Recent developments of flavor physics in the Standard Model and beyond

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- Introduction
- The other side of the Cabibbo angle: Charm Physics
- The SM Unitarity Triangle Analysis
- The Unitarity Triangle and Constraints on New Physics
- Outlook

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Introduction

- Almost all my scientific activity follows a clear path brilliantly opened by Cabibbo

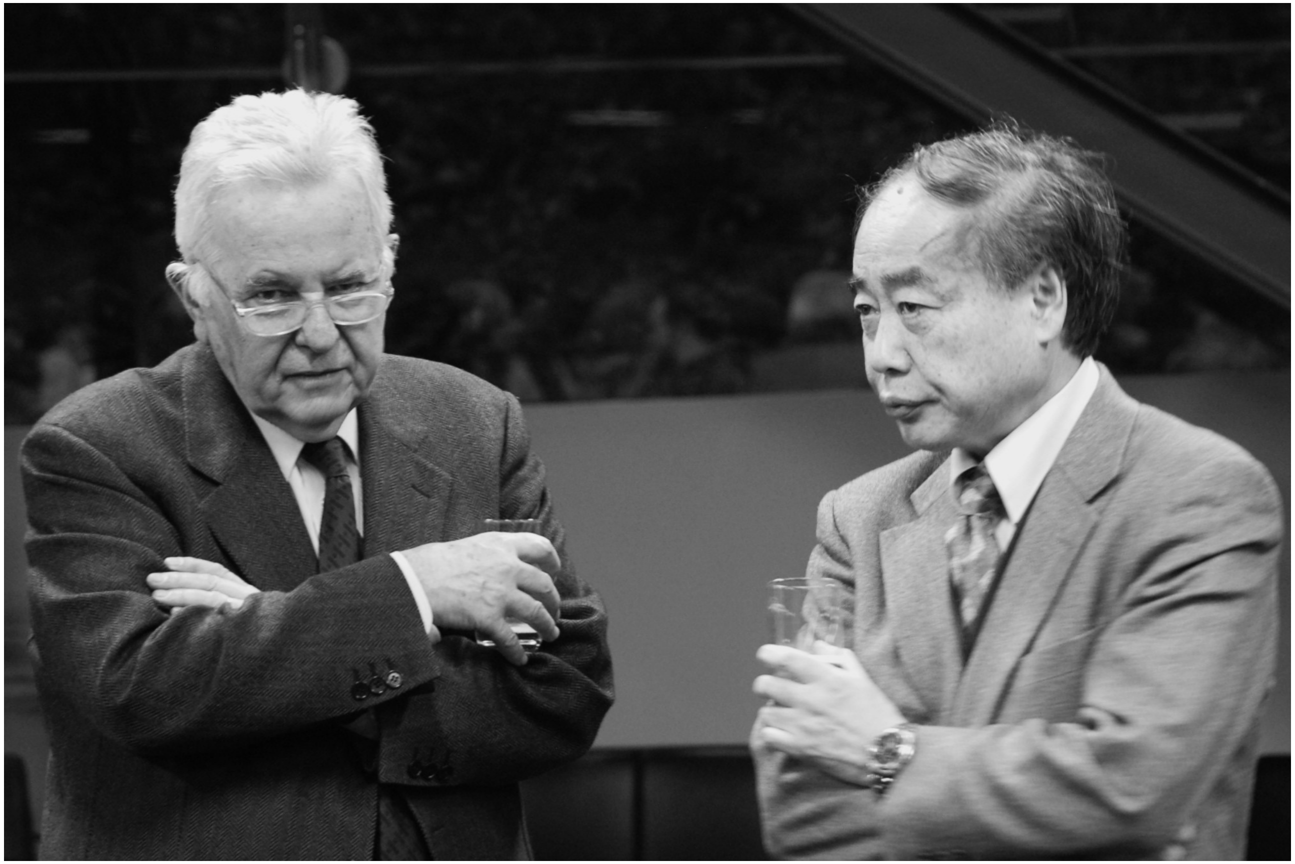


Photo by M. Bona

Introduction

- Problem: apparent violation of universality of weak interactions in strange particle decays
- Solution: The Cabibbo angle. Disentangle the symmetries of weak and strong interactions and recover universality

$$\begin{pmatrix} u \\ d \\ s \end{pmatrix}_{\text{strong}} \Rightarrow \begin{pmatrix} u \\ d\cos\theta + s\sin\theta \end{pmatrix}_{\text{weak}}$$

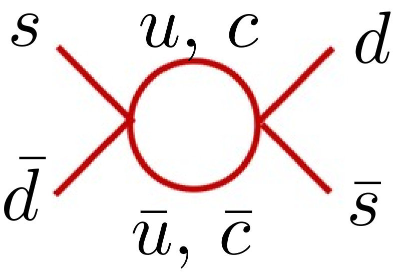
Introduction

- Problem: Flavour Changing Neutral Currents arise at rates much lower than Charged Currents.
- Solution: the GIM mechanism:
  - Get rid of tree-level FCNC:

$$\begin{pmatrix} u \\ d\cos\theta + s\sin\theta \end{pmatrix} \Rightarrow \begin{pmatrix} u & c \end{pmatrix} \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$$

