THEORY PROSPECTS FOR CP VIOLATION IN BEAUTY AND CHARM

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- Introduction
- CP violation in Beauty
  - theoretical prospects
  - extrapolating the UTA
- CP violation in Charm
  - theoretical prospects
  - extrapolating the mixing analysis
- Conclusions

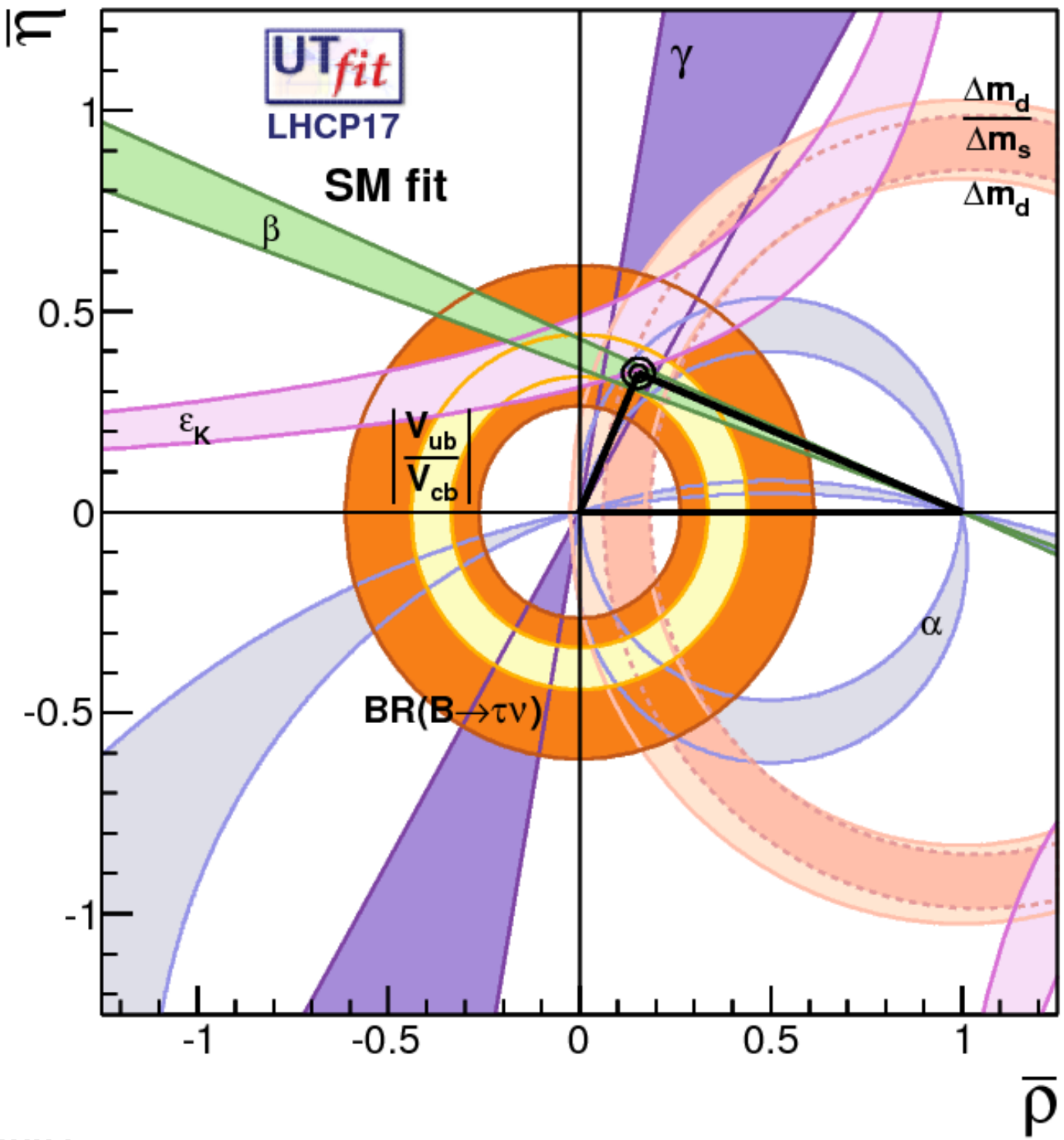
INTRODUCTION

- Search for virtual contributions of new heavy particles
- Use observables where SM contributions are either absent (BNV, LNV, LFV) or loop-suppressed (EWPO, FCNC).
- Advantage of flavour over EWPO: hierarchical structure of CKM provides very strong suppression of FCNC & CPV

CP VIOLATION IN BEAUTY

- CKM unitarity links measurements of CP-violating obs. (UT angles: α, β, γ) to CP-conserving ones (UT sides: $B_{(s)}$-$\bar{B}_{(s)}$ mixing, semileptonic decays)
  - Test the consistency of the SM both "visually" and quantitatively
  - Get constraints on deviations from the SM

