CP Violation in B and D Mesons

Luca Silvestrini
INFN, Rome

- Introduction
- CP violation in $B_{(s)}$ and D decays
- Global fits and constraints on NP
  - Generalized UTA
  - The SMEFT
- Conclusions and outlook

INFN
Istituto Nazionale di Fisica Nucleare

Introduction

- The SM has a very important accidental symmetry: no tree-level FCNC $\Rightarrow$ FCNC finite and calculable
- Flavour violation only in charged weak currents, governed by unitary CKM matrix
- Flavour violation only arises at loop level: unitarity of CKM implies GIM suppression

Introduction

- No CPV in weak interactions with two generations ⇒ CPV suppressed by hierarchical structure of CKM matrix, but CKM phase large
- CKM unitarity implies triangular relations among products of CKM elements: unitarity triangles
- CPV related to angles of unitarity triangles

The Unitarity Triangle

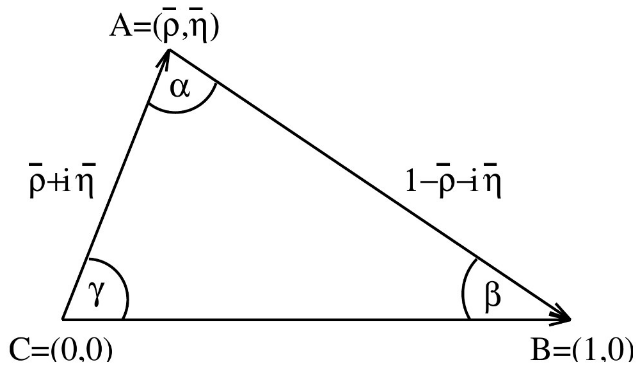
- From $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$

$$-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} - \frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*} = R_b e^{i\gamma} + R_t e^{-i\beta} = 1 \simeq (\overline{\rho} + i\overline{\eta}) + (1 - \overline{\rho} - i\overline{\eta})$$

$$R_b \equiv \left|\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right|, \quad R_t \equiv \left|\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}\right|, \quad \gamma \equiv \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right), \quad \beta \equiv \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

$$\alpha \equiv \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$$

$$\beta_s \equiv \arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right)$$



- The area of the UT is proportional to J

$b \to d$ Transitions

- $V_{ub}V_{ud}^* \sim V_{cb}V_{cd}^* \sim V_{tb}V_{td}^* \sim \lambda^3$
  - All CKM factors comparable: rich structure in $\Delta F=1$ $b \to d$
  - dispersive $\Delta F=2$ ($M_{12} \sim \Delta m_{B_d}$) dominated by top exchange: SD, calculable w. LQCD
  - absorptive $\Delta F=2$ ($\Gamma_{12} \sim \Delta\Gamma_{B_d}$) calculable in HQET, dominant contribution has top CKM: $\arg(\Gamma_{12}/M_{12})$ tiny, negligible CPV in mixing

$b \to s$ Transitions

- $V_{ub}V_{us}^* \sim \lambda^4 \ll V_{cb}V_{cd}^* \sim V_{tb}V_{td}^* \sim \lambda^2$
  - suppression of up contribution: simple structure of $\Delta F=1$ $b \to s$, squashed UT, tiny β_s
  - dispersive $\Delta F=2$ ($M_{12} \sim \Delta m_{Bs}$) dominated by top exchange: SD, calculable w. LQCD
  - absorptive $\Delta F=2$ ($\Gamma_{12} \sim \Delta\Gamma_{Bs}$) calculable in HQET, dominant contribution has top CKM: $\arg(\Gamma_{12}/M_{12})$ tiny, negligible CPV in mixing

$c \to u$ Transitions

- $V_{ub}V_{cb}^* \sim \lambda^5 \ll V_{us}V_{cs}^* \sim V_{ud}V_{cd}^* \sim \lambda$
  - very strong suppression of bottom contribution: simple structure of $\Delta F=1$ $c \to u$, super-squashed UT, no penguin operators, CPV down by $r_{CKM} \sim 6.5\ 10^{-4}$
- GIM mechanism $\Leftrightarrow$ U-spin (SU(3))
- both dispersive $\Delta F=2$ ($M_{12} \sim \Delta m_D$) and absorptive $\Delta F=2$ ($\Gamma_{12} \sim \Delta\Gamma_D$) dominated by long distance: currently not calculable (see however ongoing progress in LQCD)

ΔC=2 AMPLITUDES

- Since GIM⇔U-spin, classify ΔC=2 amplitudes in terms of U-spin: $\lambda_{d_i} \equiv V_{ud_i} V^*_{cd_i}$

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

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

$$\sim (\lambda_s - \lambda_d)^2 \mathcal{O}(\epsilon^2) + 2(\lambda_s - \lambda_d)\lambda_b \mathcal{O}(\epsilon)$$

- CPV effects expected at $O(r_{CKM}/\varepsilon) \sim 2\ 10^{-3} \sim 1/8°$ for nominal U-spin breaking ~ 30%

APPROXIMATE UNIVERSALITY

- CPV effects in $\Delta C=2$ amplitudes enhanced by $1/\varepsilon$ (factor of ~3)
- No enhancement expected (confirmed by ΔA_{CP}) for CPV in $\Delta C=1$ amplitudes
- Work at leading order in r_{CKM}/ε: take all decay amplitudes real, but allow for CPV in $\Delta C=2$, with SM~1/8° plus possible NP in M_{12}
- Corrections for DCS decays calculable and tiny
- Corrections for SCS decays not calculable but additional ε suppression from suitable U-spin combinations

APPROXIMATE UNIVERSALITY

- Working at linear order in r_{CKM}/ε, 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.

Global Fit of CPV in B and D decays

- Interference of $b \to c$ and $b \to u$ decay amplitudes measures $\gamma \equiv \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$
- Interference involves D-$\overline{D}$ mixing
- Perform a global analysis extracting γ and D mixing parameters simultaneously, combining D decays sensitive to D mixing with $B_{(s)}$ decays sensitive to γ

see LHCb 2110.02530

D-Mixing Definitions

$$|D_{\mathrm{L,S}}\rangle = p|D^0\rangle \pm q|\overline{D^0}\rangle$$

$$\phi_{12} = \arg\left(\frac{M_{12}}{\Gamma_{12}}\right), \qquad x_{12} = 2\frac{|M_{12}|}{\Gamma} \qquad \text{and} \qquad y_{12} = \frac{|\Gamma_{12}|}{\Gamma}.$$

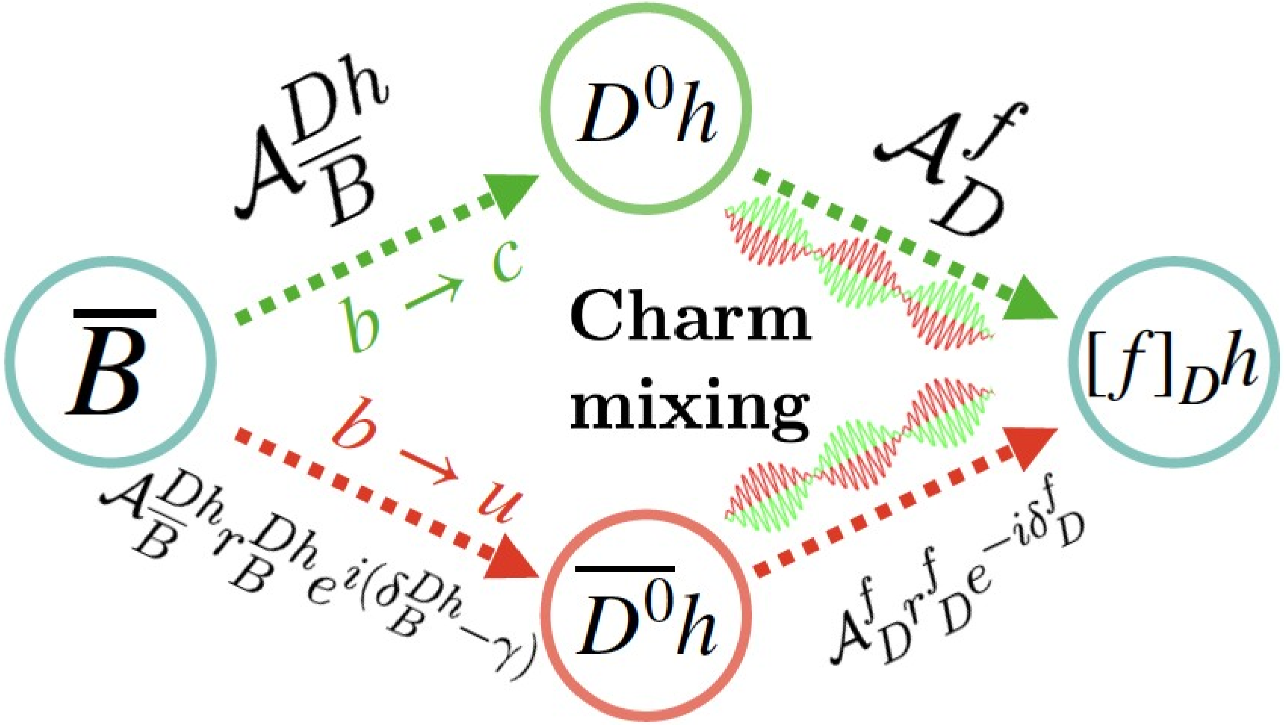
$$|x| = x_{12}, \qquad \left|\frac{q}{p}\right| - 1 = \frac{x_{12}y_{12}}{x_{12}^2 + y_{12}^2}\sin\phi_{12}, \qquad |y| = y_{12},$$

$$r_D^f e^{-i\delta_D^f} = \frac{\mathcal{A}_D^{\overline{f}}}{\mathcal{A}_D^f} \qquad \lambda_D^f \equiv \frac{q}{p}\frac{\mathcal{A}_{\overline{D}}^f}{\mathcal{A}_D^f},$$

