Status of the CKM matrix, by the *CKM*fitter Collaboration

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DISCRETE (Bratislava), 14/11/2026



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Flavour in the quark sector

(Gauge couplings to fermions)

$$\mathcal{L}_{SM(NP)} \sim -\frac{1}{4}(F_{\mu\nu})^2 + i\bar{\psi}\not{D}\psi$$

(Higgs self-interaction)

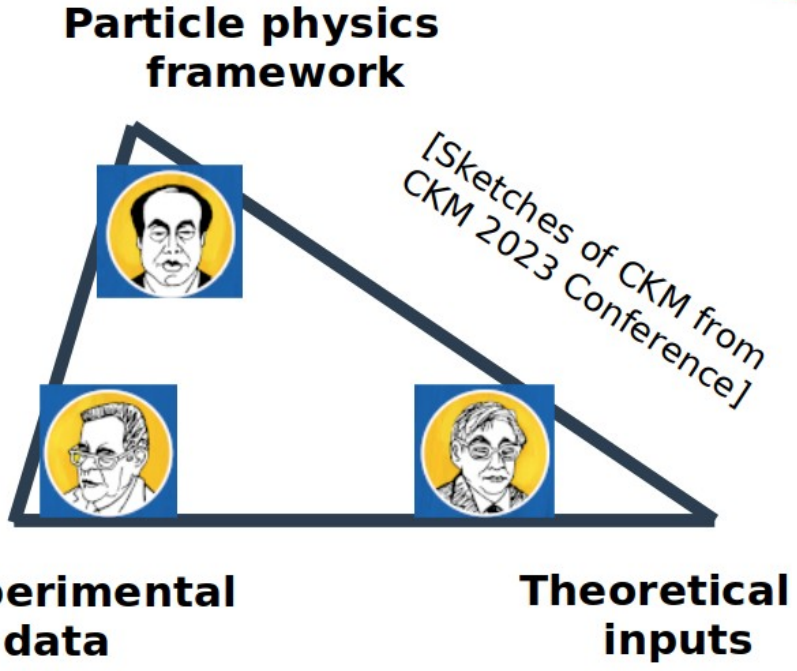
$$+ |D_\mu H|^2 - V(H)$$

(short-range weak interactions)

$$+ Y H\bar{\psi}\psi + \text{h.c.}$$

(spectrum of quark masses, CKM matrix)

$$\left(+ \sum_{d>4} \frac{1}{\Lambda_{heavy}^{d-4}} C_k O_k^d \right)$$



- Goal is **testing the SM/CKM mechanism**, and **point out possible tensions**
- Many flavour observables enjoy the status of precision physics
- Flavour transitions pattern is likely to change in the presence of NP

#42 in the **whole**
Inspire-HEP (as of yesterday)

Unitary Symmetry and Leptonic Decays #42
Nicola Cabibbo (CERN) (Jun, 1963)
Published in: *Phys.Rev.Lett.* 10 (1963) 531-533 • Contribution to: Meeting of the Italian School of Physics and Weak Interactions, 648-649
DOI cite claim reference search 8,416 citations

15 JUNE 1963

UNITARY SYMMETRY AND LEPTONIC DECAYS

Nicola Cabibbo
CERN, Geneva, Switzerland
(Received 29 April 1963)

Universality of $\Delta S=0,1$ weak transitions;
Cabibbo introduces a
phenomenological mixing angle

$$\begin{pmatrix} \cos\theta_1 & -\sin\theta_1\cos\theta_3 & -\sin\theta_1\sin\theta_3 \\ \sin\theta_1\cos\theta_2 & \cos\theta_1\cos\theta_2\cos\theta_3-\sin\theta_2\sin\theta_3 e^{i\delta} & \cos\theta_1\cos\theta_2\sin\theta_3+\sin\theta_2\cos\theta_3 e^{i\delta} \\ \sin\theta_1\sin\theta_2 & \cos\theta_1\sin\theta_2\cos\theta_3+\cos\theta_2\sin\theta_3 e^{i\delta} & \cos\theta_1\sin\theta_2\sin\theta_3-\cos\theta_2\sin\theta_3 e^{i\delta} \end{pmatrix}. \quad (13)$$

No CPV with 2 generations;
KM consider a 3rd one,
1st CKM matrix in the literature

Progress of Theoretical Physics, Vol. 49, No. 2, February 1973

CP-Violation in the Renormalizable Theory of Weak Interaction

Makoto KOBAYASHI and Toshihide MASKAWA

Department of Physics, Kyoto University, Kyoto

(Received September 1, 1972)

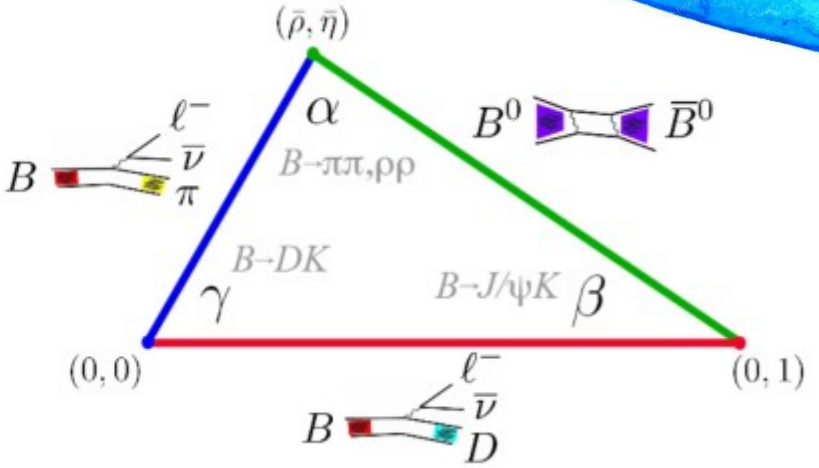
CP Violation in the Renormalizable Theory of Weak Interaction #15
Makoto Kobayashi (Kyoto U.), Toshihide Maskawa (Kyoto U.) (Feb, 1973)
Published in: *Prog.Theor.Phys.* 49 (1973) 652-657
DOI cite claim reference search 12,985 citations

#15 in the **whole** Inspire-HEP (as of yesterday)

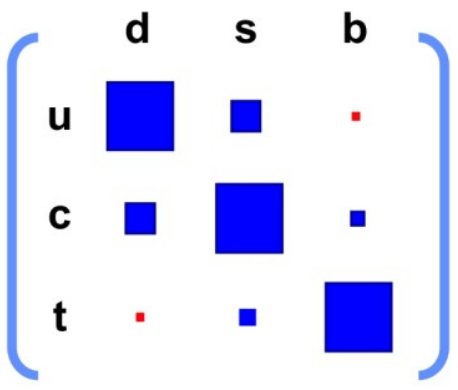
Measuring the CKM matrix

$V =$

	d	s	b
u	$n \to p\, e^- \bar{\nu}$	$K \to \pi\, \ell^- \bar{\nu}$	$B \to \pi\, \ell^- \bar{\nu}$
c	$D \to \pi\, \ell^- \bar{\nu}$	$D \to K\, \ell^- \bar{\nu}$	$B \to D\, \ell^- \bar{\nu}$
t	$B^0 \leftrightarrow \bar{B}^0$	$B_s \leftrightarrow \bar{B}_s$	$t \to W\, b$



- *Tree*: e.g., $|V_{ub}|$
- *Loop*: e.g., Δm_d, Δm_s, ϵ_K, $\sin(2\beta)$
- *$\mathcal{CP}$-conserving*: e.g., $|V_{ub}|$, Δm_d, Δm_s
- *$\mathcal{CP}$-violating*: e.g., γ, ϵ_K, $\sin(2\beta)$
- *Exp. uncs.*: e.g., α, $\sin(2\beta)$, γ
- *Syst. uncs.*: e.g., $|V_{ub}|$, $|V_{cb}|$, ϵ_K, Δm_d, Δm_s



Theo. inputs: hadronic effects

Meson-mixing	$B_{(s)}\overline{B}_{(s)}$, $K\overline{K}$: bag-parameters $\widehat{B}_{B_s}$, $\widehat{B}_{B_s}/\widehat{B}_{B_d}$, $\widehat{B}_K$ $\frac{2}{3}m_K^2 f_K^2 B_K = \langle \overline{K}\vert(\bar{s}\gamma^\mu P_L d)\,(\bar{s}\gamma_\mu P_L d)\vert K\rangle$
(semi-)leptonic decays	$\pi \to \ell\nu$, $K \to \pi\ell\nu$, etc.: decay constants, form factors Ex.: f_π, $f_+^{K\to\pi}(0)$ $-p_\mu f_\pi = \langle 0\vert(\bar{d}\gamma_\mu\gamma_5 u)\vert\pi(p)\rangle$, $f_+^{K\to\pi}(q^2)(p+p')_\mu + f_-^{K\to\pi}(q^2)(p-p')_\mu = \langle\pi(p')\vert(\bar{s}\gamma_\mu P_L u)\vert K(p)\rangle$

$\to$ Determine $\mathcal{L}^{eff}_{SM\,(NP)} \sim \Sigma_i C_i(\mu) \times O_i(\mu)$, where $\mu \sim \mathcal{O}$(few) GeV:
C_i collects *short*-distance physics; O_i collects *long*-distance physics

$\to$ Lattice QCD: extractions of non-perturbative parameters;
averages dominated by **systematic uncertainties**

Stat: essentially size of gauge configurations
Syst: fermion action, $a \to 0$, $L \to \infty$, mass extrapolations...

