Anomalies in the charm-strange sector
➡ Theoretical point of view on Cabibbo angle anomaly

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Related topics

- **Cabibbo angle anomaly** focusing on τ ➡ talk by Emilie Passemar, Antonio Pich
- Anomaly in **direct CPV of** $D^0 \to K^+K^-, \pi^+\pi^-$ ➡ talk by Luiz Vale Silva, Guy Wilkinson

CP-odd amplitudes and CP asym.

WCs , DCs , FFs , rescattering factors , and BRs

isospin decomposition: $A_0^\pi\,,\ B_0^\pi\,,\ A_2^\pi\,,\ B_2^\pi\,,\quad A_0^K\,,\ B_0^K\,,\ A_{11}^K\,,\ B_{11}^K\,,\ A_{13}^K\,,\ B_{13}^K$

$$\Delta A_{CP}^{theo} \approx -2\,\Sigma_{i=K,\pi} \underbrace{\frac{B_i}{A_i}\sin(\delta_1-\delta_2)_i}_{\text{rescattering } \mathcal{O}(0.1)} \underbrace{\frac{\text{Jarlskog}}{|\lambda_d|^2}}_{=6.2\times10^{-3}} \sim -4\times10^{-4} \quad \ll \quad \Delta A_{CP}^{exp} \simeq -2\times10^{-3}$$

A_i, B_i: full amplitude moduli (schematic)

↑ mainly from D^0 to $\pi^+\pi^-$ [LHCb ‘22]

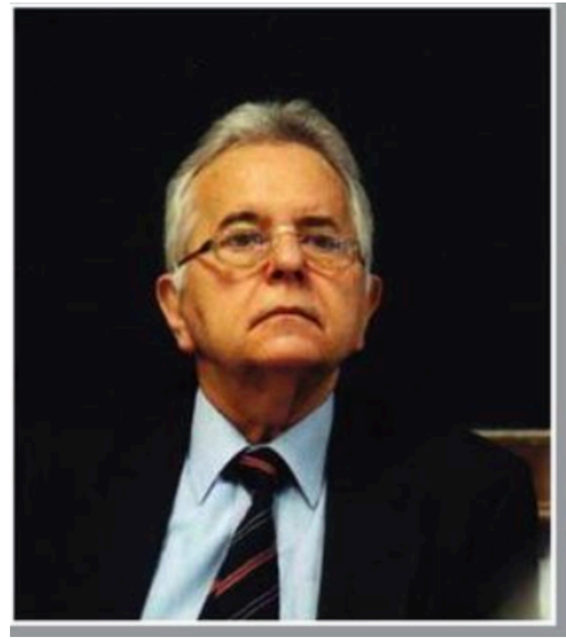
- Weak-phase: rephasing-invariant Jarlskog/$|\lambda_d|^2$ from bottom & strange
- Small CPV: rescattering effects not large enough
- It seems difficult to explain the measured CPV based on this approach

Luiz VALE SILVA – Direct CPV in charm

SM prediction of
$\Delta A_{\rm CP} = A_{\rm CP}\left(K^-K^+\right) - A_{\rm CP}\left(\pi^-\pi^+\right)$
based on the data-driven approach is significantly deviated from the data (LHCb)

CKM matrix

Cabibbo Kobayashi Maskawa



- **Cabibbo–Kobayashi–Maskawa (CKM) matrix** arises from a relative misalignment between gauge interaction and Yukawa-matrix eigenstates

$$\mathcal{L} \supset -\frac{g}{\sqrt{2}} \bar{u}_L^i \gamma^\mu d_L^i W_\mu^+ \xrightarrow{\text{mass-eigenbasis}} -\frac{g}{\sqrt{2}} \bar{u}_L^i \gamma^\mu (U_u^\dagger U_d)^{ij} d_L^j W_\mu^+$$

$$= -\frac{g}{\sqrt{2}} \bar{u}_L^i \gamma^\mu V_{\text{CKM}}^{ij} d_L^j W_\mu^+$$

$U_{u,d}$: unitary matrix

$$V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

If SM is correct :

unitarity condition $V^\dagger V = V V^\dagger = 1$

If new physics exists :

violation of unitarity $V^\dagger V \neq V V^\dagger \neq 1$

Unitarity of CKM matrix

- Each component of the CKM matrix can be measured without assuming the unitarity

  ➡ One can test the CKM unitarity conditions from data

β decays — K meson decays — B meson decays

$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

D meson decays

K and B mesons mixing,
K and B mesons FCNC

$VV^\dagger = \mathbb{I}_3$ or $\neq \mathbb{I}_3$?

SM — NP?

STCF will provide
$\mathcal{O}(0.1)\,\%$ stat. accuracy

CKM	Process	Observables	Non-perturbative theoretical inputs
$\|V_{ud}\|$	$0^+ \to 0^+ \beta$	$\|V_{ud}\|_{\text{nucl}} = 0.97373 \pm 0.00009 \pm 0.00053$	Nuclear matrix elements
$\|V_{us}\|$	$K \to \pi \ell \nu_\ell$	$\|V_{us}\|_{\text{SL}} f_+^{K\to\pi}(0) = 0.21635 \pm 0.00038$	$f_+^{K\to\pi}(0) = 0.9675 \pm 0.0011 \pm 0.0023$
	$K \to e\nu_e$	$\mathcal{B}(K \to e\nu_e) = (1.582 \pm 0.007) \cdot 10^{-5}$	
	$K \to \mu\nu_\mu$	$\mathcal{B}(K \to \mu\nu_\mu) = 0.6356 \pm 0.0011$	$f_K = 155.57 \pm 0.17 \pm 0.57$ MeV
	$\tau \to K\nu_\tau$	$\mathcal{B}(\tau \to K\nu_\tau) = (0.6986 \pm 0.0085) \cdot 10^{-2}$	
$\frac{\|V_{us}\|}{\|V_{ud}\|}$	$K \to \mu\nu_\mu / \pi \to \mu\nu_\mu$	$\frac{\mathcal{B}(K\to\mu\nu_\mu)}{\mathcal{B}(\pi\to\mu\nu_\mu)} = 1.3367 \pm 0.0028$	$f_K/f_\pi = 1.1973 \pm 0.0007 \pm 0.0014$
	$\tau \to K\nu_\tau / \tau \to \pi\nu_\tau$	$\frac{\mathcal{B}(\tau\to K\nu_\tau)}{\mathcal{B}(\tau\to\pi\nu_\tau)} = (6.437 \pm 0.092) \cdot 10^{-2}$	
$\|V_{cd}\|$	νN	$\|V_{cd}\|_{\text{not lattice}} = 0.230 \pm 0.011$	
	$D \to \tau\nu_\tau$	$\mathcal{B}(D \to \tau\nu_\tau) = (1.20 \pm 0.27) \cdot 10^{-3}$	
	$D \to \mu\nu_\mu$	$\mathcal{B}(D \to \mu\nu_\mu) = (3.77 \pm 0.17) \cdot 10^{-4}$	$f_{D_s}/f_D = 1.1782 \pm 0.0006 \pm 0.0033$
	$D \to \pi\ell\nu_\ell$	$\|V_{cd}\|_{\text{SL}} f_+^{D\to\pi}(0) = 0.1426 \pm 0.0018$	$f_+^{D\to\pi}(0) = 0.624 \pm 0.004 \pm 0.006$
$\|V_{cs}\|$	$W \to c\bar{s}$	$\|V_{cs}\|_{\text{not lattice}} = 0.967 \pm 0.011$	
	$D_s \to \tau\nu_\tau$	$\mathcal{B}(D_s \to \tau\nu_\tau) = (5.32 \pm 0.10) \cdot 10^{-2}$	
	$D_s \to \mu\nu_\mu$	$\mathcal{B}(D_s \to \mu\nu_\mu) = (5.43 \pm 0.16) \cdot 10^{-3}$	$f_{D_s} = 249.23 \pm 0.27 \pm 0.65$ MeV
	$D \to K\ell\nu_\ell$	$\|V_{cs}\|_{\text{SL}} f_+^{D\to K}(0) = 0.7180 \pm 0.0033$	$f_+^{D\to K}(0) = 0.742 \pm 0.002 \pm 0.004$
$\|V_{ub}\|$	semileptonic B	$\|V_{ub}\|_{\text{SL}} = (3.86 \pm 0.07 \pm 0.12) \cdot 10^{-3}$	form factors, shape functions
	$B \to \tau\nu_\tau$	$\mathcal{B}(B \to \tau\nu_\tau) = (1.09 \pm 0.24) \cdot 10^{-4}$	$f_{B_s}/f_B = 1.2118 \pm 0.0020 \pm 0.0058$
$\|V_{cb}\|$	semileptonic B	$\|V_{cb}\|_{\text{SL}} = (41.22 \pm 0.24 \pm 0.37) \cdot 10^{-3}$	form factors, OPE matrix elements
$\|V_{ub}/V_{cb}\|$	semileptonic Λ_b	$\frac{\gamma(\Lambda_b\to p\mu^-\bar{\nu}_\mu)_{q^2>15}}{\gamma(\Lambda_b\to\Lambda_c\mu^-\bar{\nu}_\mu)_{q^2>7}} = (0.918 \pm 0.083) \cdot 10^{-2}$	$\frac{\zeta(\Lambda_b\to p\mu^-\bar{\nu}_\mu)_{q^2>15}}{\zeta(\Lambda_b\to\Lambda_c\mu^-\bar{\nu}_\mu)_{q^2>7}} = 1.471 \pm 0.096 \pm 0.290$
	semileptonic B_s	$\frac{\gamma(B_s\to K^+\mu^-\bar{\nu}_\mu)_{q^2>15}}{\gamma(B_s\to D_s^+\mu^-\bar{\nu}_\mu)_{q^2>7}} = (3.25 \pm 0.28) \cdot 10^{-3}$	$\frac{\zeta(B_s\to K^+\mu^-\bar{\nu}_\mu)_{q^2>7}}{\zeta(B_s\to D_s^+\mu^-\bar{\nu}_\mu)_{q^2>7}} = 0.363 \pm 0.001 \pm 0.065$
	inclusive	$\|V_{ub}/V_{cb}\|_{\text{incl}} = 0.100 \pm 0.006 \pm 0.003$	
α	$B \to \pi\pi,\ \rho\pi,\ \rho\rho$	branching ratios, CP asymmetries	isospin symmetry
β	$B \to (c\bar{c})K$	$\sin(2\beta)_{[c\bar{c}]} = 0.708 \pm 0.011$	subleading penguins neglected
	$B^0 \to D^{(*)}h^0$	$\cos(2\beta) = 0.91 \pm 0.25$	
γ	$B \to D^{(*)}K^{(*)}$	$\gamma = (65.9^{+3.3}_{-3.5})^\circ$	GGSZ, GLW, ADS methods
ϕ_s	$B_s \to J/\psi(KK, \pi\pi)$	$(\phi_s)_{b\to c\bar{c}s} = -0.039 \pm 0.016$	
$V_{tq}^* V_{tb}$	Δm_d	$\Delta m_d = 0.5065 \pm 0.0019\ \text{ps}^{-1}$	$\hat{B}_{B_s}/\hat{B}_{B_d} = 1.007 \pm 0.010 \pm 0.014$
	Δm_s	$\Delta m_s = 17.765 \pm 0.006\ \text{ps}^{-1}$	$\hat{B}_{B_s} = 1.313 \pm 0.012 \pm 0.030$
	$B_s \to \mu\mu$	$\mathcal{B}(B_s \to \mu\mu) = (3.45 \pm 0.29) \cdot 10^{-9}[\times(1 - 0.063)]$	$f_{B_s} = 228.75 \pm 0.69 \pm 1.87$ MeV
$V_{td}^* V_{ts}$ and $V_{cd}^* V_{cs}$	ε_K	$\|\varepsilon_K\| = (2.228 \pm 0.011) \cdot 10^{-3}$	$\hat{B}_K = 0.7567 \pm 0.0020 \pm 0.0123$
			$\kappa_\varepsilon = 0.940 \pm 0.013 \pm 0.023$