Introduction

- Problem: Flavour Changing Neutral Currents arise at rates much lower than Charged Currents.
- Solution: the GIM mechanism:
  - Get rid of loop contributions of $O(1/\Lambda^2)$:



$$\propto \sin^2\theta\cos^2\theta\,\frac{m_c^2 - m_u^2}{\Lambda^4}$$

GIM suppression

Introduction

- Problem: accommodate CP violation in weak interactions
  - Solution: Kobayashi-Maskawa: with 3 generations, a phase in the CKM matrix induces CP violation in weak interactions

$$\begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}_{\mathrm{CM}} \Rightarrow$$

$$V_{CKM} = \begin{pmatrix} \cos\theta_{12}\cos\theta_{13} & \sin\theta_{12}\cos\theta_{13} & \sin\theta_{13}\,e^{-i\delta} \\ -\sin\theta_{12}\cos\theta_{23} - \cos\theta_{12}\sin\theta_{13}\sin\theta_{23}\,e^{i\delta} & \cos\theta_{12}\cos\theta_{23} - \sin\theta_{12}\sin\theta_{13}\sin\theta_{23}\,e^{i\delta} & \cos\theta_{13}\sin\theta_{23} \\ \sin\theta_{12}\sin\theta_{23} - \cos\theta_{12}\sin\theta_{13}\cos\theta_{23}\,e^{i\delta} & -\cos\theta_{12}\sin\theta_{23} - \sin\theta_{12}\sin\theta_{13}\cos\theta_{23}\,e^{i\delta} & \cos\theta_{13}\cos\theta_{23} \end{pmatrix}.$$

Introduction

- In the Standard Model, FCNC processes only arise through virtual loop contributions, are finite and calculable, and GIM suppressed
  - not true in generic extensions of the SM: FCNC very sensitive probes of New Physics
- CP violation requires three generations:
  - further suppressed by small mixing angles in the SM
- The flavour way to NP: find evidence of NP through deviations from SM expectations in FCNC and CPV

The Other Side of the Cabibbo Angle: Charm Physics

- Short-distance contribution of bottom quarks negligible in $c \to u$ transitions
- Effectively a two-generation theory with slightly non-unitary mixing matrix:
  - $\lambda_d + \lambda_s = - \lambda_b$, where $\lambda_q = V_{cq}^* V_{uq}$
  - CP violation arises at $O(\theta^5)$, suppressed by $r_{CKM} = \mathrm{Im}(\lambda_b/\lambda_{d,s}) \sim 6.5\ 10^{-4}$
  - GIM cancellation ⇔ $s \leftrightarrow d$ ⇔ U-spin subgroup of SU(3) flavour symmetry of strong interactions

CP Violation in Singly Cabibbo Suppressed D Decays

- effective Hamiltonian for SCS decays:

$$\mathcal{H}_{\rm eff}^{\rm SCS} = \frac{2G_F}{\sqrt{2}}\Big\{ (\lambda_d - \lambda_s)\, C_1\, (Q_1^{dd} - Q_1^{ss}) + C_2\, (Q_2^{dd} - Q_2^{ss}) \qquad \Delta U=1$$

$$-\lambda_b\, C_1\, (Q_1^{dd} + Q_1^{ss}) + C_2\, (Q_2^{dd} + Q_2^{ss}) \Big\} \qquad \Delta U=0$$

- to get CPV in decay, i.e. $|A(D\to f)| \neq |A(\overline{D}\to \overline{f})|$, need λ_b and strong phase difference δ between contribution of $\Delta U=1$ and $\Delta U=0$ terms:

$$A_{CP} = r_{CKM} \langle \Delta U=0\rangle / \langle \Delta U=1\rangle \sin\delta$$

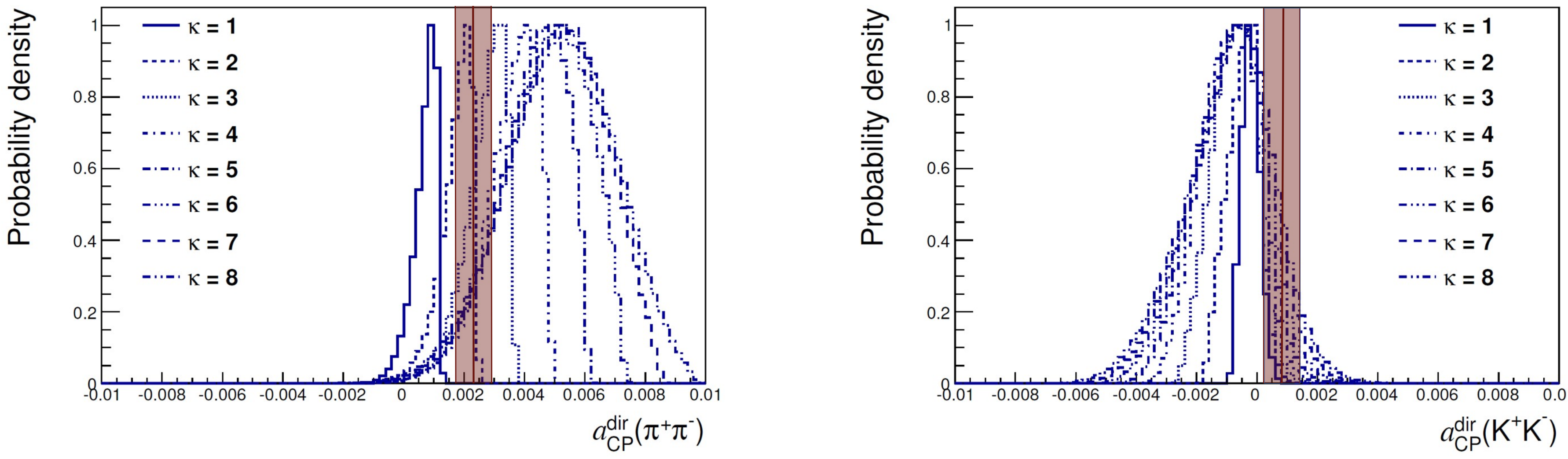
- Perform isospin analysis of $D\to\pi\pi$ decays:
  - $|A_0| \sim 2\, |A_2|$, $\mathrm{Arg}(A_0/A_2) \sim 90°$

