INTRODUCTION TO FLAVOUR PHYSICS

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- Introduction
- CP violation and the CKM matrix
- Rare decays and Lepton Universality/Flavour Violation
- Conclusions and outlook

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INTRODUCTION

- The LHC has so far confirmed the validity of the SM: the most general renormalizable theory w. gauge group $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$, 3 generations of quarks and leptons and one Higgs doublet
- No new particle has been detected, pushing lower bounds on NP in the multi-TeV range (with caveats)

INTRODUCTION

- The SM has several accidental symmetries, among which the absence of tree-level Flavour Changing Neutral Currents
- All flavour mixing & weak CPV in the SM occurs in charged currents, described by CKM parameters, e.g. λ, A, $\bar{\rho}$, $\bar{\eta}$
- FCNC couplings arise at loop level and are CKM- and GIM-suppressed
  - highly sensitive to virtual effects of heavy NP
  - Any observable FCNC for charged leptons would be a clean signal of NP
  - In the quark sector, FCNC Z vertices and $\Delta F=2$ offer best sensitivity
  - Dispersive CPV in charm mixing null test of the SM
- Flavour physics crucial for indirect NP searches, waiting for the energy frontier to be pushed further

INTRODUCTION

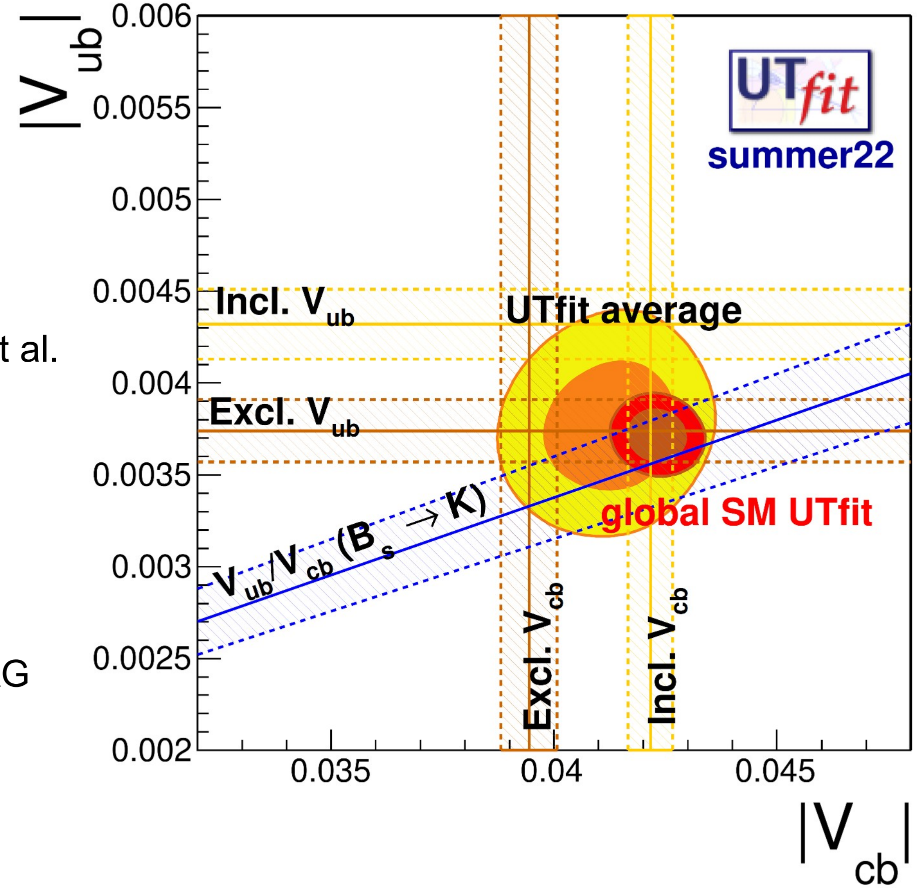
- Given the current bounds from direct searches, it is reasonable to assume that NP is negligible in tree-level SM processes:
  - determine CKM parameters from tree-level amplitudes
  - search for NP by comparing SM predictions for loop-mediated processes ($\Delta F=2$, rare decays) to experimental data

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

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

- Skeptic 2D combination of inclusive and exclusive:
  - $|V_{cb}|_{excl} = (39.44 \pm 0.63)\ 10^{-3}$ UTfit
  - $|V_{cb}|_{incl} = (42.16 \pm 0.50)\ 10^{-3}$ Bordone et al.
  - $|V_{ub}|_{excl} = (3.74 \pm 0.17)\ 10^{-3}$ FLAG
  - $|V_{ub}|_{incl} = (4.32 \pm 0.29)\ 10^{-3}$ GGOU
  - $|V_{ub}/V_{cb}| = (8.44 \pm 0.56)\ 10^{-2}$ LHCb/FLAG
- we get:
  - $|V_{ub}| = (3.77 \pm 0.24)\ 10^{-3}$
  - $|V_{cb}| = (41.25 \pm 0.95)\ 10^{-3}$, ρ=0.11



