 & 0.07 \\
 & & & & & 1 & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0.01 & 0.01 & -0.02 & 0. & 0. \\
 & & & & & & 1 & 0. & 0. & 0. & 0. & 0.02 & 0.55 & 0. & 0. & 0. & 0. & 0.01 \\
 & & & & & & & 1 & -0.997 & 0. & 0. & -0.997 & 0. & 0. & 0. & 0. & 0.99 & 0.98 \\
 & & & & & & & & 1 & -0.03 & -0.01 & 0.9996 & 0. & 0.01 & 0.04 & -0.01 & -0.997 & -0.98 \\
 & & & & & & & & & 1 & 0. & -0.03 & 0. & 0.66 & -0.73 & -0.68 & 0.02 & -0.07 \\
 & & & & & & & & & & 1 & -0.01 & 0. & 0. & 0. & 0. & 0.01 & 0.01 \\
 & & & & & & & & & & & 1 & 0.01 & 0.01 & 0.04 & -0.01 & -0.997 & -0.98 \\
 & & & & & & & & & & & & 1 & 0. & 0. & 0. & 0. & 0. \\
 & & & & & & & & & & & & & 1 & -0.03 & -0.95 & -0.01 & -0.04 \\
 & & & & & & & & & & & & & & 1 & 0.1 & -0.04 & 0.05 \\
 & & & & & & & & & & & & & & & 1 & 0.01 & 0.07 \\
 & & & & & & & & & & & & & & & & 1 & 0.98 \\
 & & & & & & & & & & & & & & & & & 1
\end{pmatrix}
$$

Cirigliano, Diaz, AA, Gonzalez-Alonso, Rodriguez-Sanchez
to appear

Global fit

$$
\begin{pmatrix}
\hat{V}_{us} \equiv V_{us}\left(1+\epsilon_L^{se}+\epsilon_R^{s}\right) \\
\epsilon_L^{dse} \equiv \epsilon_L^{de} + \frac{\hat{V}_{us}^2}{1-\hat{V}_{us}^2}\epsilon_L^{se} \\
\epsilon_R^{d} \\
\epsilon_S^{de} \\
\epsilon_P^{de} \\
\epsilon_T^{de} \\
\epsilon_L^{s\mu} - \epsilon_L^{se} \\
\epsilon_R^{s} \\
\epsilon_P^{se} \\
\epsilon_{LP}^{d\mu} \equiv \epsilon_L^{d\mu} - \epsilon_L^{de} - \epsilon_P^{d\mu}\frac{m_{\pi^\pm}^2}{m_\mu(m_u+m_d)} \\
\epsilon_S^{s\mu} \\
\epsilon_P^{s\mu} \\
\epsilon_T^{s\mu} \\
\epsilon_L^{d\tau} - \epsilon_L^{de} \\
\epsilon_P^{d\tau} \\
\epsilon_T^{d\tau} \\
\epsilon_{LP}^{s\tau} \equiv \epsilon_L^{s\tau} - \epsilon_L^{se} - \epsilon_P^{s\tau}\frac{m_{K^\pm}^2}{m_\tau(m_u+m_s)} \\
\epsilon_{LSPT}^{s\tau} \equiv \epsilon_L^{s\tau} - \epsilon_L^{se} + 0.08(1)\epsilon_S^{s\tau} - 0.39\epsilon_P^{s\tau} + 0.4(1)\epsilon_T^{s\tau}
\end{pmatrix}
=
\begin{pmatrix}
0.22306(56) \\ 1.1(9.6) \\ -2.1(9.2) \\ 3.1(9.9) \\ 0.6(3.6) \\ -0.4(1.1) \\ 0.8(2.2) \\ 0.1(5.0) \\ -0.3(2.0) \\ -0.2(2.0) \\ -2.6(4.4) \\ -0.6(4.1) \\ 0.2(2.2) \\ 0.5(2.0) \\ 8.1(8.8) \\ 0.9(4.6) \\ 0.0(1.0) \\ -0.7(5.2)
\end{pmatrix}
\times 10\hat{}
\begin{pmatrix}
0 \\ -3 \\ -3 \\ -4 \\ -6 \\ -3 \\ -3 \\ -2 \\ -5 \\ -2 \\ -4 \\ -3 \\ -2 \\ -2 \\ -3 \\ -2 \\ -1 \\ -2
\end{pmatrix}
$$