D-Mixing Data

Observables	D^0 decays	Ref.	Observables	D^0 decays	Ref.
$(x^2+y^2)/2$	$D \to K l \bar{\nu}_l$	[24–28]	$x'^{\pm}_{K\pi\pi^0}$, $y'^{\pm}_{K\pi\pi^0}$	$D \to K\pi\pi^0$	[29]
x, y	$D \to K^0_S XX$	[30]	x, y	$D \to K^0_S \pi\pi$	[31]
x, y	$D \to \pi^+\pi^-\pi^0$	[32]	x, y, $\lvert q/p \rvert$, ϕ_2	$D \to K^0_S \pi\pi$	[36]
$(r_D^{K\pi})^2$, x^2, y, $\cos\delta_D^{K\pi}$, $\sin\delta_D^{K\pi}$	$D \to K\pi$	[33]	$\frac{\mathcal{B}(D^0\to K^0_s K^+\pi^-)}{\mathcal{B}(D^0\to K^0_s K^-\pi^+)}$, $\delta_D^{K^0_S K\pi}$, $\kappa_D^{K^0_S K\pi}$	$D \to K^0_S K\pi$	[34]
$F_+^{4\pi}$	$D \to 4\pi$	[39, 41]	$F_+^{XX\pi^0}$	$D \to XX\pi^0$	[39, 40]
$\frac{\mathcal{B}(D\to K^0_s K^+\pi^-)}{\mathcal{B}(D^0\to K^0_s K^-\pi^+)}$	$D \to K^0_S K\pi$	[42]	$F_+^{KK\pi\pi}$	$D \to K^+K^-\pi^+\pi^-$	[43]
$x_{\rm CP}$, $y_{\rm CP}$, Δx, Δy	$D \to K^0_S \pi\pi$	[37, 38]	$(x^2+y^2)/4$	$D \to K3\pi$	[44]
$r_D^{K3\pi}$, $\delta_D^{K3\pi}$, $\kappa_D^{K3\pi}$, $r_D^{K\pi\pi^0}$, $\delta_D^{K\pi\pi^0}$, $\kappa_D^{K\pi\pi^0}$	$D \to K3\pi$ $D \to K\pi\pi^0$	[44, 46–48]	$A_D(f^+)$, $A_D(\pi\pi\pi^0)$, $r_D^{K\pi}\cos\delta_D^{K\pi}$, $r_D^{K\pi}\sin\delta_D^{K\pi}$	$D \to f^+$, $D \to K\pi$ $D \to XX\pi^0$	[49]
$\tilde{y}_{\rm CP}$	$D \to XX$	[55–64]	$\Delta Y^{KK} - \Delta Y^{\pi\pi}$, ΔY	$D \to XX$	[66–69]
$(r_D^{K\pi})^2$, $c^{(\prime)}_{K\pi}$, $\Delta c^{(\prime)}_{K\pi}$, $\Delta\tilde{c}^{(\prime)}_{K\pi}$	$D \to K\pi$	[54]	$(r_D^{K\pi})^2$, $(x'^{\pm}_{K\pi})^2$, $y'^{\pm}_{K\pi}$	$D \to K\pi$	[51–53]
$A_D^{\rm CP}(KK)$, $\langle\tau\rangle_E^{KK}$	$D \to K^+K^-$	[70–72]	$\Delta A_D^{\rm CP}$, $\langle\tau\rangle_E^{KK}$, $\langle\tau\rangle_E^{\pi\pi}$	$D \to XX$	[72–74]
ΔY^{KK}, $\Delta Y^{\pi\pi}$	$D \to XX$	[65]	$A_D^{\rm CP}(XX)$, $\langle\tau\rangle_E^{KK}$, $\langle\tau\rangle_E^{\pi\pi}$	$D \to XX$	[75–78]

Time-Integrated B Decays



$$\Gamma(\overline{B} \to [f]_D h) \propto 1 + (r_D^f r_B^{Dh})^2 + 2\kappa_D^f \kappa_B^{Dh} r_D^f r_B^{Dh} \cos\left(\delta_B^{Dh} - \delta_D^f - \gamma\right) + \Gamma_{\rm mix}(x, y, \gamma, f, h)$$

$$x_\pm^{Dh} = r_B^{Dh} \cos(\delta_B^{Dh} \pm \gamma), \qquad y_\pm^{Dh} = r_B^{Dh} \sin(\delta_B^{Dh} \pm \gamma)$$

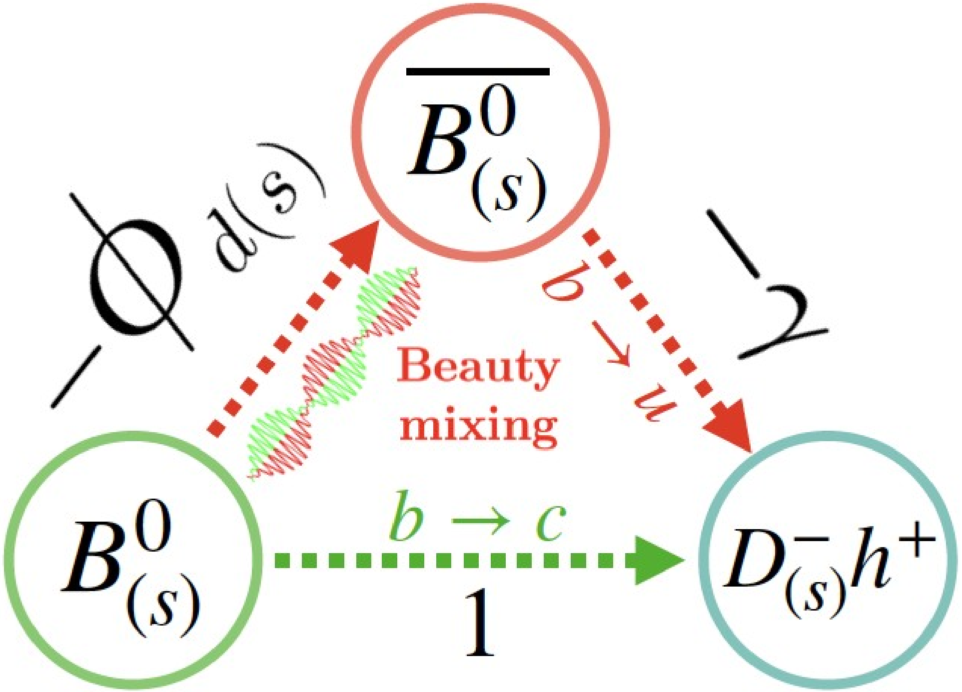
Time-Integrated data
ADS & GLW

GLW Observables	ADS Observables	$\mathrm{B} \to \mathrm{D}^0$ decays	D^0 decays	Ref.
$A_B^{\rm CP}(XX\pi^0, h)$, $R^{\rm CP}(XX\pi^0, K\pi\pi^0, K, \pi)$	$A^{\rm fav,sup}(K\pi\pi^0, h)$, $R_\pm(K\pi\pi^0, h)$	$B^\pm \to Dh^\pm$	$D \to K\pi\pi^0$, $D \to XX\pi^0$	[90]
$A_B^{\rm CP}(XX, h\pi\pi)$, $R^{\rm CP}(XX, K\pi, K\pi\pi, \pi\pi\pi)$	$A^{\rm fav}(K\pi, h\pi\pi)$, $R_\pm(K\pi, h\pi\pi)$	$B^\pm \to Dh^\pm\pi\pi$	$D \to K\pi$, $D \to XX$	[85]
$A_B^{\rm CP}(XX, K^{*\pm})$, $R(XX, K\pi, K^{*\pm})$ $A_B^{\rm CP}(4\pi, K^{*\pm})$, $R(4\pi, K3\pi, K^{*\pm})$	$A^{\rm fav,sup}(K\pi, K^{*\pm})$, $R^{\rm ADS}(K\pi, K^{*\pm})$ $A^{\rm fav,sup}(K3\pi, K^{*\pm})$, $R^{\rm ADS}(K3\pi, K^{*\pm})$	$B^\pm \to DK^{*\pm}$	$D \to K\pi$, $D \to XX$, $D \to K3\pi$, $D \to 4\pi$	[95]
$A_B^{\rm CP}(XX, K^{*0})$, $R(XX, K\pi, K^{*0})$ $A_B^{\rm CP}(4\pi, K^{*0})$, $R(4\pi, K3\pi, K^{*0})$	$A^{\rm fav}(K\pi, K^{*0})$, $R_\pm(K\pi, K^{*0})$ $A^{\rm fav}(K3\pi, K^{*0})$, $R_\pm(K3\pi, K^{*0})$	$B^0 \to DK^{*0}$ $B_s^0 \to D\overline{K^{*0}}$	$D \to K\pi$, $D \to XX$, $D \to K3\pi$, $D \to 4\pi$	[93]
$A_B^{\rm CP}(XX, h)$, $R^{\rm CP}(XX, K\pi, K, \pi)$	$A^{\rm fav}(K\pi, K)$, $R_\pm(K\pi, h)$	$B^\pm \to Dh^\pm$	$D \to K\pi$, $D \to XX$	[88]
$A_B^{\rm CP}(XX, h(\gamma, \pi^0))$, $R^{\rm CP}(XX, K\pi, K(\gamma, \pi^0), \pi(\gamma, \pi^0))$	$A^{\rm fav}(K\pi, K(\gamma, \pi^0))$, $R_\pm(K\pi, h(\gamma, \pi^0))$	$B^\pm \to [D\pi^0]_{D^*}h^\pm$ $B^\pm \to [D\gamma]_{D^*}h^\pm$	$D \to K\pi$, $D \to XX$	[88]
——	$A^{\rm fav,sup}(K_S^0 K\pi, h)$, $R^{\rm fav,sup}(K_S^0 K\pi, K, \pi)$, $R^{\rm ADS}(K_S^0 K\pi, \pi)$	$B^\pm \to Dh^\pm$	$D \to K_S^0 K\pi$	[89], [91]
$A_B^{\rm CP}(XX\pi\pi, h)$, $R^{\rm CP}(XX\pi\pi, K3\pi, K, \pi)$	——	$B^\pm \to Dh^\pm$	$D \to XX\pi\pi$	[100]
	$R^{\rm ADS}(K\pi, h)$, $A^{\rm sup}(K\pi, h)$	$B^\pm \to Dh^\pm$	$D \to K\pi$	[83]
	$R^{\rm ADS}(K\pi\pi^0, h)$, $A^{\rm sup}(K\pi\pi^0, h)$	$B^\pm \to Dh^\pm$	$D \to K\pi\pi^0$	[84]
$A_B^{\rm CP}(K^+K^-, K)$, $R^{\rm CP}(K^+K^-, K\pi, K, \pi)$ $A_B^{\rm CP}(K_S^0\pi^0, K)$, $R^{\rm CP}(K_S^0\pi^0, K\pi, K, \pi)$	——	$B^\pm \to Dh^\pm$	$D \to K^+K^-$, $D \to K\pi$, $D \to K_S^0\pi^0$	[92]
$A_B^{\rm CP}(f^\pm, K(\pi^0))$, $R^{\rm CP}(f^\pm, K\pi, K(\pi^0), \pi(\pi^0))$	——	$B^\pm \to [D\pi^0]_{D^*}h^\pm$	$D \to f^\pm$, $D \to K\pi$	[82]