- Global fit:
  $|V_{ub}| = (3.71 \pm 0.09)\ 10^{-3}$,
  $|V_{cb}| = (42.00 \pm 0.45)\ 10^{-3}$

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

- Recent progress on exclusive $|V_{cb}|$ from Dispersive Matrix approach: Di Carlo et al.
  - $|V_{cb}|_{DM} = (41.2 \pm 0.8)\ 10^{-3}$, compatible with inclusive and with UTfit prediction
- Further theoretical and experimental progress needed: e^+e^- machines crucial

NP ANALYSIS: RESULTS

$\bar{\rho} = 0.169 \pm 0.025$

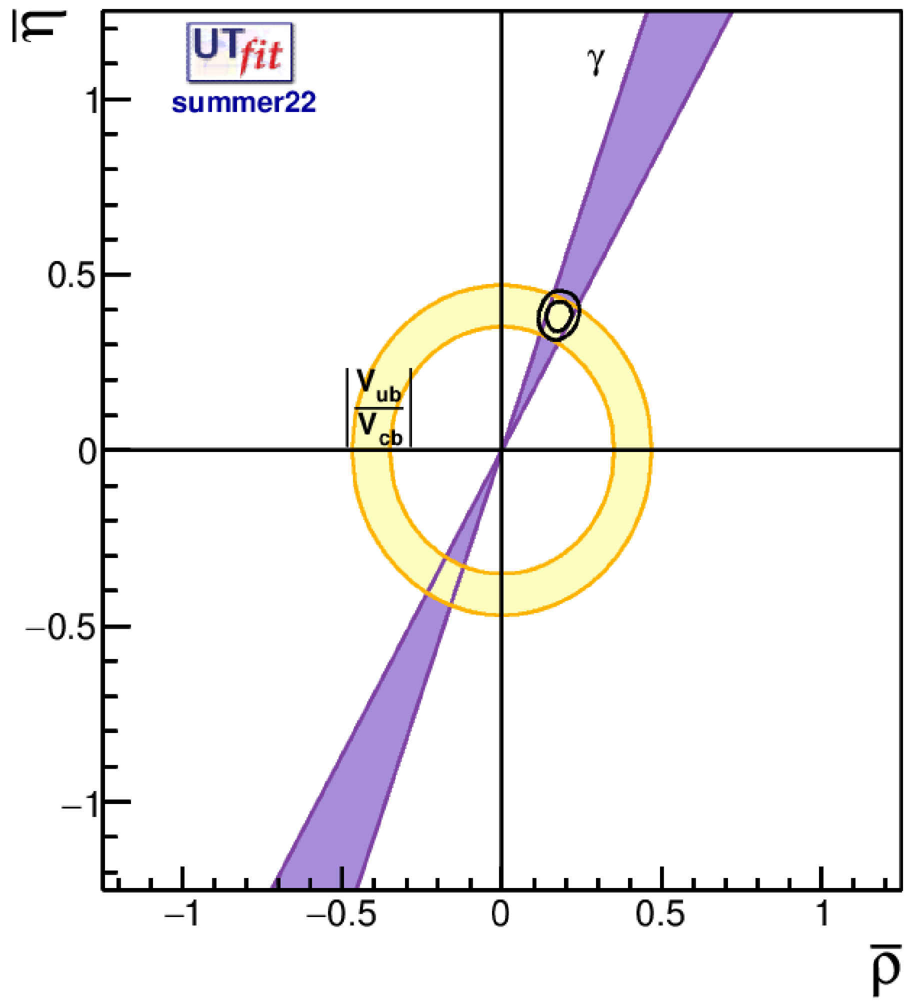
$\bar{\eta} = 0.365 \pm 0.026$

to be compared w.

$\bar{\rho} = 0.161 \pm 0.009$

$\bar{\eta} = 0.347 \pm 0.010$

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



NP CONTRIBUTIONS TO ΔF=2

- Phenomenological parameterization:

$$C_{B_q} e^{2i\phi_{B_q}} = \frac{\langle B_q | H_{\text{eff}}^{\text{full}} | \bar{B}_q \rangle}{\langle B_q | H_{\text{eff}}^{\text{SM}} | \bar{B}_q \rangle} = 1 + \frac{A_q^{\text{NP}}}{A_q^{\text{SM}}} e^{2i\phi_q^{\text{NP}}}$$