This result describes an
18 parameter likelihood function
with all correlations taken into account.
No specific flavor structure assumed.
All epsilon's can be present at the same time
in completely arbitrary patterns
The likelihood can be applied to constraining
a broad class of new physics models
as long as non-SM particles are heavy enough

Global fit

$$
\begin{pmatrix}
\hat{V}_{us} \equiv V_{us}\left(1+\epsilon_L^{se}+\epsilon_R^{s}\right) \\
\epsilon_L^{dse} \equiv \epsilon_L^{de} + \frac{\hat{V}_{us}^2}{1-\hat{V}_{us}^2}\epsilon_L^{se} \\
\epsilon_R^{d} \\
\epsilon_S^{de} \\
\epsilon_P^{de} \\
\epsilon_T^{de} \\
\epsilon_L^{s\mu} - \epsilon_L^{se} \\
\epsilon_R^{s} \\
\epsilon_P^{se} \\
\epsilon_{LP}^{d\mu} \equiv \epsilon_L^{d\mu} - \epsilon_L^{de} - \epsilon_P^{d\mu}\frac{m_{\pi^\pm}^2}{m_\mu(m_u+m_d)} \\
\epsilon_S^{s\mu} \\
\epsilon_P^{s\mu} \\
\epsilon_T^{s\mu} \\
\epsilon_L^{d\tau} - \epsilon_L^{de} \\
\epsilon_P^{d\tau} \\
\epsilon_T^{d\tau} \\
\epsilon_{LP}^{s\tau} \equiv \epsilon_L^{s\tau} - \epsilon_L^{se} - \epsilon_P^{s\tau}\frac{m_{K^\pm}^2}{m_\tau(m_u+m_s)} \\
\epsilon_{LSPT}^{s\tau} \equiv \epsilon_L^{s\tau} - \epsilon_L^{se} + 0.08(1)\epsilon_S^{s\tau} - 0.39\epsilon_P^{s\tau} + 0.4(1)\epsilon_T^{s\tau}
\end{pmatrix}
=
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0.22306(56) \\ 1.1(9.6) \\ -2.1(9.2) \\ 3.1(9.9) \\ 0.6(3.6) \\ -0.4(1.1) \\ 0.8(2.2) \\ 0.1(5.0) \\ -0.3(2.0) \\ -0.2(2.0) \\ -2.6(4.4) \\ -0.6(4.1) \\ 0.2(2.2) \\ 0.5(2.0) \\ 8.1(8.8) \\ 0.9(4.6) \\ 0.0(1.0) \\ -0.7(5.2)
\end{pmatrix}
\times 10\wedge
\begin{pmatrix}
0 \\ -3 \\ -3 \\ -4 \\ -6 \\ -3 \\ -3 \\ -2 \\ -5 \\ -2 \\ -4 \\ -3 \\ -2 \\ -2 \\ -3 \\ -2 \\ -1 \\ -2
\end{pmatrix}
$$

One additional linear combination of new physics Wilson coefficients constrained because we used the relation between polluted CKM matrix elements:

$$
\hat{V}_{ud} = \sqrt{1-\hat{V}_{us}^2}\left[1+\epsilon_L^{dse}+\epsilon_R^{d}+\frac{\hat{V}_{us}^2}{1-\hat{V}_{us}^2}\epsilon_R^{s}\right]
$$