Time-Integrated Data GGSZ

GGSZ Observables	B → D⁰ decays	D⁰ decays	Ref.
$x_\pm^{DK^{*0}}, y_\pm^{DK^{*0}}$	$B^0 \to DK^{*0}$	$D \to K_S^0 XX$	[103]
$x_\pm^{DK}, x_\xi^{D\pi}$ $y_\pm^{DK}, y_\xi^{D\pi}$	$B^\pm \to DK^\pm$ $B^\pm \to D\pi^\pm$	$D \to K_S^0 \pi^+\pi^-\pi^0$	[97]
$x_\pm^{DK}, x_\xi^{D\pi}$ $y_\pm^{DK}, y_\xi^{D\pi}$	$B^\pm \to DK^\pm$ $B^\pm \to D\pi^\pm$	$D \to K_S^0 XX$	[98, 99]
$x_\pm^{DK}, x_\xi^{D\pi}$ $y_\pm^{DK}, y_\xi^{D\pi}$	$B^\pm \to DK^\pm$ $B^\pm \to D\pi^\pm$	$D \to XX\pi^+\pi^-$	[100]
$x_\pm^{[D\pi^0]_{D^*}K}, x_\pm^{[D\gamma]_{D^*}K}$ $y_\pm^{[D\pi^0]_{D^*}K}, y_\pm^{[D\gamma]_{D^*}K}$	$B^\pm \to [D\pi^0]_{D^*}K^\pm$ $B^\pm \to [D\gamma]_{D^*}K^\pm$	$D \to K_S^0 \pi^+\pi^-$	[96]
$x_\pm^{D^*K}, x_\xi^{D^*\pi}$ $y_\pm^{D^*K}, y_\xi^{D^*\pi}$	$B^\pm \to D^*K^\pm$ $B^\pm \to D^*\pi^\pm$	$D \to K_S^0 XX$	[101, 102]
$x_\pm^{DK^{*\pm}}, y_\pm^{DK^{*\pm}}$	$B^\pm \to DK^{*\pm}$	$D \to K_S^0 XX$	[95]
$x_\pm^{DK}, x_\xi^{D\pi}$ $y_\pm^{DK}, y_\xi^{D\pi}$	$B^\pm \to DK^\pm$ $B^\pm \to D\pi^\pm$	$D \to K^\mp\pi^\pm\pi^+\pi^-$	[94][a]

Time-Dependent B Decays



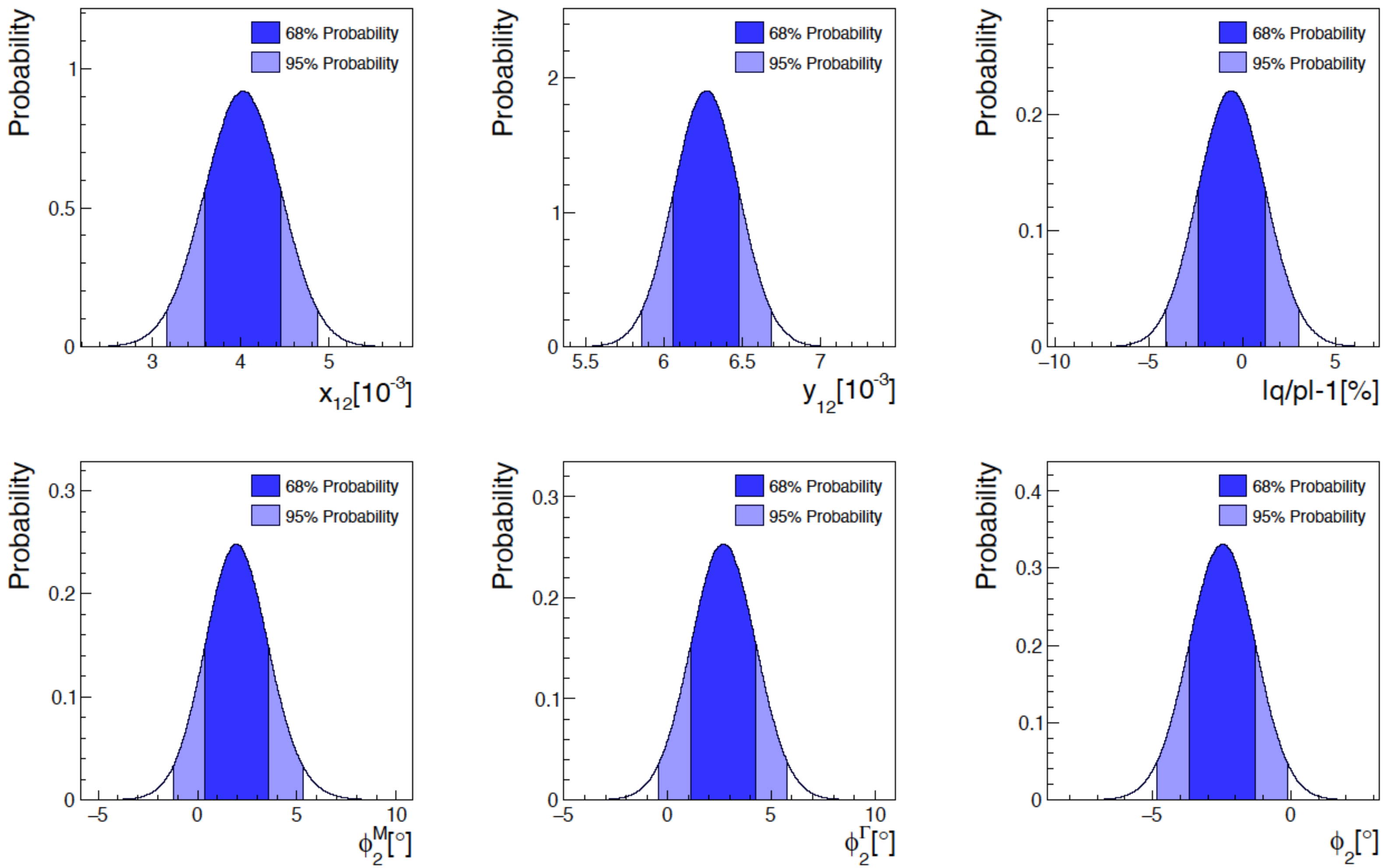
$$\Gamma(B^0_{(s)} \to f, t) \propto \cosh\big(t\Delta\Gamma_{(s)}/2\big) - G_f \sinh\big(t\Delta\Gamma_{(s)}/2\big) + C_f \cos\big(t\Delta m_{(s)}\big) - S_f \sin\big(t\Delta m_{(s)}\big)$$

$$C_f = \frac{1-(r^f_{B^0_{(s)}})^2}{1+(r^f_{B^0_{(s)}})^2}, \quad G_f = \frac{-2\eta_{(s)}\kappa^f_{B^0_{(s)}} r^f_{B^0_{(s)}}}{1+(r^f_{B^0_{(s)}})^2} \cos\Big(\delta^f_{B^0_{(s)}} - (\phi_{d(s)}+\gamma)\Big), \quad S_f = \frac{2\eta_{(s)}\kappa^f_{B^0_{(s)}} r^f_{B^0_{(s)}}}{1+(r^f_{B^0_{(s)}})^2} \sin\Big(\delta^f_{B^0_{(s)}} - (\phi_{d(s)}+\gamma)\Big),$$