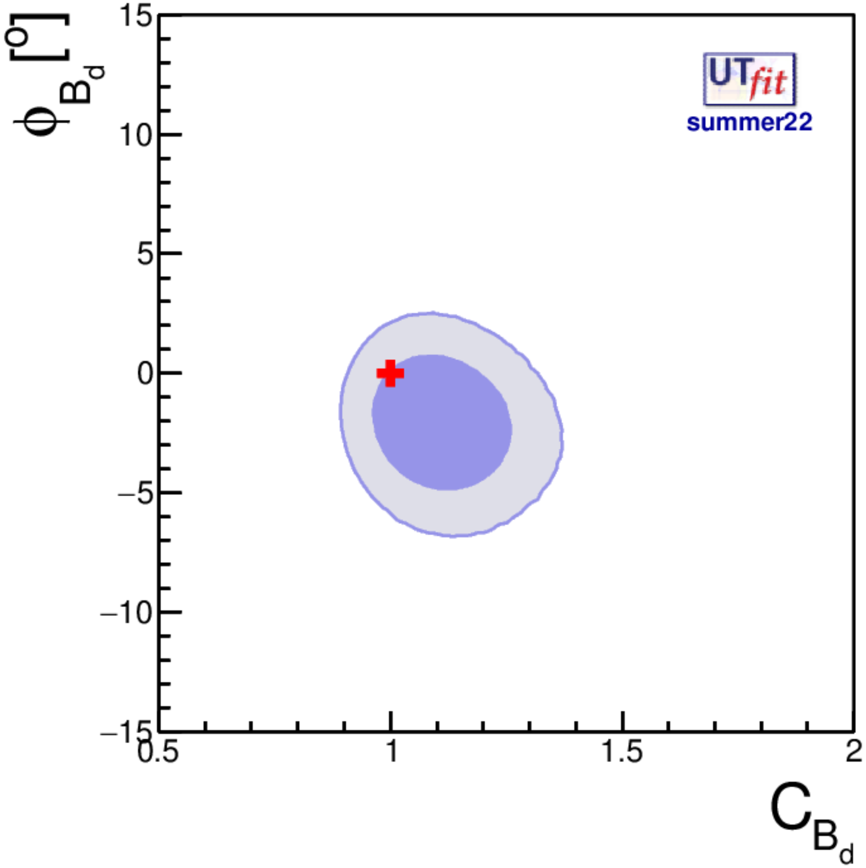
$$\Delta m_{d,s}^{\text{exp}} = C_{B_{d,s}} \Delta m_{d,s}^{\text{SM}}$$

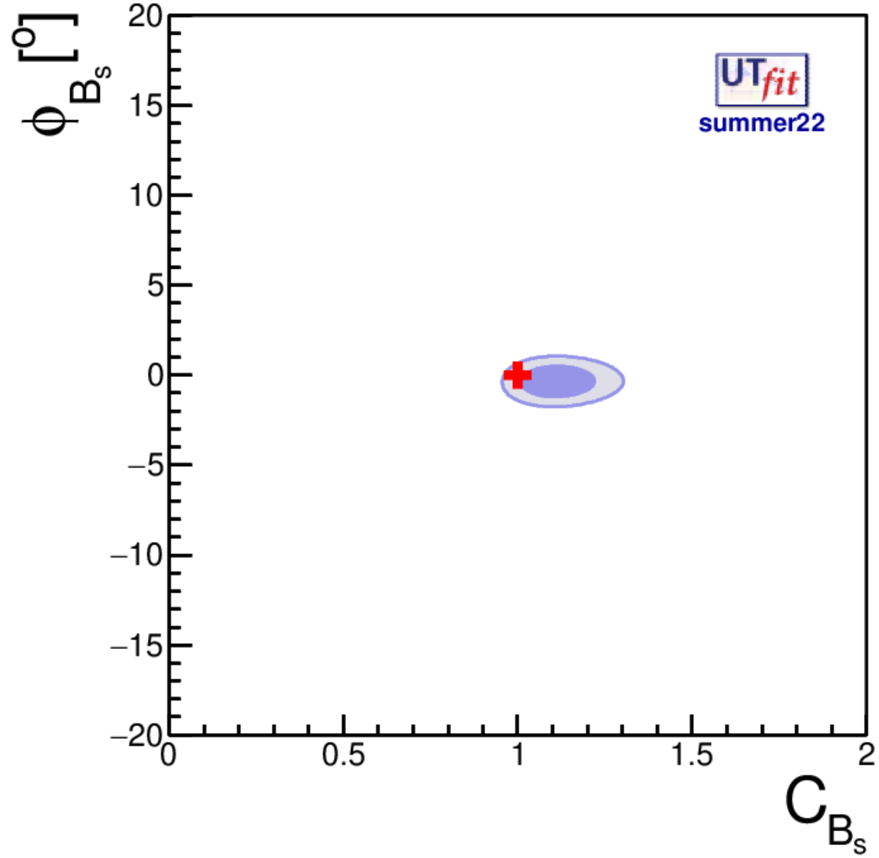
$$\sin 2\beta^{\text{exp}} = \sin(2\beta + 2\phi_{B_d}) \qquad \phi_s^{\text{exp}} = \beta_s - \phi_{B_s}$$