black: no or slight change; **red**: substantial update since CKM'21

slide from Luiz Vale Silva@CKM2023

STCF will provide $\mathcal{O}(0.1)\ \%$ stat. accuracy for D decays

CKM unitarity triangle

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

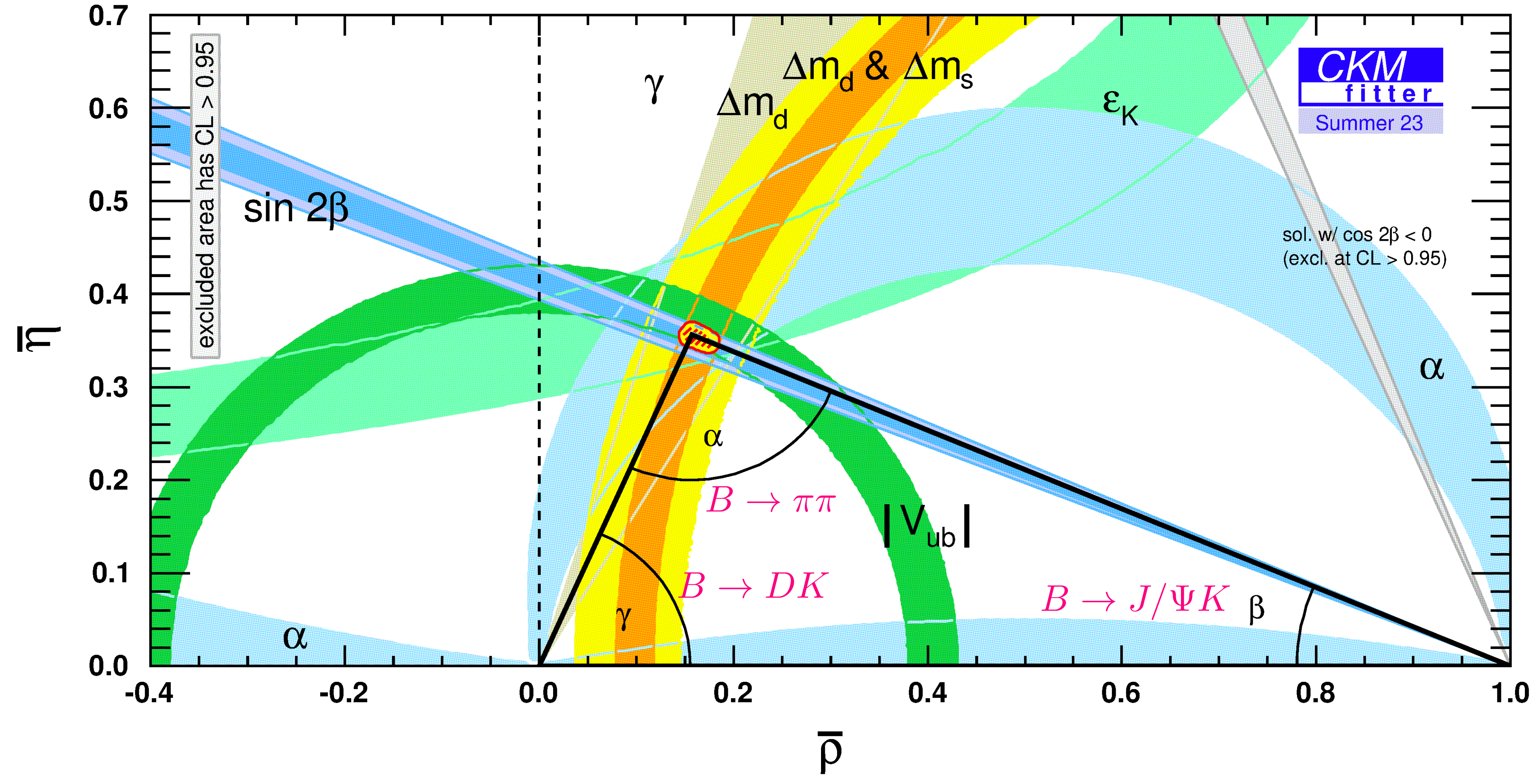
Unitarity condition

$$V^\dagger V = \mathbb{I}_3$$

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

A triangle can be drawn on a complex plane

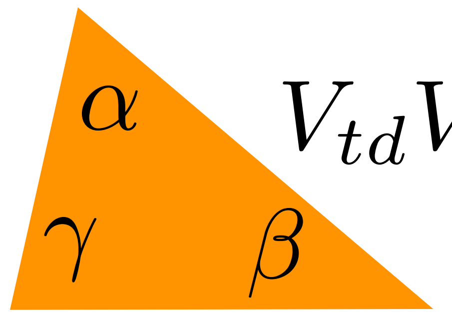
[CKM fitter 2023]



CPV

B triangle

$V_{ud}V_{ub}^* \sim \lambda^3$



$V_{td}V_{tb}^* \sim \lambda^3$

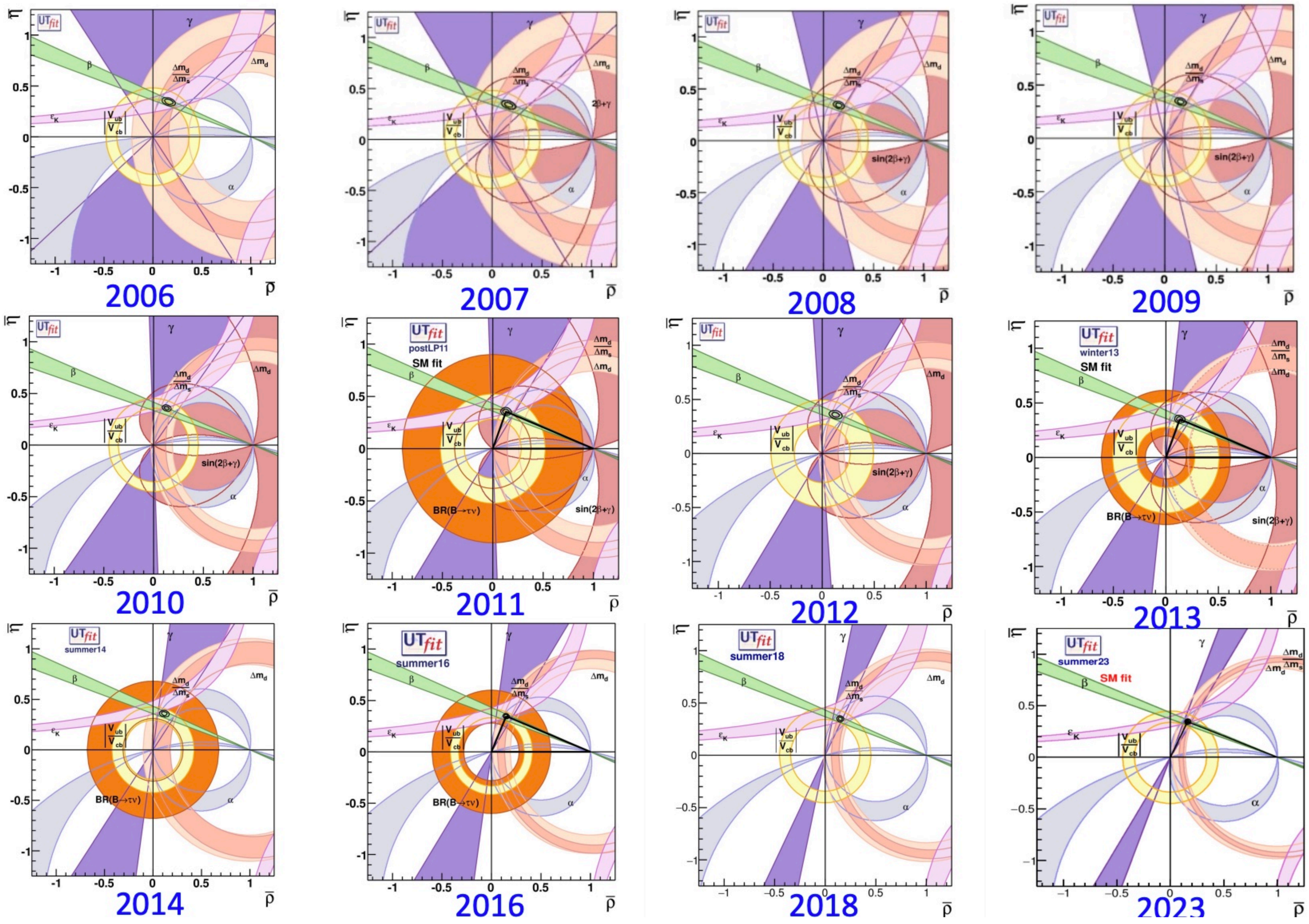
$V_{cd}V_{cb}^* \sim \lambda^3$

Many data are available! Currently, they are consistent with the triangle

Long journey to reach here…

slide from Vincenzo Vagnoni

From 2010 onwards with crucial LHCb contributions



1st-row Unitarity test in CKM matrix

$$\begin{pmatrix} \boxed{V_{ud} \quad V_{us} \quad V_{ub}} \\ V_{cd} \quad V_{cs} \quad V_{cb} \\ V_{td} \quad V_{ts} \quad V_{tb} \end{pmatrix}$$