Franco, Mishima & L.S. '12

CP Violation in Singly Cabibbo Suppressed D Decays

- LHCb obtained the first observation of CPV in charm: $\Delta A_{CP} = A_{CP}(K^+K^-)-A_{CP}(\pi^+\pi^-) = (-15.4 \pm 2.9)\ 10^{-4}$
- And very recently the first evidence of CPV in a single channel:
  - $a_{CP}(\pi^+\pi^-) = (23.2 \pm 6.1)\ 10^{-4}$
  - $a_{CP}(K^+K^-) = (7.7 \pm 5.7)\ 10^{-4}$
- Confirms the large violation of U-spin seen in $BR(D \to K_S K_S)$: $a_{CP}(K^+K^-) \neq -a_{CP}(\pi^+\pi^-)$

CPV IN SCS D DECAYS

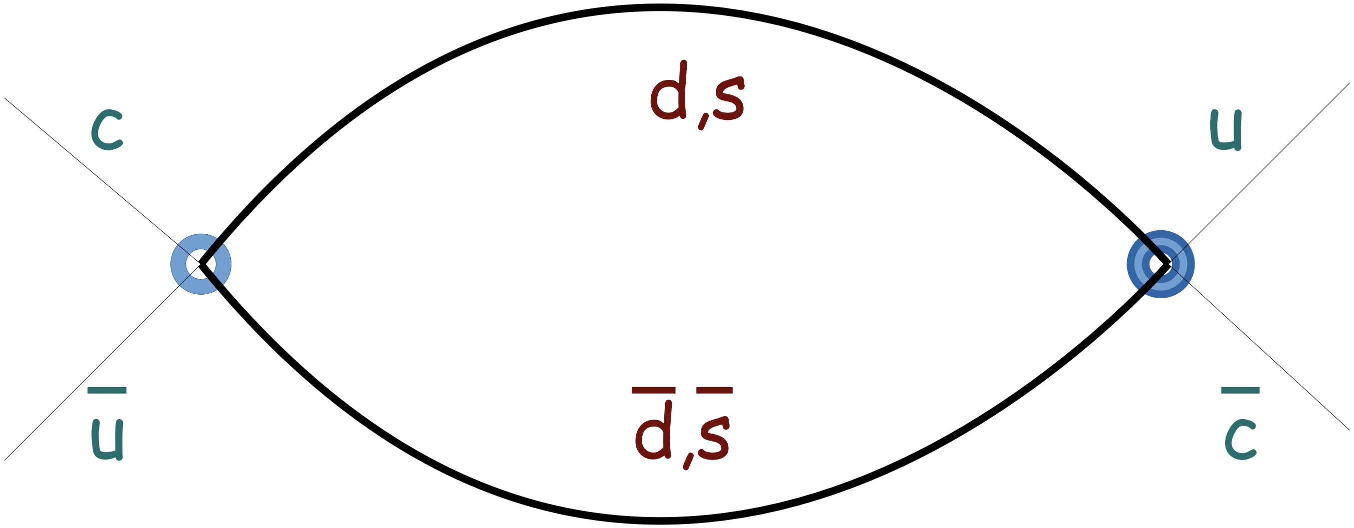


Franco, Mishima & L.S. '12

- The very recent LHCb results require a reasonable ratio k~<U=0>/<U=1>~2. Updated analysis including FSI in progress. See also Pich et al '23

D-$\bar{D}$ MIXING

- D mixing in the SM is described by the T-product of two $\Delta C=1$ Hamiltonians:



- Long distance, not calculable. NP might add a local contribution to the dispersive amplitude M_{12}

APPROXIMATE UNIVERSALITY

$$M_{12}\,,\ \Gamma_{12} \sim (\lambda_s-\lambda_d)^2(f_{ss}+f_{dd}-2f_{sd})+2(\lambda_s-\lambda_d)\lambda_b(f_{ss}-f_{dd})+\mathcal{O}(\lambda_b^2)$$

$$=(\lambda_s-\lambda_d)^2(\Delta U=2)+2(\lambda_s-\lambda_d)\lambda_b(\Delta U=1)$$

CPV

- GIM mechanism: amplitudes must be proportional to U-spin breaking; dominant term requires breaking by two units, CPV term less suppressed
- CPV effects in Γ_{12} further enhanced by large U-spin breaking as observed in $a_{CP}(\pi\pi)$ ⇒ take all decay amplitudes real, but allow for CPV in ΔC=2; valid up to $O(r_{CKM})$.
- Corrections due to subleading amplitudes can be worked out where needed