$$A_{\text{SL}}^{d,s;\text{exp}} = \text{Im}\left(\frac{\Gamma_{12}^{\text{SM}}}{M_{12}^{\text{SM}}}\right) \frac{\cos 2\phi_{B_{d,s}}}{C_{B_{d,s}}} - \text{Re}\left(\frac{\Gamma_{12}^{\text{SM}}}{M_{12}^{\text{SM}}}\right) \frac{\sin 2\phi_{B_{d,s}}}{C_{B_{d,s}}}$$

$$C_{\varepsilon_K} = \frac{\varepsilon_K^{exp}}{\varepsilon_K^{\text{SM}}} = \frac{\text{Im}\langle K^0 | \mathcal{H}_{\text{eff}}^{\text{full}} | \bar{K}^0 \rangle}{\text{Im}\langle K^0 | \mathcal{H}_{\text{eff}}^{\text{SM}} | \bar{K}^0 \rangle} \qquad C_{\Delta m_K} = \frac{\Delta m_K^{exp}}{\Delta m_K^{\text{SM}}} = \frac{\text{Re}\langle K^0 | \mathcal{H}_{\text{eff}}^{\text{full}} | \bar{K}^0 \rangle}{\text{Re}\langle K^0 | \mathcal{H}_{\text{eff}}^{\text{SM}} | \bar{K}^0 \rangle}$$