Unitarity condition

$$VV^\dagger = \mathbb{I}_3$$

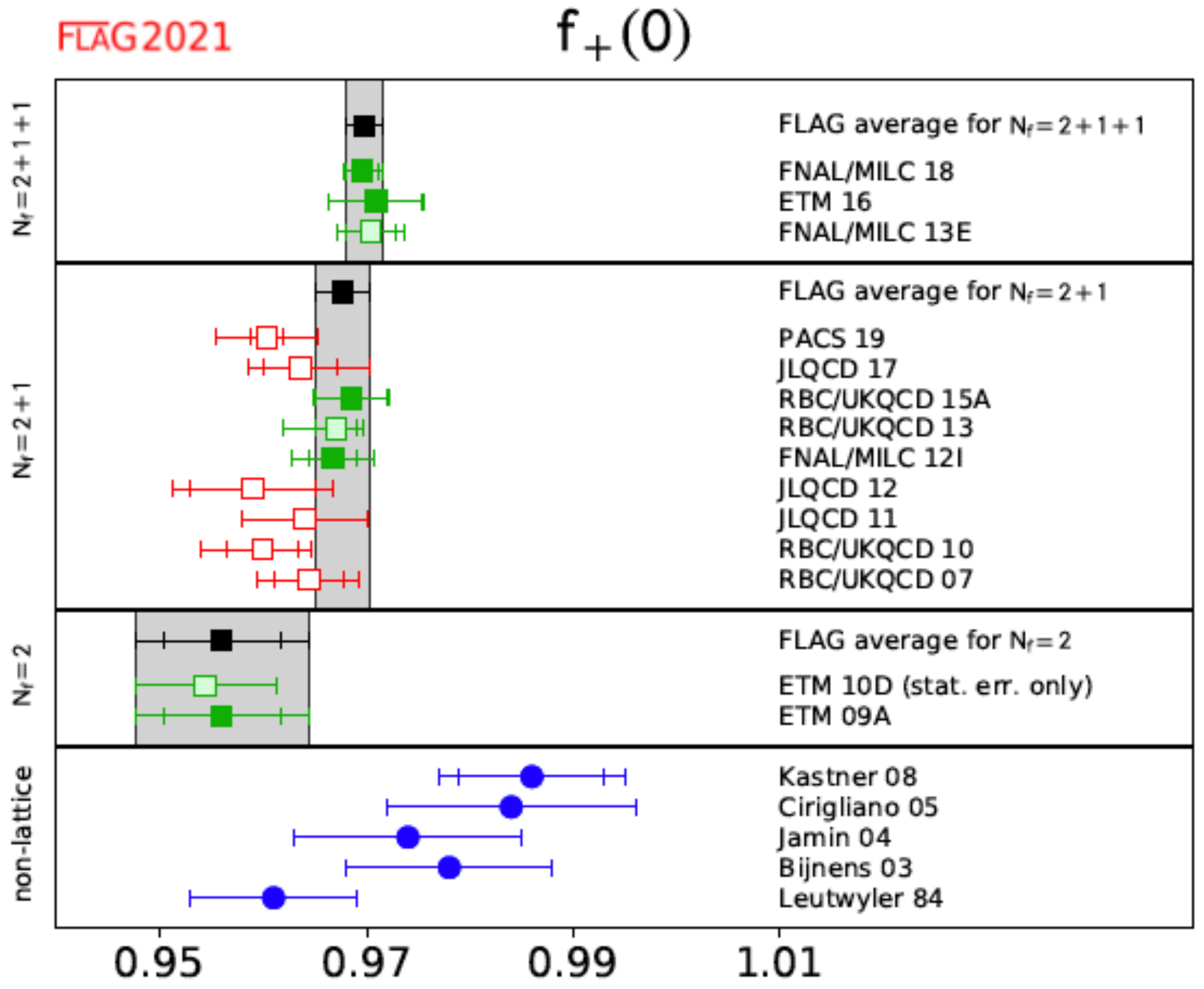
1st-row unitarity condition

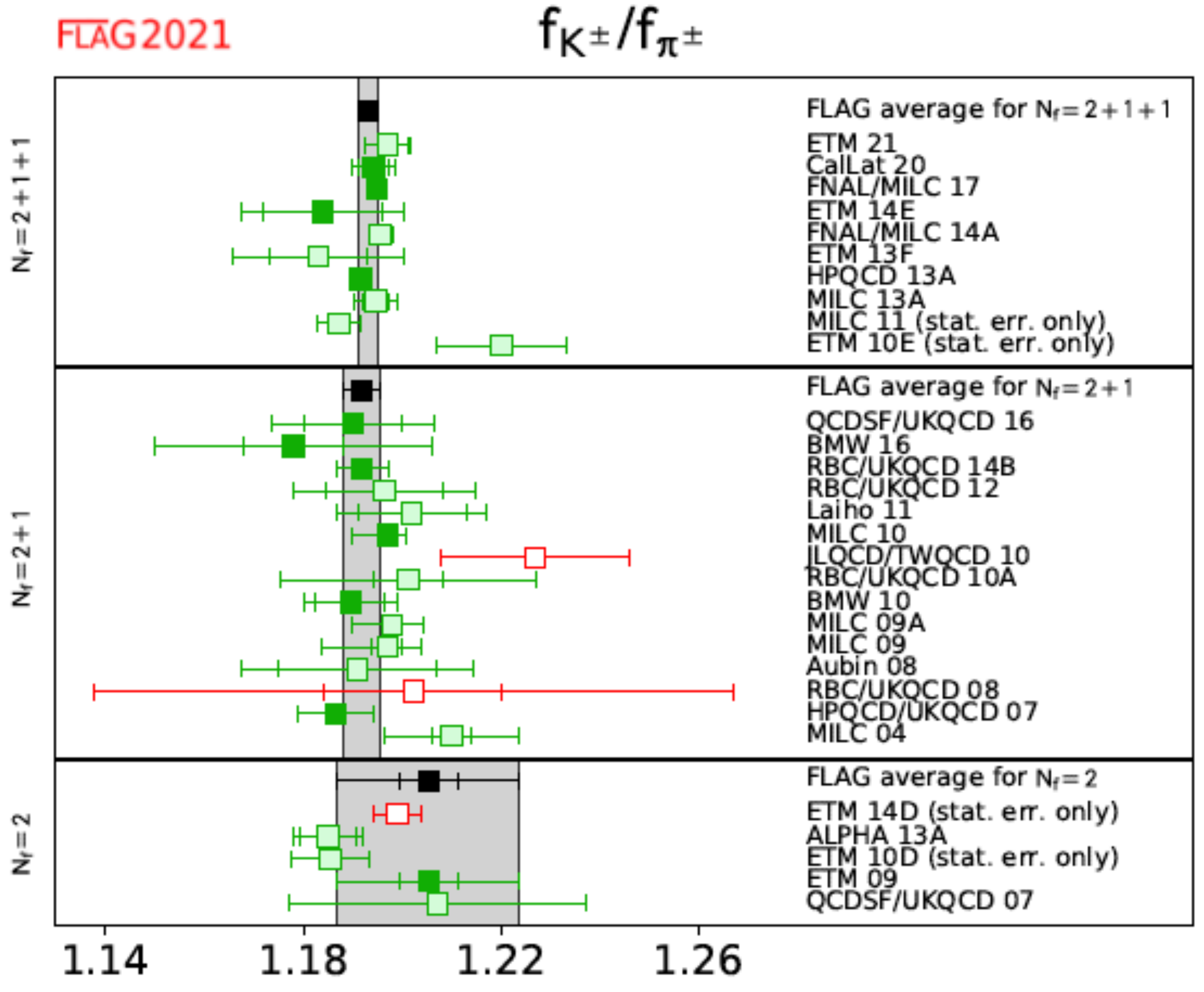
$$|V_{ud}|^2 + |V_{us}|^2 + \cancelto{10^{-5}}{|V_{ub}|^2} = 1$$

Sum of the absolute values must become **exact 1**

- Why these components?
- Leading uncertainties from kaon form factors have been improved significantly

[FLAG2021, 2111.09849]

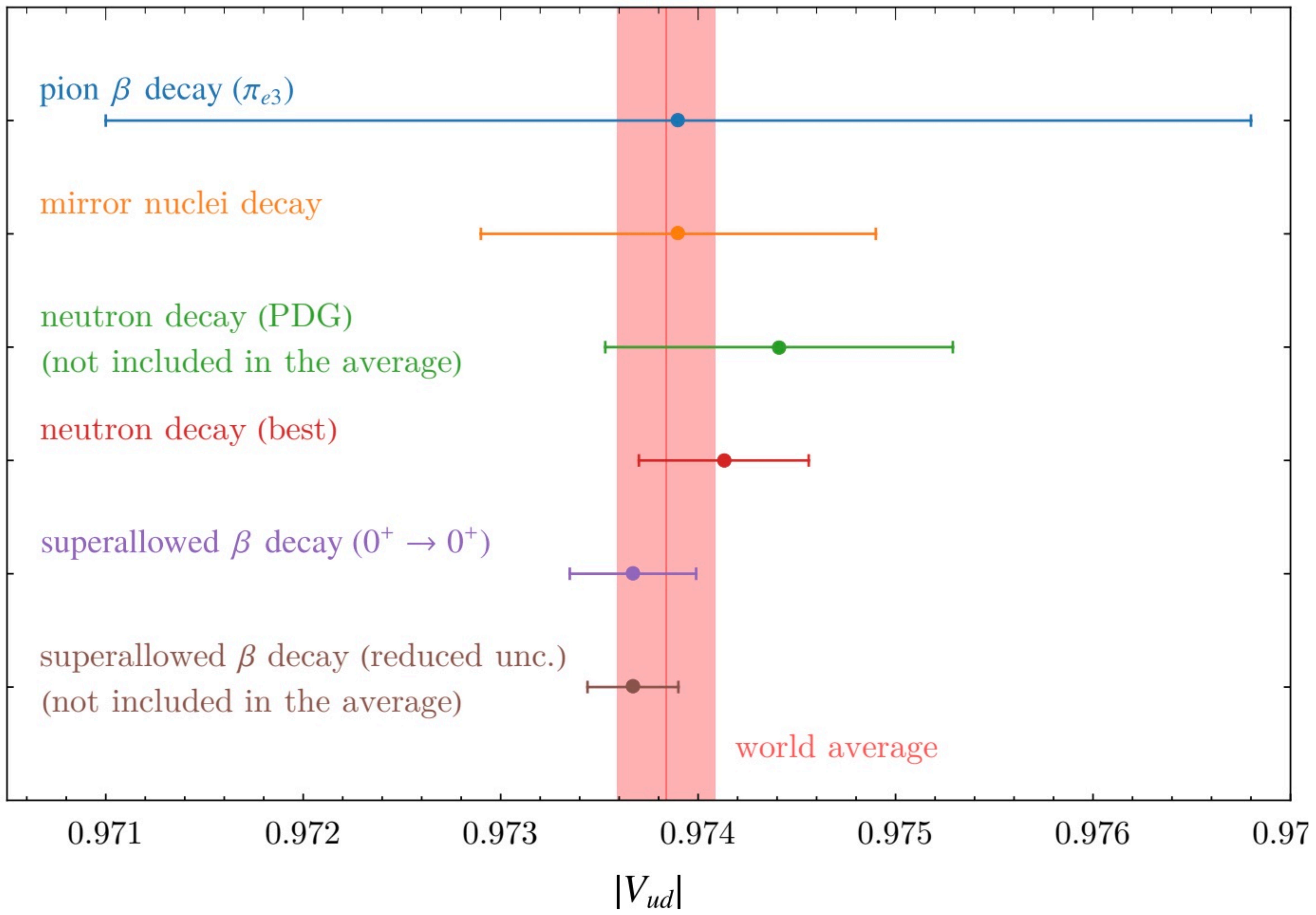


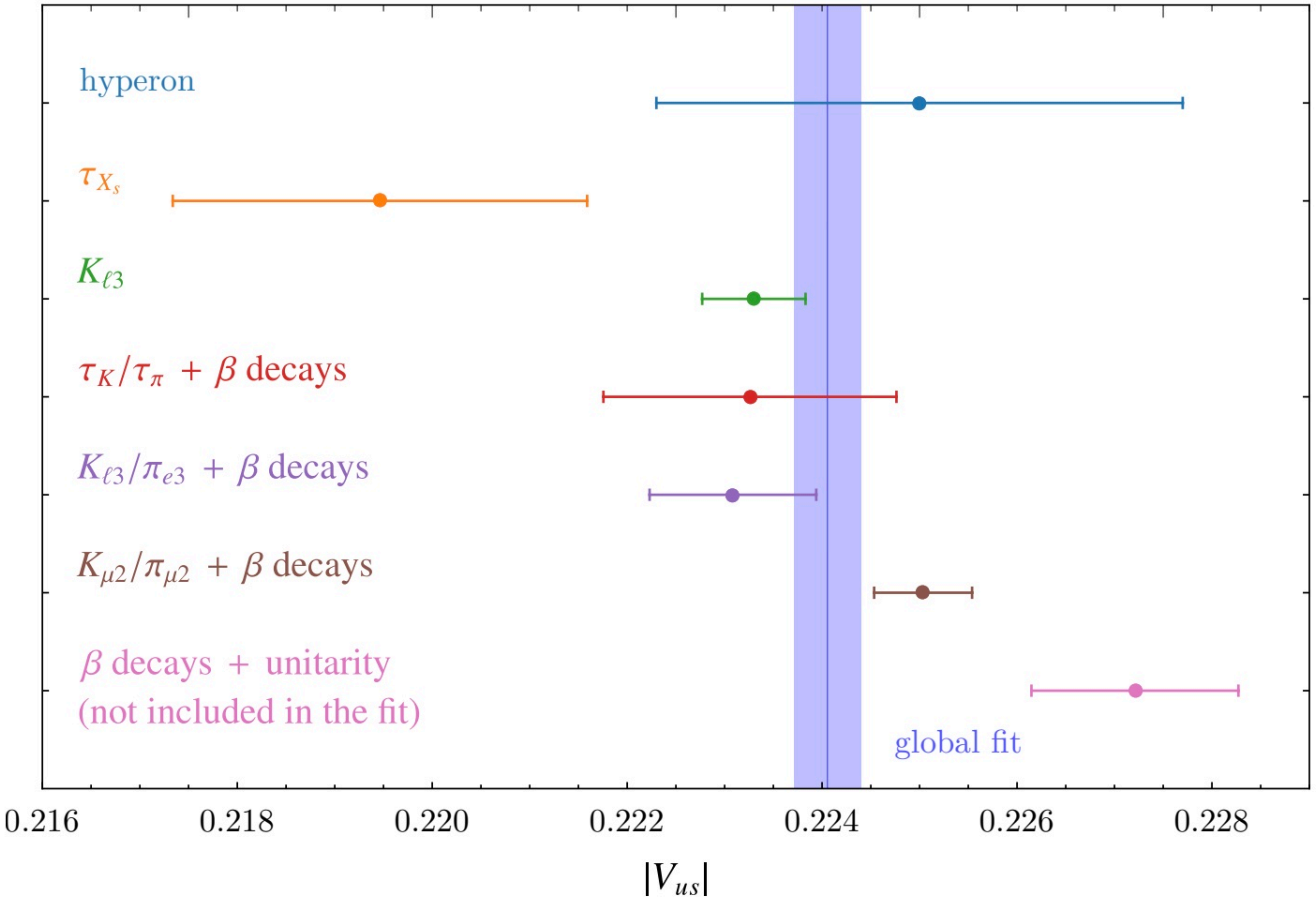


time

$|V_{ud}|$ and $|V_{us}|$ determinations

[Crivellin, Kirk, TK, Mescia, 2212.06862]





* new lattice result for super-allowed β decays is not included [Ma, et al., 2308.16755] (reduce CAA tension 0.5σ level)

One can see several tensions in $|V_{us}|$ determinations

Super-allowed ($0^+ \to 0^+$) nuclear β decays

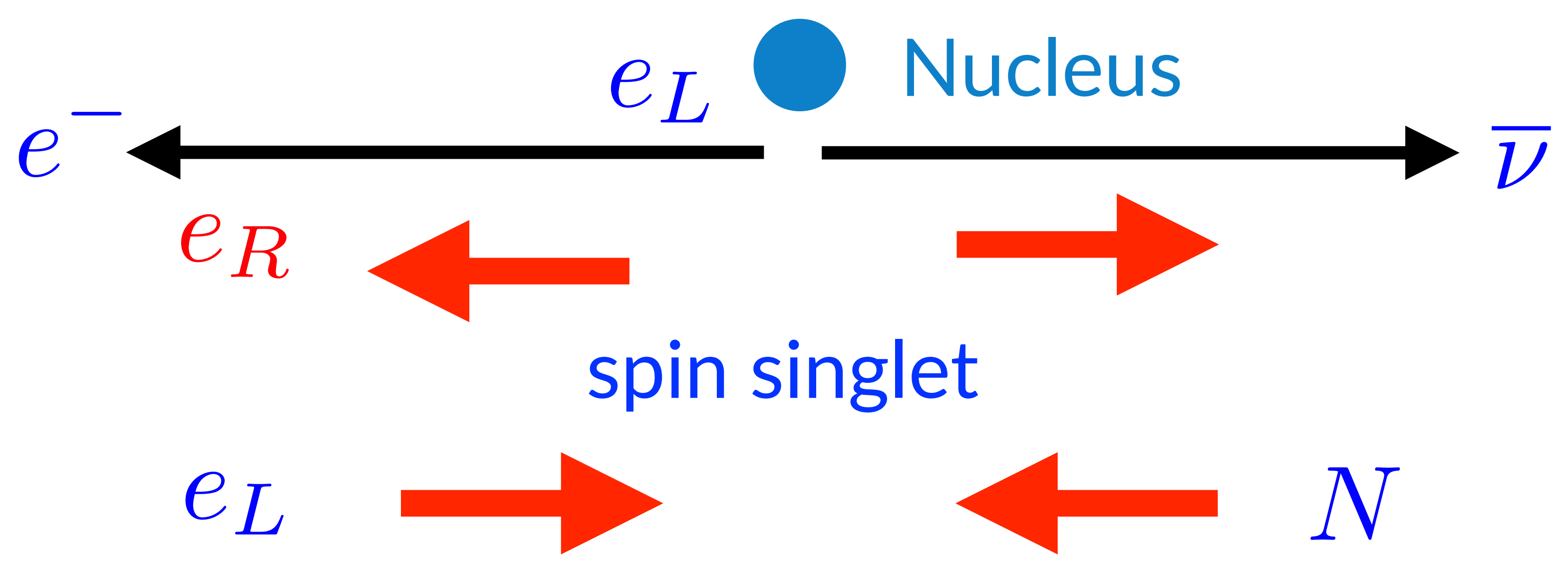
- $|V_{us}|$ is mostly determined buy the global fit of the super-allowed ($0^+ \to 0^+$) nuclear β decays