FLAG reports:
guide to sort results

Statistical framework

- ***CKM*fitter**: frequentist statistics based on a χ^2 analysis
- χ^2_{min}: **goodness-of-fit** under SM (or NP), **estimators** for $q=V_{CKM}$
- $\Delta\chi^2$: **Confidence Level** (CL) intervals

$$\mathcal{L}(q) = \prod_{\mathcal{O}} \mathcal{L}_{\mathcal{O}}(q)\,, \quad \chi^2(q) = -2\ell n\mathcal{L}(q) = \sum_{\mathcal{O}} \left(\frac{\mathcal{O}_{\rm th}(q) - \mathcal{O}_{\rm meas}}{\sigma_{\mathcal{O}_{\rm meas}}} \right)^2$$

max likelihood — ratio of likelihoods

$$\chi^2(\hat{q}) = \min_q \chi^2(q)\,, \quad \Delta\chi^2(q) = \chi^2(q) - \chi^2(\hat{q})$$

goodness-of-fit, best fit estimators — confidence levels

*R*fit

***Range* fit** scheme incorporates theoretical uncertainties

- stat: agreement of data & prediction; theo: accuracy of (QCD) parameters
- Theoretical uncertainties strictly contained in a range. Ex.: $\xi \in [-\Delta, \Delta]$
- Different sources of syst. uncertainty are combined linearly

product of likelihoods

$$\mathcal{L} \overset{Rfit}{=} \mathcal{L}_{stat} \times \mathcal{L}_{theo},$$

$$\chi^2 = -2\,\ell\mathrm{n}\,\mathcal{L}$$

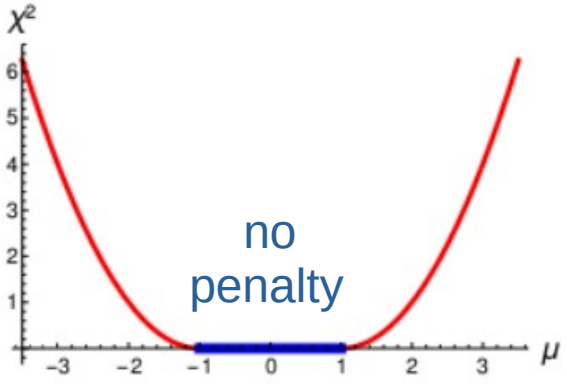
$\mathcal{L}_{stat}$: exp. data

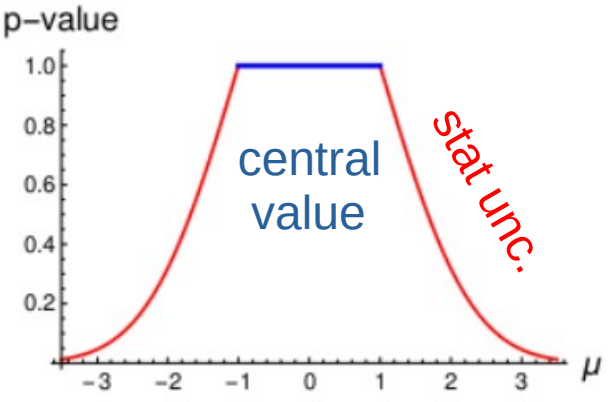
$\mathcal{L}_{theo}$: had. inputs

[cf. Charles, Descotes-G., Niess, LVS '17]

[Hoecker et al. '01, Charles et al. '04]

Example in 1D, $0 \pm 1_{stat} \pm 1_{theo}$ $(N_{dof} = 1)$





χ^2: flat bottom, quadratic walls

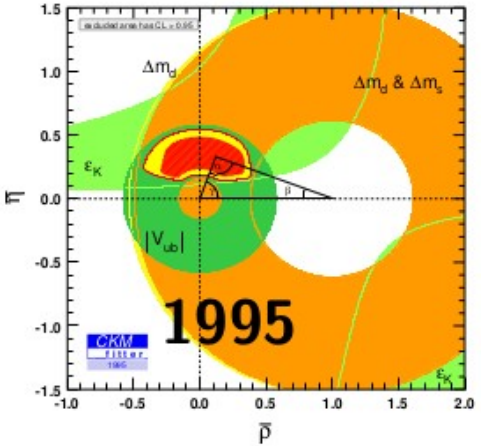
Three decades of CKM fits



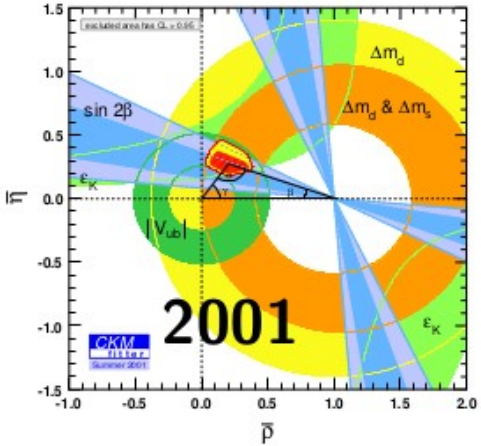
Deschamps
CKM’25

Progress over the years

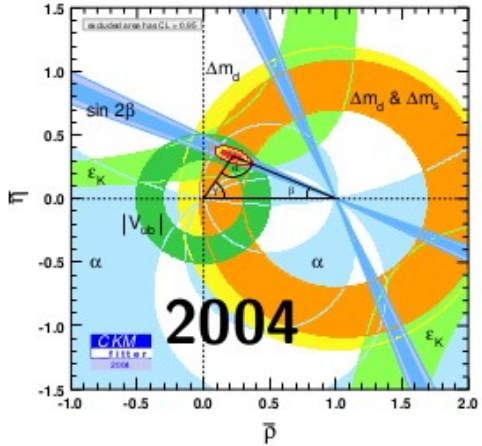
Early era: CDF, LEP, CLEO



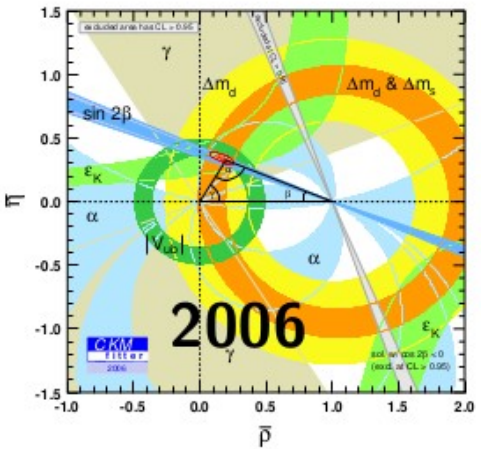
The B-factory era; σ_J/J ~20%



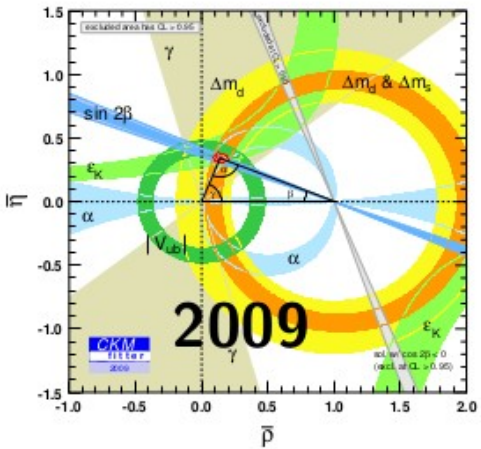
Charmless show up; σ_J/J ~13%



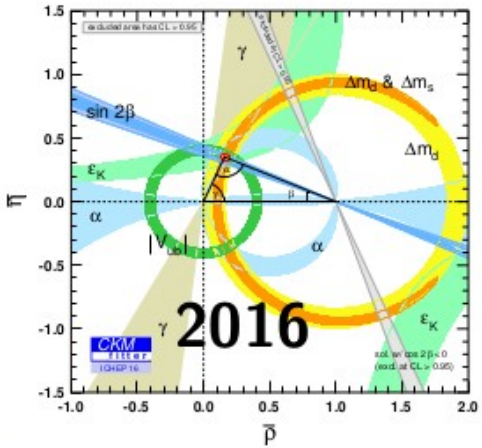
B_s oscillation (CDF); σ_J/J ~6%



B-factory legacy; σ_J/J ~5%



LHC(b) phase I; σ_J/J ~2%



2025

|V_xy|, mostly from (semi) leptonic decays

UT angles

Oscillations, Rare, Kaons

CKM	Process	Observables			Non-perturbative theo. inputs		
$\lvert V_{ud}\rvert$	$0^+ \to 0^+$ β	$\lvert V_{ud}\rvert_{\rm nucl}$	=	$0.97373 \pm 0.00009 \pm 0.00053$	Nuclear matrix elements		
$\lvert V_{us}\rvert$	$K \to \pi\ell\nu_\ell$	$\lvert V_{us}\rvert_{\rm SL} f_+^{K\to\pi}(0)$	=	0.21635 ± 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 ± 0.0011	f_K	=	$155.47 \pm 0.18 \pm 0.57$ MeV
	$\tau \to K\nu_\tau$	$\mathcal{B}(\tau \to K\nu_\tau)$	=	$(0.6986 \pm 0.0085) \cdot 10^{-2}$			
$\frac{\lvert V_{us}\rvert}{\lvert V_{ud}\rvert}$	$K \to \mu\nu_\mu / \pi \to \mu\nu_\mu$	$\frac{\mathcal{B}(K\to\mu\nu_\mu)}{\mathcal{B}(\pi\to\mu\nu_\mu)}$	=	1.3367 ± 0.0028	f_K/f_π	=	$1.1987 \pm 0.0009 \pm 0.0007$
	$\tau \to K\nu_\tau / \tau \to \pi\nu_\tau$	$\frac{\mathcal{B}(\tau\to K\nu_\tau)}{\mathcal{B}(\tau\to\pi\nu_\tau)}$	=	$(6.437 \pm 0.092) \cdot 10^{-2}$			
$\lvert V_{cd}\rvert$	νN	$\lvert V_{cd}\rvert_{\rm not\ lattice}$	=	0.230 ± 0.011			
	$D \to \tau\nu_\tau$	$\mathcal{B}(D \to \tau\nu_\tau)$	=	$(1.20 \pm 0.27) \cdot 10^{-3}$	f_{D_s}/f_D	=	$1.1784 \pm 0.0006 \pm 0.0033$
	$D \to \mu\nu_\mu$	$\mathcal{B}(D \to \mu\nu_\mu)$	=	$(3.77 \pm 0.17) \cdot 10^{-4}$			
	$D \to \pi\ell\nu_\ell$	$\lvert V_{cd}\rvert_{\rm SL} f_+^{D\to\pi}(0)$	=	0.1426 ± 0.0018	$f_+^{D\to\pi}(0)$	=	$0.624 \pm 0.004 \pm 0.006$
$\lvert V_{cs}\rvert$	$W \to c\bar{s}$	$\lvert V_{cs}\rvert_{\rm not\ lattice}$	=	$0.94^{+0.32}_{-0.26} \pm 0.13$			
	$D_s \to \tau\nu_\tau$	$\mathcal{B}(D_s \to \tau\nu_\tau)$	=	$(5.39 \pm 0.09) \cdot 10^{-2}$	f_{D_s}	=	$249.09 \pm 0.25 \pm 0.65$ MeV
	$D_s \to \mu\nu_\mu$	$\mathcal{B}(D_s \to \mu\nu_\mu)$	=	$(5.36 \pm 0.12) \cdot 10^{-3}$			
	$D \to K\ell\nu_\ell$	$\lvert V_{cs}\rvert_{\rm SL} f_+^{D\to K}(0)$	=	0.7180 ± 0.0033	$f_+^{D\to K}(0)$	=	$0.742 \pm 0.002 \pm 0.004$
$\lvert V_{ub}\rvert$	semileptonic B	$\lvert V_{ub}\rvert_{\rm SL}$	=	$(3.86 \pm 0.07 \pm 0.12) \cdot 10^{-3}$	form factors, shape functions		
	$B \to \tau\nu_\tau$	$\mathcal{B}(B \to \tau\nu_\tau)$	=	$\mathbf{(1.12 \pm 0.19) \cdot 10^{-4}}$	f_{B_s}/f_B	=	$1.2118 \pm 0.0020 \pm 0.0058$
$\lvert V_{cb}\rvert$	semileptonic B	$\lvert V_{cb}\rvert_{\rm SL}$	=	$(41.22 \pm 0.24 \pm 0.37) \cdot 10^{-3}$	form factors, OPE matrix elements		
$\lvert V_{ub}/V_{cb}\rvert$	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	$\lvert V_{ub}/V_{cb}\rvert_{\rm incl}$	=	$0.100 \pm 0.006 \pm 0.003$			
α	$B \to \pi\pi$, $\rho\pi$, $\rho\rho$	branching ratios, CP asymmetries			isospin symmetry		
β	$B \to (c\bar{c})K$	$\sin(2\beta)_{[c\bar{c}]}$	=	0.710 ± 0.011	subleading penguins neglected		
	$B^0 \to D^{(*)}h^0$	$\cos(2\beta)$	=	0.91 ± 0.25			
γ	$B \to D^{(*)}K^{(*)}$	γ	=	$(\mathbf{66.4^{+2.7}_{-2.8}})^\circ$	GGSZ, GLW, ADS methods		
ϕ_s	$B_s \to J/\psi(KK, \pi\pi)$	$(\phi_s)_{b\to c\bar{c}s}$	=	-0.052 ± 0.013			
$V_{tq}^* V_{tb}$	Δm_d	Δm_d	=	0.5069 ± 0.0019 ps^{-1}	$\hat{B}_{B_s}/\hat{B}_{B_d}$	=	$1.007 \pm 0.010 \pm 0.014$
	Δm_s	Δm_s	=	17.766 ± 0.006 ps^{-1}	$\hat{B}_{B_s}$	=	$1.313 \pm 0.012 \pm 0.030$
	$B_s \to \mu\mu$	$\mathcal{B}(B_s \to \mu\mu)$	=	$(3.34 \pm 0.27) \cdot 10^{-9} [\times(1 - 0.063)]$	f_{B_s}	=	$228.75 \pm 0.69 \pm 1.87$ MeV
$V_{td}^* V_{ts}$ and $V_{cd}^* V_{cs}$	ε_K	$\lvert\varepsilon_K\rvert$	=	$(2.228 \pm 0.011) \cdot 10^{-3}$	$\hat{B}_K$	=	$0.7692 \pm 0.0019 \pm 0.0120$
					κ_ε	=	$0.940 \pm 0.013 \pm 0.023$