Global fit

$$
\begin{pmatrix}
\hat{V}_{us} \equiv V_{us}\left(1+\epsilon_L^{se}+\epsilon_R^{s}\right) \\
\epsilon_L^{dse} \equiv \epsilon_L^{de} + \frac{\hat{V}_{us}^2}{1-\hat{V}_{us}^2}\epsilon_L^{se} \\
\epsilon_R^{d} \\
\epsilon_S^{de} \\
\epsilon_P^{de} \\
\epsilon_T^{de} \\
\epsilon_L^{s\mu}-\epsilon_L^{se} \\
\epsilon_R^{s} \\
\epsilon_P^{se} \\
\epsilon_{LP}^{d\mu} \equiv \epsilon_L^{d\mu} - \epsilon_L^{de} - \epsilon_P^{d\mu}\frac{m_{\pi^\pm}^2}{m_\mu(m_u+m_d)} \\
\epsilon_S^{s\mu} \\
\epsilon_P^{s\mu} \\
\epsilon_T^{s\mu} \\
\epsilon_L^{d\tau}-\epsilon_L^{de} \\
\epsilon_P^{d\tau} \\
\epsilon_T^{d\tau} \\
\epsilon_{LP}^{s\tau} \equiv \epsilon_L^{s\tau} - \epsilon_L^{se} - \epsilon_P^{s\tau}\frac{m_{K^\pm}^2}{m_\tau(m_u+m_s)} \\
\epsilon_{LSPT}^{s\tau} \equiv \epsilon_L^{s\tau} - \epsilon_L^{se} + 0.08(1)\epsilon_S^{s\tau} - 0.39\epsilon_P^{s\tau} + 0.4(1)\epsilon_T^{s\tau}
\end{pmatrix}
=
\begin{pmatrix}
0.22306(56) \\ 1.1(9.6) \\ -2.1(9.2) \\ 3.1(9.9) \\ 0.6(3.6) \\ -0.4(1.1) \\ 0.8(2.2) \\ 0.1(5.0) \\ -0.3(2.0) \\ -0.2(2.0) \\ -2.6(4.4) \\ -0.6(4.1) \\ 0.2(2.2) \\ 0.5(2.0) \\ 8.1(8.8) \\ 0.9(4.6) \\ 0.0(1.0) \\ -0.7(5.2)
\end{pmatrix}
\times 10\hat{}
\begin{pmatrix}
0 \\ -3 \\ -3 \\ -4 \\ -6 \\ -3 \\ -3 \\ -2 \\ -5 \\ -2 \\ -4 \\ -3 \\ -2 \\ -2 \\ -3 \\ -2 \\ -1 \\ -2
\end{pmatrix}
$$

Both nuclear beta decay and hadronic tau decay probe the same new physics parameter ϵ_R^d with similar precision.
Constraints on V+A currents considerably stronger in the global fit than in the individual fits