$J^P = 0^+ \to 0^+$ with β^+ decay $(p^+ \to n + e^+ \nu_e)$

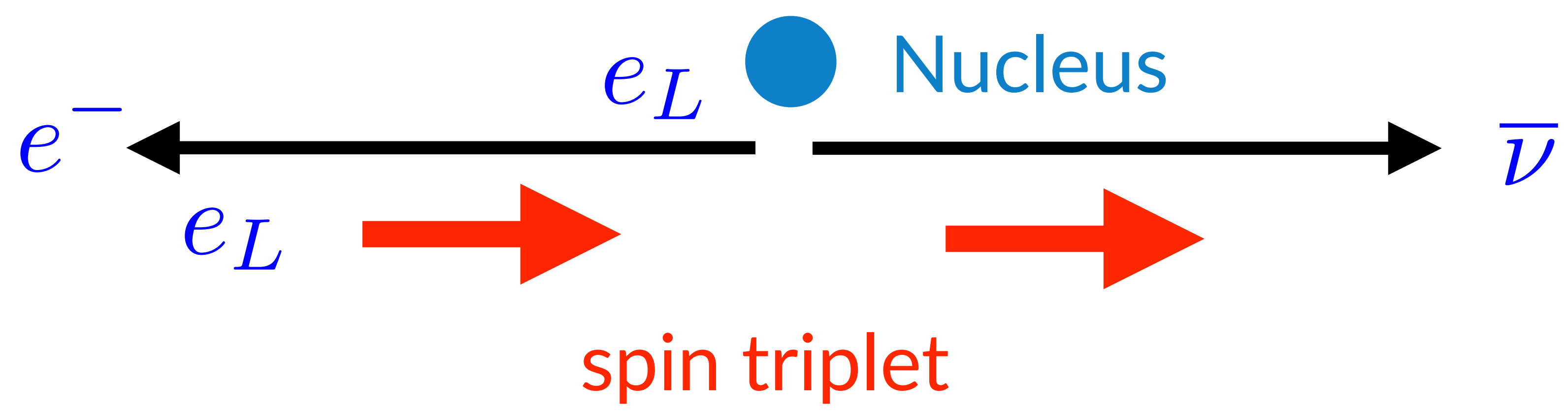
J is total nuclear angular momentum, $P = (-1)^L$ = parity and L is orbital angular

positron-neutrino pair must be spin singlet

Fermi decay (vector current)



Gamow-Teller decay (axial-vector current)



Forbidden in the super-allowed decays

Advantages

1. Theoretically clean and nucleus independent
2. Precisely measurable in experiments

Global fit of $|V_{ud}|$ and $|V_{us}|$

[Crivellin, Kirk, TK, Mescia, 2212.06862]

$K_{\ell 3}$

$K^0_{L,S} \to \pi^+ \ell \bar{\nu}$

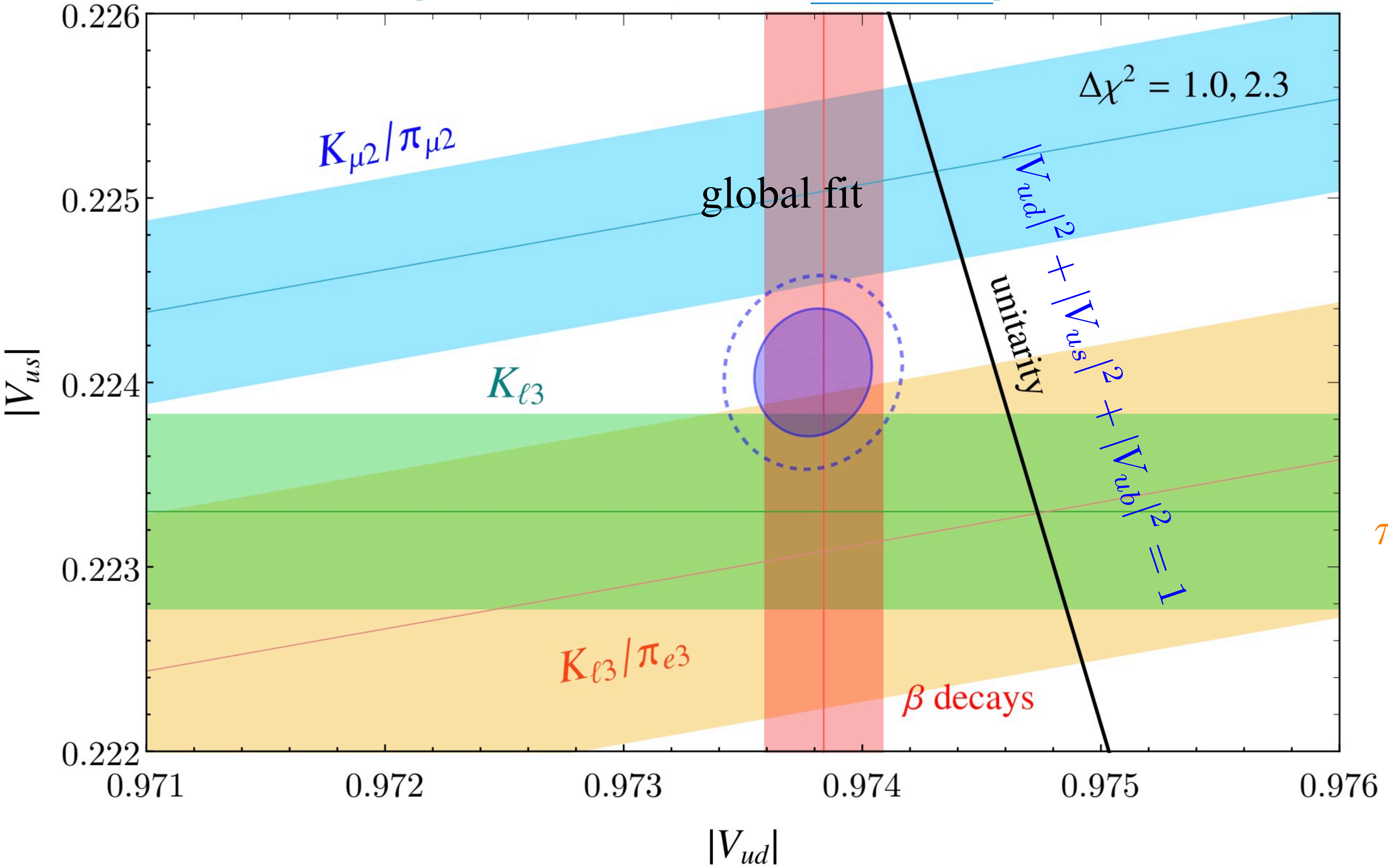
$K^- \to \pi^0 \ell \bar{\nu}$

$(\ell = e,\ \mu)$

Error budgets:

LO: data, FFs

NLO: Isospin breaking correction



$K_{\mu 2}/\pi_{\mu 2}$

$$\frac{K^- \to \mu \bar{\nu}}{\pi^- \to \mu \bar{\nu}}$$

Error budgets:

LO: FFs

NLO: data, radiative correction

$\pi_{e3} : \pi^+ \to \pi^0 e^+ \nu$

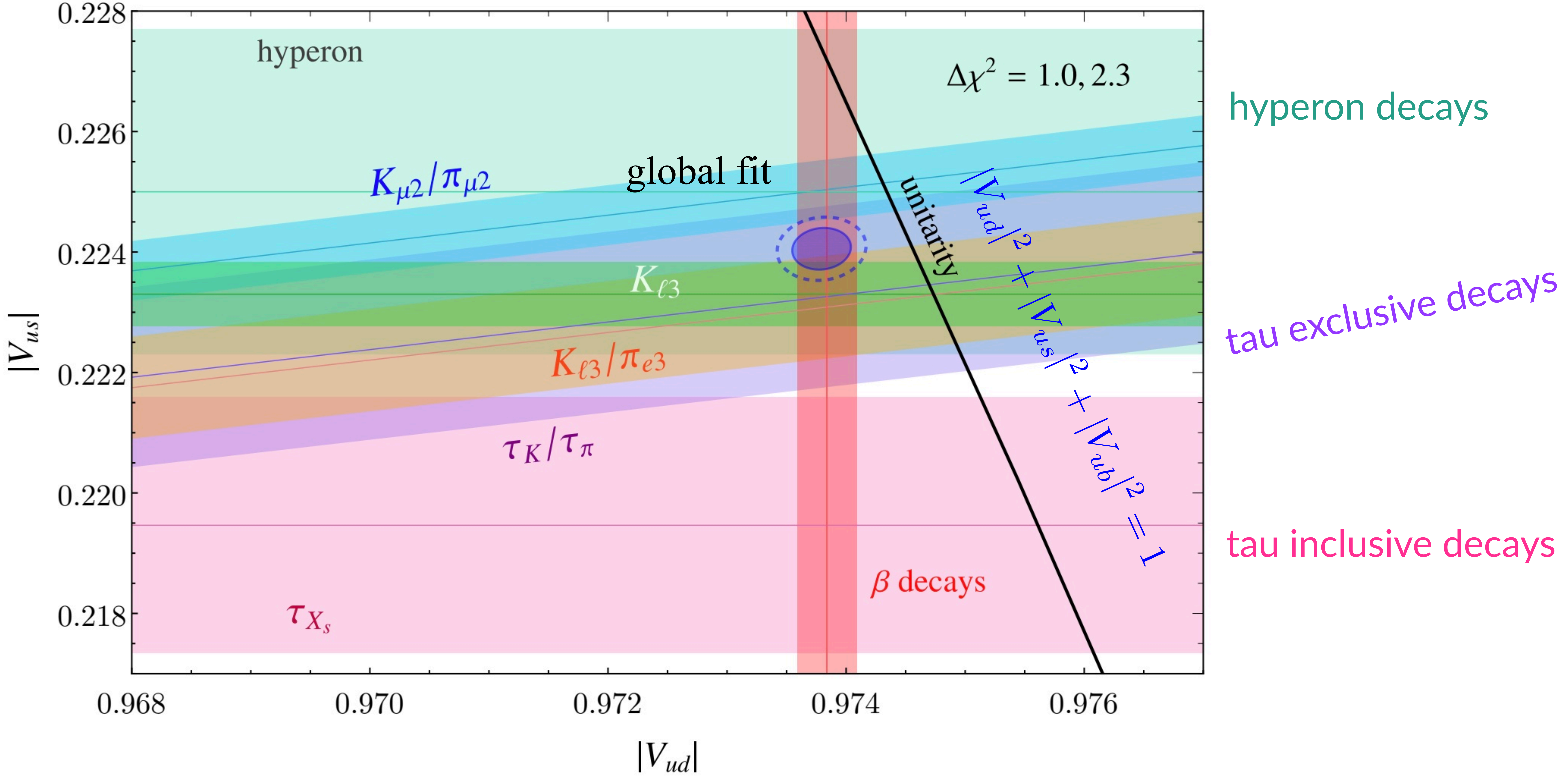
Error budgets:

LO: data

Uncertainty from $|V_{ub}|$ is negligible

Global fit of $|V_{ud}|$ and $|V_{us}|$

[Crivellin, Kirk, TK, Mescia, 2212.06862]

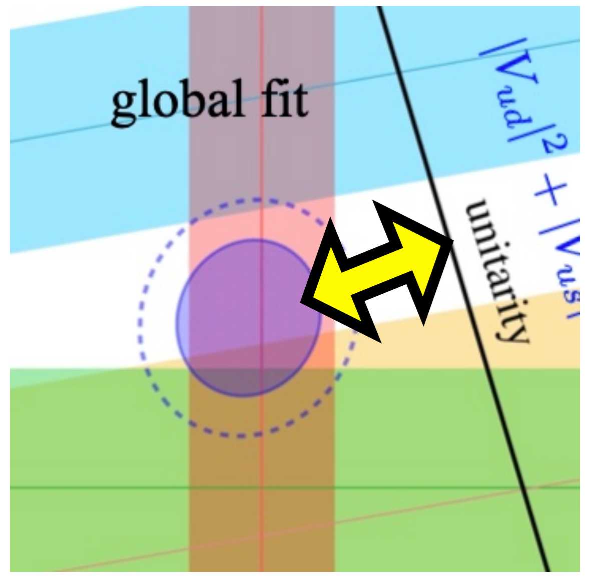


Significance of Cabibbo-Angle Anomaly (CAA)

- Global fit (including with correlations) [Crivellin, Kirk, TK, Mescia, 2212.06862]

$$|V_{ud}|_{\text{global}} = 0.973\,79(25)\,,$$ w/ bottle UCN best

$$|V_{us}|_{\text{global}} = 0.224\,05(35)\,, \quad \rho(V_{ud}, V_{us}) = 0.09$$



the single most precise data

$$\tau_n^{\text{bottle}} = 877.75(36)\text{sec} \qquad |V_{ud}|_n^{\text{bottle}} = 0.974\,13(43)$$

$$\tau_n^{\text{beam}} = 887.7(2.2)\text{sec} \qquad |V_{ud}|_n^{\text{beam}} = 0.968\,66(131)$$

Long-standing 4σ inconsistency (neutron lifetime anomaly)

test of unitarity

neutron-lifetime data dependence (bottle vs beam)

$$\Delta_{\text{CKM}}^{\text{global}} \equiv |V_{ud}|^2_{\text{global}} + |V_{us}|^2_{\text{global}} + |V_{ub}|^2 - 1 = \begin{cases} -1.51(53) \times 10^{-3} & (\text{w/ bottle UCN best})\,, \\ -2.34(62) \times 10^{-3} & (\text{w/ in-beam best})\,, \end{cases}$$

-2.8σ (UCN) and -3.8σ level (in-beam) deviations from SM [TK, Tobioka, 2308.13003]

2nd-row Unitarity tests

$$\begin{pmatrix} \boxed{V_{ud} \quad V_{us} \quad V_{ub}} \\ \boxed{V_{cd} \quad V_{cs} \quad V_{cb}} \\ V_{td} \quad V_{ts} \quad V_{tb} \end{pmatrix}$$

Unitarity condition

$$VV^\dagger = \mathbb{I}_3$$

current uncertainty

$$|V_{cd}|(\text{unc.}) \sim 2\%$$

$$|V_{cs}|(\text{unc.}) \sim 0.6\%$$

STCF will provide $\mathcal{O}(0.1)\,\%$ stat. accuracy for *D* decays

1st-row unitarity $\quad |V_{ud}|^2 + |V_{us}|^2 + \cancelto{10^{-5}}{|V_{ub}|^2} - 1 = -(15.1 \pm 5.3) \times 10^{-4}$ [Crivellin, Kirk, TK, Mescia, 2212.06862]

2nd-row unitarity $\quad |V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2 - 1 = (2^{+15}_{-13}) \times 10^{-4}$ given by Luiz Vale Silva (CKMfitter), thank you!