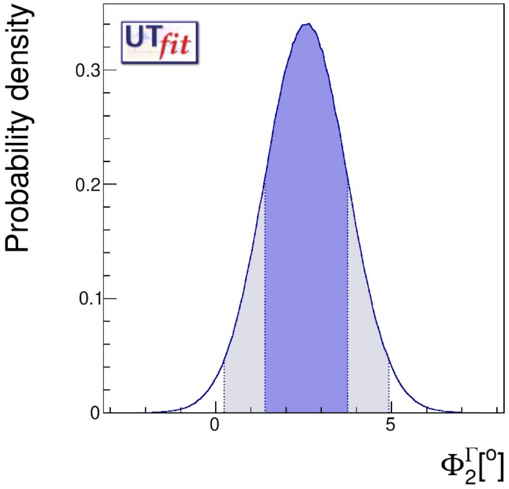
Kagan & L.S., PRD '21

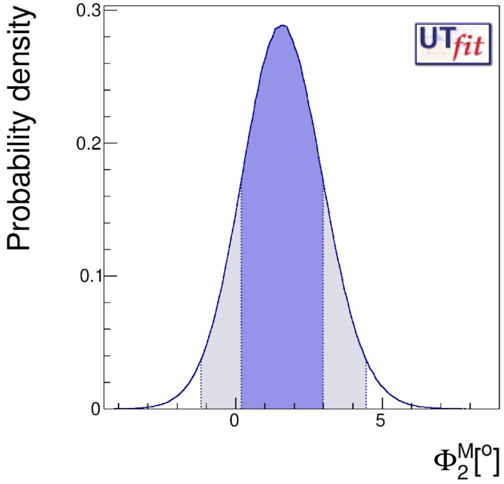
APPROXIMATE UNIVERSALITY

- At this order, two different sources of CPV arise:
  - "dispersive CPV", measured by $\Phi_M = \arg(M_{12})$, sensitive to NP in $\Delta C=2$;
  - "absorptive CPV", measured by $\Phi_\Gamma = \arg(\Gamma_{12})$, sensitive to CPV in decay amplitudes thanks to the U-spin enhancement.
  - Interpret experimental data in terms of $x_{12}=|M_{12}|/\Gamma$, $y_{12}=|\Gamma_{12}|/\Gamma$, Φ_M and Φ_Γ

Kagan & L.S., PRD '21

UTfit 2023 average





- Combining all available data we find:
  - $x_{12} = (4.28 \pm 0.33)\ 10^{-3}$
  - $y_{12} = (6.24 \pm 0.23)\ 10^{-3}$

  - $\Phi_M = (1.3 \pm 1.3)^\circ$
  - $\Phi_\Gamma = (2.6 \pm 1.2)^\circ$
- No evidence of CPV

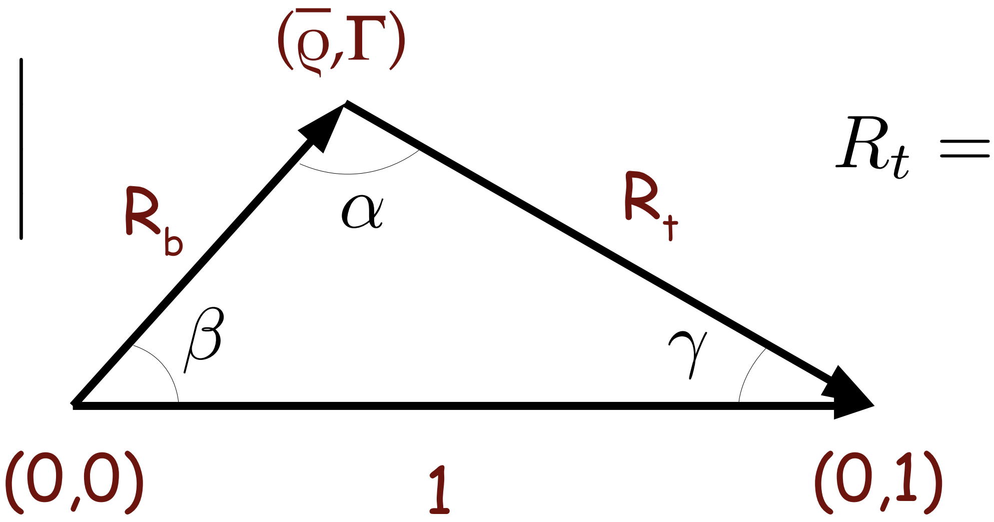
UTfit '23 (preliminary)

Unitarity Triangle(s)

- CKM Unitarity ⇔ Triangular relations a.k.a. Unitarity Triangles:

$$\left(VV^{\dagger}\right)_{i,j\neq i}=\sum_{k}V_{ik}V_{jk}^{*}=0$$

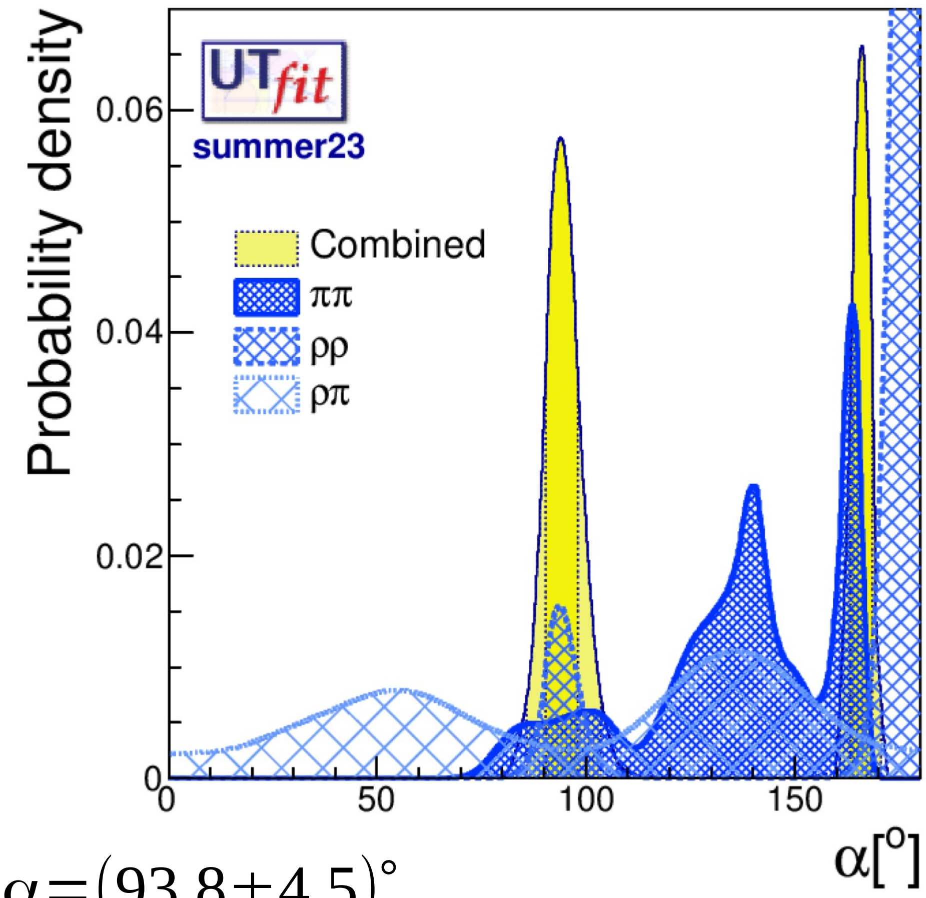
$$R_b=\left|\frac{V_{ud}V_{ub}}{V_{cd}V_{cb}}\right|$$