Time-Dependent Data

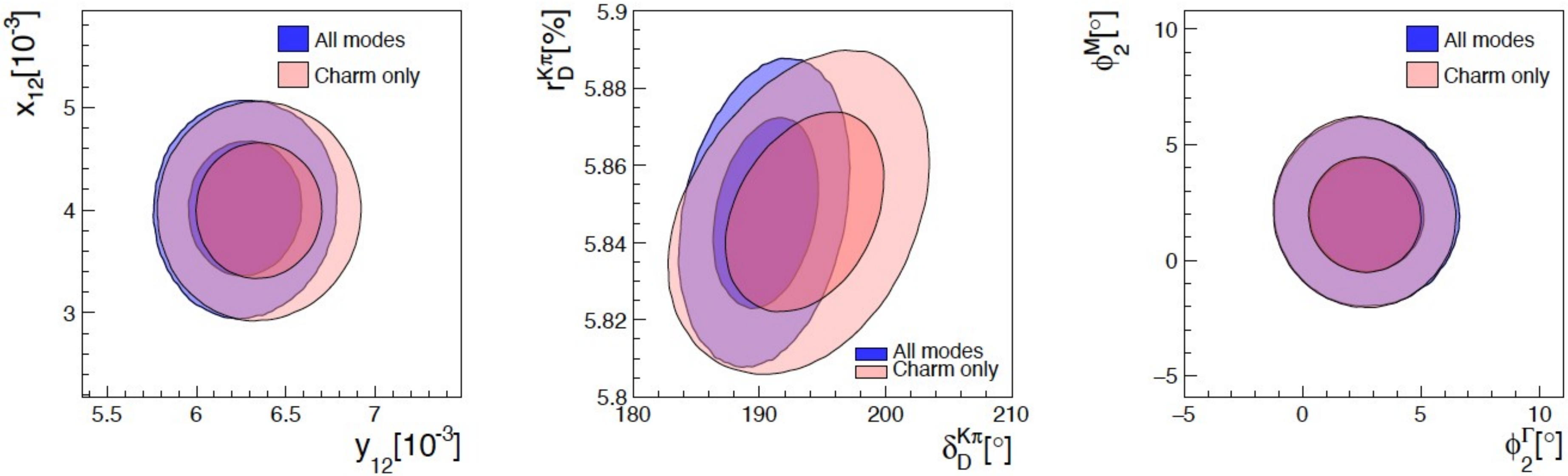
Observables			$\mathbf{B^0_{(s)} \to D^{\mp}_{(s)} h^{\pm}}$ **decays**	**Ref.**
$C_{D_s^{\mp} K^{\pm}}$,	$G_{D_s^{\mp} K^{\pm}}$,	$S_{D_s^{\mp} K^{\pm}}$	$B_s^0 \to D_s K$	[106]
	$S_{D^{\mp}\pi^{\pm}}$		$B^0 \to D\pi$	[104]
$C_{D_s^{\mp} K^{\pm}\pi\pi}$,	$G_{D_s^{\mp} K^{\pm}\pi\pi}$,	$S_{D_s^{\mp} K^{\pm}\pi\pi}$	$B_s^0 \to D_s K\pi\pi$	[105]

Results: D mixing parameters



Betti et al. 2409.06449

Results: D mixing parameters



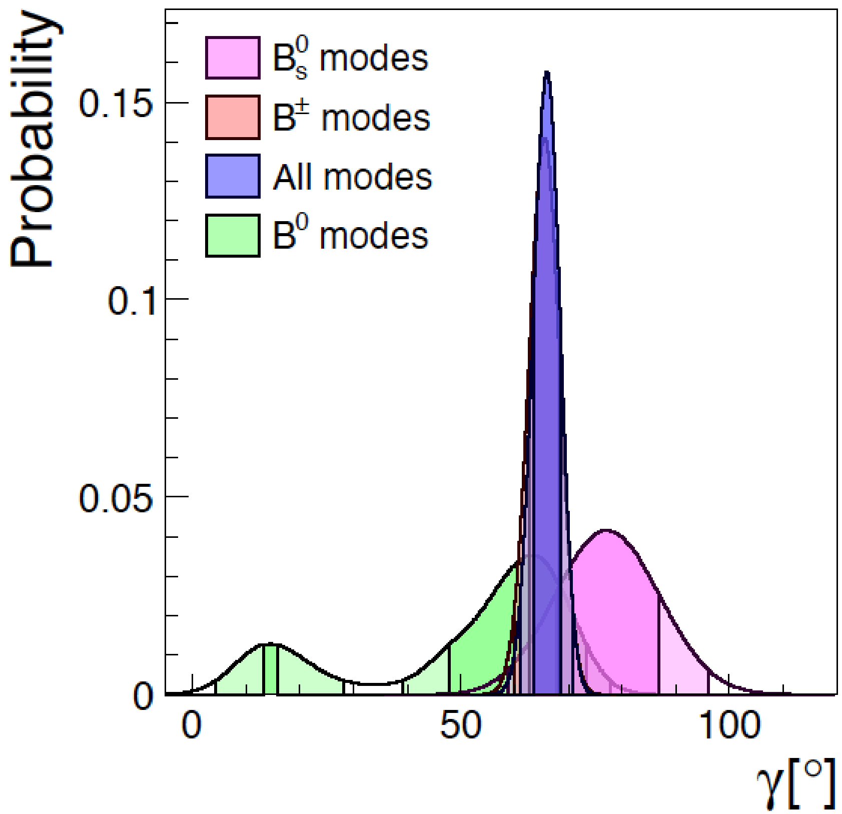
Betti et al. 2409.06449

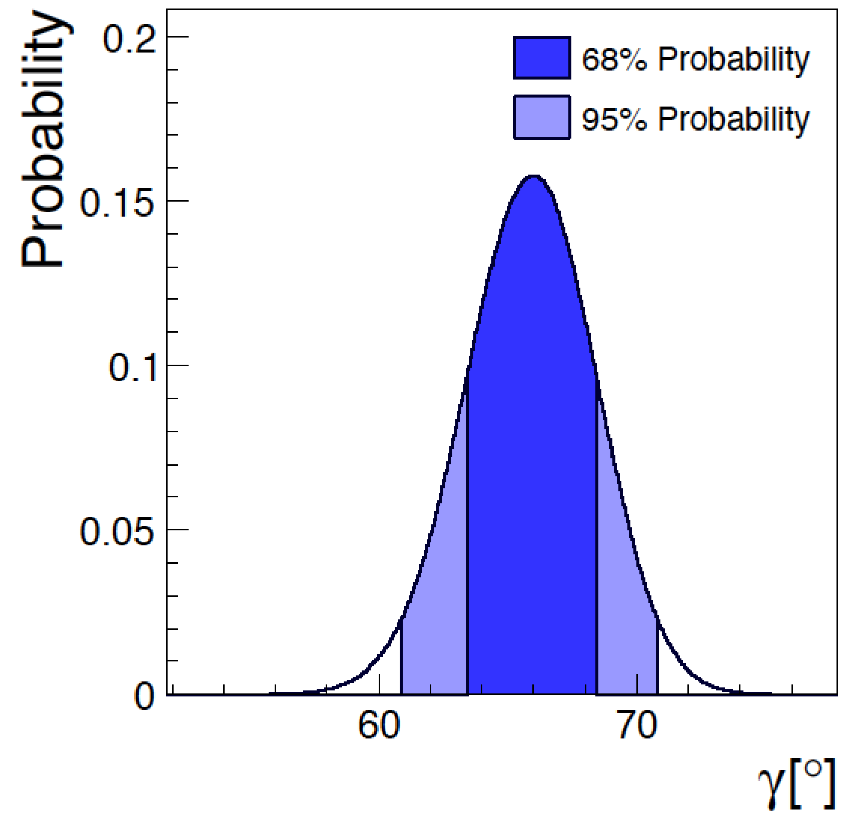
Results: D mixing parameters

Par.	All modes			Charm only		
	Value	Unc.	95% Prob.	Value	Unc.	95% Prob.
$\phi_2^M[°]$	1.9	±1.6	$[-1.3, 5.4]$	2.0	±1.7	$[-1.3, 5.4]$
$\phi_2^\Gamma[°]$	2.7	±1.6	$[-0.5, 5.8]$	2.6	±1.6	$[-0.5, 5.7]$
$\phi_2[°]$	-2.5	±1.2	$[-4.9, -0.1]$	-2.4	±1.2	$[-4.8, 0.0]$
$\lvert q/p\rvert - 1[\%]$	-0.6	±1.8	$[-4.2, 3.1]$	-0.5	±1.8	$[-4.1, 3.2]$
$x_{12} \simeq x[‰]$	4.02	±0.44	$[3.15, 4.89]$	4.00	±0.44	$[3.12, 4.87]$
$y_{12} \simeq y[‰]$	6.27	±0.21	$[5.85, 6.69]$	6.35	±0.23	$[5.88, 6.82]$
$a_D^{KK}[‰]$	0.39	±0.57	$[-0.76, 1.52]$	0.38	±0.57	$[-0.76, 1.51]$
$a_D^{\pi\pi}[‰]$	2.40	±0.63	$[1.14, 3.66]$	2.39	±0.63	$[1.14, 3.66]$
$\phi_{12}[°]$	-0.7	±2.3	$[-5.3, 4.0]$	-0.7	±2.3	$[-5.2, 4.1]$
$r_D^{K\pi}[\%]$	5.848	±0.016	$[5.815, 5.880]$	5.848	±0.017	$[5.813, 5.881]$
$\delta_D^{K\pi}[°]$	190.5	±2.8	$[184.9, 196.0]$	193.7	±4.2	$[184.9, 201.7]$