1st * 2nd-row unitarity $\quad V_{ud}V_{cd}^* + V_{us}V_{cs}^* + \cancelto{10^{-4}}{V_{ub}V_{cb}^*} = 0$ BES III/**STCF could probe this test**

$$\approx \; -|V_{ud}||V_{cd}| + |V_{us}||V_{cs}| = (3 \pm 4_{(V_{cd})} \pm 1_{(V_{cs})}) \times 10^{-3}$$

(my rough analysis)

W inclusive decay

- Inclusive-hadronic decay of W boson, $W \to q\bar{q}'$, is proportional to (in the massless q limit)

$$\propto \underbrace{|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2}_{1} + \underbrace{|V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2}_{1}$$

= 2 in the CKM unitarity

= $1.9987^{+0.0016}_{-0.0014}$ from flavor

- $W \to q\bar{q}'$ can determine $|V_{cs}|$ and probe the CKM unitarity test directly

[d'Enterria, Srebre, 1603.06501; CMS, 2201.07861]

CMS Run2 35.9fb-1 result:

$$\mathrm{BR}(W \to q\bar{q}') = (67.46 \pm 0.04_{\rm stat} \pm 0.28_{\rm syst})\ \%$$

direct measurement

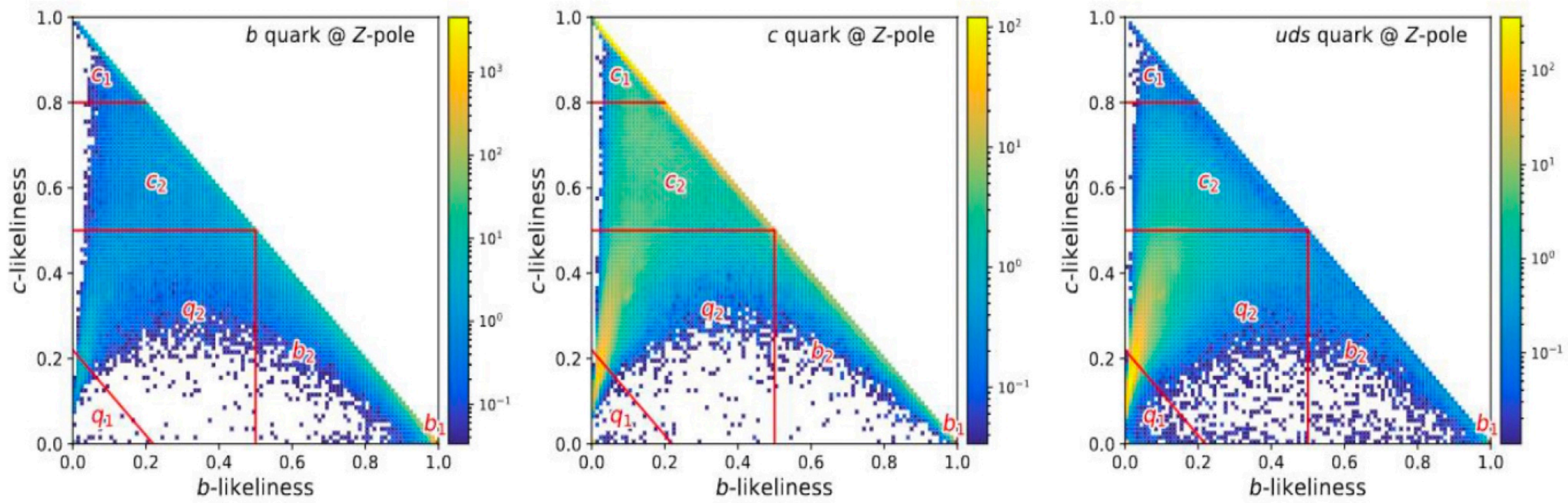
$$\mathrm{BR}(W \to q\bar{q}') = (67.32 \pm 0.02_{\rm stat} \pm 0.23_{\rm syst})\ \%$$

assuming LFU

	$\lvert V_{cs} \rvert$	unitarity test
CMS Run2	0.967 (11)	1.984 (21)
flavor	0.975 (6)	1.9987 ($^{+16}_{-14}$)

$|V_{cb}|$ from W exclusive decay

- CEPC plans to probe $|V_{cb}|$ from $e^+e^- \to W^+W^-, W \to bc, W \to \ell\nu$

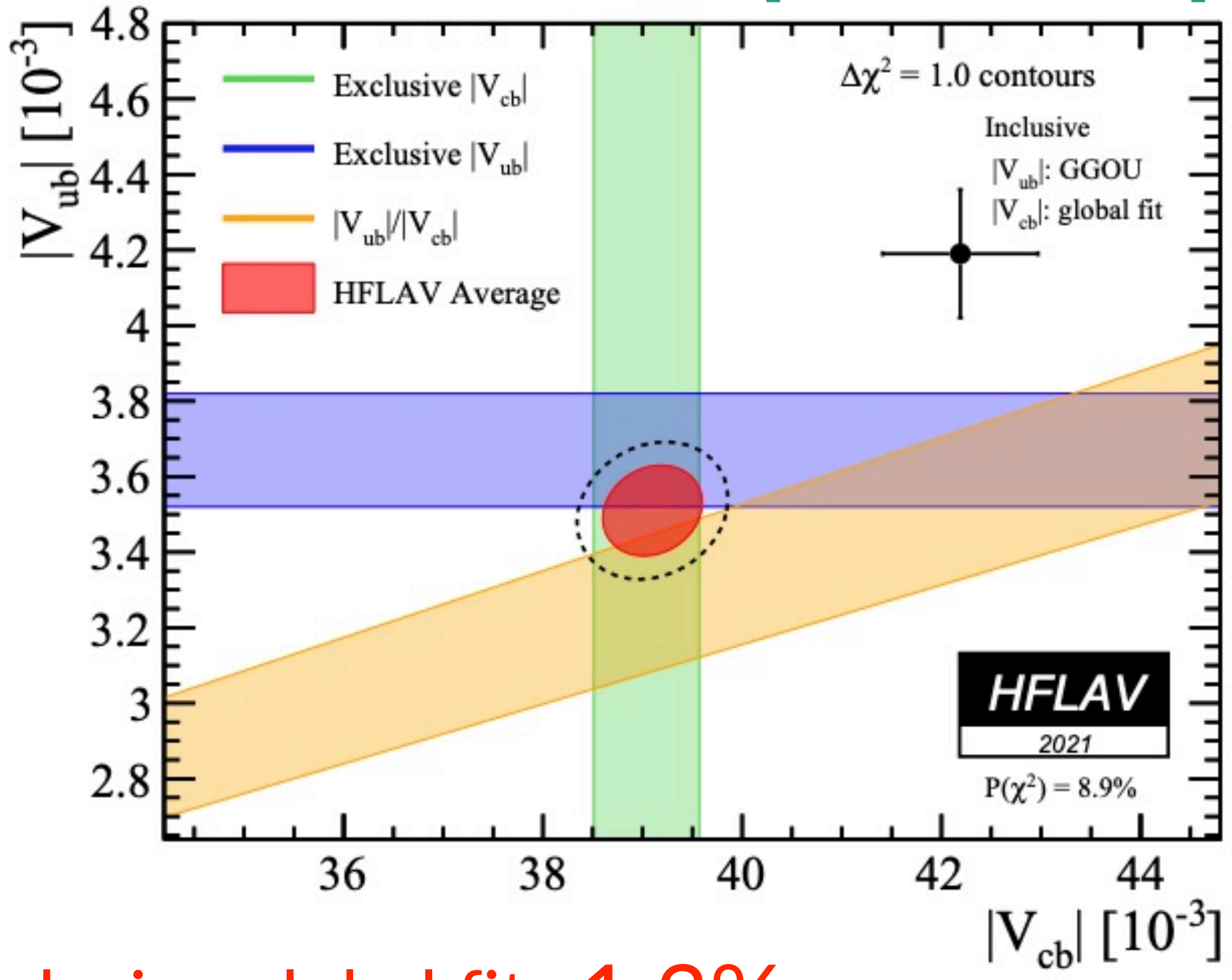


quark \ tag	b_1	b_2	c_1	c_2	q_1	q_2
b	0.47	0.378	0.0197	0.0965	0.00397	0.0315
c	0.00042	0.078	0.298	0.373	0.0682	0.182
uds	0.000104	0.00477	0.00145	0.054	0.538	0.401

Figures and Table from Manqi Ruan @Higgs2023

$|V_{cb}|$ could be measured to a relative uncertainty of 0.4% at the CEPC

[HFLAV2021]



1.8% inclusive global fit

exclusive global fit 1.3%

New physics in quark sector?

SMEFT

- In general new physics scenario, if the new physics scale is much higher than the EW scale, one can consider the dimension-six Standard Model Effective Field Theory (SMEFT)

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_i C_i Q_i$$

[Grzadkowski, et al., 1008.4884]

$$Q_{Hq}^{(1)ij} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_i \gamma^\mu P_L q_j)\,, \qquad Q_{Hq}^{(3)ij} = (H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{q}_i \tau^I \gamma^\mu P_L q_j)\,,$$

$$Q_{Hu}^{ij} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_i \gamma^\mu P_R u_j)\,, \qquad Q_{Hd}^{ij} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_i \gamma^\mu P_R d_j)\,,$$

$$Q_{Hud}^{ij} = i(\tilde{H}^\dagger D_\mu H)(\bar{u}_i \gamma^\mu P_R d_j)\,.$$

Modified W and Z couplings

- After the spontaneous electroweak symmetry breaking $\langle H^0 \rangle = v/\sqrt{2}$ with $v = 246$ GeV,

  W and *Z* quark currents are modified

SM terms

Observed V_{CKM} matrix (non-unitarity)

$$
\begin{aligned}
\mathcal{L}_{W,Z} = & -\frac{g_2}{\sqrt{2}} W_\mu^+ \bar{u}_i \gamma^\mu \left(\left[V \cdot \left(1 + v^2 C_{Hq}^{(3)} \right) \right]_{ij} P_L + \frac{v^2}{2} \left[C_{Hud} \right]_{ij} P_R \right) d_j + \text{ h.c.} \\
& - \frac{g_2}{6c_W} Z_\mu \bar{u}_i \gamma^\mu \left(\left[\left(3 - 4s_W^2 \right) + 3v^2 V \cdot \left\{ C_{Hq}^{(3)} - C_{Hq}^{(1)} \right\} \cdot V^\dagger \right]_{ij} P_L - \left[4s_W^2 + 3v^2 C_{Hu} \right]_{ij} P_R \right) u_j \\
& - \frac{g_2}{6c_W} Z_\mu \bar{d}_i \gamma^\mu \left(\left[\left(2s_W^2 - 3 \right) + 3v^2 \left\{ C_{Hq}^{(3)} + C_{Hq}^{(1)} \right\} \right]_{ij} P_L + \left[2s_W^2 + 3v^2 C_{Hd} \right]_{ij} P_R \right) d_j
\end{aligned}
$$

- Non-unitary V_{CKM} provides non-trivial effects to *Z* currents including FCNCs

SMEFT fitting for CAA

[Grossman, Passemar, Schacht, 1911.07821]
[Crivellin, Kirk, TK, Mescia, 2212.06862]

- SMEFT global fit implies that right-handed W-u-d and W-u-s currents C_{Hud} are preferred

[unit of $(10^{-3}v^{-2})$]

no contribution to $D-\bar{D}$ mixing

EFT Scenario	Best fit point	$-\Delta\chi^2$	Pull
$\left[C_{Hq}^{(3)}\right]_{11}$	-0.50	3.3	$1.8\,\sigma$
$\left[C_{Hq}^{(3)}\right]_{11}=\left[C_{Hq}^{(3)}\right]_{22}$	-0.27	1.1	$1.1\,\sigma$
$\left[C_{Hq}^{(3)}\right]_{11}=\left[C_{Hq}^{(1)}\right]_{11}$	-0.55	3.7	$1.9\,\sigma$
$[C_{Hud}]_{11}$	-1.0	3.1	$1.8\,\sigma$
$[C_{Hud}]_{12}$	-2.0	7.4	$2.7\,\sigma$
$([C_{Hud}]_{11}, [C_{Hud}]_{12})$	$(-1.4, -2.1)$	13	$3.2\,\sigma$
$\left(\left[C_{Hq}^{(3)}\right]_{11}, [C_{Hud}]_{12}\right)$	$(-0.43, -2.0)$	11	$2.8\,\sigma$
$\left(\left[C_{Hq}^{(3)}\right]_{11}, [C_{Hud}]_{11}, [C_{Hud}]_{12}\right)$	$(0.27, -1.9, -2.4)$	16	$2.9\,\sigma$
$\left(\left[C_{Hq}^{(3)}\right]_{11}, \left[C_{Hq}^{(3)}\right]_{22}, [C_{Hud}]_{11}, [C_{Hud}]_{12}\right)$	$(0.59, 0.76, -2.6, -2.5)$	17	$2.9\,\sigma$
$\left(\left[C_{Hq}^{(3)}\right]_{11}, \left[C_{Hq}^{(1)}\right]_{11}, [C_{Hud}]_{11}, [C_{Hud}]_{12}\right)$	$(0.29, 0.11, -2.0, -2.4)$	13	$2.6\,\sigma$