RESULTS ON NP PARAMETERS

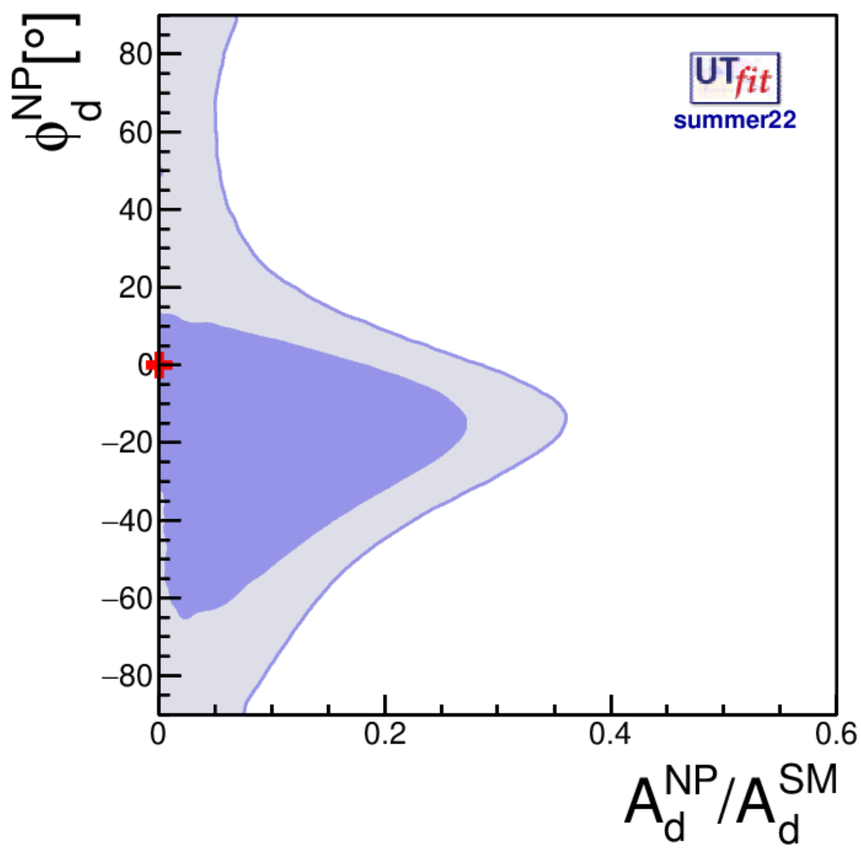


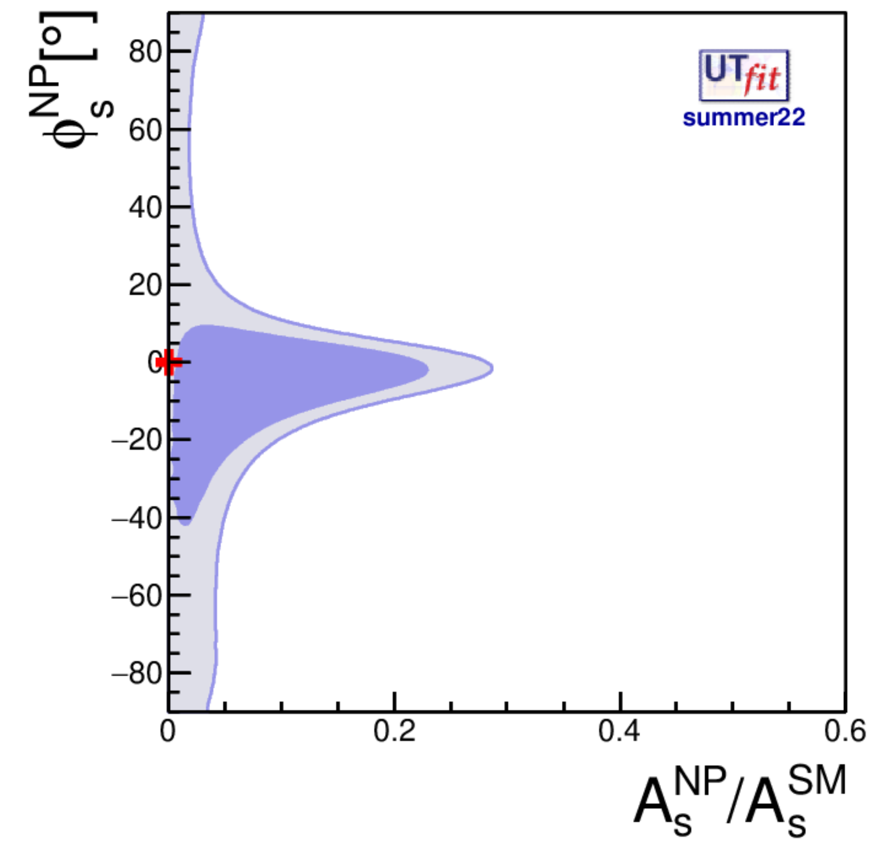


$C_{Bd} = 1.14 \pm 0.11$, $\phi_{Bd} = (-3.4 \pm 2.0)^\circ$, $C_{Bs} = 1.14 \pm 0.08$, $\phi_{Bs} = (-0.3 \pm 0.6)^\circ$

$C_{\varepsilon K} = 1.12 \pm 0.12$

RESULTS ON NP PARAMETERS





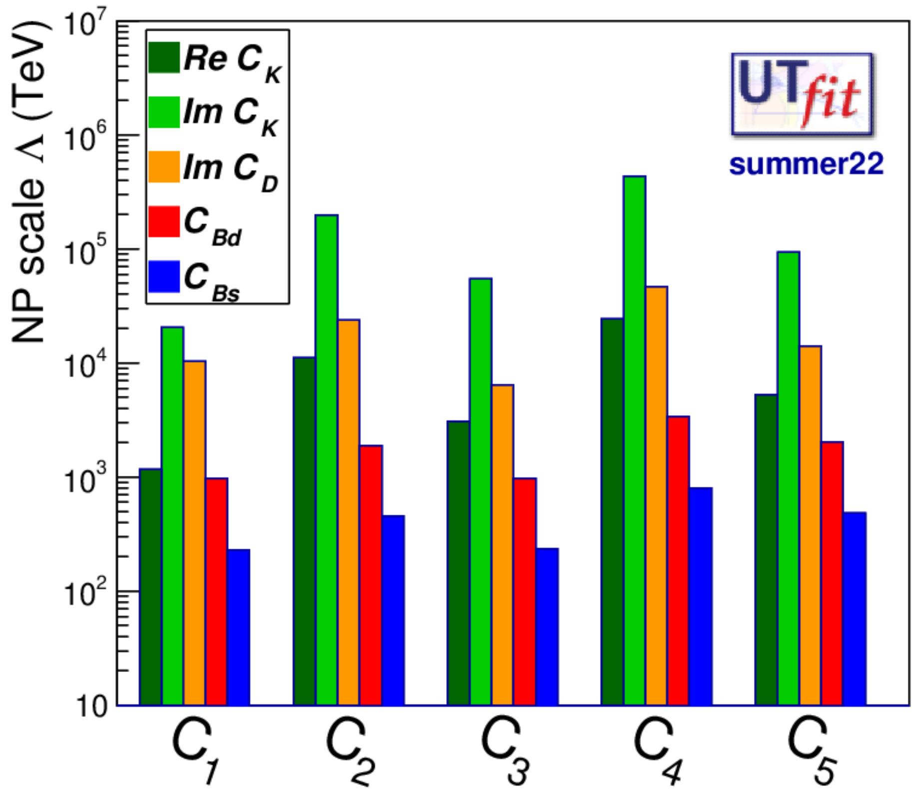
Marginalizing on the phase: $A_{NP}{}^d/A_{SM}{}^d < 35\%$ and $A_{NP}{}^s/A_{SM}{}^s < 30\%$ at 95% probability