Betti et al. 2409.06449

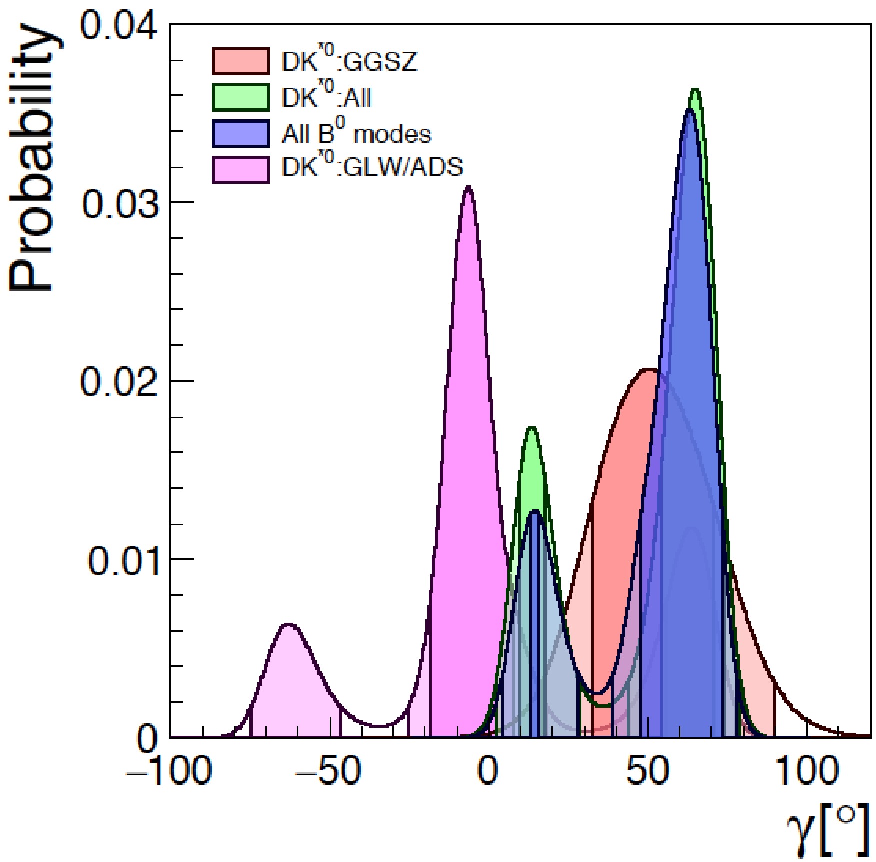
Results: γ

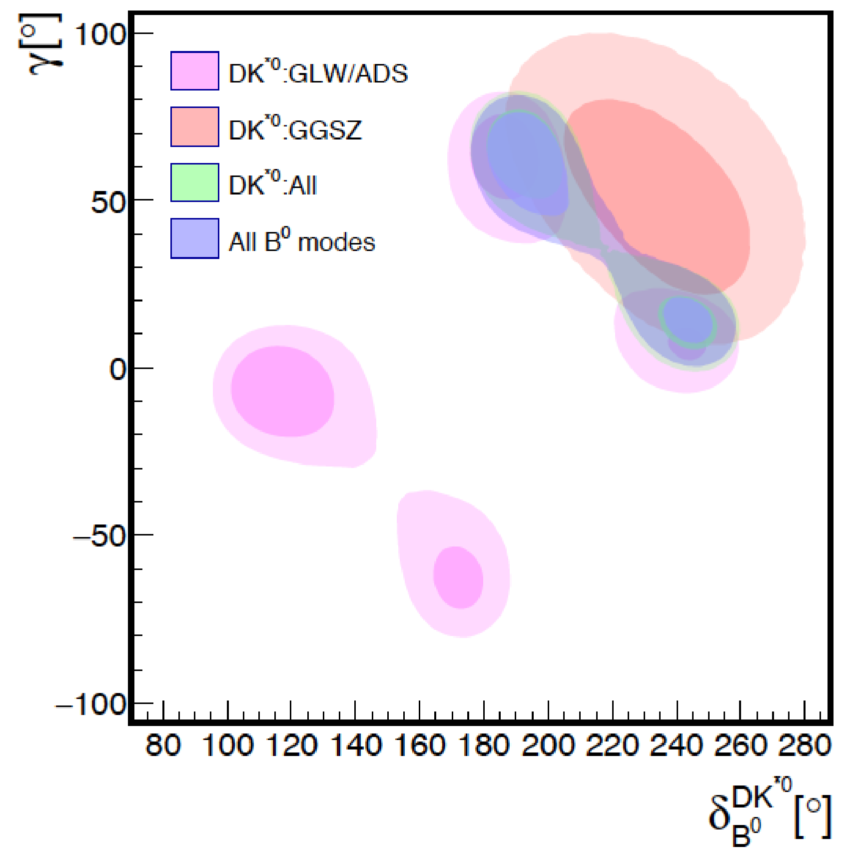




Betti et al. 2409.06449

Results: γ





Betti et al. 2409.06449

Results: γ

B meson types	Value	Unc.	95% Prob.
All modes : $\gamma[^\circ]$	66.0	± 2.5	$[60.8, 70.9]$
$\mathbf{B}^{\pm}$: $\gamma_{B^\pm}[^\circ]$	65.5	± 2.8	$[59.7, 71.0]$
$\mathbf{B}^{0}$: $\gamma_{B^0}[^\circ]$	$[12.8, 14.6] \cup [47, 74]$ @ 68.7% probability		
$\mathbf{B}^{0}_{\mathbf{s}}$: $\gamma_{B^0_s}[^\circ]$	77.3	± 9.6	$[58.3, 96.3]$

Betti et al. 2409.06449

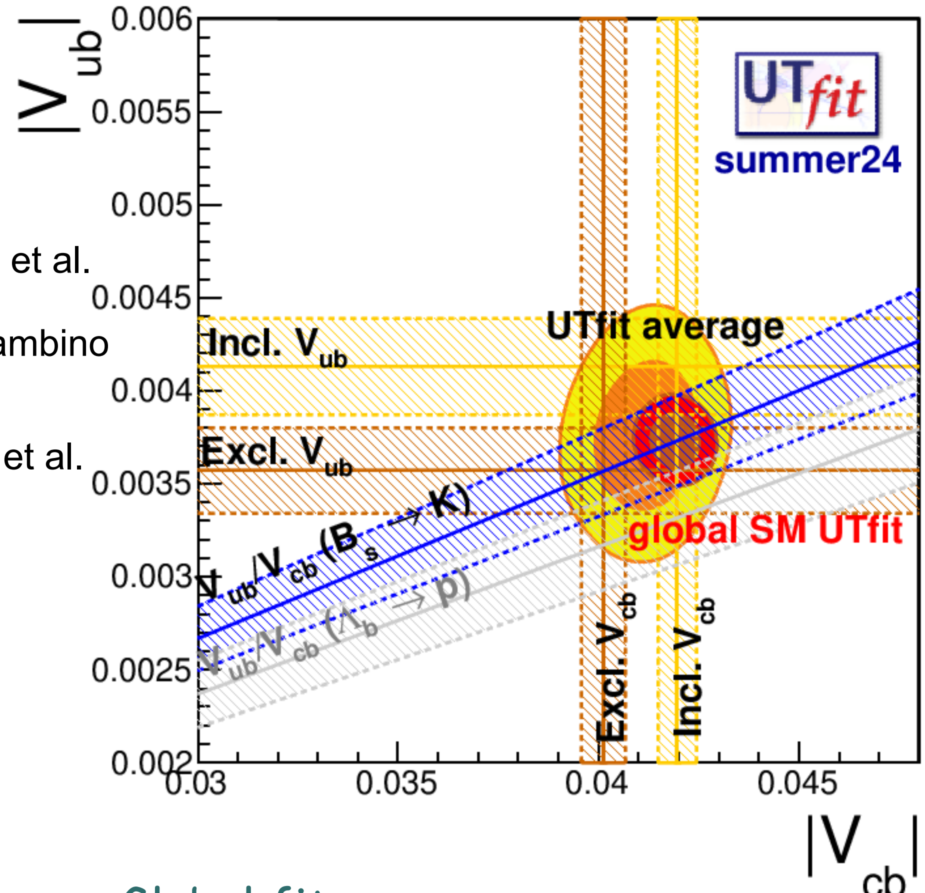
The UTA

- Recent improvements/extensions in UTfit:
  - skeptic combination of V_{ud} and V_{us} given the tension with unitarity - otherwise get artificially small uncertainty as in CKMfitter talk yesterday
  - revised exclusive V_{cb} and V_{ub} with new FFs
  - skeptic 2D combination of V_{ub} and V_{cb} given the tension among inclusive and exclusive
  - inclusion of ε'/ε with lattice matrix elements

See also CKMfitter

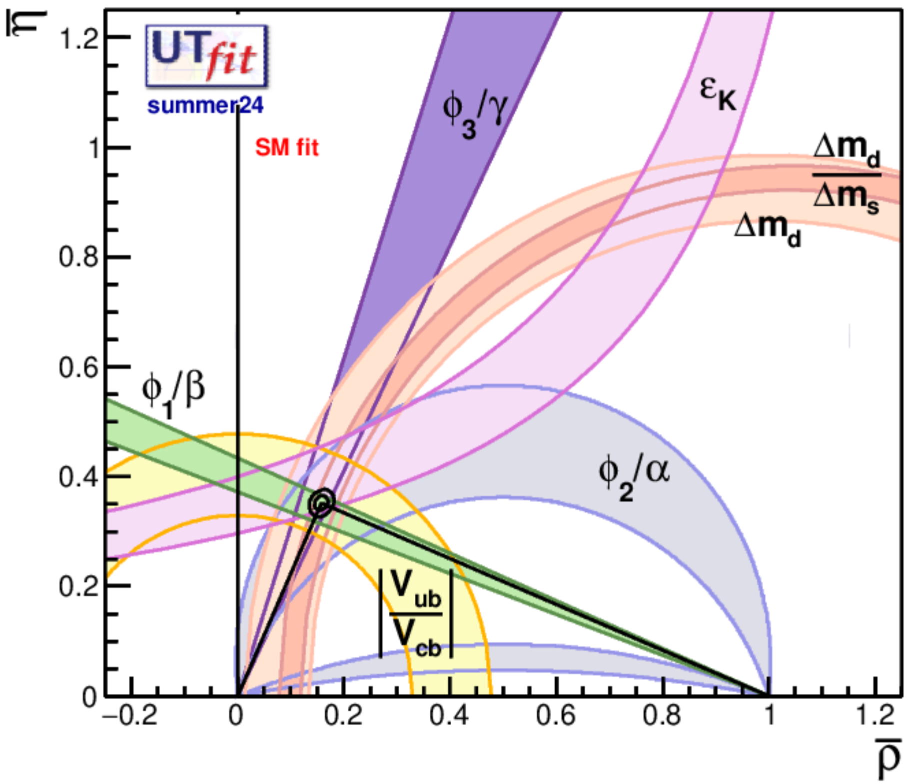
$|V_{ub}|$ AND $|V_{cb}|$ INCL. & EXCL.