Best pull

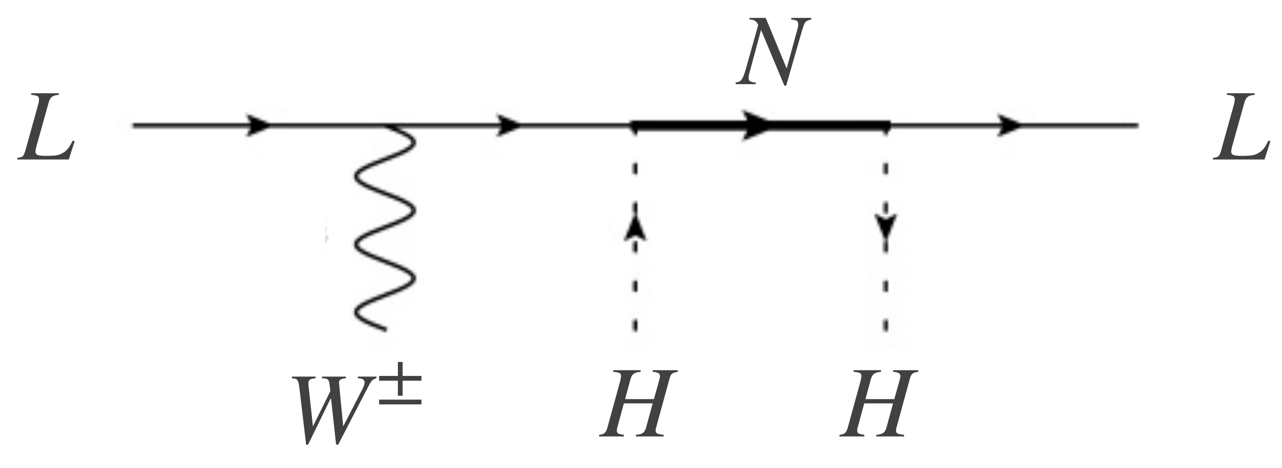
New physics interpretations of CAA

Heavy New Physics

- EFT fittings: $(H^\dagger i D_\mu^I H)(\bar{L}\gamma^\mu \tau^I L)$ fit [Coutinho, et al, 1912.08823]; **right-handed current fit** [Grossman, et al, 1911.07821, Cirigliano, et al, 2112.02087]; W-ℓ-ν fit [Crivellin, et al, 2002.07184]; G_F fit [Crivellin, et al, 2102.02825]
  Best pull
- Heavy SU(2)$_L$ vector boson (~10 TeV) [Capdevila, et al, 2005.13542]
- Leptoquark (~5TeV) [Marzocca, Trifinopoulos, 2104.05730]
- **Vector-like Quark (1-5 TeV)** [Belfatto, et al, 1906.02714, 2103.05549; Cheung, et al, 2001.02853; Branco, et al, 2103.13409]
  Best pull
- Vector-like Lepton (1-2 TeV) [Endo, Mishima, 2005.03933; Crivellin, et al, 2008.01113; Kirk, 2008.03261

Vector-like quark can explain CAA with EWPO, FCNC, collider bounds [Crivellin, Kirk, TK, Mescia, 2212.06862]

- **Heavy right-handed neutrino** (type I seesaw) **can not explain** the tension [the unphysical region $|\text{mixing}|^2 < 0$ is favored]



W-ℓ-ν coupling

Light NP

- MeV sterile neutrino [TK, Tobioka, 2308.13003]

Heavy NP: VLQ models

- The most natural extension of the SM that leads to modified gauge couplings to quarks are the vector-like quarks (VLQs); theoretically well-motivated, e.g., by GUTs, composite and extra-dimensional models and little Higgs models

- Five kinds of VLQs that can provide the modified gauge coupling after integrated out

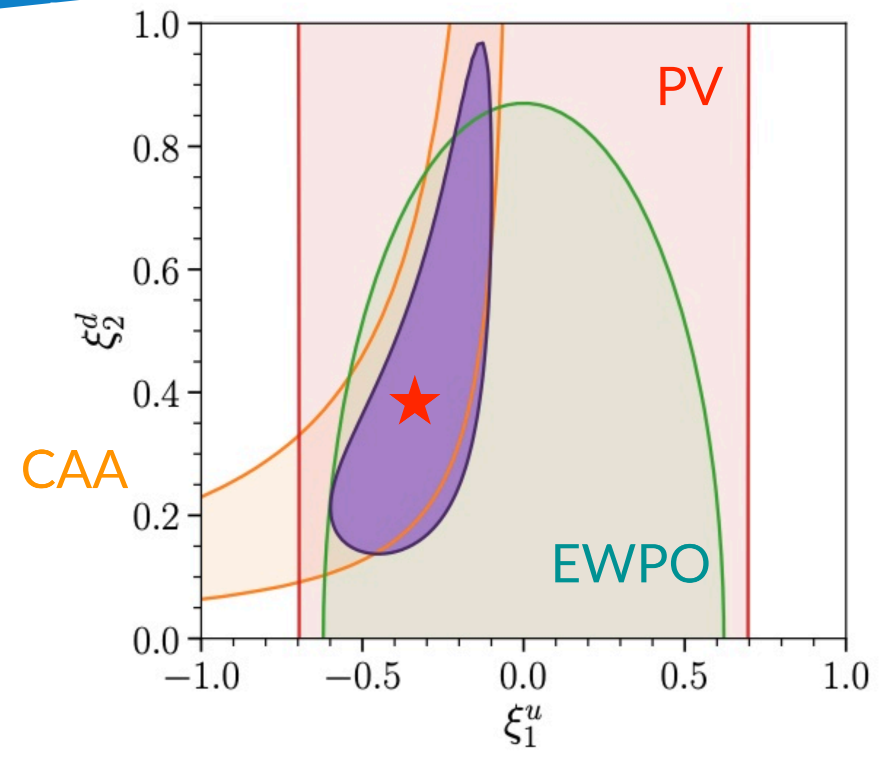
$$U : (\mathbf{3}, \mathbf{1}, {}^{2}\!/\!{}_{3})\,, \quad D : (\mathbf{3}, \mathbf{1}, -{}^{1}\!/\!{}_{3})\,, \quad Q : (\mathbf{3}, \mathbf{2}, {}^{1}\!/\!{}_{6})\,, \quad T_1 : (\mathbf{3}, \mathbf{3}, -{}^{1}\!/\!{}_{3})\,, \quad T_2 : (\mathbf{3}, \mathbf{3}, {}^{2}\!/\!{}_{3})\,.$$

$C_{Hq}^{(3)}$

LH-W current

C_{Hud}

RH-W current (preferred)



SM pull is 2.1σ

Light NP: sterile neutrinos?

- New right-handed gauge-singlet fermions N_I $(I = 1,2,\ldots)$ are introduced

$$\mathcal{L} = \mathcal{L}_{\rm SM} + i\overline{N}_I \partial\!\!\!/ N_I - (\overline{L}_\ell \tilde{H}) y^{\ell I} N_I - \frac{1}{2} M_I \overline{N}{}^c_I N_I + \text{ h.c.}$$

- The mass matrix and mixings

$$\mathcal{L}_{\rm mass} = -\frac{1}{2} \begin{pmatrix} \overline{\nu}_\ell & \overline{N}{}^c_I \end{pmatrix} \begin{pmatrix} 0 & M_D \\ M_D^T & M_I \end{pmatrix} \begin{pmatrix} \nu_\ell^c \\ N_I \end{pmatrix} + \text{h.c.} \qquad M_D = v y^{\ell I}$$

mass eigenstates

$$m_{\rm light} = \mathcal{O}\left(\frac{y^2 v^2}{M}\right), \quad m_{\rm heavy} = \mathcal{O}(M)$$

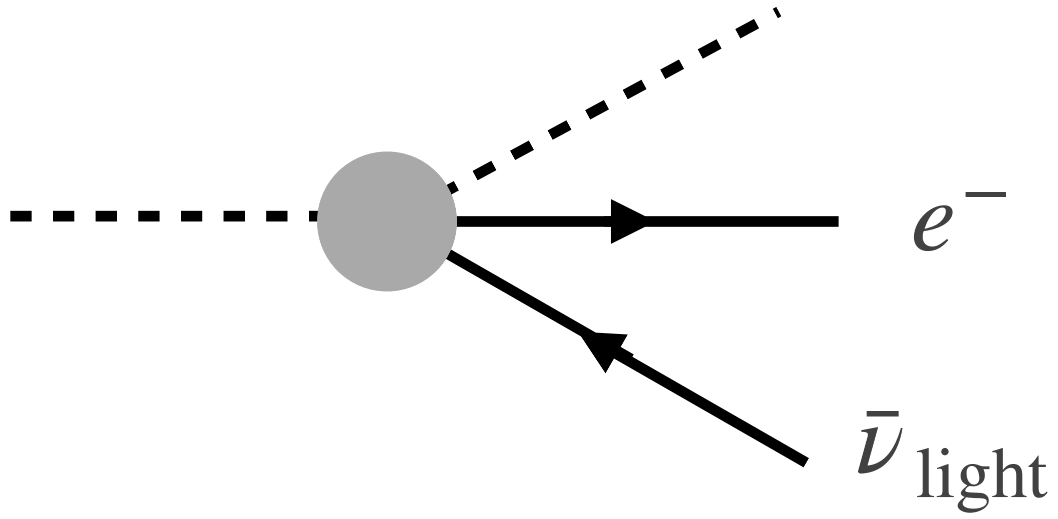
massive SM neutrinos — Sterile neutrinos

active-sterile mixing matrix $\quad U_{\ell I} = \dfrac{v y^{\ell I}}{M_I}$

Sterile neutrino contributions

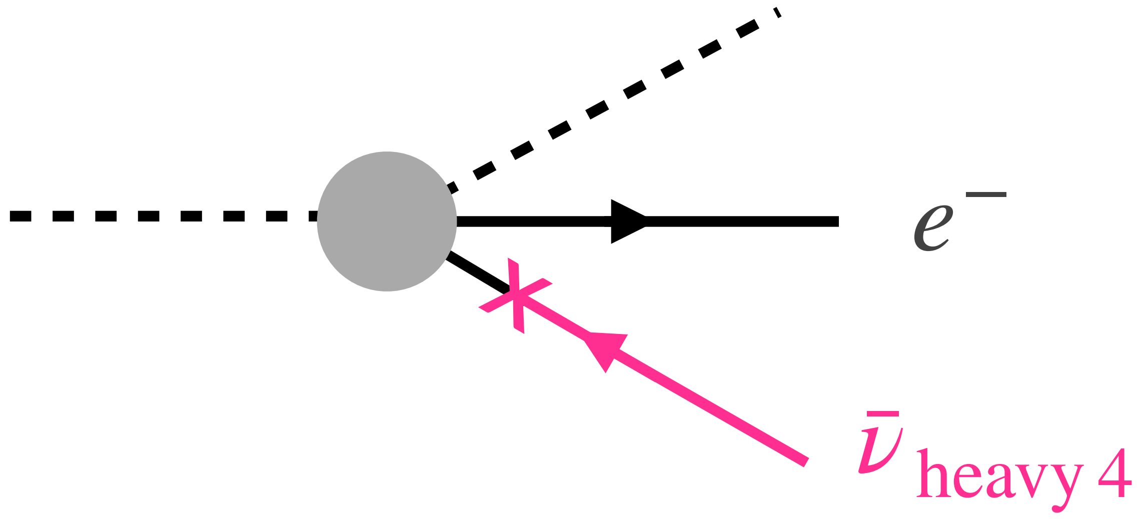
- **Two contributions** to the leptonic and semi-leptonic decays

1. modifies active neutrino coupling



$\propto \cos\theta_e$

2. decay into sterile neutrino if kinematically possible



$\propto \sin\theta_e^{(4)}$ with phase space suppression

- When the sterile neutrino masses are much smaller than the decay Q-value ($M_N \ll Q$),

the total contribution from 1+2 is canceled

$$|\mathcal{M}|^2 = |\mathcal{M}_{\rm SM}|^2 \cos^2\theta_e + |\mathcal{M}_{\rm SM}|^2 \sin^2\theta_e \times f(M_N, Q)$$
$$\simeq |\mathcal{M}_{\rm SM}|^2 (\cos^2\theta_e + \sin^2\theta_e) = |\mathcal{M}_{\rm SM}|^2$$