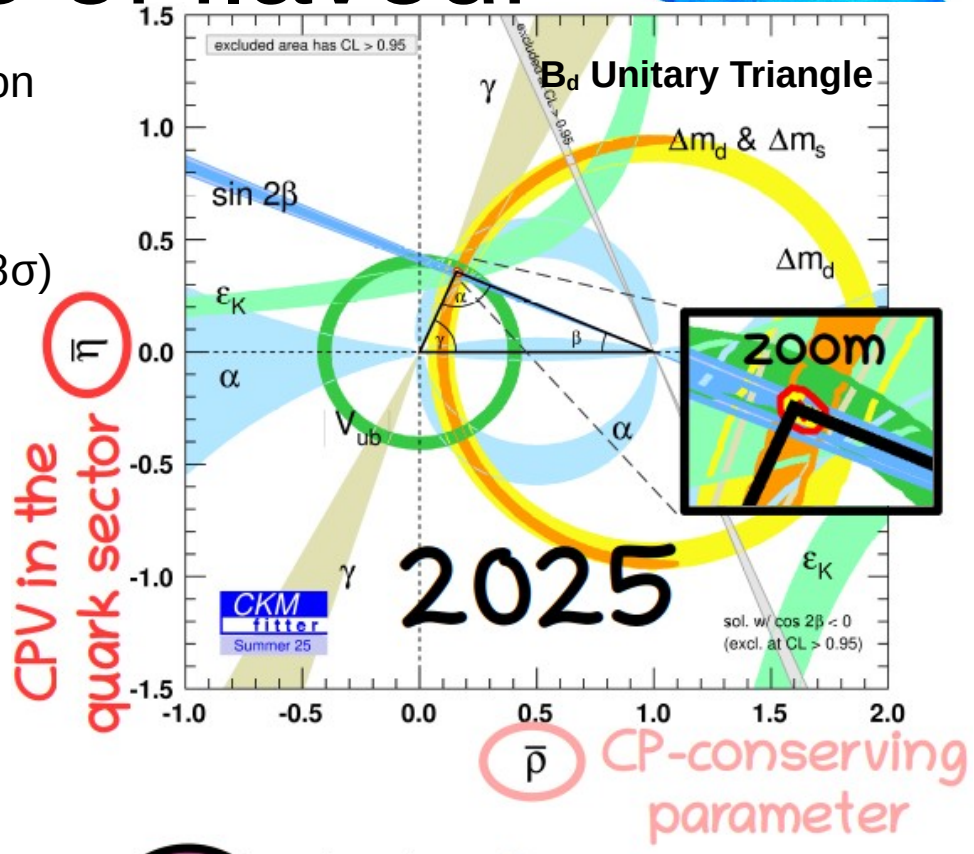
black: no change; **red**: update since CKM '23 (color does not reflect the impact of the exp./theo. input!)

Current status of flavour

- A **single** phase must be responsible for CP violation across distinct flavour sectors
- Observables of very different natures
- The global fit remains excellent: p-value ~44% (0.8σ)

$$A = 0.822^{+0.005}_{-0.015} \text{ (1.2\% unc.)}$$
$$\lambda = 0.2250 \pm 0.0002 \text{ (0.09\% unc.)}$$
$$\bar{\rho} = 0.156^{+0.010}_{-0.005} \text{ (4.7\% unc.)}$$
$$\bar{\eta} = 0.356^{+0.006}_{-0.007} \text{ (1.8\% unc.)}$$

68% C.L. intervals



Rephasing invariant:

$$\frac{|V_{us}|}{(|V_{ud}|^2+|V_{us}|^2)^{1/2}} = \lambda\,, \quad \frac{|V_{cb}|}{(|V_{ud}|^2+|V_{us}|^2)^{1/2}} = A\lambda^2\,, \quad -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} = \bar{\rho}+i\bar{\eta}$$

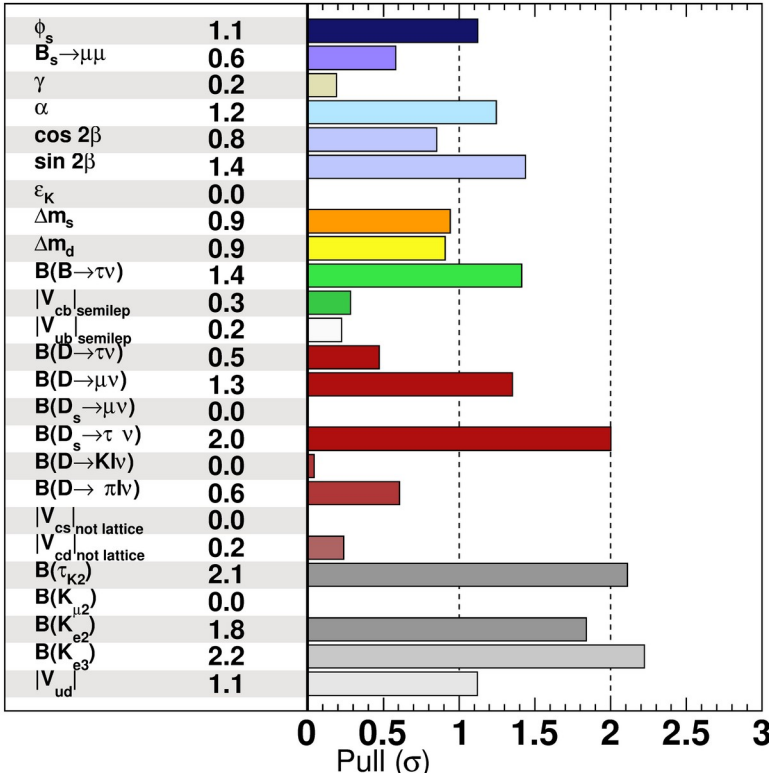
b : $|V_{xb}|$, α, β, γ, Δm_d, Δm_s

s : ε_K

Consistency among observables

$$pull_{\mathcal{O}_{exp}} = \sqrt{\chi^2_{min} - \chi^2_{min,!\mathcal{O}_{exp}}}$$

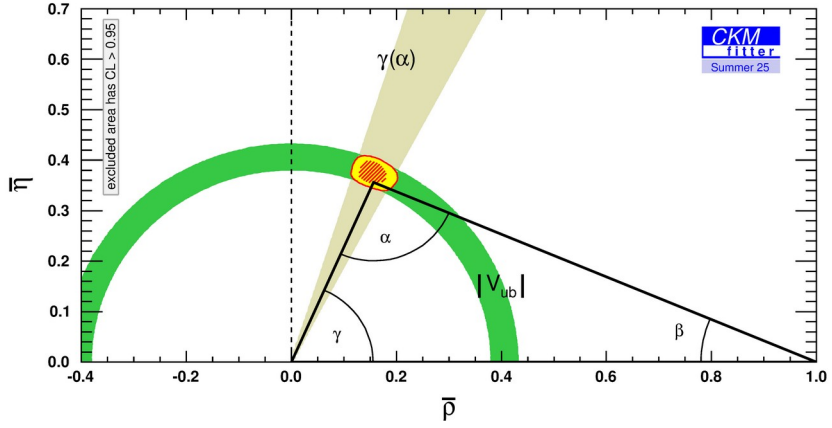
$$!\mathcal{O}_{exp}: \ \chi^2_{min} \ \text{w/o} \ \mathcal{O}_{exp}$$