Unitarity Triangle analysis in the SM:



levels @
95% Prob

~10 %

$\bar{\rho} = 0.154 \pm 0.015$

$\bar{\eta} = 0.346 \pm 0.013$

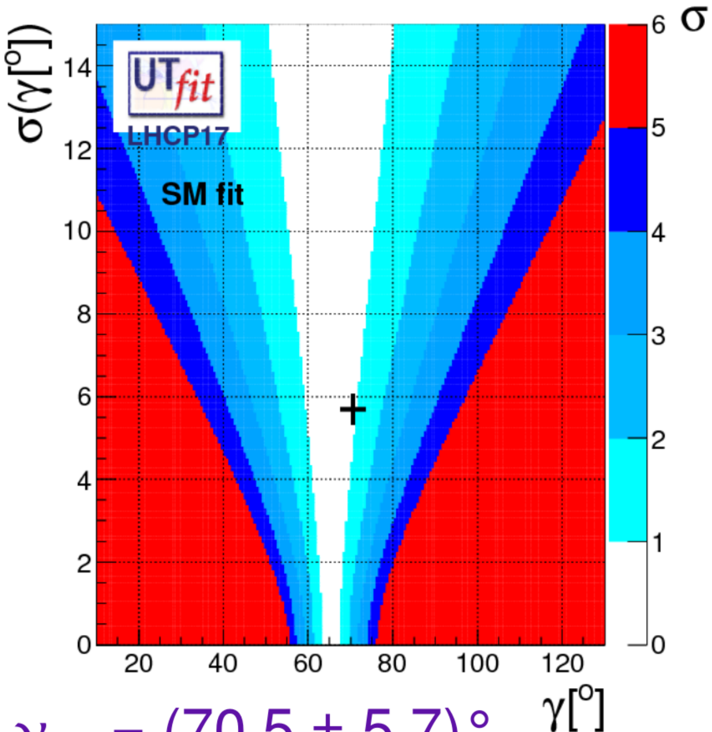
~4%

compatibility plots

A way to “measure” the agreement of a single measurement with the indirect determination from the fit using all the other inputs: test for the SM description of the flavour physics

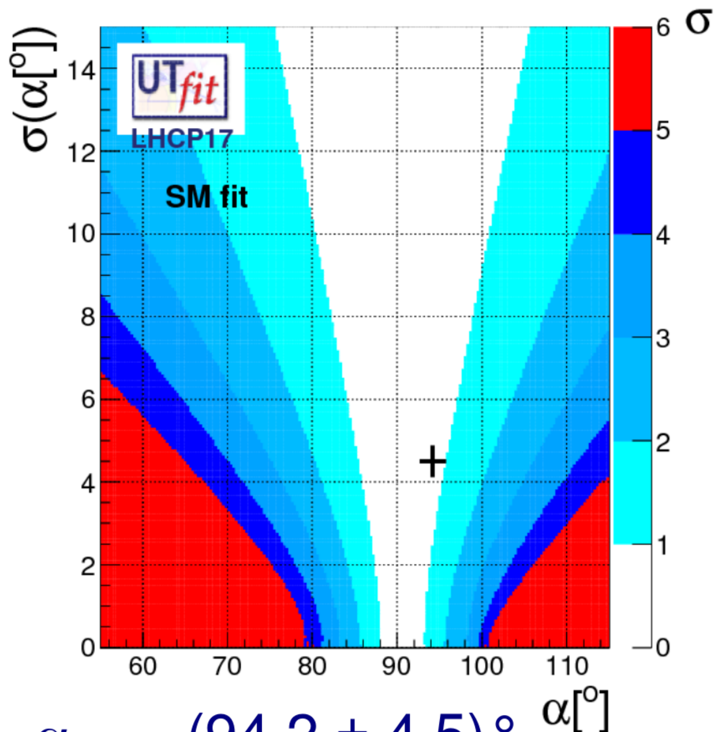
Color code: agreement between the predicted values and the measurements at better than 1, 2, ...nσ

The cross has the coordinates (x,y)=(central value, error) of the direct measurement