- Skeptic 2D combination of inclusive and exclusive:
  - $|V_{cb}|_{excl} = (40.13 \pm 0.55)\ 10^{-3}$ Martinelli et al.
  - $|V_{cb}|_{incl} = (41.97 \pm 0.48)\ 10^{-3}$ Finauri & Gambino
  - $|V_{ub}|_{excl} = (3.57 \pm 0.23)\ 10^{-3}$ Martinelli et al.
  - $|V_{ub}|_{incl} = (4.13 \pm 0.26)\ 10^{-3}$ PDG24
  - $|V_{ub}/V_{cb}| = (8.7 \pm 0.9)\ 10^{-2}$ LHCb/FLAG
- we get:
  - $|V_{ub}| = (3.84 \pm 0.35)\ 10^{-3}$
  - $|V_{cb}| = (41.20 \pm 0.74)\ 10^{-3}$, Ξ=0.11



- Global fit:
  $|V_{ub}| = (3.73 \pm 0.09)\ 10^{-3}$,
  $|V_{cb}| = (41.91 \pm 0.40)\ 10^{-3}$

Full UTA



$\bar{\rho} = 0.158 \pm 0.009$

$\bar{\eta} = 0.352 \pm 0.010$

$\lambda = 0.2250 \pm 0.0007$

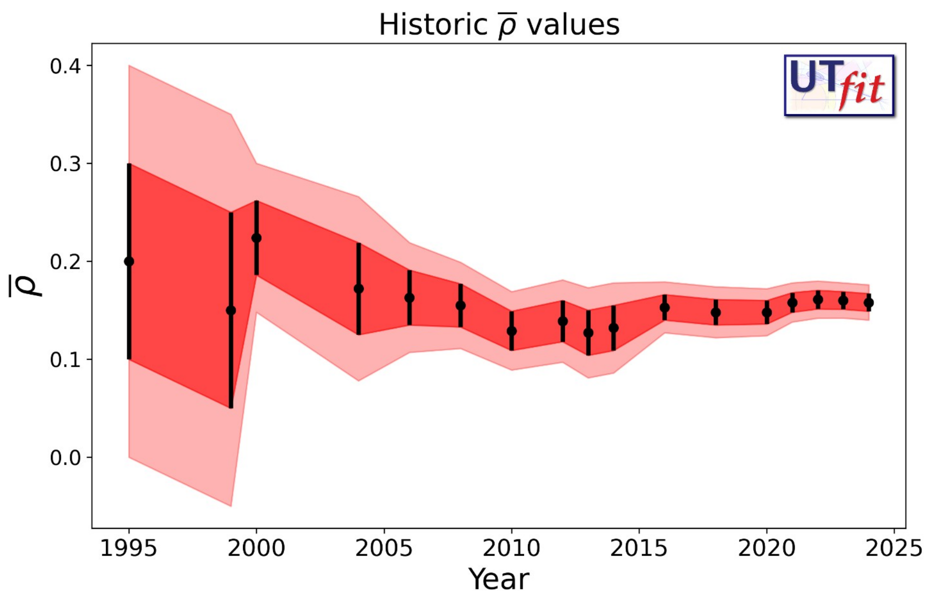
$A = 0.826 \pm 0.009$

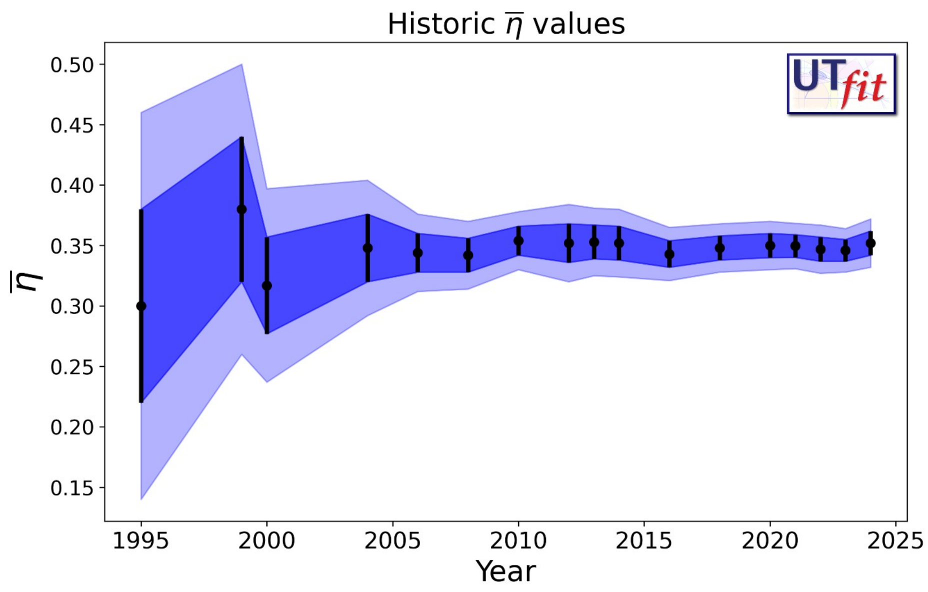
$Re(\varepsilon'/\varepsilon) = (1.60 \pm 0.28)\ 10^{-3}$

$\overline{BR}(B_s \to \mu^+\mu^-) = (3.44 \pm 0.12)\ 10^{-9}$

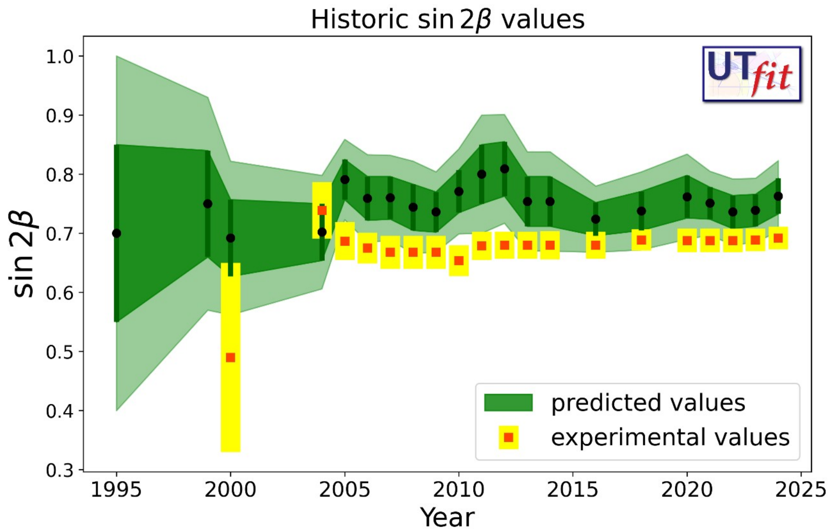
$BR(B \to \tau\nu) = (8.72 \pm 0.41)\ 10^{-5}$

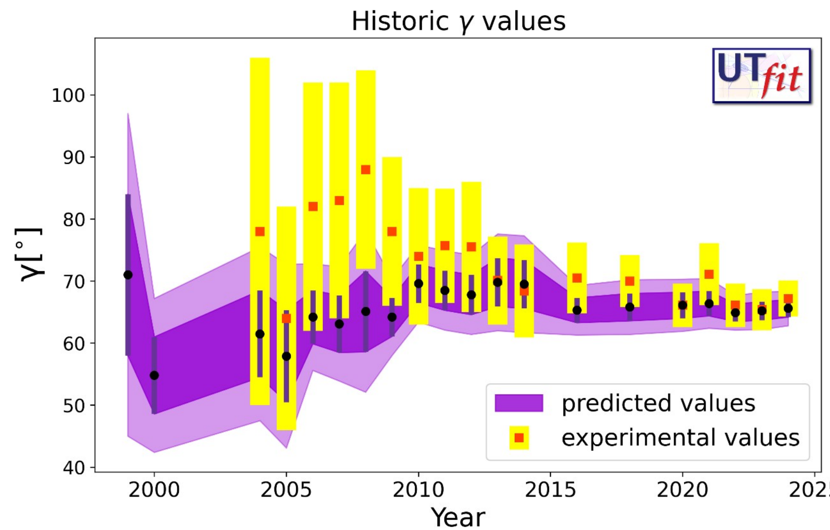
UTfit Over the Years

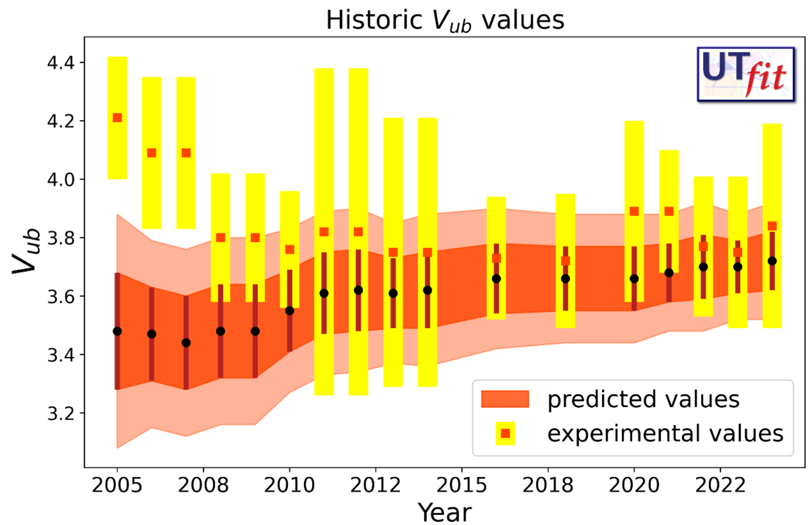




UTfit & Exp Over the Years







NEW PHYSICS IN $\Delta F=2$

- Generalize the UTA allowing for NP in loop-mediated processes:
  - V_{ud}, V_{cb}, V_{ub}, γ from trees and α unaffected (provided no huge NP effect in EWP)
  - NP allowed in $\Delta F=2$ processes
- Extract both CKM parameters and NP contributions