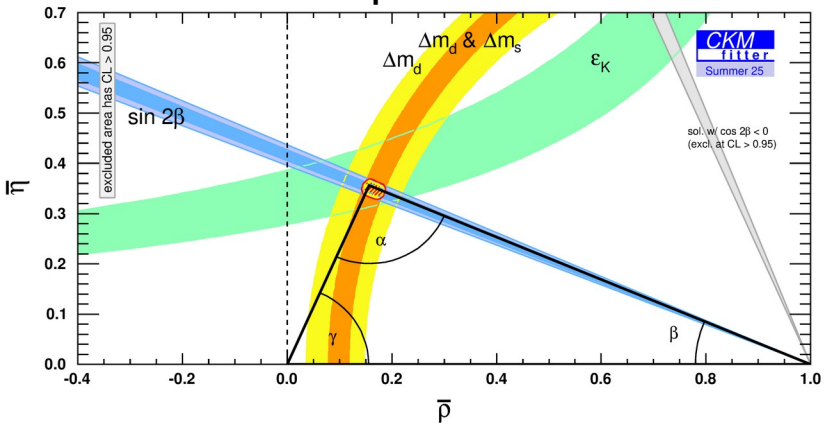
- Global fit: χ^2_{min} ~26.4 (N_{dof} ~26 naively)
- If Gaussian uncs., uncorrelated random vars.: mean 0 and variance 1
- Here, correlations are expected; pulls can be 0 due to the *R*fit model for systematics
- Overall agreement w/ the SM, no clear indication of significant deviations from CKM picture

Consistency among observables

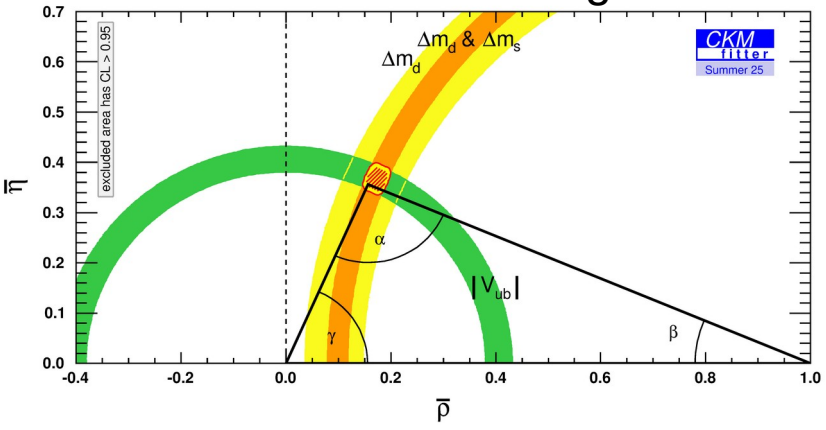
tree level



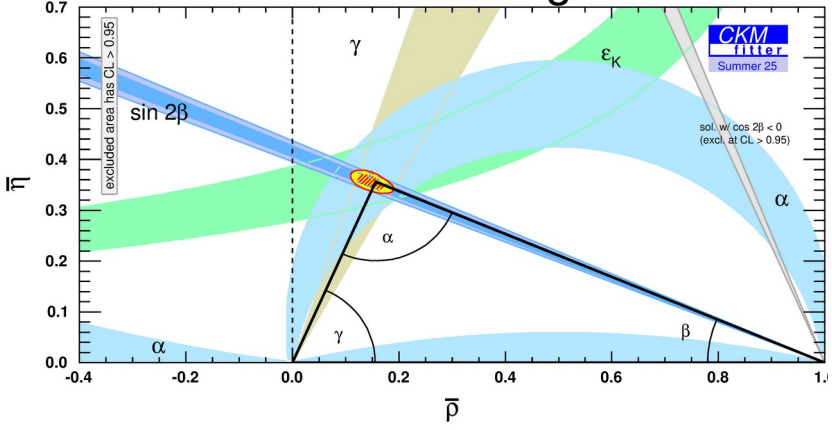
loop induced



CP-conserving



CP-violating



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

First two rows:

→ $|V_{ud}|$ from nuclear transitions

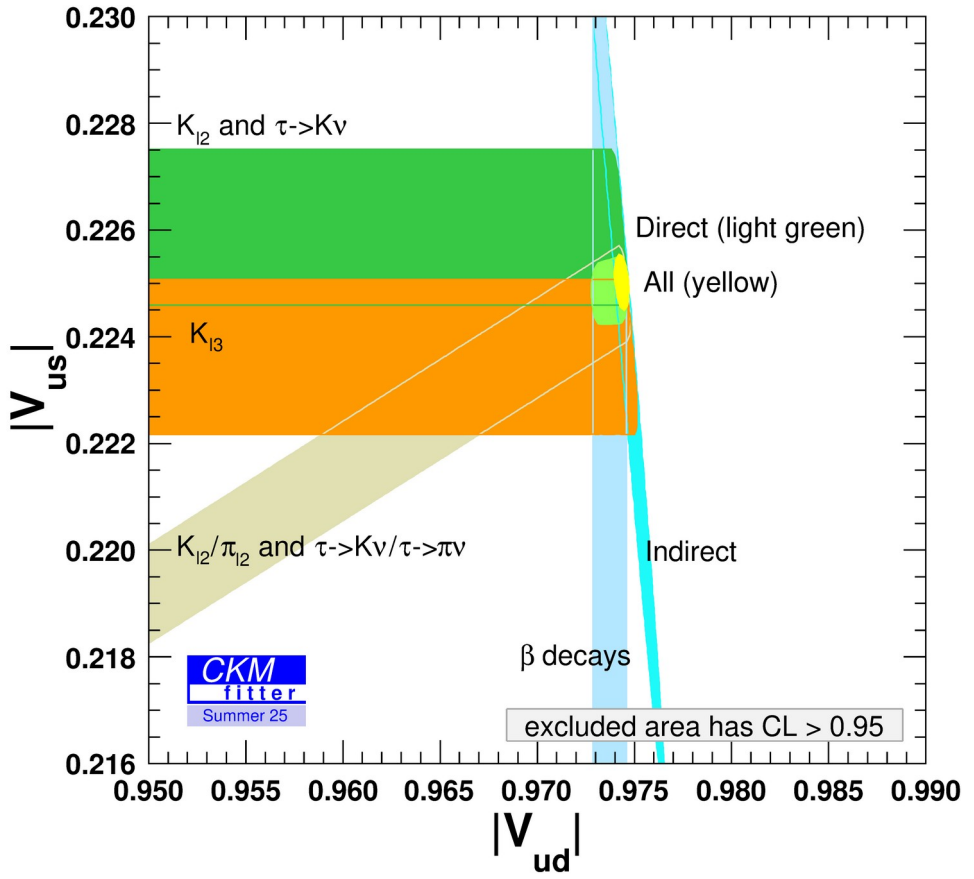
*R*fit: add theo. uncs. linearly

[Hardy, Towner '20]

→ $|V_{us}|$ from K, π, τ decays

[rad. correcs.: χPT, Cirigliano, Neufeld '11; RχT, Arroyo-U., Hernandez-T., Lopez-C., Roig, Rosell '21 '21]

- Observables used in the extraction of λ display a <u>good agreement</u>
  - $|V_{ud}|$, $K_{\mu 2}/\pi_{\mu 2}$, $K_{\mu 2}$: p-value ~98%
  - $|V_{ud}|$, $K_{\mu 2}/\pi_{\mu 2}$, $K_{\mu 2}$, $|V_{us}|f_+(0)$, K_{e2}: p-value ~19%
- Test of unitarity: $|V_{ud}|^2+|V_{us}|^2+|V_{ub}|^2-1$ consistent with 0 at ~<2σ



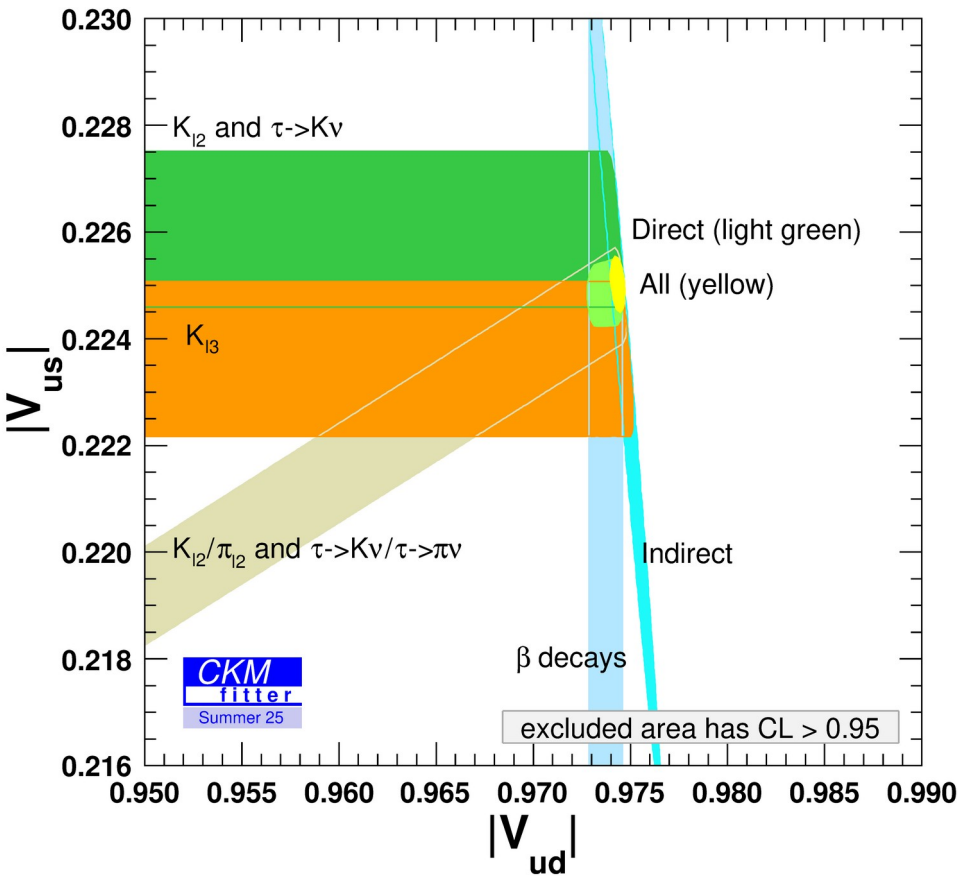
First two rows:

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

- **Finite nuclear size effects** reassessed recently; shift by ~1 standard deviation in the extracting of $|V_{ud}|$

  Concerns about nuclear structure dependence and isospin breaking remain
- Recent update of $|V_{us}|f_+(0)$ by FLAVIANET
- The two above would improve slightly our test of unitarity (preliminary)

[Gorchtein, Seng '23; Gorchtein, Katyal, Ohayon, Sahoo, Seng '25; He, Gorchtein, Heinz, Ohayon, Platter, Seng '26]
[Seng, Galviz, Gorchtein, Meissner '21]