FROM ΔF=2 TO THE NP SCALE

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

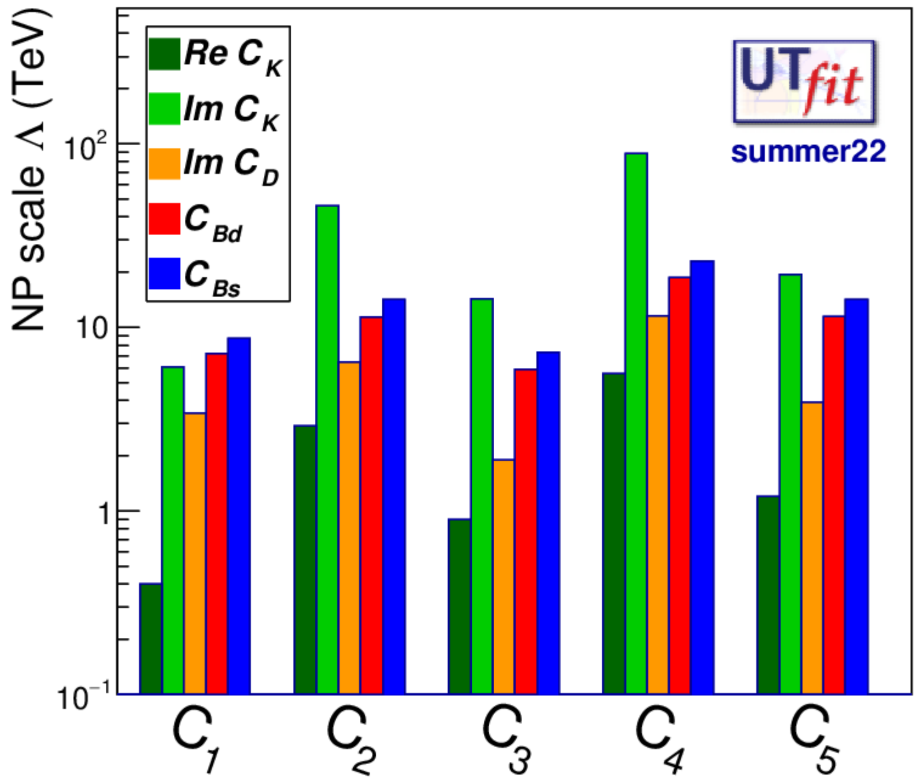
GENERIC STRONGLY-INTERACTING NP

- Best bound from ε_K, dominated by CKM error
- CPV in charm mixing follows, exp error dominant
- B_d and B_s behind, error from both CKM and B-params
- Non-perturbative NP:
  - $\Lambda > 4\ 10^5$ TeV
- Weakly interacting:
  - $\Lambda > 10^4$ TeV



NMFV STRONGLY-INTERACTING NP

- If new chiral structures present, ε_K still gives best constraint
- B_d and B_s most powerful if no new operators arise
- Non-perturbative NMFV NP (e.g. composite Higgs)
  - $\Lambda > 95$ TeV
- Weakly interacting:
  - $\Lambda > 3$ TeV



PROSPECTS: LHCb UPGRADES + BELLE II

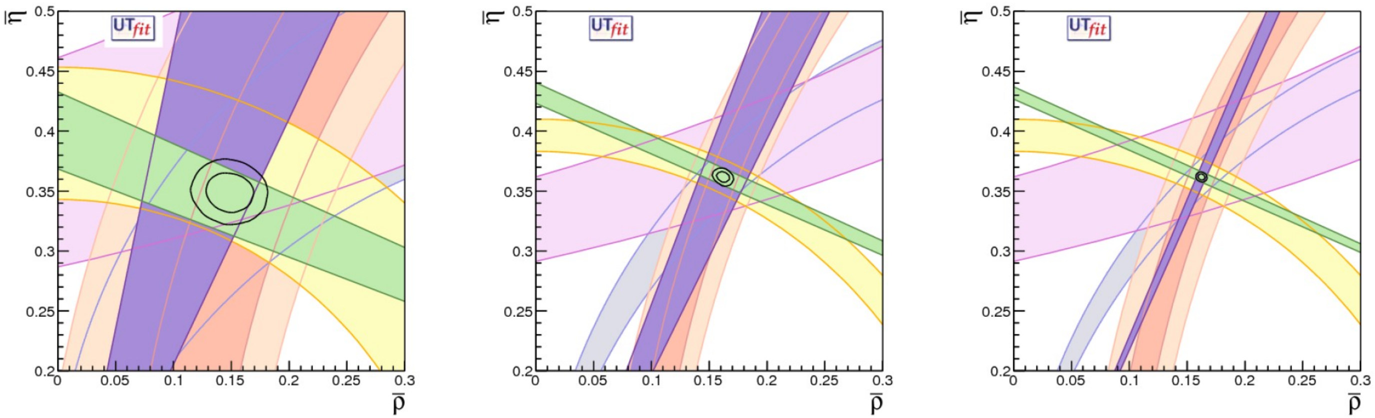


Fig. 23: Present (left) and future (center: phase 1, right: phase 2) constraints in the $(\bar{\rho}, \bar{\eta})$ plane (UTfit collaboration).

Phase I: 23/fb LHCb; Phase II: 300/fb LHCb, 50/ab Belle II

Table 10: Relative uncertainties on the predictions of UT parameters and angles, using current and extrapolated input values for measurements and theoretical parameters (UTfit collaboration).