[Isakov, Strikman, ’86; Deutxh, Lebrun, Prieels, '90]

sterile-neutrino contributions are suppressed when $M_N \ll Q$

Super-allowed β-decay Q values

[Cirigliano et al, 2208.11707]

$$V_{ud}^{n;\,\mathrm{bottle}} = 0.97413(43)$$

Q = 0.78 MeV

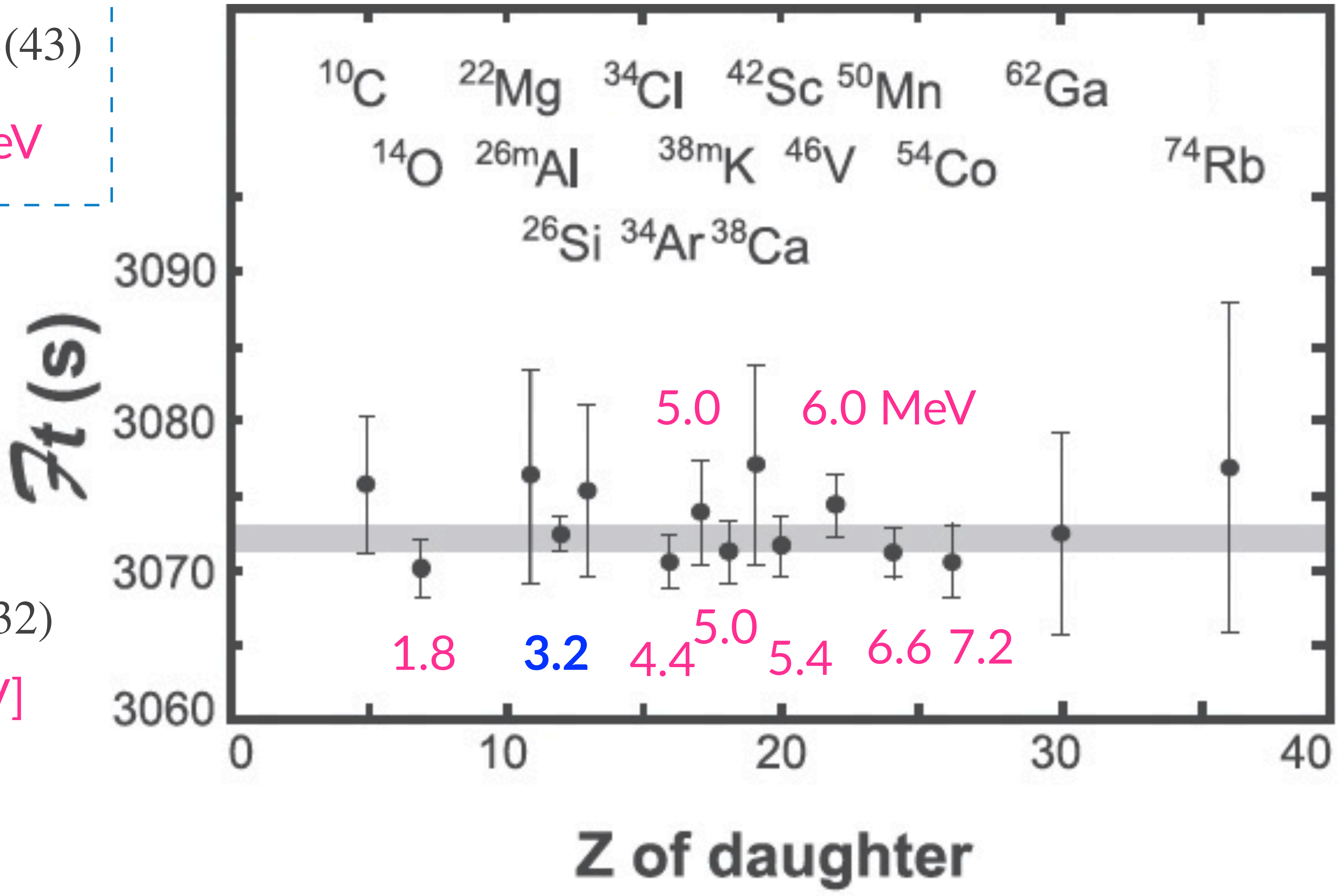
super-allowed

$$V_{ud}^{0^+\to 0^+} = 0.97367(32)$$

Q values [MeV]

$$Q = E_\nu^{\max}$$

[Hardy, Towner, '20]



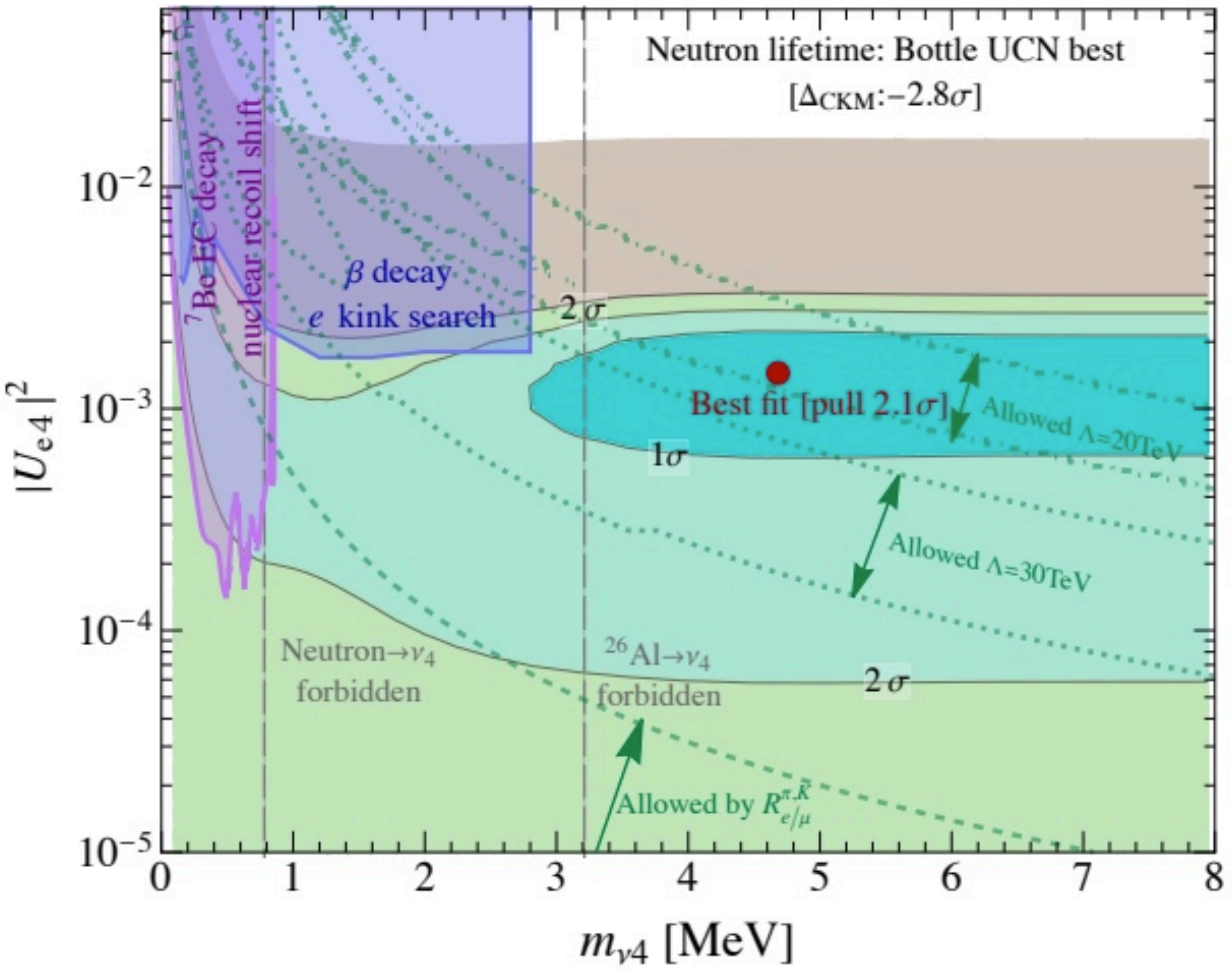
There are 15 super-allowed β-decay data

$|V_{ud}|$ is predominantly determined by data of Al $\to$ Mg transition (Q=3.2 MeV)

~3MeV sterile neutrino provides a big impact on the CAA tension

Sterile neutrino solution for CAA

[TK, Tobioka, 2308.13003]



MeV sterile neutrino provides good effects on $|V_{ud}|$ from super-allowed β decays, and no impacts on the other meson decays

But, viable model is challenging

1. To avoid 0νββ bound, the inverse seesaw model is needed
2. To avoid cosmological bounds, mechanism for the shorter lifetime is needed
3. To avoid $\pi^+ \to e^+ N$ bound, additional dim-6 interaction is needed

Conclusion

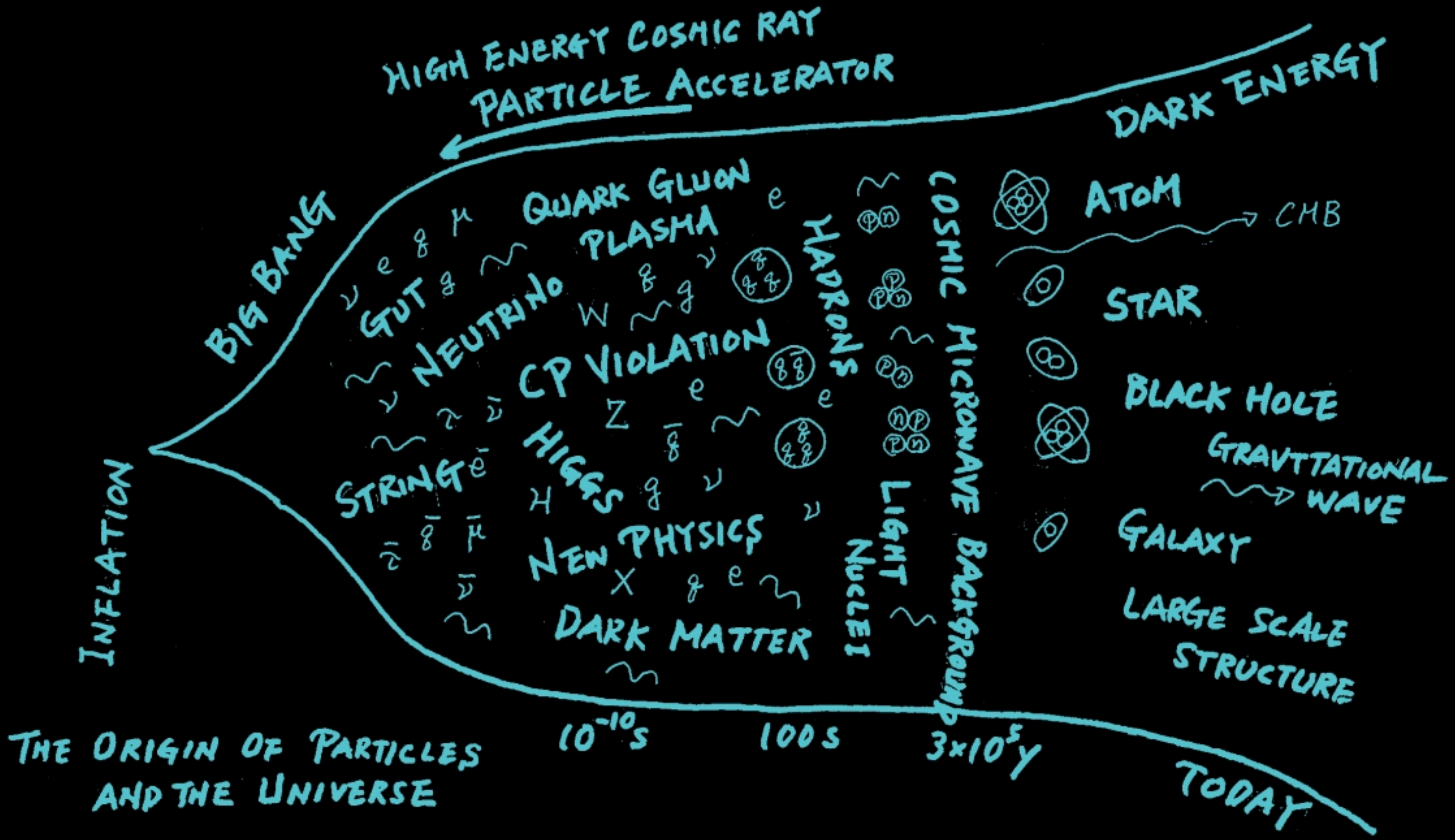
- Improvements of lattice results for the kaon form factors and also the radiative corrections have revealed a mild tension in the 1st-row CKM unitarity (Cabibbo Angle Anomaly: CAA)
- STCF is needed for the 2nd-row unitarity test
- Right-handed W currents are preferred in light of the CAA
- The prime candidate for a corresponding UV completion is the vector-like quark extension

$$Q : (\mathbf{3}, \mathbf{2}, {}^{1}\!/_{6})$$

- Explanation by MeV sterile neutrino is possible, although the viable model is challenging