Global fit

$$
\begin{pmatrix}
\hat{V}_{us} \equiv V_{us}\left(1+\epsilon_L^{se}+\epsilon_R^{s}\right) \\
\epsilon_L^{dse} \equiv \epsilon_L^{de} + \frac{\hat{V}_{us}^2}{1-\hat{V}_{us}^2}\epsilon_L^{se} \\
\epsilon_R^{d} \\
\epsilon_S^{de} \\
\epsilon_P^{de} \\
\epsilon_T^{de} \\
\epsilon_L^{s\mu} - \epsilon_L^{se} \\
\epsilon_R^{s} \\
\epsilon_P^{se} \\
\epsilon_{LP}^{d\mu} \equiv \epsilon_L^{d\mu} - \epsilon_L^{de} - \epsilon_P^{d\mu}\frac{m_{\pi^\pm}^2}{m_\mu(m_u+m_d)} \\
\epsilon_S^{s\mu} \\
\epsilon_P^{s\mu} \\
\epsilon_T^{s\mu} \\
\epsilon_L^{d\tau} - \epsilon_L^{de} \\
\epsilon_P^{d\tau} \\
\epsilon_T^{d\tau} \\
\epsilon_{LP}^{s\tau} \equiv \epsilon_L^{s\tau} - \epsilon_L^{se} - \epsilon_P^{s\tau}\frac{m_{K^\pm}^2}{m_\tau(m_u+m_s)} \\
\epsilon_{LSPT}^{s\tau} \equiv \epsilon_L^{s\tau} - \epsilon_L^{se} + 0.08(1)\epsilon_S^{s\tau} - 0.39\epsilon_P^{s\tau} + 0.4(1)\epsilon_T^{s\tau}
\end{pmatrix}
=
\begin{pmatrix}
0.22306(56) \\ 1.1(9.6) \\ -2.1(9.2) \\ 3.1(9.9) \\ 0.6(3.6) \\ -0.4(1.1) \\ 0.8(2.2) \\ 0.1(5.0) \\ -0.3(2.0) \\ -0.2(2.0) \\ -2.6(4.4) \\ -0.6(4.1) \\ 0.2(2.2) \\ 0.5(2.0) \\ 8.1(8.8) \\ 0.9(4.6) \\ 0.0(1.0) \\ -0.7(5.2)
\end{pmatrix}
\times 10\text{^}
\begin{pmatrix}
0 \\ -3 \\ -3 \\ -4 \\ -6 \\ -3 \\ -3 \\ -2 \\ -5 \\ -2 \\ -4 \\ -3 \\ -2 \\ -2 \\ -3 \\ -2 \\ -1 \\ -2
\end{pmatrix}
$$

~~No hint of new physics here~~

The chi^2 difference between the SM fit and the general EFT fit is

$$\chi^2_{\mathrm{SM}} - \chi^2_{WEFT} = 37$$

with 17 additional degrees of freedom in the EFT fit. This corresponds to 2.9 sigma preference for new physics!

Lessons

SM fit

$$\mathscr{L}_{\rm WEFT} \supset -\sum_{D=d,s}\sum_{\ell=e,\mu,\tau}\frac{V_{uD}}{v^2}\Big\{ \left(1+\epsilon_L^{D\ell}\right)\ \bar{\ell}\gamma_\mu P_L\nu_\ell\cdot\bar{u}\gamma^\mu(1-\gamma_5)D + \epsilon_R^{D}\ \bar{\ell}\gamma_\mu P_L\nu_\ell\cdot\bar{u}\gamma^\mu(1+\gamma_5)D + \epsilon_T^{D\ell}\frac{1}{4}\bar{\ell}\sigma_{\mu\nu}P_L\nu_\ell\cdot\bar{u}\sigma^{\mu\nu}(1-\gamma_5)D + \epsilon_S^{D\ell}\ \bar{\ell}P_L\nu_\ell\cdot\bar{u}D - \epsilon_P^{D\ell}\ \bar{\ell}P_L\nu_\ell\cdot\bar{u}\gamma_5 D\Big\} + \text{hc}$$

For the moment we assume the SM paradigm, that is to say, our EFT is UV-completed at the W mass scale by the Standard Model, rather than by the general SMEFT. This implies