NP ANALYSIS: RESULTS

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

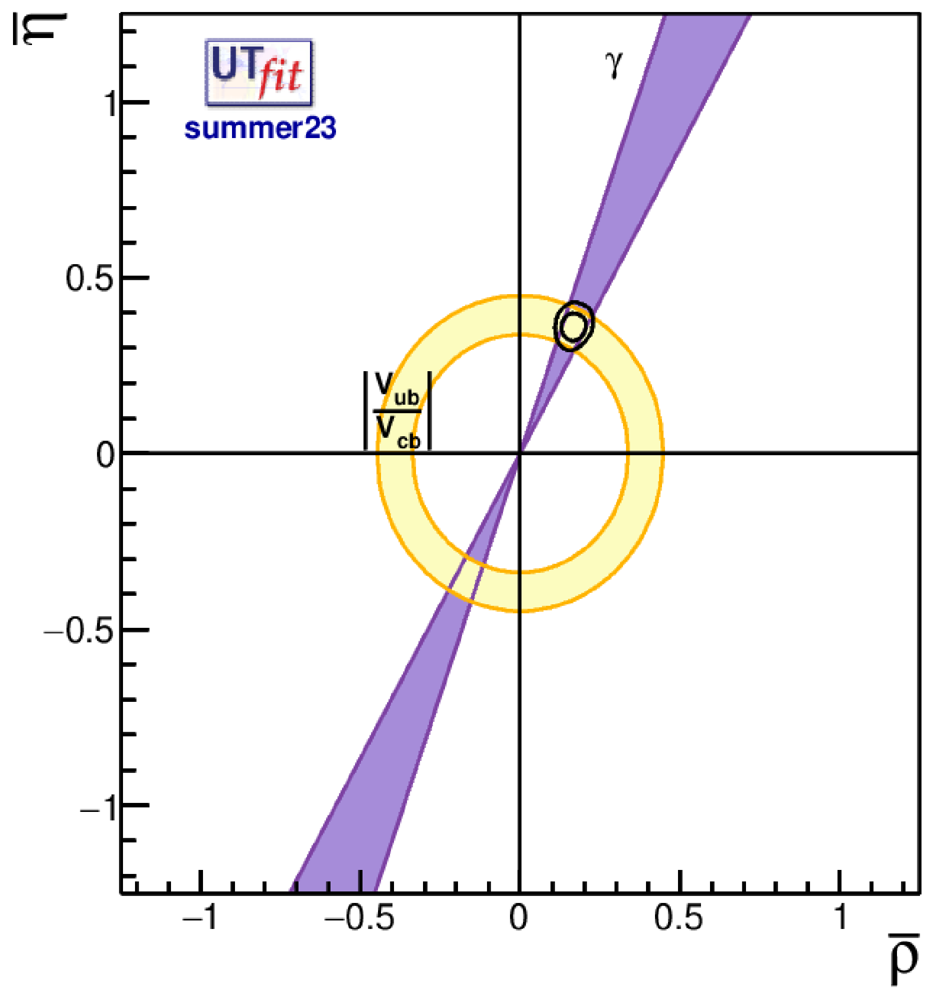
$\bar{\eta} = 0.361 \pm 0.027$

to be compared w.

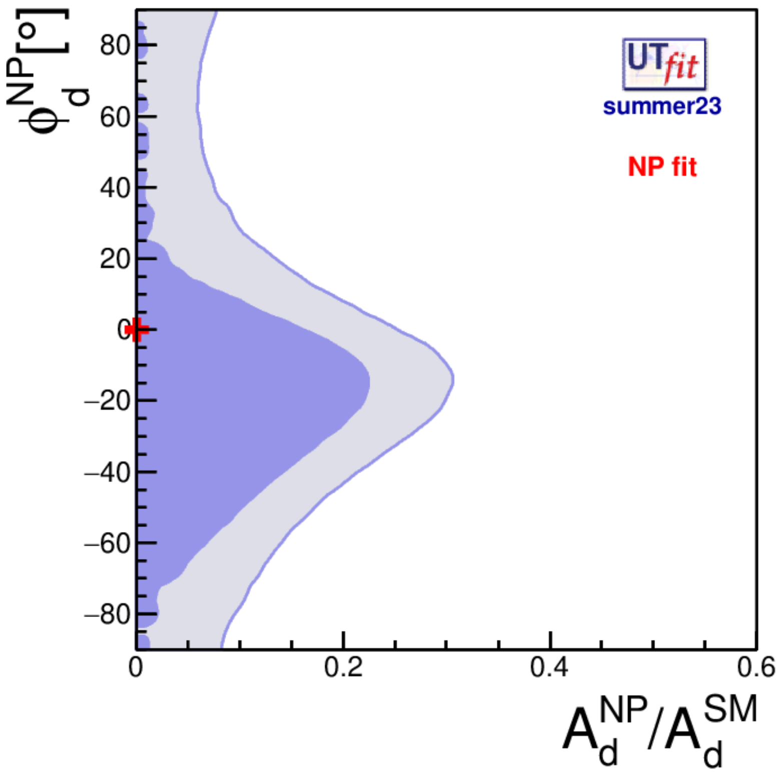
$\bar{\rho} = 0.158 \pm 0.009$

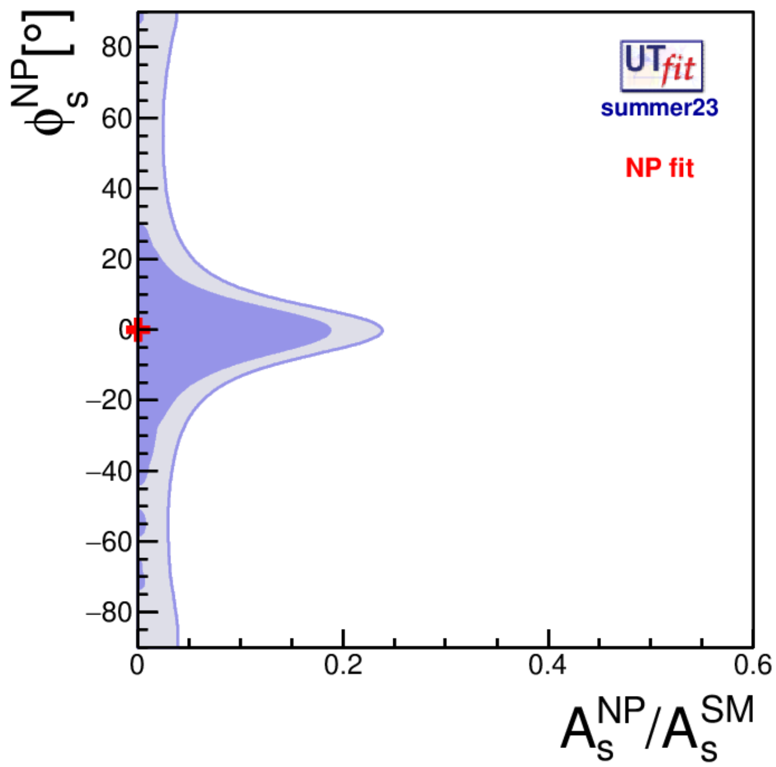
$\bar{\eta} = 0.352 \pm 0.010$

in the SM. Improvements in $|V_{ub}|$, $|V_{cb}|$, γ and α crucial to increase the sensitivity to NP!



NP Contributions



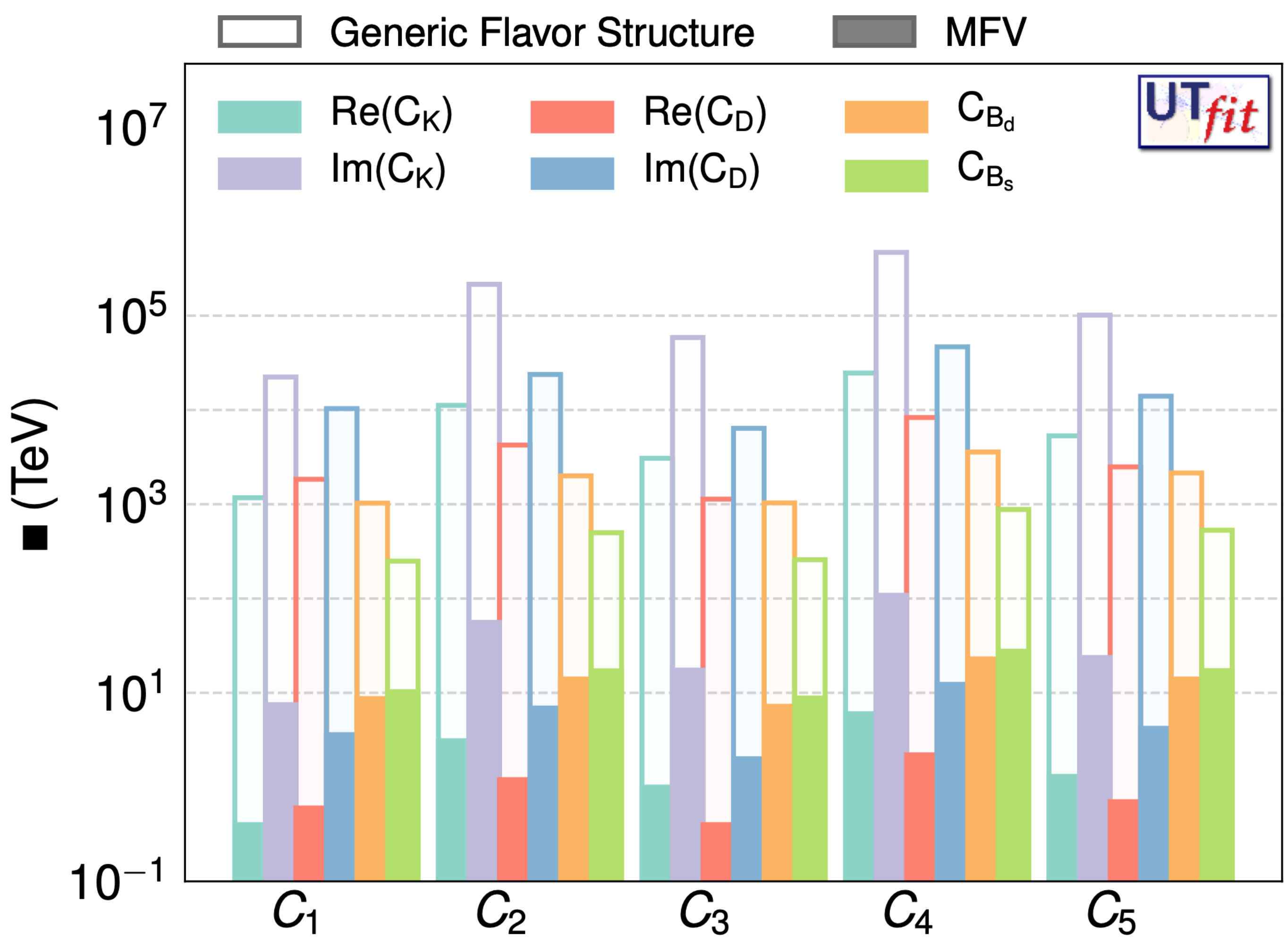


Marginalizing on the phase: $A_{NP}{}^d/A_{SM}{}^d < 30\%$ and $A_{NP}{}^s/A_{SM}{}^s < 25\%$ at 95% probability