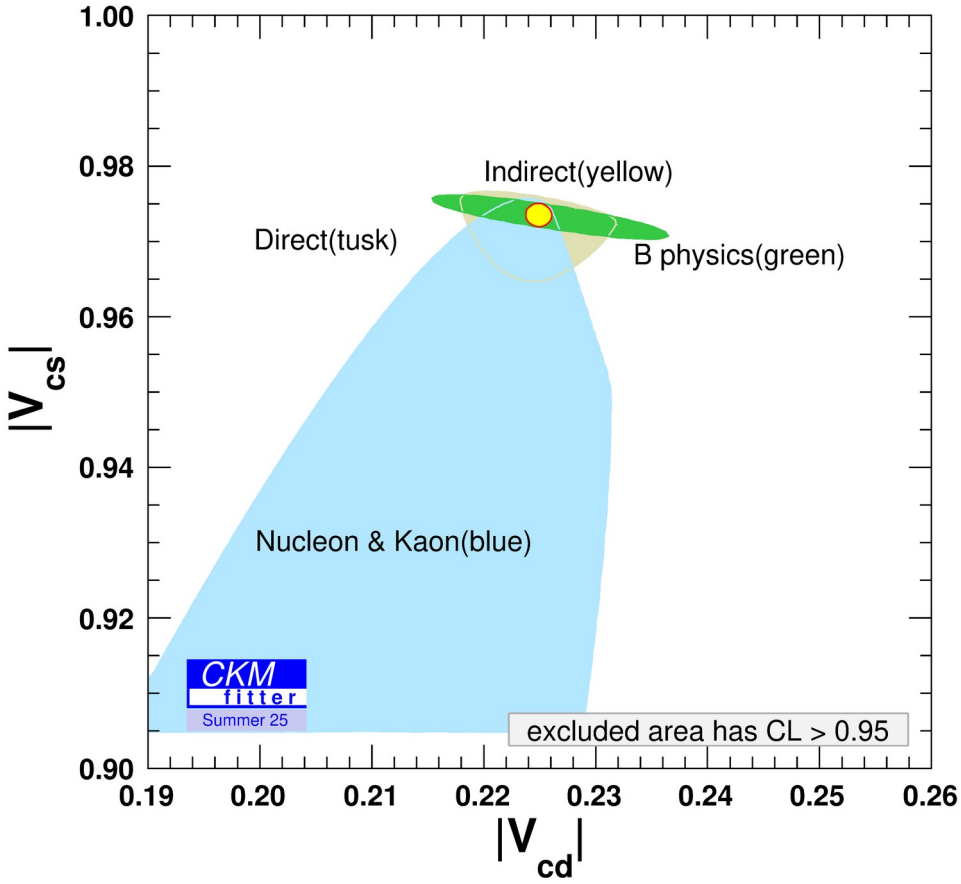
First two rows:

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

- High precision: $D_s \to \ell\nu$ and $D \to K\ell\nu$
- Test of unitarity: $|V_{cd}|^2+|V_{cs}|^2+|V_{cb}|^2-1$ consistent with 0 at ~<1σ
- Universal Short Distance (SD) QED corrections would push $|V_{cs}|$ towards lower values
- Long Distance (LD) QED estimates for $D_s \to \ell\nu$ point at a large effect opposite to SD
- Structure dependent QED corrections under discussion. LD QED not fully estimated for semi-leptonic

[Bolognani, Reboud, van Dyk, Keri Vos '24]

[Kitahara, Miyamoto, Sasaki '25]



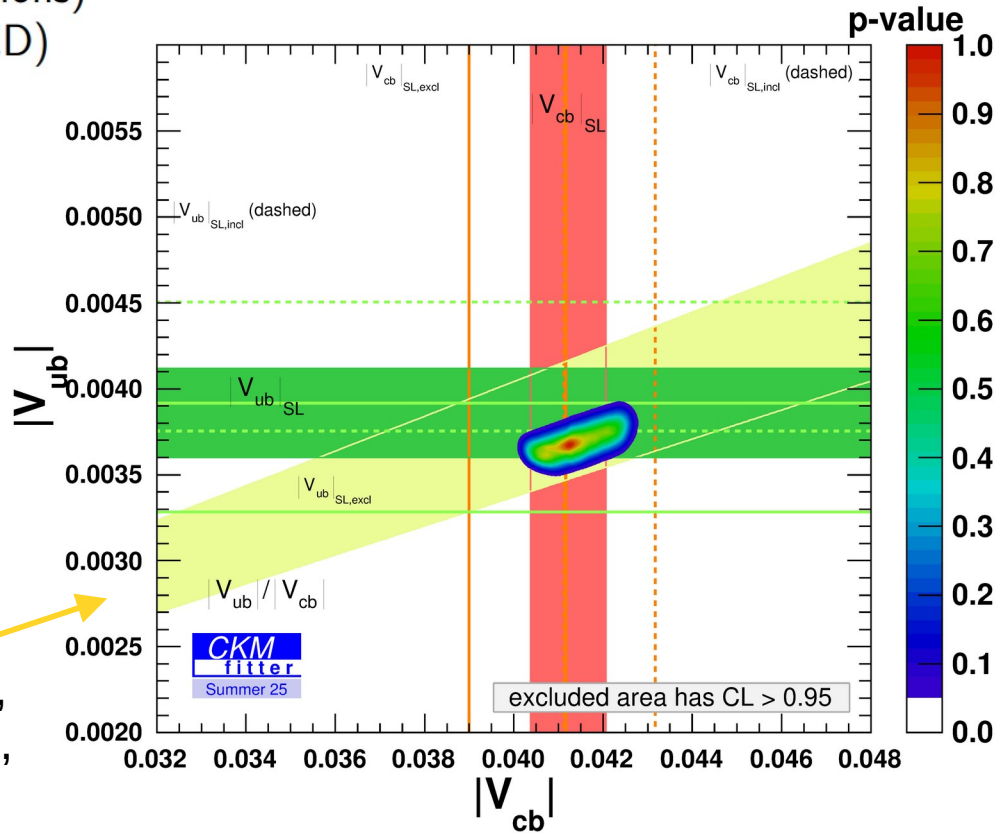
First two rows:

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

similar theo. frameworks for **charmed** and **charmless** modes, but different tools for **inclusive** (OPE in $1/m_b^{\#}$, shape functions) and **exclusive** (HQET, Form Factors from Lattice QCD)

- Exclusive and inclusive have similar error budgets
- Our inputs for excl. and incl. are compatible at about 1-2σ
- Semi-leptonic $|V_{cb}|_{incl.}$ and $|V_{ub}|_{excl.}$ are preferred by their indirect extractions

$|V_{ub}/V_{cb}|$:
$\Lambda_b \to p/\Lambda_b \to \Lambda_c$ (LHCb),
$B_s \to K/B_s \to D_s$ (LHCb),
inclusive (Belle)

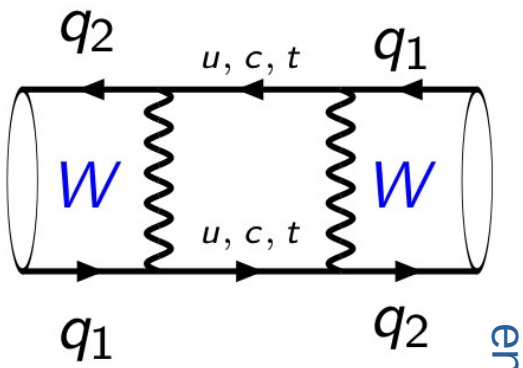


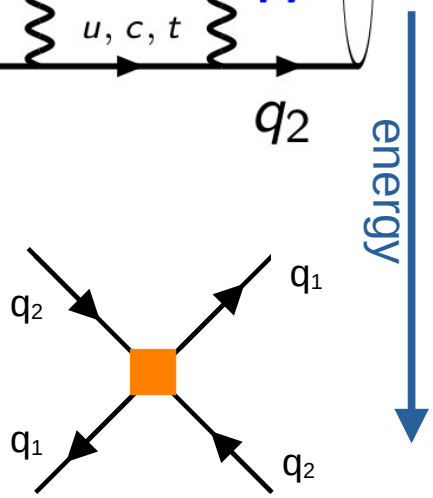
|ΔF|=2

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

- Precision SM observables: Δm_s, Δm_d, ϵ_K
- ϵ_K: ut-tt scheme [Brod, Gorbahn, Stamou '19]
  - Scheme conversion to NNLO (~2% shift) [Gorbahn, Jaeger, Kvedaraite '24]
  - Higher order EW corrections (~1% shift) [Brod, Kvedaraite, Polonsky '21; Brod, Kvedaraite, Polonsky, Youssef '22]
  - $1/m_c^2$ corrections: dimension-8 local operators (~1% shift) [Ciuchini, Franco, Lubicz, Martinelli, Silvestrini, Tarantino '21]
- Lattice accuracy for the Bag Parameters around a few percent

  Indirect extractions consistent, but indirect Bag Parameters not competitive w/ Lattice QCD





The unitary α angle

→ Branching ratios and $\mathcal{CP}$ asymmetries for $B \to \pi\pi, \rho\pi, \rho\rho$

→ Isospin analysis constrains hadronic penguin and tree amplitudes

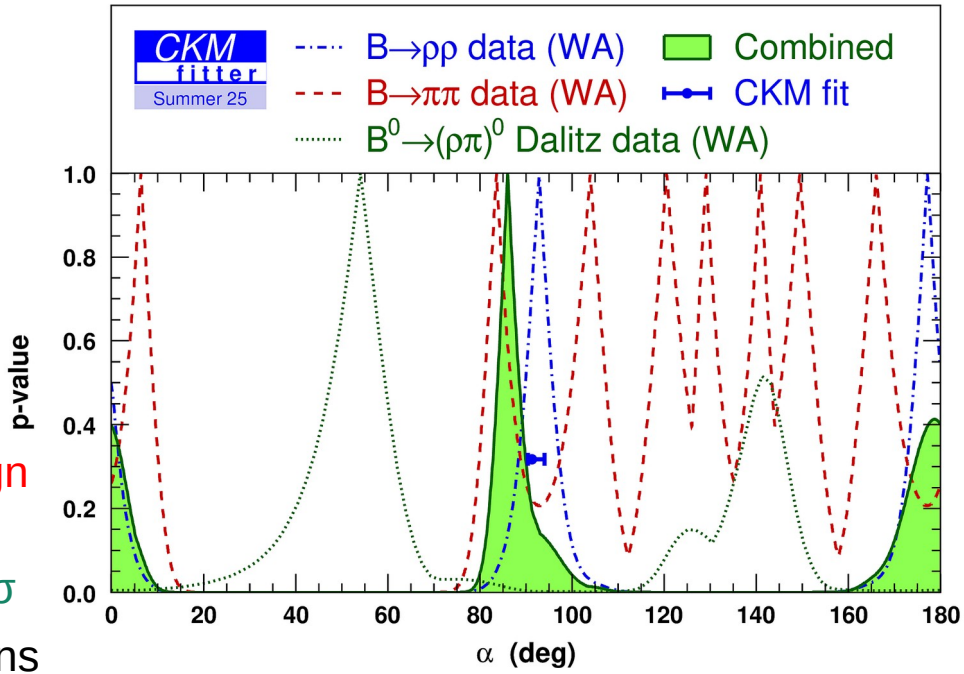
As in previous editions:

→ Average dominated by $B \to \pi\pi$ and $B \to \rho\rho$

→ $B \to \pi\pi, \rho\rho$ agree w/ α [ind.]