$$\epsilon_X^{D\ell} = 0$$

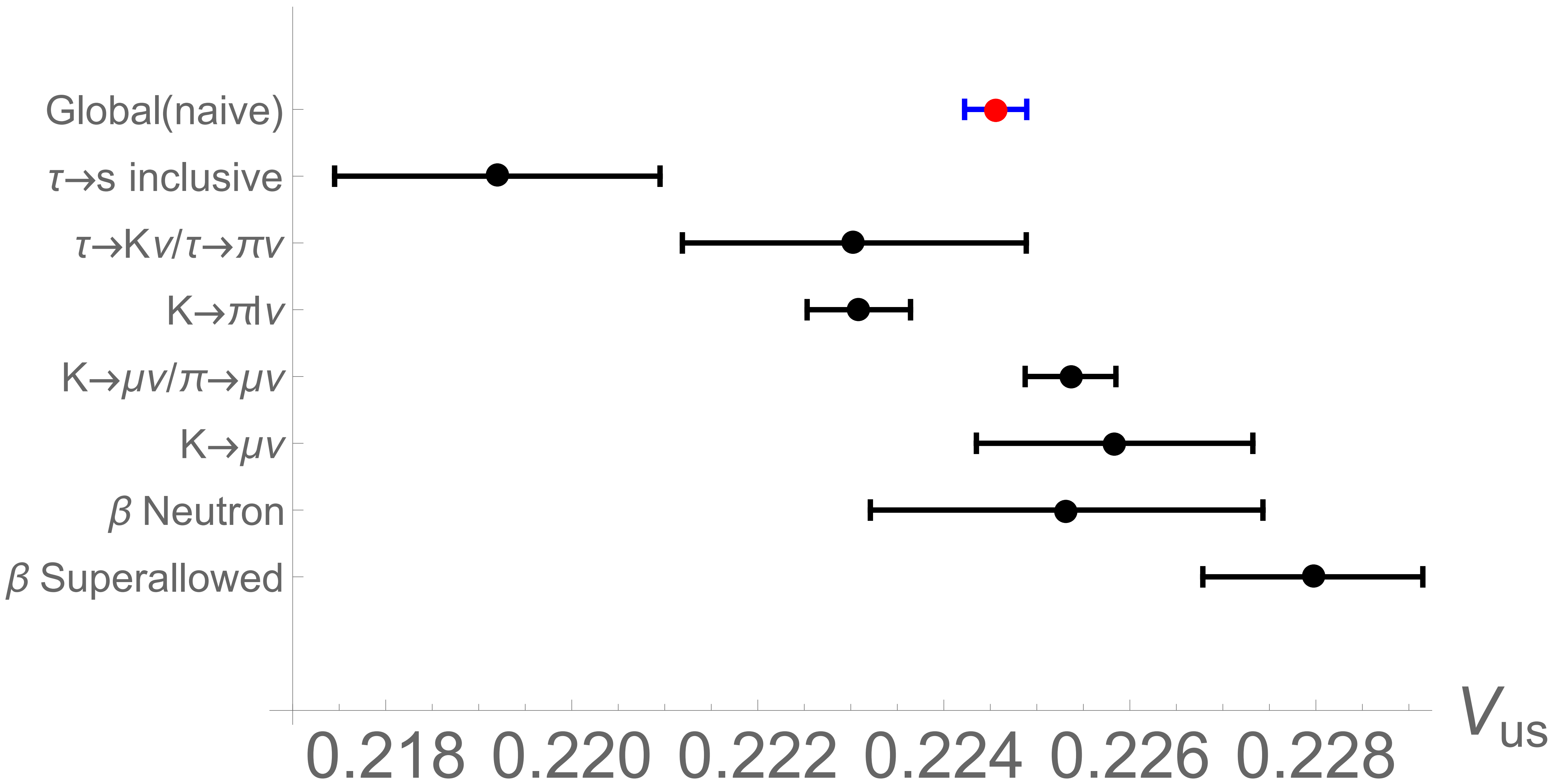
In this limit the only unknown fundamental parameter in our effective Lagrangian is the Cabibbo angle, that is V_{us}. Naively one obtains