	λ	$\bar{\rho}$	$\bar{\eta}$	A	$\sin 2\beta$	γ	α	β_s
Current	0.12%	9%	3%	1.5%	4.5%	3%	2.5%	3%
Phase 1	0.12%	2%	0.8%	0.6%	0.9%	0.9%	0.7%	0.8%
Phase 2	0.12%	1%	0.6%	0.5%	0.6%	0.8%	0.4%	0.5%

1812.07638

PROSPECTS: LHCb UPGRADES + BELLE II

Table 11: Present and future uncertainties on CKM and NP parameters from the generalized UT analysis (UTfit collaboration).

	$\bar{\rho}$	$\bar{\eta}$	C_{ε_K}	C_{B_d}	$\phi_{B_d}[^\circ]$	C_{B_s}	$\phi_{B_s}[^\circ]$
Current	0.030	0.028	0.12	0.11	1.8	0.09	0.89
Phase 2	0.0047	0.0040	0.036	0.030	0.28	0.026	0.29

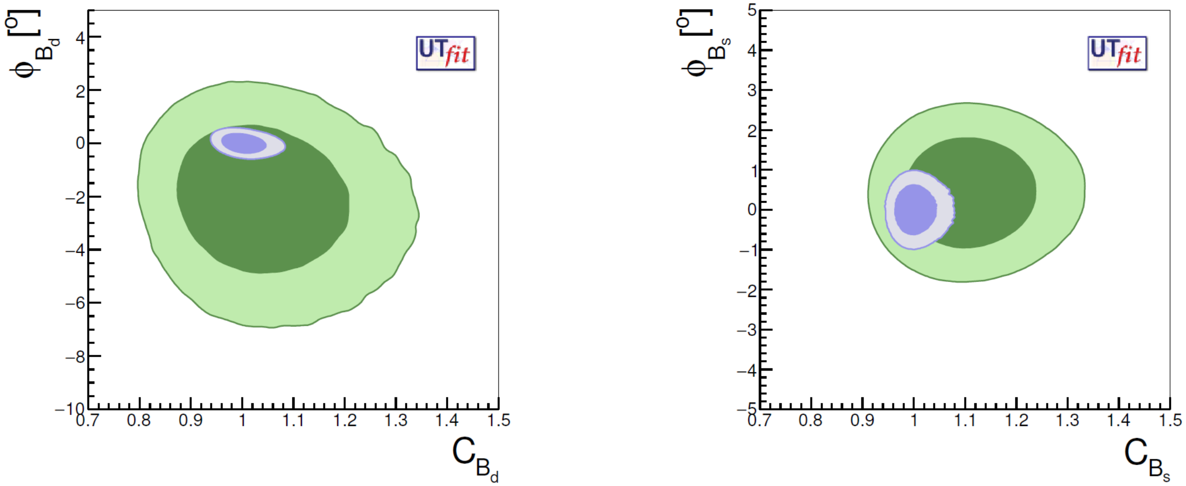


Fig. 24: The present (green) and future Phase 2 (blue) constraints on NP contributions to B_d-$\bar{B}_d$ (left) and B_s-$\bar{B}_s$ (right) mixing, with 1σ (2σ) regions shown with darker (lighter) shading.

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PROSPECTS: LHCb UPGRADES + BELLE II