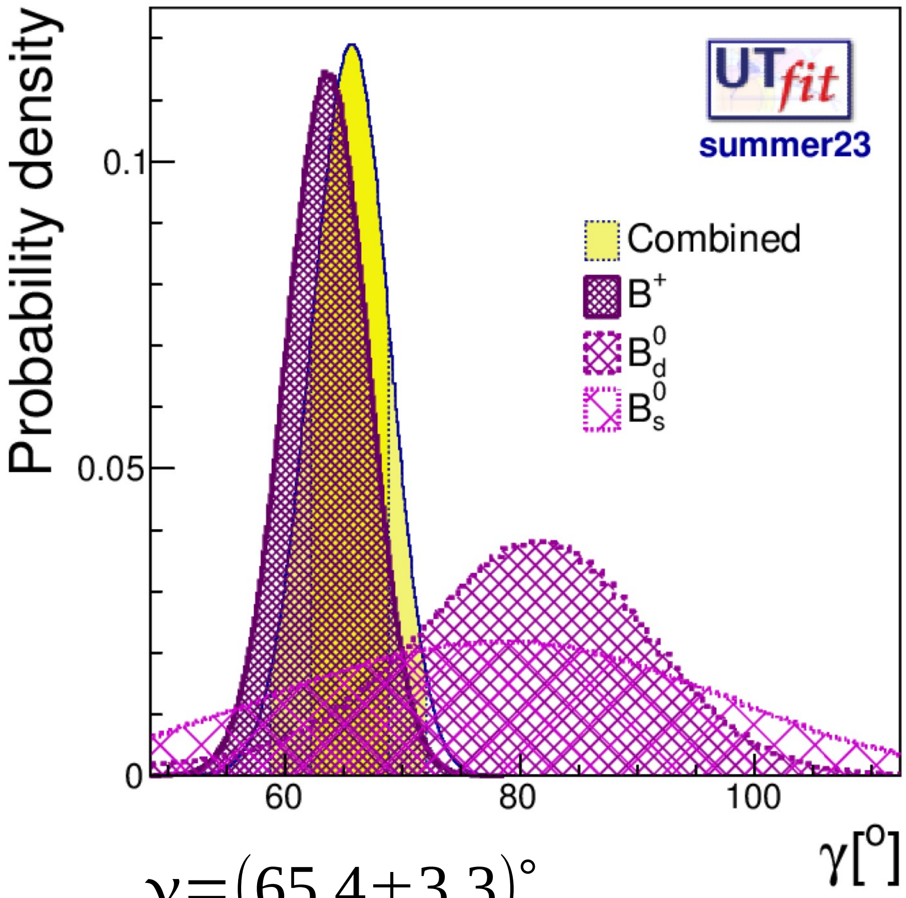


$$R_t=\left|\frac{V_{td}V_{tb}}{V_{cd}V_{cb}}\right|$$

$$\alpha=\arg\left(-\frac{V_{td}V_{tb}^{*}}{V_{ud}V_{ub}^{*}}\right)\quad\beta=\arg\left(-\frac{V_{cd}V_{cb}^{*}}{V_{td}V_{tb}^{*}}\right)\quad\gamma=\arg\left(-\frac{V_{ud}V_{ub}^{*}}{V_{cd}V_{cb}^{*}}\right)$$