FROM ΔF=2 TO THE NP SCALE

- $H_{\mathrm{eff}\Delta}^{F=2} = \sum_{i=1}^{5} C_i \, O_i + \sum_{i=1}^{3} C_i' \, O_i'$
- In the SM only O_1 (V-A)
- Operators with i>1 are RG- and chirally-enhanced
- In general, $C_i \sim F_i L_i / \pi^2$
- Take L_i=1 and F_i = 1 (generic) or $F_i \sim F_1^{SM}$ (next-to-minimal flavour violation)

FROM ΔF=2 TO THE NP SCALE



The Next Frontier: Global Fits in the SMEFT

- Assuming no sizable NP effect in tree-level processes is reasonable, but can we be more general?
- Most general gauge-invariant effective theory built with SM fields: the SMEFT
- 2499 B- and L-conserving operators at D=6
- Goal for the next decades: explore the full landscape of the SMEFT

First steps in the SMEFT

- Flavour assumptions: $U(3)^5$ (59 ops), $U(2)^5$ (124 ops), MFV, ...
- Work at linear order in the SMEFT
- Determine simultaneously SM parameters + SMEFT coefficients
- Need to generalize expressions for all observables
- Combine with EW, Higgs, top & DY
- Everything implemented from scratch in HEPfit

$U(2)^5$ Results - PRELIMINARY

	C	$\Lambda/\sqrt{C}$		C	$\Lambda/\sqrt{C}$		C	$\Lambda/\sqrt{C}$
C_G	1.26 ± 0.77	1.8	C_W	-0.70 ± 0.46	2.4	$C_{\phi G}$	-0.014 ± 0.010	16.3
$C_{\phi W}$	-0.071 ± 0.046	7.5	$C_{\phi B}$	-0.020 ± 0.015	13.5	$C_{\phi WB}$	0.040 ± 0.027	9.9
$C_{\phi D}$	0.032 ± 0.084	6.6	$C_{\phi box}$	-3.2 ± 2.1	1.1	C_{ϕ}	$--$	$--$
$C_{\phi l}^{(1)a}$	-0.031 ± 0.040	9.0	$C_{\phi l}^{(1)3}$	0.04 ± 0.16	5.1	$C_{\phi l}^{(3)a}$	-0.067 ± 0.054	7.2
$C_{\phi l}^{(3)3}$	0.10 ± 0.14	4.9	$C_{\phi e}^{a}$	0.068 ± 0.053	7.2	$C_{\phi e}^{3}$	-0.16 ± 0.17	4.3
$C_{\phi q}^{(1)a}$	0.0016 ± 0.0033	34.4	$C_{\phi q}^{(1)3}$	-0.0019 ± 0.0033	33.9	$C_{\phi q}^{(3)a}$	0.0018 ± 0.0031	34.9
$C_{\phi q}^{(3)3}$	-0.0016 ± 0.0028	37.1	$C_{\phi u}^{a}$	0.34 ± 0.37	2.9	$C_{\phi u}^{3}$	-0.01 ± 0.15	5.4
$C_{\phi d}^{a}$	-0.76 ± 0.76	2.0	$C_{\phi d}^{3}$	-2.0 ± 1.0	1.5	$C_{\phi ud}^{3}$	-3.9 ± 6.0	0.8
$C_{\phi eH}^{3}$	0.131 ± 0.070	5.8	$C_{\phi uH}^{3}$	8.1 ± 4.6	0.8	$C_{\phi dH}^{3}$	-0.037 ± 0.074	7.0
$C_{u_3 G}$	-0.151 ± 0.096	5.2	$C_{u_3 W}$	-0.35 ± 0.28	3.2	$C_{u_3 B}$	-0.24 ± 0.17	3.9
$C_{d_3 G}$	-4.6 ± 3.8	0.9	$C_{d_3 W}$	-0.29 ± 0.43	3.0	$C_{d_3 B}$	3.2 ± 5.3	0.8
$C_{e_3 W}$	3.1 ± 1.8	1.2	$C_{e_3 B}$	10.0 ± 5.1	0.8	C_{ll}^{aabb}	-0.20 ± 0.23	3.7
C_{ll}^{abba}	-0.016 ± 0.099	6.6	C_{ll}^{aa33}	-0.02 ± 0.32	3.8	C_{ll}^{a33a}	0.06 ± 0.29	3.8
C_{ll}^{3333}	2.8 ± 4.6	0.9	$C_{lq}^{(1)aabb}$	0.0044 ± 0.0046	27.8	$C_{lq}^{(1)aa33}$	-0.0043 ± 0.0047	27.4
$C_{lq}^{(1)33aa}$	0.31 ± 0.23	3.4	$C_{lq}^{(1)3333}$	-0.47 ± 0.81	2.2	$C_{lq}^{(3)aabb}$	0.0006 ± 0.0037	33.7
$C_{lq}^{(3)aa33}$	-0.0042 ± 0.0048	27.8	$C_{lq}^{(3)33aa}$	-0.020 ± 0.031	10.7	$C_{lq}^{(3)3333}$	0.42 ± 0.39	2.7
C_{ee}^{aabb}	-0.12 ± 0.14	4.8	C_{ee}^{aa33}	-0.01 ± 0.18	4.9	C_{ee}^{3333}	6.8 ± 7.2	0.8
C_{eu}^{aabb}	0.020 ± 0.040	9.5	C_{eu}^{aa33}	0.56 ± 0.46	2.5	C_{eu}^{33aa}	0.23 ± 0.17	4.0
C_{eu}^{3333}	-1.4 ± 1.5	1.4	C_{ed}^{aabb}	-0.06 ± 0.12	5.5	C_{ed}^{aa33}	1.1 ± 2.0	1.3
C_{ed}^{33aa}	-0.68 ± 0.51	2.3	C_{ed}^{3333}	-7.9 ± 7.2	0.8	C_{le}^{aabb}	0.05 ± 0.38	3.4
C_{le}^{aa33}	-0.74 ± 0.96	1.8	C_{le}^{33aa}	-0.55 ± 0.95	1.9	C_{le}^{3333}	-0.53 ± 0.18	0.9
C_{lu}^{aabb}	0.049 ± 0.084	6.6	C_{lu}^{aa33}	-0.29 ± 0.22	3.7	C_{lu}^{33aa}	0.48 ± 0.35	2.8
C_{lu}^{3333}	0.2 ± 1.4	1.7	C_{ld}^{aabb}	-0.13 ± 0.25	3.8	C_{ld}^{aa33}	0.5 ± 4.7	1.0
C_{ld}^{33aa}	-1.4 ± 1.0	1.6	C_{ld}^{3333}	-5.6 ± 9.2	0.8	C_{qe}^{aabb}	0.051 ± 0.098	6.0
C_{qe}^{aa33}	0.57 ± 0.39	2.6	C_{qe}^{33aa}	-0.45 ± 0.32	3.0	C_{qe}^{3333}	0.8 ± 1.1	1.8
C_{ledq}^{3333}	-6.1 ± 8.9	0.8	$C_{qq}^{(1)aabb}$	-0.023 ± 0.017	13.5	$C_{qq}^{(1)abba}$	-0.024 ± 0.015	13.5
$C_{qq}^{(1)aa33}$	0.0102 ± 0.0090	19.1	$C_{qq}^{(1)a33a}$	0.0119 ± 0.0079	18.8	$C_{qq}^{(1)3333}$	-0.010 ± 0.016	15.7
$C_{qq}^{(3)aabb}$	-0.017 ± 0.014	14.4	$C_{qq}^{(3)abba}$	-0.022 ± 0.016	13.6	$C_{qq}^{(3)aa33}$	0.0083 ± 0.0064	21.1
$C_{qq}^{(3)a33a}$	0.0132 ± 0.0082	18.5	$C_{qq}^{(3)3333}$	-0.020 ± 0.014	14.3	C_{uu}^{aabb}	0.65 ± 0.93	1.9
C_{uu}^{abba}	1.1 ± 1.3	1.6	C_{uu}^{aa33}	1.2 ± 1.2	1.6	C_{uu}^{a33a}	0.49 ± 0.45	2.6
C_{uu}^{3333}	-0.29 ± 0.61	2.6	C_{dd}^{aabb}	4.2 ± 5.3	0.8	C_{dd}^{abba}	5.3 ± 6.7	0.8
C_{dd}^{aa33}	6.7 ± 8.1	0.8	C_{dd}^{a33a}	-6.65 ± 0.35	0.8			

deBlas et al; see also Allwicher et al; Bartocci et al; Hiller et al;

Conclusions

- Impressive experimental progress in CPV in B and D decays, best summarized by the UTA
- Current data still allow for NP contributions in $\Delta F=2$ processes at the level of 25-30% of the SM. This however already corresponds to impressive bounds on the NP scale.
- First steps towards a fully general SMEFT analysis, long way to go but leads to unbiased NP search and hopefully to evidence of NP!