谢谢你！

Backup slides

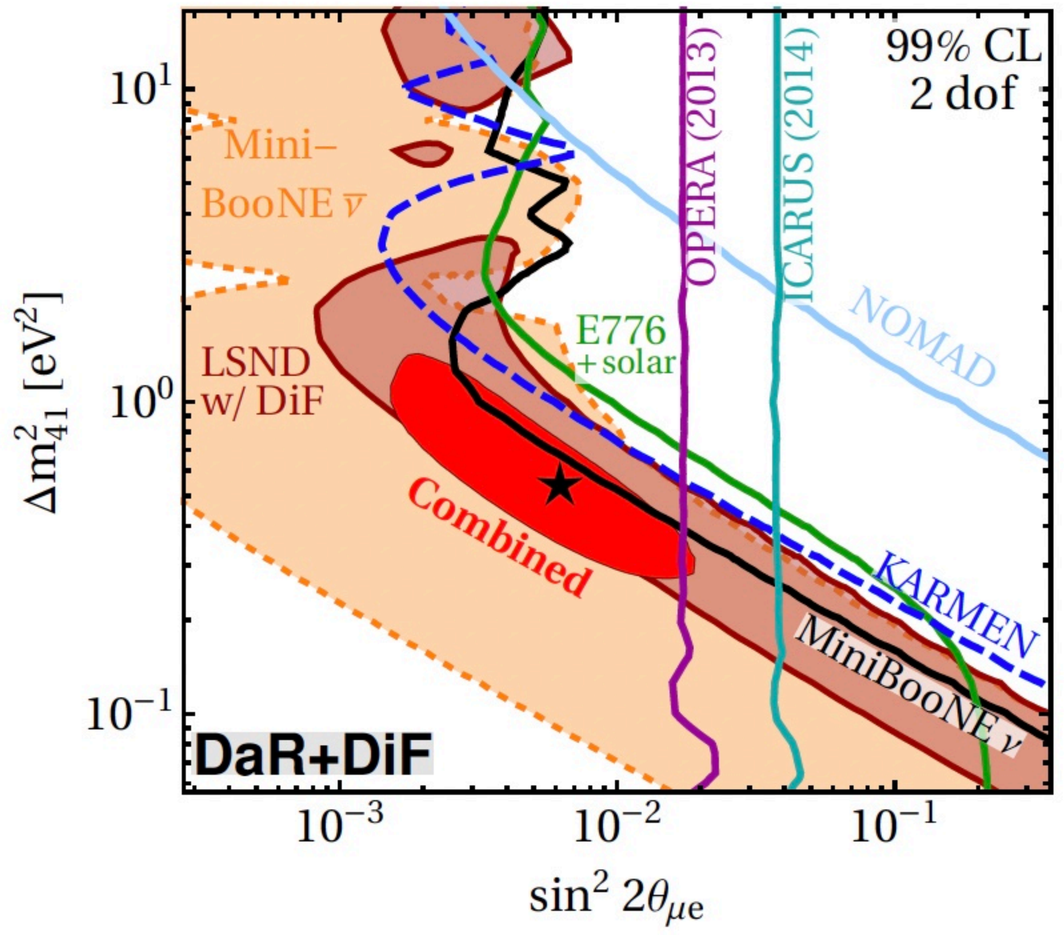


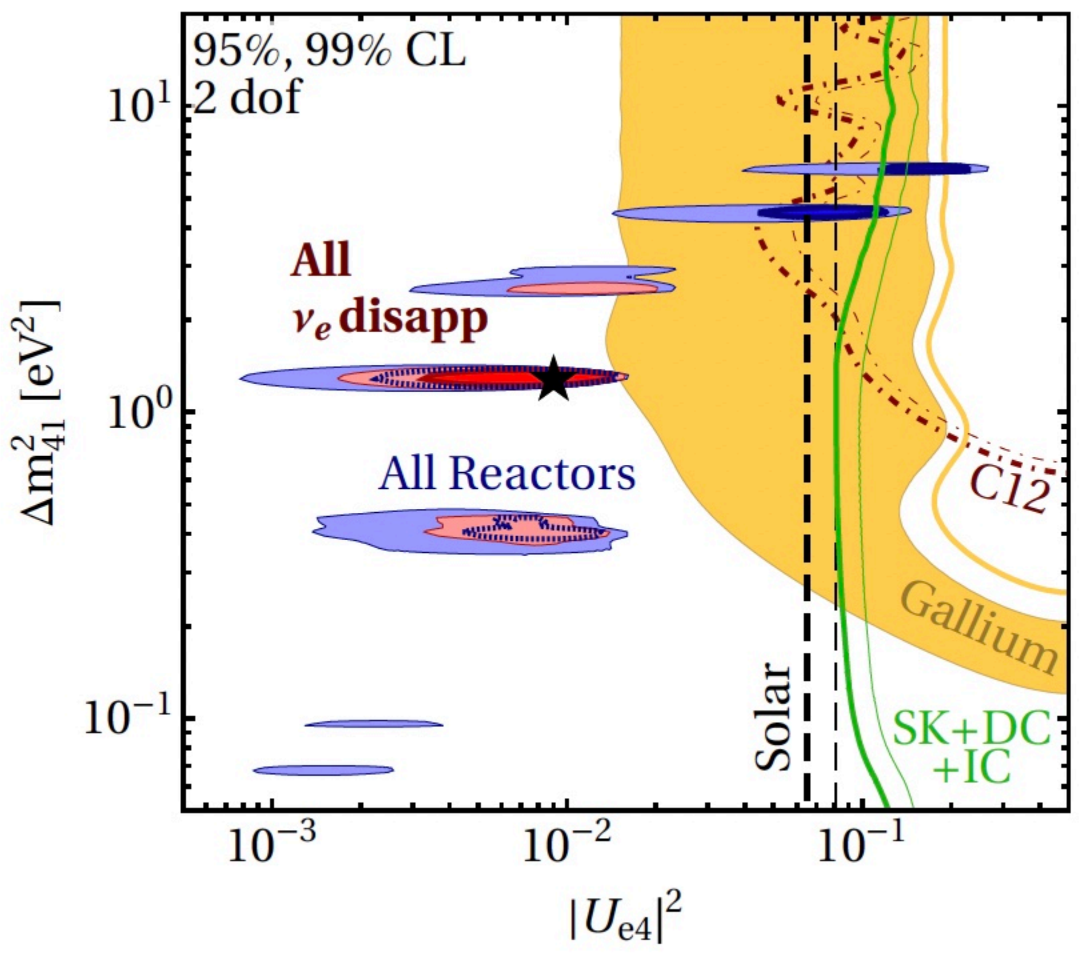
(c) KMI/Nagoya-U

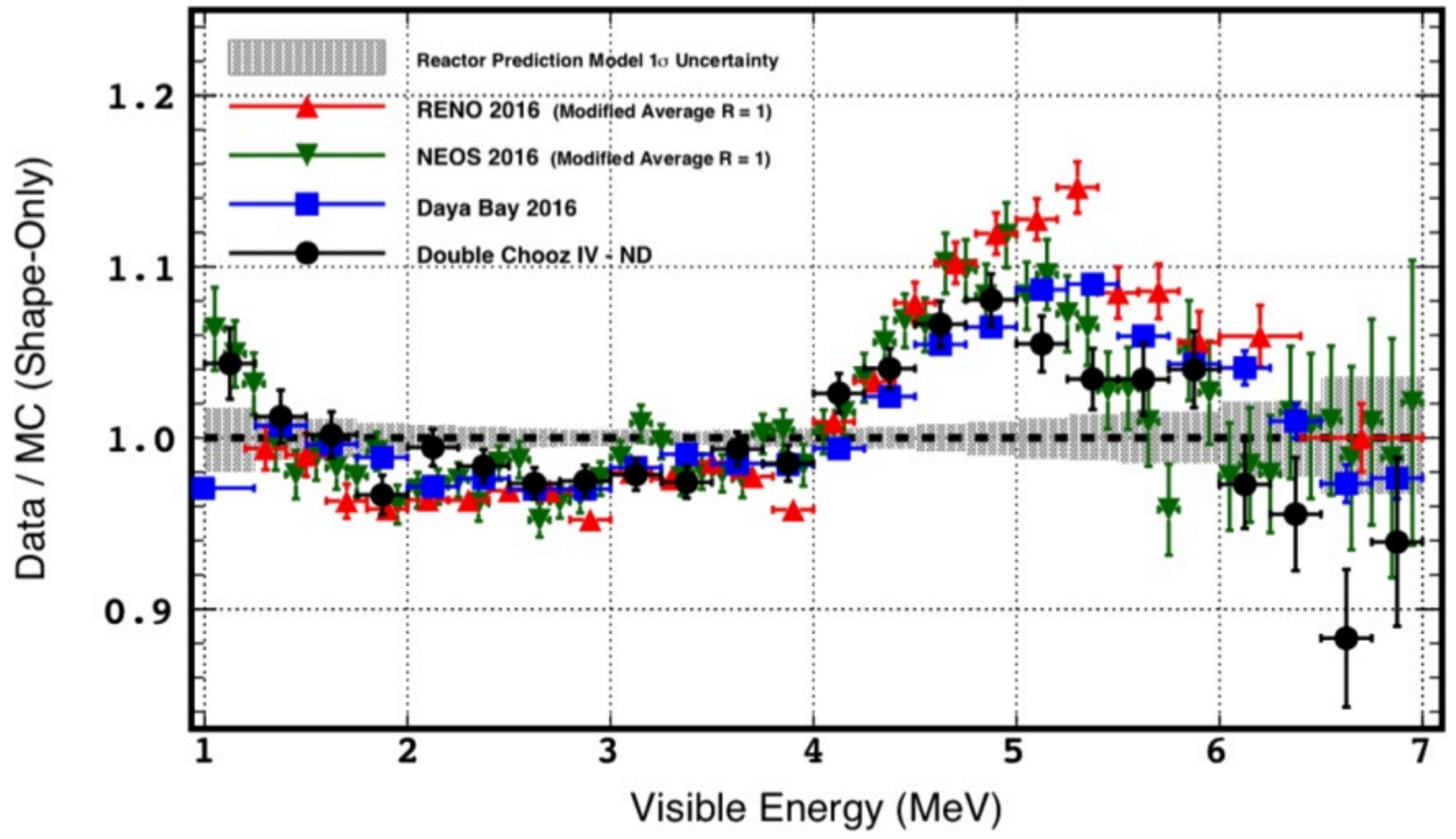
Neutrino anomalies on the market

- O(1) eV sterile neutrino (neutrino oscillations from LSND, MiniBooNE, Gallium Anomaly, Reactor Antineutrino Anomaly)
- 7 keV decaying sterile neutrino (3.5 keV photon emission from galaxy clusters)
- 5 MeV bump in antineutrino energy spectrum (RENO, NEOS, Daya Bay, Double Chooz)
- But, no conclusive measurements yet

[Dentler et al, 1803.10661]



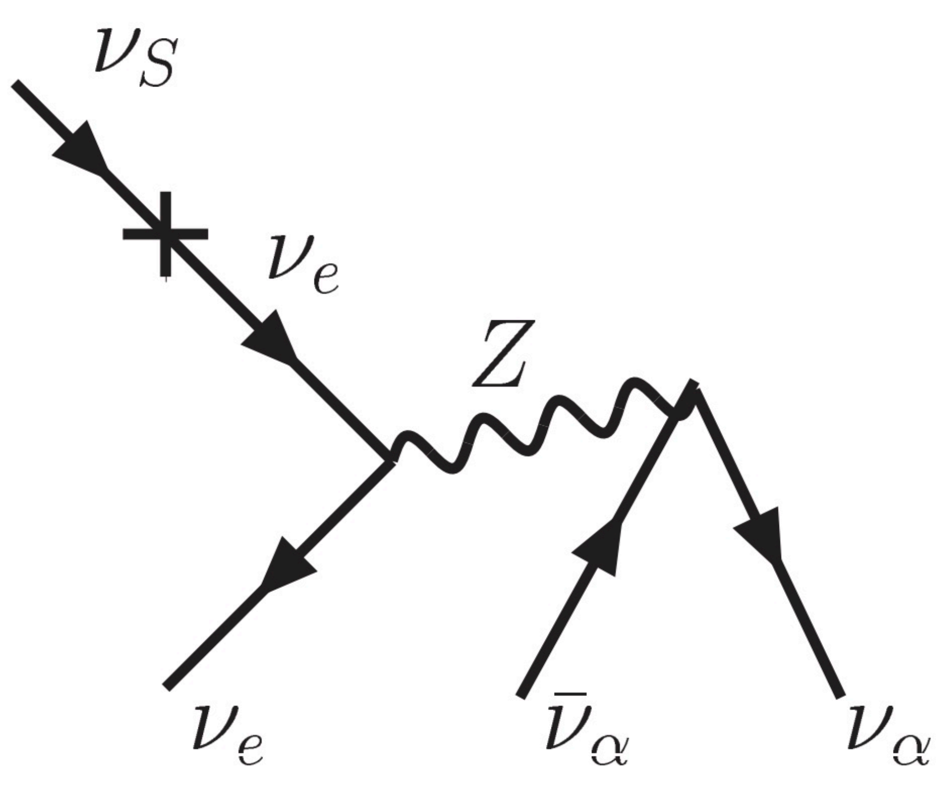




[Double Chooz, 1901.09445]

Sterile neutrino lifetime

- The O(MeV) sterile neutrino lifetime $(N \to \nu_e \bar{\nu}_\ell \nu_\ell,\ \nu_e e^+ e^-)$ [e.g. 1202.2841, 1504.04855]



$$\tau_N \sim 300 \times \left(\frac{M_I}{2\text{MeV}}\right)^{-5} \left|U_{eN}\right|^{-2} \text{ sec} \gg \text{ BBN time } [100\text{-}1000 \text{ sec}]$$

Energy injection from such a long-lived sterile neutrino modifies the light nuclei abundance after the BBN;
The MeV sterile neutrino is excluded by the primordial abundance of ^{4}He (Y_p measurement)

- We assume that the O(MeV) sterile neutrino can promptly decay into dark sector to avoid the BBN bound

Sterile neutrino constraint

[Bolton, Deppisch, Dev, 1912.03058]