Recent Updates: α and γ



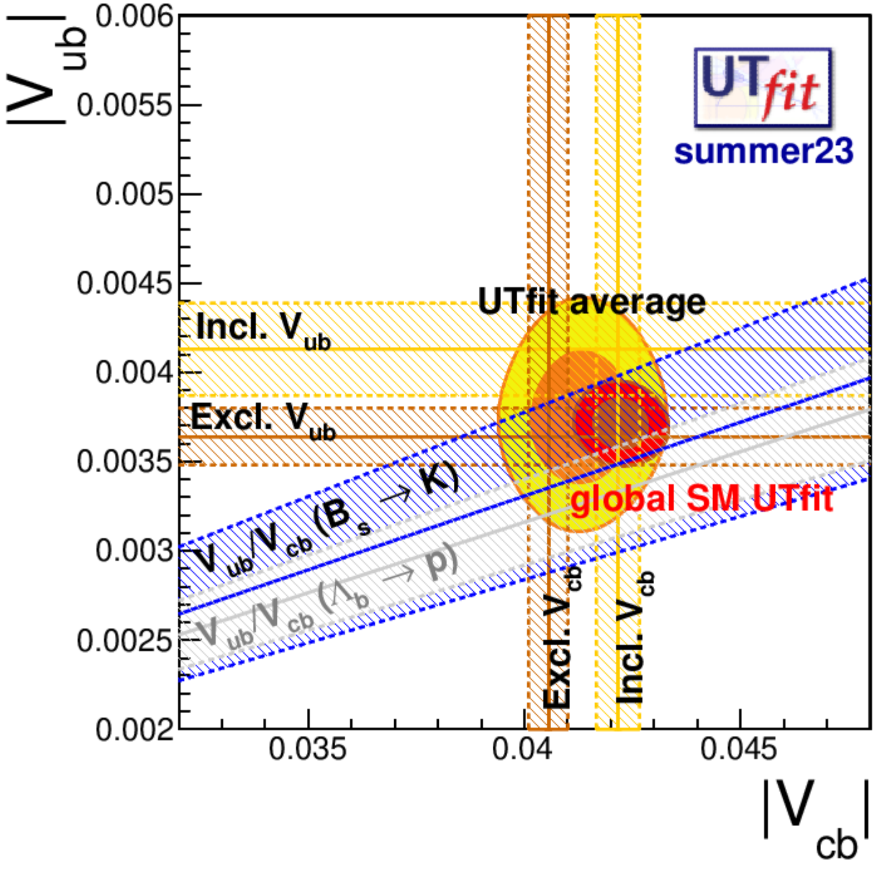


$\alpha=(93.8\pm4.5)^\circ$

$\gamma=(65.4\pm3.3)^\circ$

from combined B&D analysis

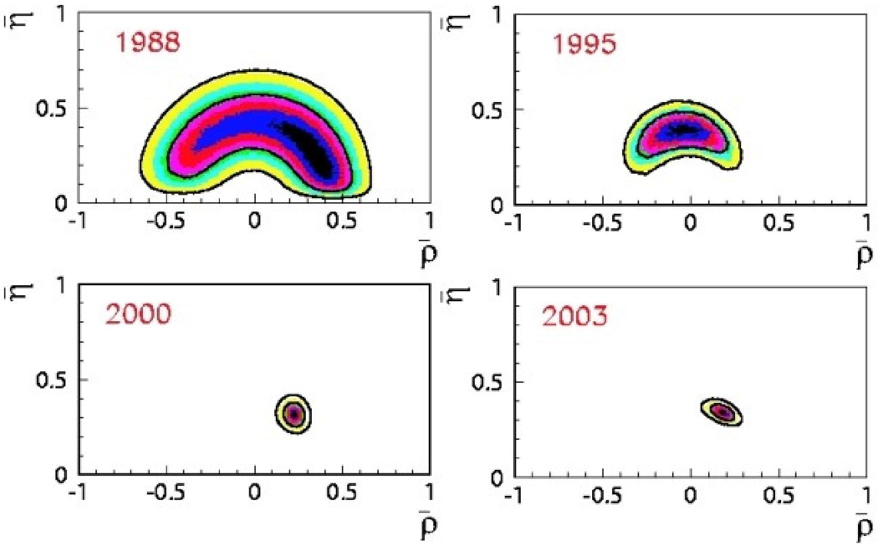
Recent Updates: V_{ub} & V_{cb}

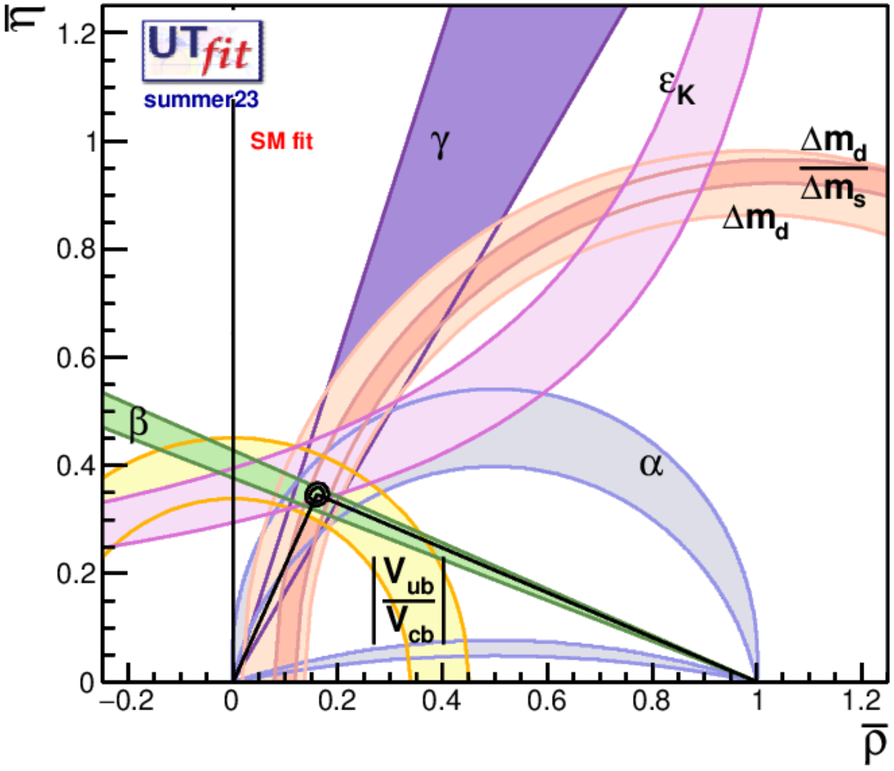


- $|V_{cb}|_{excl}=(40.55\pm0.46)\ 10^{-3}$
  (UTfit)
- $|V_{cb}|_{incl}=(42.16\pm0.50)\ 10^{-3}$
  (Bordone et al.)
- $|V_{ub}|_{excl}=(3.64\pm0.16)\ 10^{-3}$
  (UTfit)
- $|V_{ub}|_{incl}=(4.13\pm0.26)\ 10^{-3}$
  (UTfit)
- $|V_{ub}/V_{cb}|_{Bs}=(8.27\pm1.17)\ 10^{-2}$
  (LCHb + FLAG)
- $|V_{ub}/V_{cb}|_{\Lambda b}=(7.9\pm0.6)\ 10^{-2}$
  (LCHb, not used)