$$V_{us} = 0.22456 \pm 0.00033$$

Naively, relative per-mille level precision on V_{us}

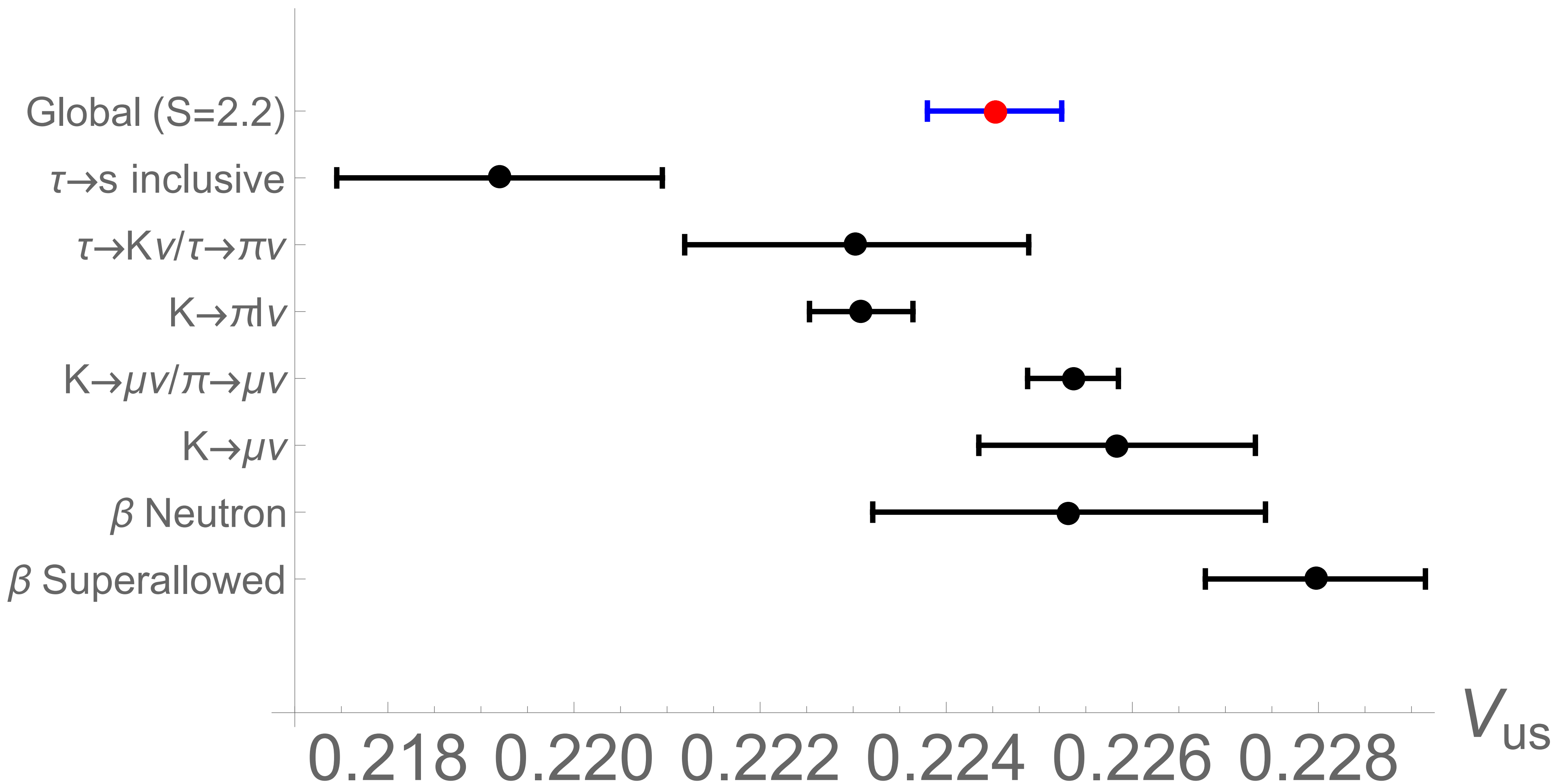
It follows that $V_{ud} = 0.974453(77)$, that is precision better than 10^{-4}

SM fit



Within the SM paradigm, it is absurd to say that the Cabibbo angle lies in the narrow interval suggested by the global fit. The internal inconsistency between the data sets suggests the existence of unaccounted for systematic effects, such that some errors are underestimated