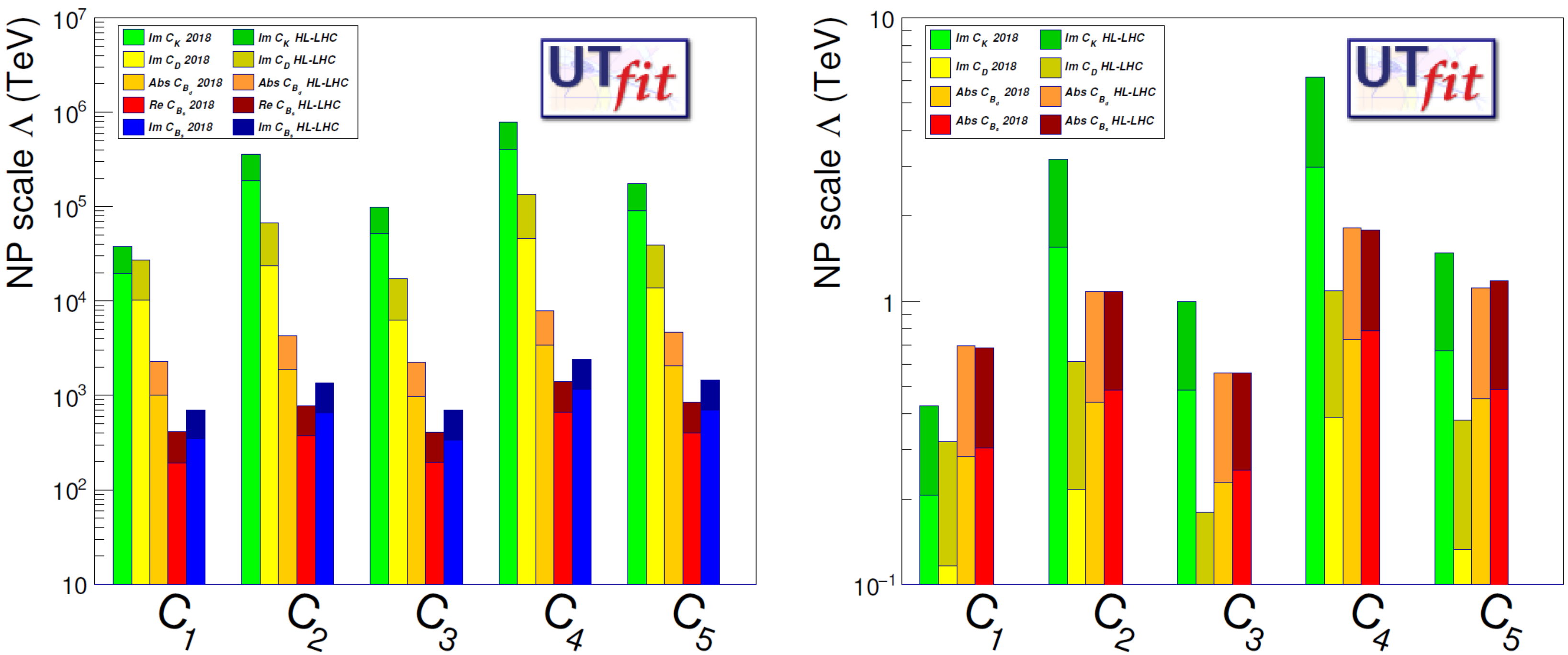

Fig. 25: Present (lighter) and future Phase 2 (darker) constraints on the NP scale from the UTfit NP analysis. The right panel shows constraints assuming NP is weakly coupled, has MFV structure of couplings, and enters observables only at one loop, see text for details.

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PROSPECTS: FCC-ee

Observable / Experiments	Current W/A	Belle II (50 /ab)	LHCb-U1 (23/fb)	FCC-ee
CKM inputs				
γ (uncert., rad)	$1.296^{+0.087}_{-0.101}$	1.136 ± 0.026	1.136 ± 0.025	1.136 ± 0.004
$\lvert V_{ub}\rvert$ (precision)	5.9%	2.5%	6%	1%
Mixing-related inputs				
$\sin(2\beta)$	0.691 ± 0.017	0.691 ± 0.008	0.691 ± 0.009	0.691 ± 0.005
ϕ_s (uncert. rad 10^{-2})	-1.5 ± 3.5	n/a	-3.65 ± 0.05	-3.65 ± 0.01
Δm_d (ps^{-1})	0.5065 ± 0.0020	same	same	same
Δm_s (ps^{-1})	17.757 ± 0.021	same	same	same
$a^d_{\rm fs}$ (10^{-4}, precision)	23 ± 26	-7 ± 15	-7 ± 15	-7 ± 2
$a^s_{\rm fs}$ (10^{-4}, precision)	-48 ± 48	n/a	0.3 ± 15	0.3 ± 2

FCC Phys. Opp.

RARE DECAYS & LUV

- Z-mediated FCNC decays are theoretically very clean and very sensitive to NP:
  - $B_{s,d} \to l^+l^-$
  - $B \to K^{(*)}\nu\bar{\nu}$, $B \to \pi/\rho\nu\bar{\nu}$
- Decays receiving also photon contributions theoretically less clean, would need a theoretical breakthrough:
  - $B \to K^{(*)}l^+l^-$, $B \to \pi/\rho l^+l^-$ (inclusive cleaner)

  except, of course, for LUV

GAUGE BOSON FLAVOUR COUPLINGS AND LFV

- Flavour changing tau decays excellent probe of NP

  Alberto’s talk

- At the Z-pole, FCNC Z couplings can be directly constrained/measured

- Above the Z-pole, it would be very interesting to measure directly CKM elements from W decays

  M.-H. Schune

CONCLUSIONS

- 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.
- There is ample room for improvement. LHCb phase 2 and Belle II will make considerable progress, hopefully revealing some deviation from the SM
- Next generation of e^+e^- machines surely has the potential to push the frontier much further

BACKUP

INPUT TO THE UTA: V_{us} & V_{ud}

- V_{us} and V_{ud} can be extracted from data on semileptonic Kaon and Pion decays. Assuming unitarity one gets (averaging 2+1 and 2+1+1):
  $|V_{ud}| = 0.974387(98)$ FLAG
- This should be combined with $|V_{ud}| = 0.97373(31)$ from superallowed nuclear β decays Hardy, Towner '20
- Given the tension between the two measurements, we apply the PDG scaling factor S=2.0 to obtain
  $|V_{ud}| = 0.97433(19)$