See also Martinelli, Simula & Vittorio '23

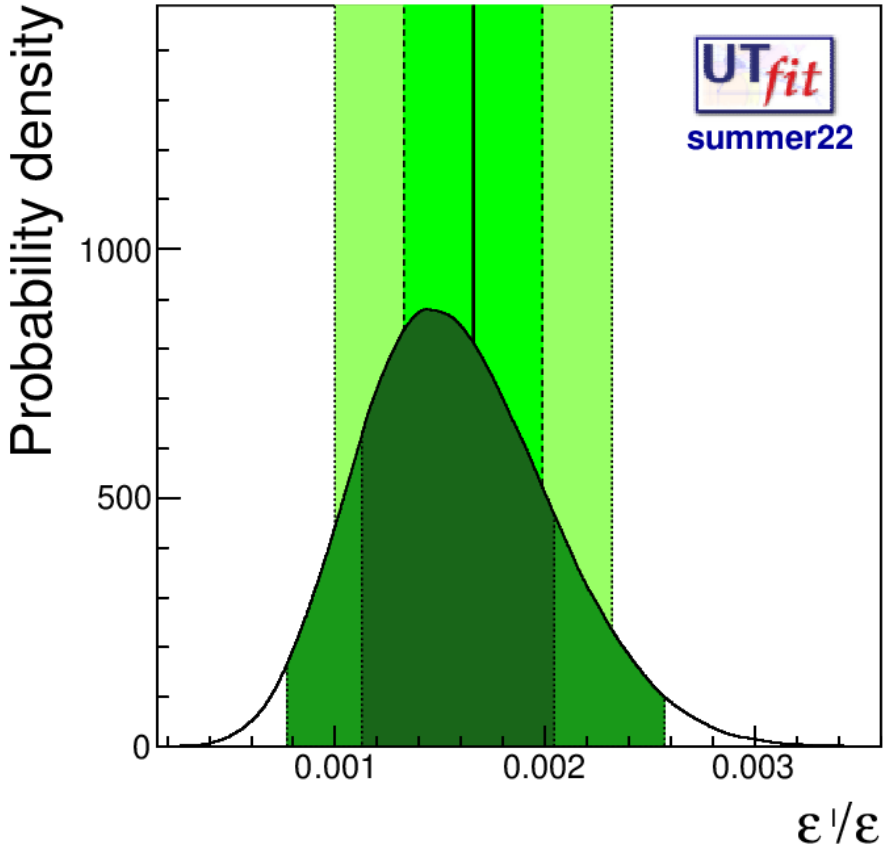
From the past to the present





Direct CPV in K Decays

- Prediction for ε'/ε obtained from the UTA with matrix elements from Lattice QCD
- Excellent agreement with experiment



UTfit '22

The Quest for New Physics

- The UT is overconstrained: generalize to NP
- Working hypothesis: neglect NP contributions to tree-level decays, search for NP in loop-mediated processes
- Derive constraints on NP contributions to meson-antimeson mixing
- Translate into bounds on the NP scale for a given NP coupling and flavour structure

NP Analysis: Results

$\bar{\rho} = 0.167 \pm 0.025$

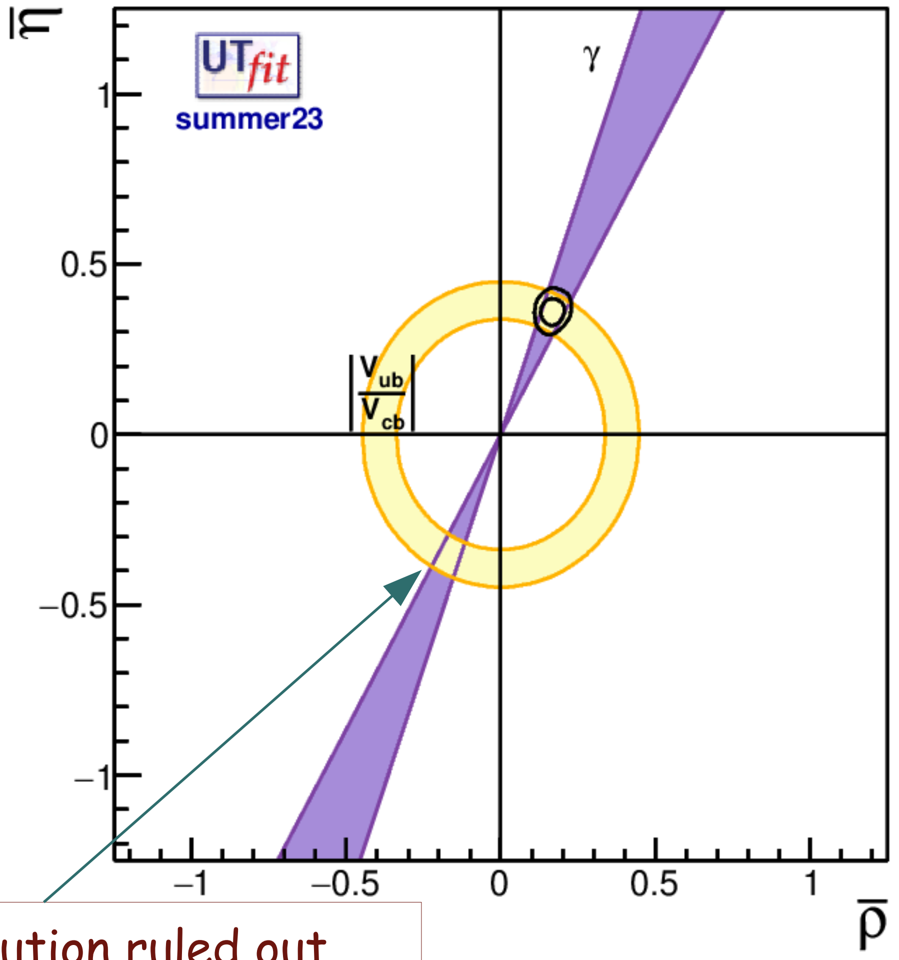
$\bar{\eta} = 0.361 \pm 0.027$

to be compared w.