SM fit



An ad hoc procedure, routinely practised by PDG is to inflate democratically all errors, such that overall goodness of fit is acceptable. The inflated errors better reflect our current knowledge concerning the Cabibbo angle in the SM

$$V_{us} = 0.22456 \pm 0.00072 \qquad S = 2.2$$

It follows that $V_{ud} = 0.97445(17)$

One-by-one BSM fit

$$\mathscr{L}_{\text{WEFT}} \supset -\sum_{D=d,s}\sum_{\ell=e,\mu,\tau}\frac{V_{uD}}{\text{v}^2}\Big\{ \left(1+\epsilon_L^{D\ell}\right)\ \bar{\ell}\gamma_\mu P_L \nu_\ell \cdot \bar{u}\gamma^\mu(1-\gamma_5)D$$
$$+\epsilon_R^{D}\,\bar{\ell}\gamma_\mu P_L\nu_\ell \cdot \bar{u}\gamma^\mu(1+\gamma_5)D$$
$$+\epsilon_T^{D\ell}\frac{1}{4}\bar{\ell}\sigma_{\mu\nu}P_L\nu_\ell \cdot \bar{u}\sigma^{\mu\nu}(1-\gamma_5)D$$
$$+\epsilon_S^{D\ell}\,\bar{\ell}P_L\nu_\ell \cdot \bar{u}D$$
$$-\epsilon_P^{D\ell}\,\bar{\ell}P_L\nu_\ell \cdot \bar{u}\gamma_5 D\Big\} + \text{hc}$$

We now assume new physics is well approximated by a single Wilson coefficient $\epsilon_X^{D\ell}$ in the EFT Lagrangian

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

- Preference for ϵ_L^{de} and ϵ_R^{s} is highly correlated, that is a combination of the two adjusts to ease the tension between nuclear beta decay and kaon decay determinations of the Cabibbo angle
- Preference for $\epsilon_L^{s\tau}$ is independent of the above two, and in this case $\epsilon_L^{s\tau}$ adjusts to ease the tension between the inclusive $\tau \to s$ and kaon determinations of the Cabibbo angle
- In the 2-parameter scenario with ϵ_L^{de} and $\epsilon_L^{s\tau}$ the chi^2 is improved by 18 compared to the SM fit, which corresponds to 3.8 sigma preference for such a scenario.

On LFUV

Another simple BSM scenario: assume SM-like V-A interaction,
but violating lepton flavor universality.

$$\begin{pmatrix} \epsilon_L^{se} \\ \epsilon_L^{s\mu} - \epsilon_L^{se} \\ \epsilon_L^{s\tau} - \epsilon_L^{se} \end{pmatrix} = \begin{pmatrix} -0.0145(52) \\ 0.0004(12) \\ -0.0176(62) \end{pmatrix}$$

There's a strong hint for lepton flavor universality violation in the strange-tau sector

For recent UV models addressing the Cabibbo anomaly see e.g.

Belfatto et al 1906.02714
Kirk 2008.03261
Belfatto Berezhiani 2103.05549
Branco et al 2103.13409

Summary

Summary

- Lots of high-quality precision data to probe $d(s) \to u\ell\nu$ transitions, for all lepton flavors.

- Individual datasets (nuclear, pion, kaon, tau) do not show a particular preference for new physics

- However a global combination of these shows a strong preference for new physics. This takes the form of the Cabibbo anomaly, that is different datasets point to a different value of the Cabibbo angle.

- Note that the tension is more than "CKM unitarity problem", in particular different determinations of V_{us} (kaons, hadronic taus) are also in tension with each other

- As any hint of physics beyond the Standard Model, this is most likely a problem with underestimated systematics in experiment and/or in theory

- However at face value the data point to lepton flavor universality violation in the strange quark sector, intriguingly adding to the hints of lepton flavor universality violation in the bottom quark sector