→ $B \to \rho\pi$ is in tension [Charles+'17]

- New: B → ρπ tension may be due to mismatch in sign conventions in experimental analyses [Zlebcik '26]
- B → ρπ discrepancy would then go from 3.0σ to 2.1σ
- Currently under scrutiny by the original collaborations

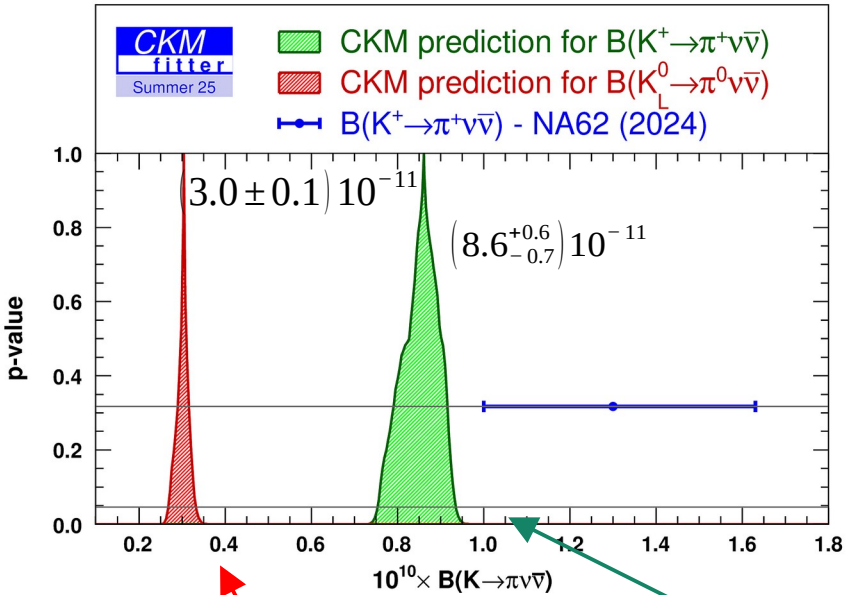


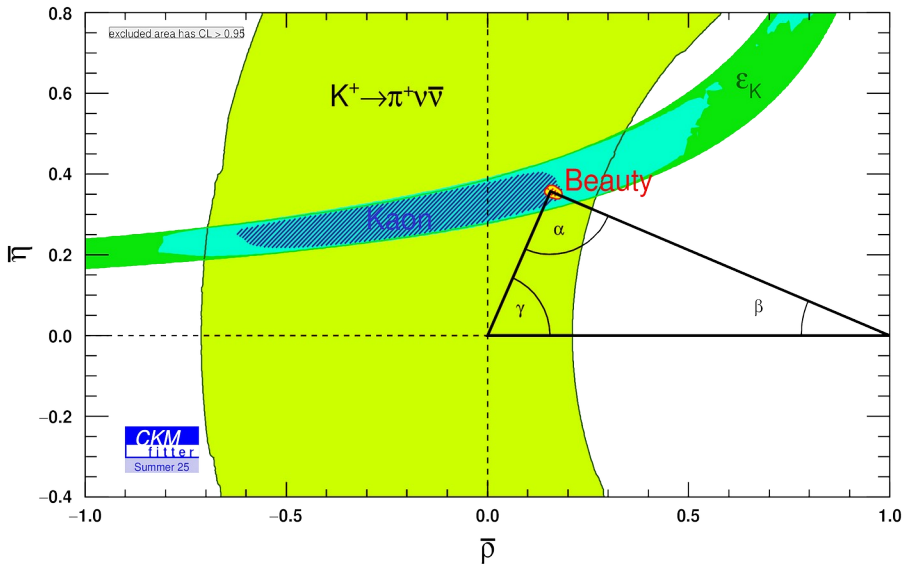
Other observables: very rare Kaon FCNC

- NA62 2412.12015 first observation; 2016-2022 data
- |Amplitude| α $|V_{td}^* V_{ts}|$ clean measurement of the R_t side
- KOTO Step-2 (starting ~2030) aims at discovery, 20% precision expected

$$\mathcal{B}\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = \left(13.0^{+3.3}_{-3.0}\right) \times 10^{-11}$$

smallest ever BR measured with >5σ





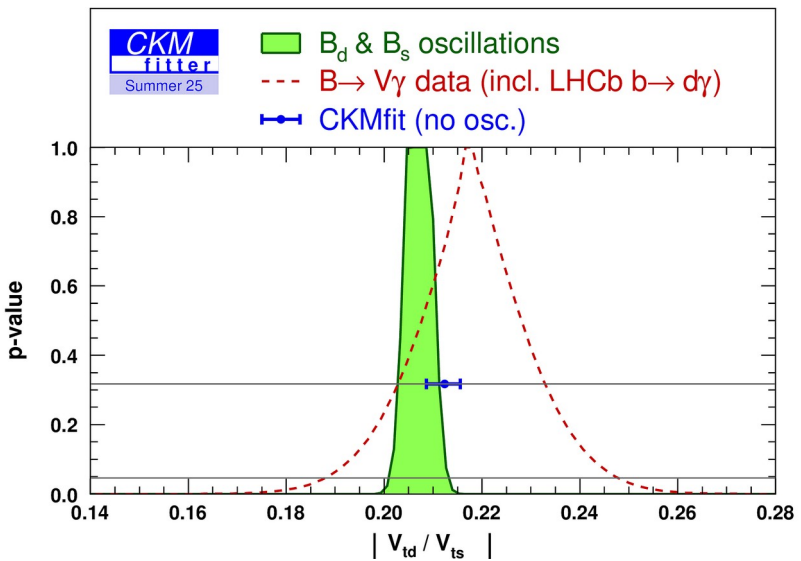
NA62 goal: O(15)% precision when including 2023-2026 data

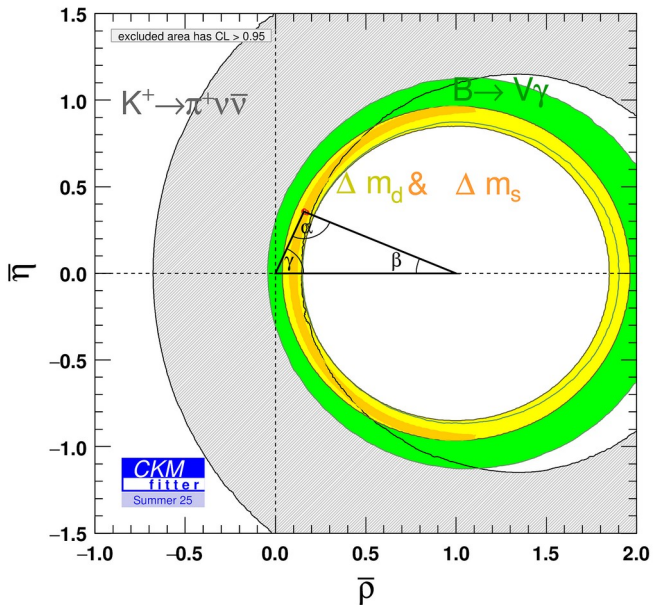
|Amplitude| α Im{$V_{td}^* V_{ts}$} direct measurement of |η|

LVS

Other observables: rare b → dγ transitions

- LHCb 2507.14401 $\dfrac{\mathcal{B}(B^0 \to \rho(770)^0\gamma)}{\mathcal{B}(B^0 \to K^*(892)^0\gamma)} = 0.0189 \pm 0.0007 \pm 0.0005$
- Constraint on $|V_{td}/V_{ts}|$: limited by the current resolution on form-factor ratios [Ball, Zwicky '06; Ball, Jones, Zwicky '06] $\xi_\rho \equiv \dfrac{T_1^{B\to K^*}(0)}{T_1^{B\to\rho}(0)} = 1.17 \pm 0.09$





Other (yet unobserved) b → dγ modes to show up at LHCb in the (near) future

Status of NP in B meson mixing

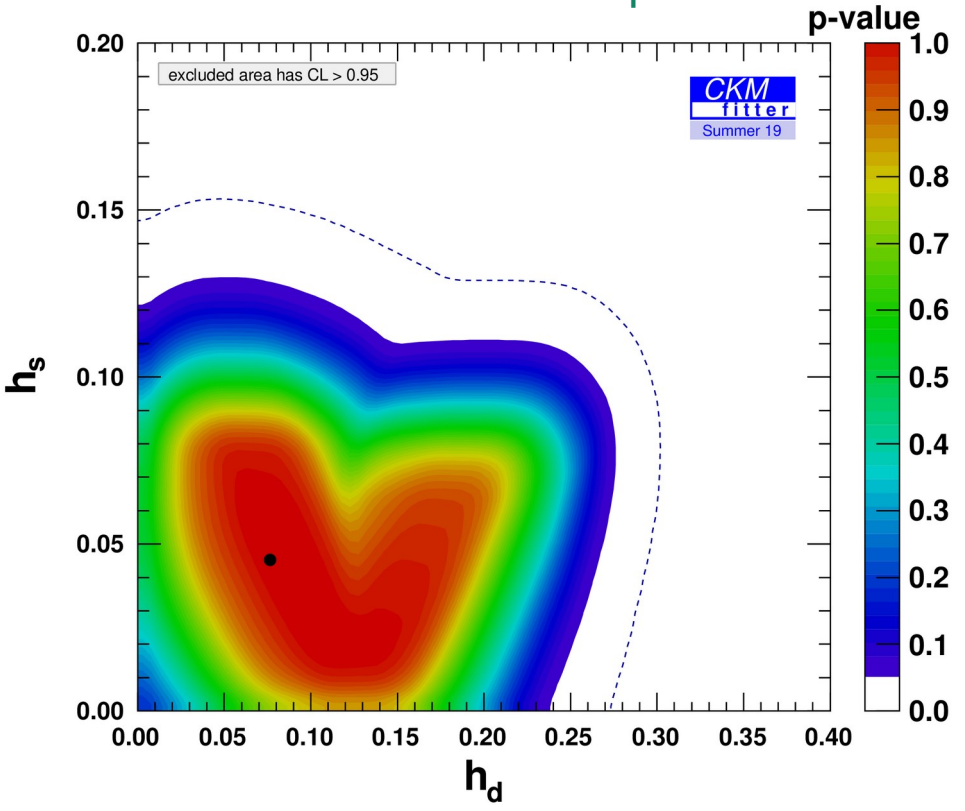
$$M_{12} = M_{12}^{\mathrm{SM}} \times (1 + h\, e^{2i\sigma})$$