$\bar{\rho} = 0.160 \pm 0.009$

$\bar{\eta} = 0.346 \pm 0.009$

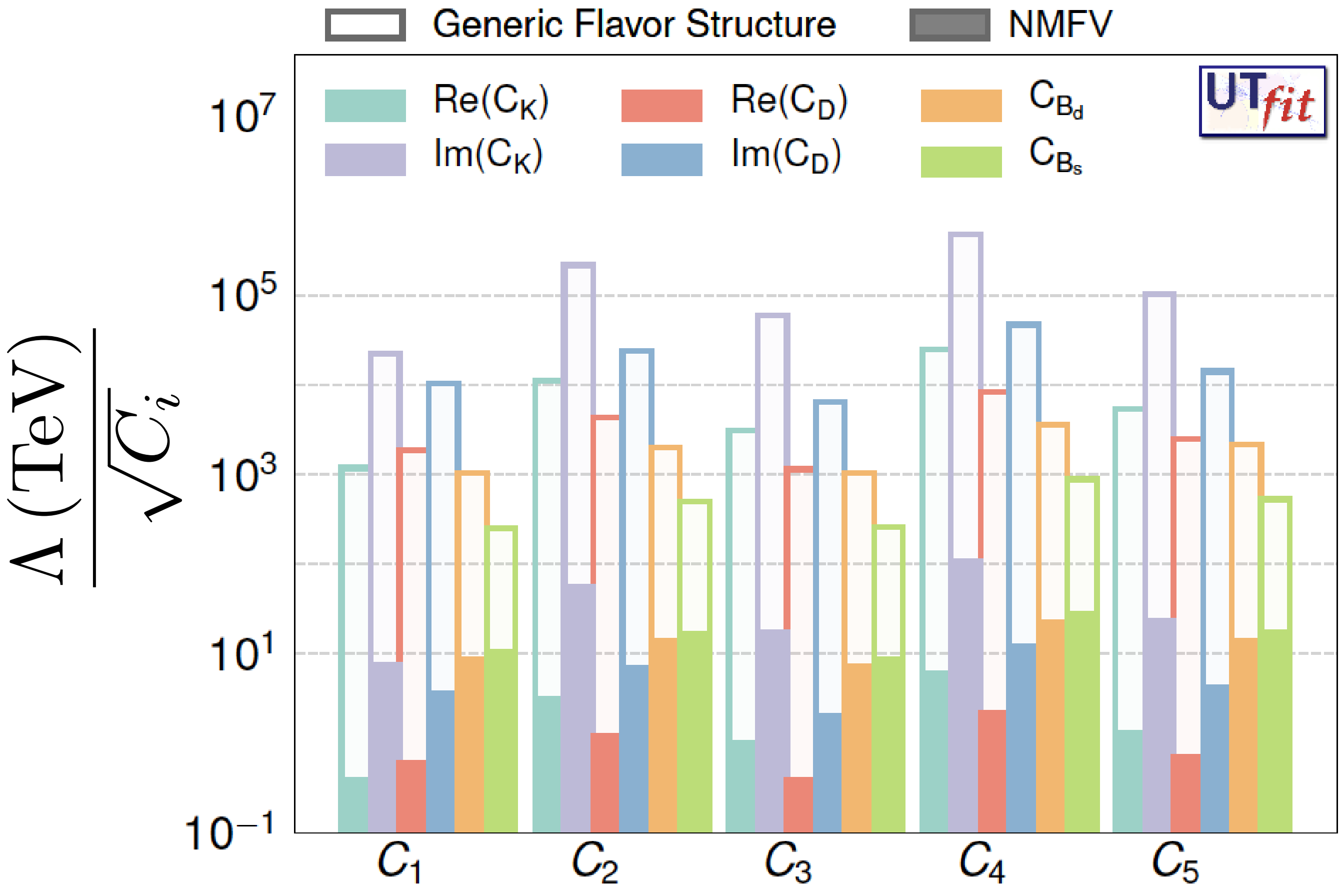
in the SM



Second solution ruled out
by semileptonic asymmetries

Laplace et al '02

NP Analysis: Bounds on the NP Scale



Meson-antimeson mixing generated by 1(8) operators in SM(NP)

Consistency of SM UTA implies stringent bounds on NP contributions

Consider one operator at a time and bound $\Lambda/\sqrt{C_i}$

Two examples: generic flavour structure or NMFV

Very demanding for model building!

Outlook

- After 60 years, precision weak interactions and flavour physics still play a key role:
  - $\Delta F=2$ processes most sensitive probe of NP
  - systematic study of a wide range of processes with unprecedented precision might reveal the presence of NP (CPV, LUV, rare decays, …)
  - HL-LHC and BelleII call for a global analysis in the context of the Standard Model Effective Theory, a formidable task requiring a change of paradigm in phenomenological studies
  - Solving the problem of the origin of the flavour hierarchy might yield precious information on NP and hopefully lead us to its discovery

Exciting times ahead for the Cabibbo angle and its practitioners!

Photo by M. Bona