NP parameters

- Agreement with the SM (h_d=h_s=0) at ~1σ
- Allowed size for NP at the level of O(20%)
- Extractions of ρ and η (Wolfenstein parameters) **degrade by factor ~3**

[Charles, Descotes-Genon, Ligeti, Monteil, Papucci, Trabelsi, LVS '20]

Black dot: best fit point

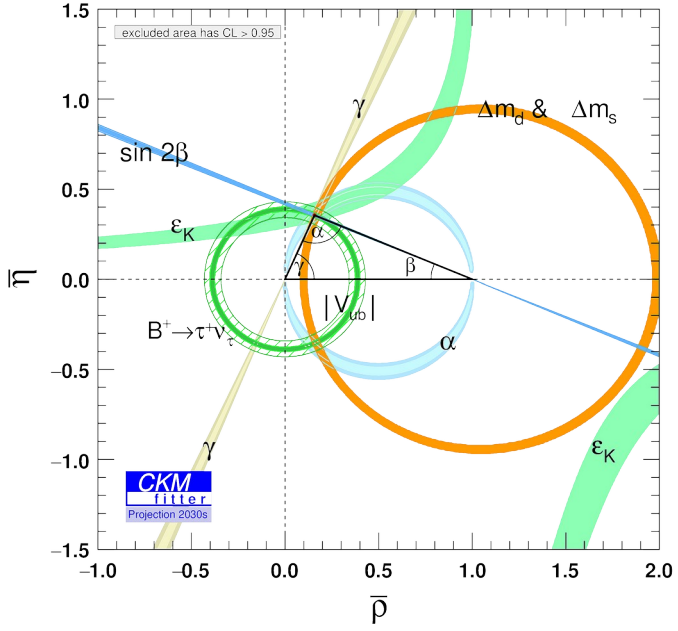


[See also: UTfit; De Bruyn, Fleischer, Malami, van Vliet '23]

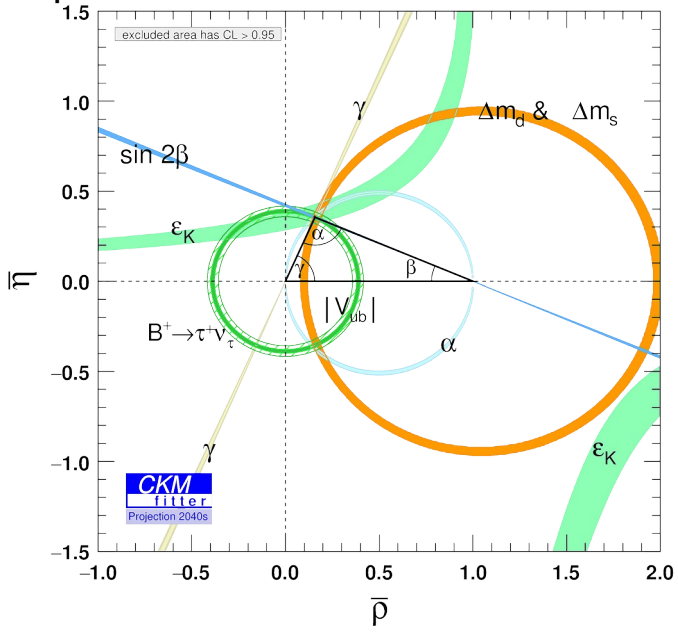
Prospective for the next decades

- Sensitivity projections from ATLAS, CMS, LHCb and Belle: 2503.24346

Early '30 (LHCb 50/fb - Belle 10/ab)
σ_J/J ~1.7%
<1% precision on η



Early '40 (LHCb 300/fb - Belle 50/ab)
σ_J/J ~1.2%



- Using best-fit for the central values, i.e., SM will continue providing a good description of the data
- **Theory will have to match experimental** (e.g., penguin pollution in β, isospin breaking in α, etc.)

Conclusions

Global fits shown here:

- SM framework: CKM mechanism for quark flavor transitions

  Theoretical inputs (mainly Lattice QCD)

  Experimental results (B factories, LHCb, etc.)

$\rightarrow$ Global fit of a **rich variety of processes sensitive to $\mathcal{CP}$ Violation and SM predictions in agreement**

$\rightarrow$ We are then able to extract accurate values for parameters describing the CKM matrix: $\mathcal{O}(1\,\%)$ or much better

$\rightarrow$ The **mechanism of $\mathcal{CP}$ Violation in the SM** (still) gives an **accurate picture of nature**: *no clear indication of NP*

CKMfitter Collaboration

MORE DETAILS @ ▸ CKMfitter

Jérôme Charles, Theory
Olivier Deschamps, LHCb
Sébastien Descotes-Genon, Theory
Stéphane Monteil, LHCb
Jean Orloff, Theory
Wenbin Qian, LHCb/BESIII
Vincent Tisserand, LHCb/BABAR
Karim Trabelsi, Belle/Belle II
Philip Urquijo, Belle/Belle II
Luiz Vale Silva, Theory

THANKS!



Theo. uncertainties

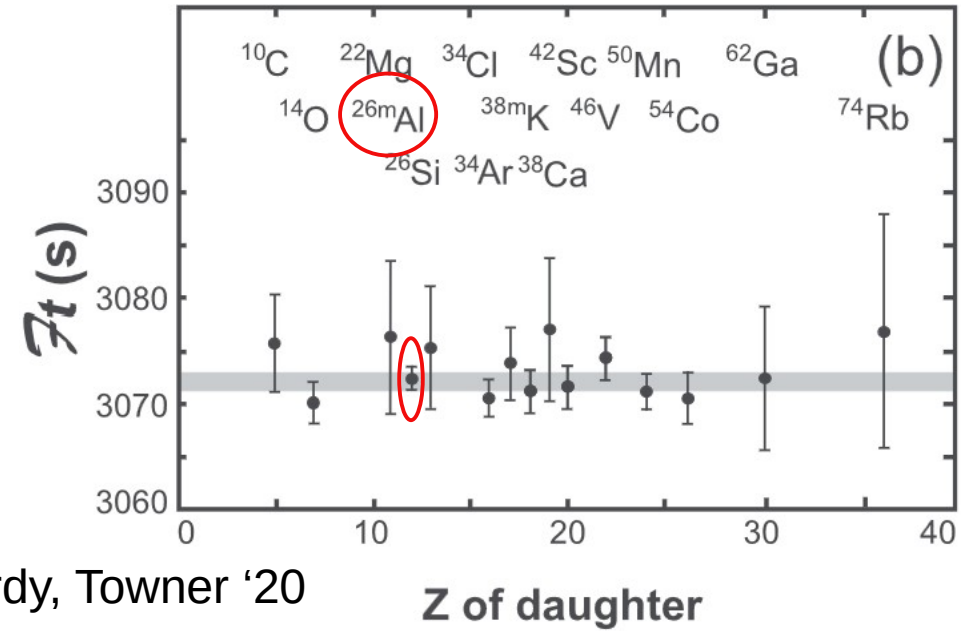


- **Statistical uncertainties** result from the intrinsic variability of data, typically distributed normally
- **Theoretical uncertainties** are different in nature: they are modeling parameters (ξ), fixed and unknown, that incorporate our incomplete knowledge about the properties of a distribution (Ex.: truncation of a perturbative series)
- Though *a priori* theoretical uncertainties are a universal issue, in the context of **quark flavor physics** they are particularly important, due to the **strong dynamics**

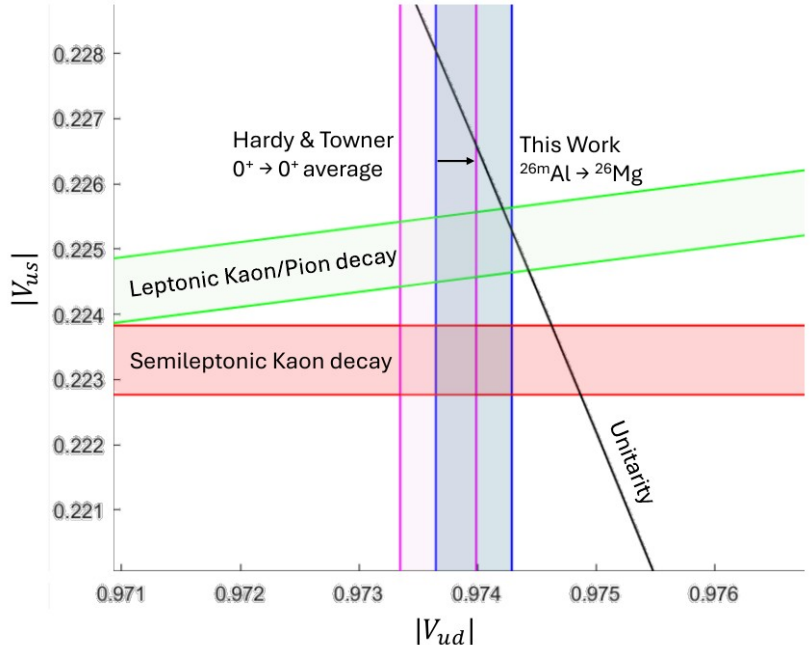
Finite size effects in superallowed nuclear β decays

Gorchtein, Katyal, Ohayon, Sahoo, Seng 2502.17070

- $^{26m}Al \rightarrow {}^{26}Mg$: most precise case
- New analysis: **shift towards agreement with unitarity**
- Gorchtein @ Implications ‘26: “Cabibbo anomaly disappears? […] But: **only *f* was revisited; need to check δ_{NS} and δ_C**”



Hardy, Towner ‘20



2025: our inputs for $|V_{cd}|$, $|V_{cs}|$

- $|V_{cs}|$ leptonic & $|V_{cd}|$ and $|V_{cs}|$ semi-leptonic: **O(1)%**

$\|V_{cd}\|$ (νN)	4.8 %	0.230 ± 0.011
$\|V_{cs}\|$ $(W \to c\bar{s})$	34 %	$0.94^{+0.32}_{-0.26} \pm 0.13$
$\mathcal{B}(D_s^- \to \mu^- \overline{\nu}_\mu)$	**2.2 %**	$(5.36 \pm 0.12) \times 10^{-3}$
$\mathcal{B}(D_s^- \to \tau^- \overline{\nu}_\tau)$	**1.7 %**	$(5.39 \pm 0.09) \times 10^{-2}$
$\mathcal{B}(D^- \to \mu^- \overline{\nu}_\mu)$	4.8 %	$(3.77 \pm 0.18) \times 10^{-4}$
$\mathcal{B}(D^- \to \tau^- \overline{\nu}_\tau)$	23 %	$(1.20 \pm 0.27) \times 10^{-3}$
$\|V_{cd}\| f_+^{D\to\pi}(0)$	**1.3 %**	0.1426 ± 0.0018
$\|V_{cs}\| f_+^{D\to K}(0)$	**0.5 %**	0.7180 ± 0.0033
f_{D_s}	**0.3 %**	$(249.09 \pm 0.25 \pm 0.65)$ MeV
f_{D_s}/f_D	0.3 %	$1.1784 \pm 0.0006 \pm 0.0033$
$f_+^{D\to\pi}(0)$	**1.2 %**	$0.624 \pm 0.004 \pm 0.006$
$f_+^{D\to K}(0)$	**0.6 %**	$0.742 \pm 0.002 \pm 0.004$

QED in $|V_{cs}|$ leptonic?

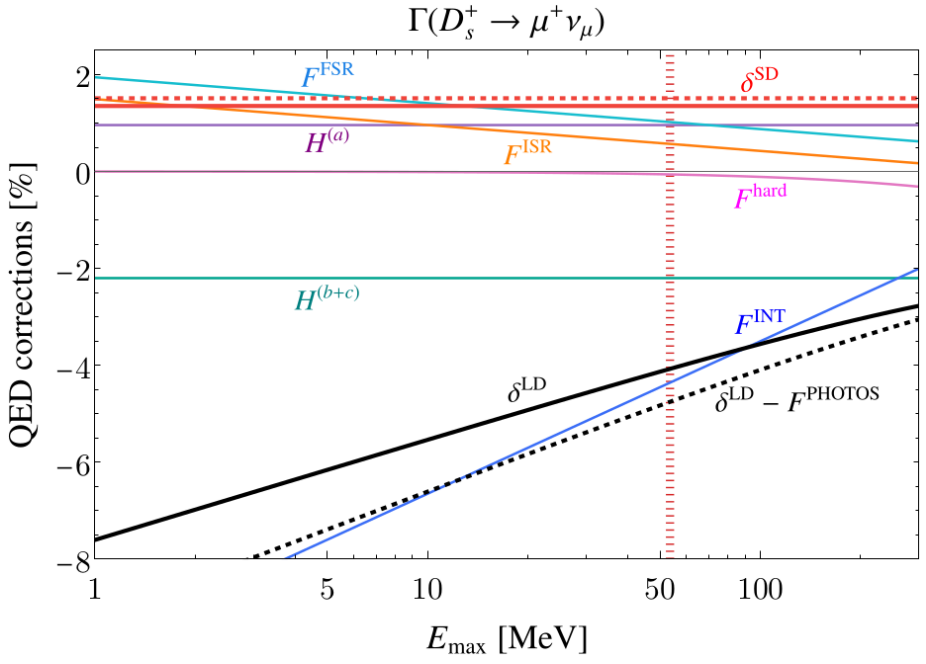
QED in $|V_{cd}|$, $|V_{cs}|$ semi-leptonic? ($|V_{cs}|$ more critical)

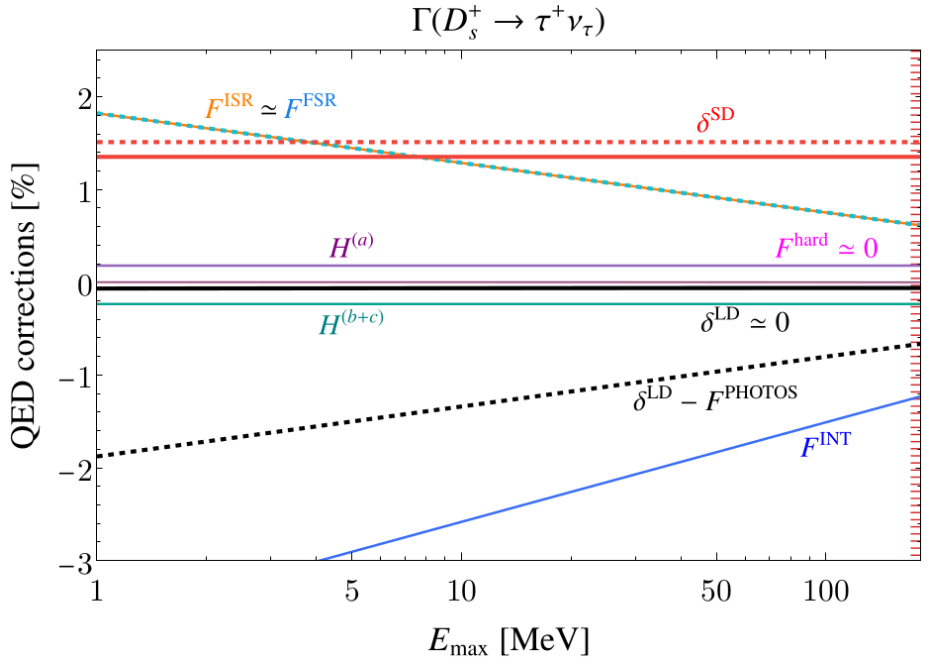
EW-QED corrections, leptonic D_s decays

Kitahara, Miyamoto, Sasaki 2511.22383

- "PHOTOS": experimental values already corrected for $|\mathrm{FSR}|^2$
- Beyond PHOTOS: $|\mathrm{ISR}|^2$ and interference INT=ISR*FSR
- "Hard": γ above E_{max} (theo. estimated value: vertical line at 54 MeV for ℓ=μ)
- SD: NDR scheme (dotted: HV scheme); include small 2-loop QCD*QED

for τ: extra neutrino(s) & smaller kinematic region for real photons; inclusive reconstruction

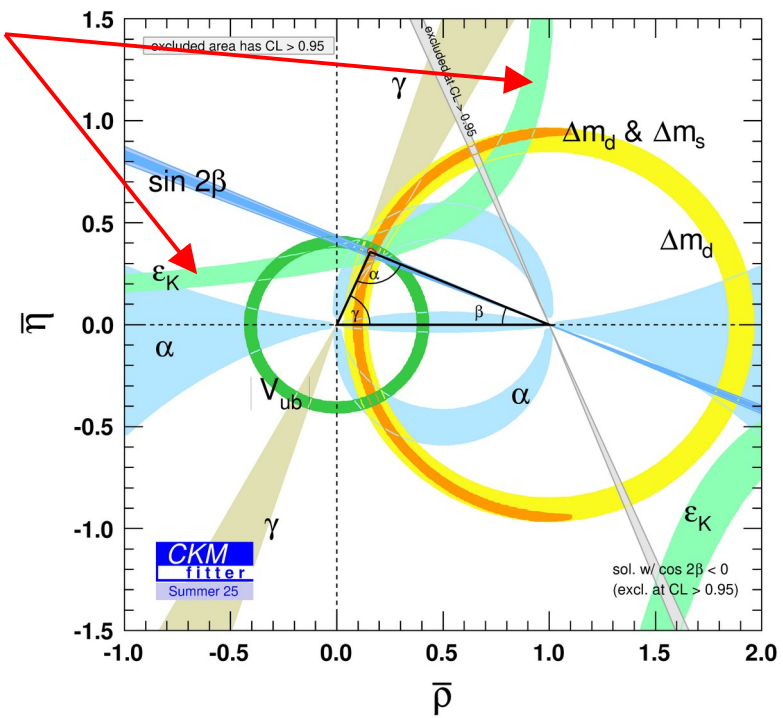




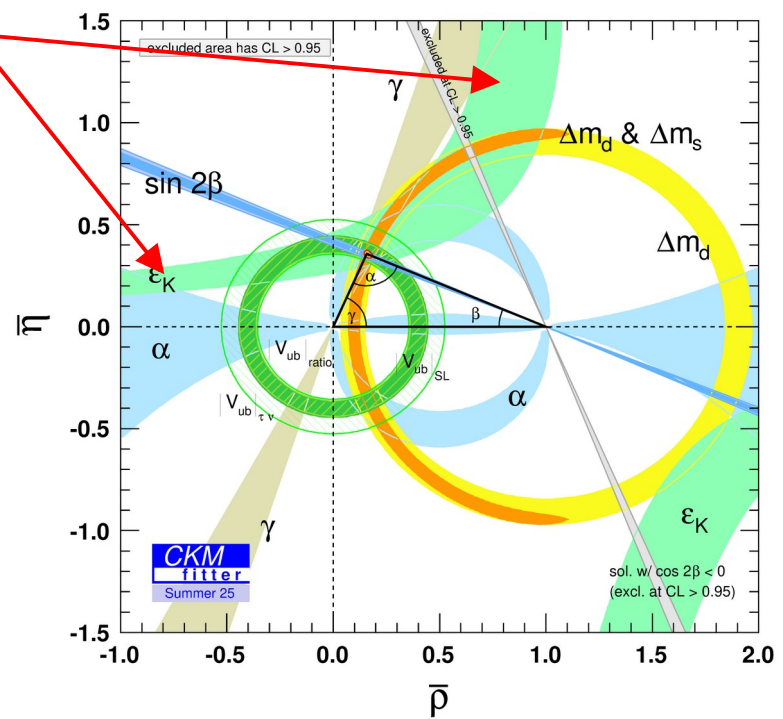
Scheme for calculations

- Unitarity: $\lambda_c = -\lambda_t - \lambda_u$, where $\lambda_q = V_{qs}^* V_{qd}$ (q=u, c, t); $\{\lambda_c^2, \lambda_c^2, \lambda_c \lambda_t\}$ vs. $\{\lambda_u^2, \lambda_t^2, \lambda_u \lambda_t\}$
- “c-t” vs. “u-t” parameterizations [Brod, Gorbahn, Stamou ‘19]

“u-t”



“c-t”



Extraction of the α angle

- Claim Zlebcik 2609.31828: sign conventions adopted by BaBar and Belle in $B \to \rho\pi$ are not consistent throughout their whole analyses (compare left/right dotted green below)
- $B \to \pi\pi$: recent Belle II 2606.20797 measurement of mixing-induced CP-violating S^{00} (compare left/right dashed red below) [Dorigo, Raiz, Tonelli, Zlebcik '25]
- Belle's, BaBar's, Cleo's ρρ, ππ BRs are corrected according to f^{00}/f^{+-}, i.e., Upsilon to $B^0\bar{B}^0$ and B^+B^-