$\gamma_{exp} = (70.5 \pm 5.7)°$

$\gamma_{UTfit} = (65.5 \pm 2.1)°$



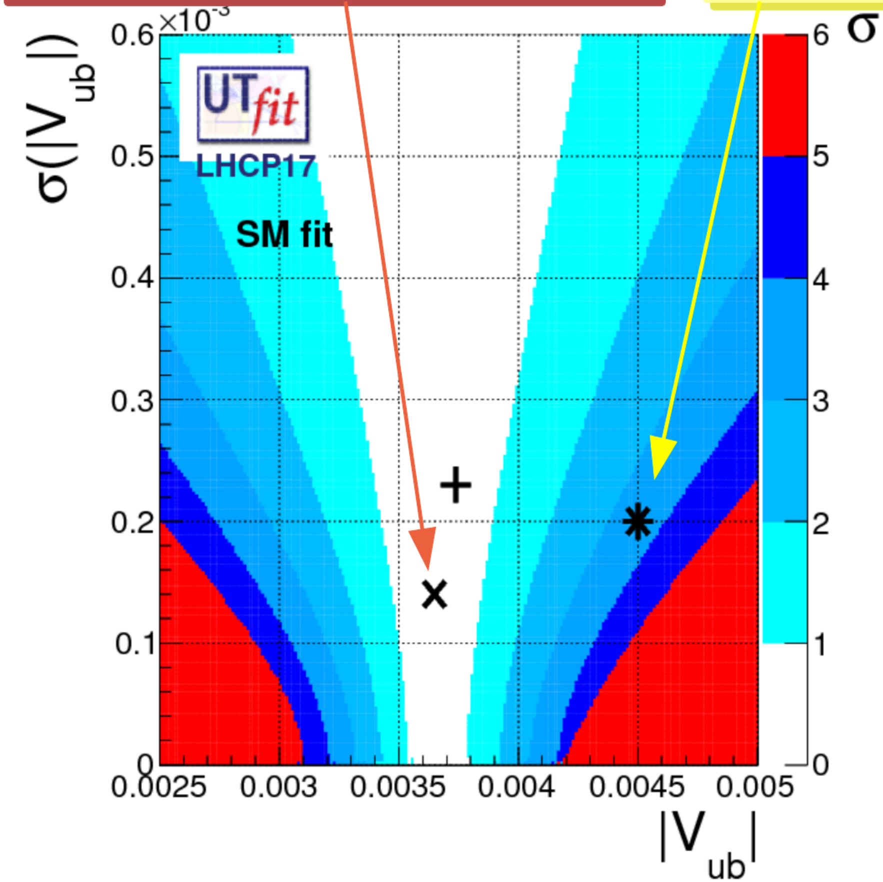
$\alpha_{exp} = (94.2 \pm 4.5)°$

$\alpha_{UTfit} = (90.6 \pm 2.5)°$

tensions? not really.. still that V_{ub} inclusive

V_{ub} *(excl)* = $(3.65 \pm 0.14)\ 10^{-3}$

Vub (incl) = (4.50 ± 0.20) 10-3



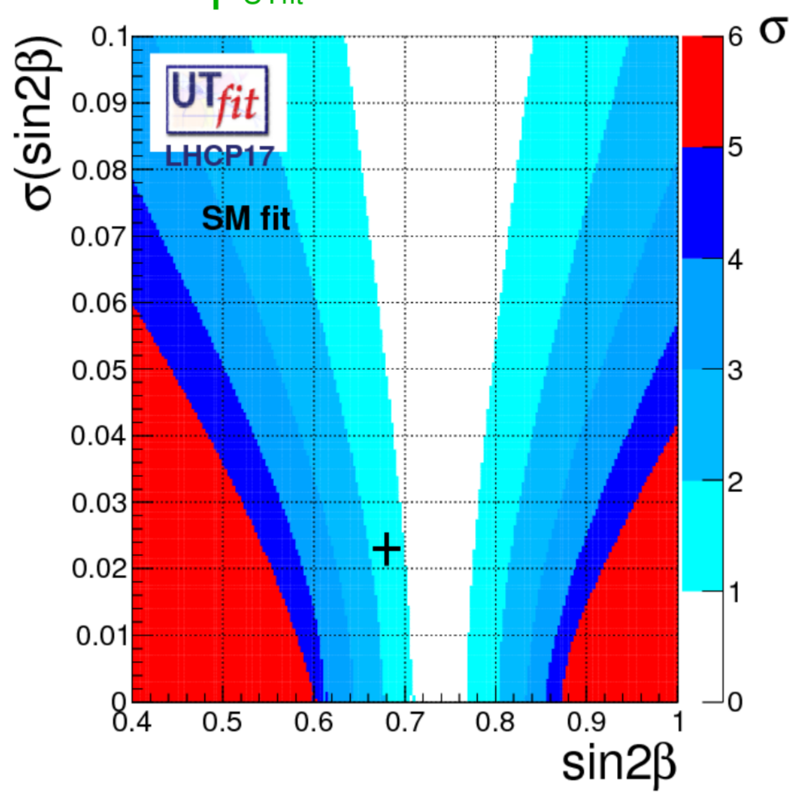
$Vub_{exp} = (3.74 \pm 0.23) \cdot 10^{-3}$

$Vub_{UTfit} = (3.66 \pm 0.13) \cdot 10^{-3}$

~1.4σ

$\sin 2\beta_{exp} = 0.680 \pm 0.023$

$\sin 2\beta_{UTfit} = 0.737 \pm 0.031$



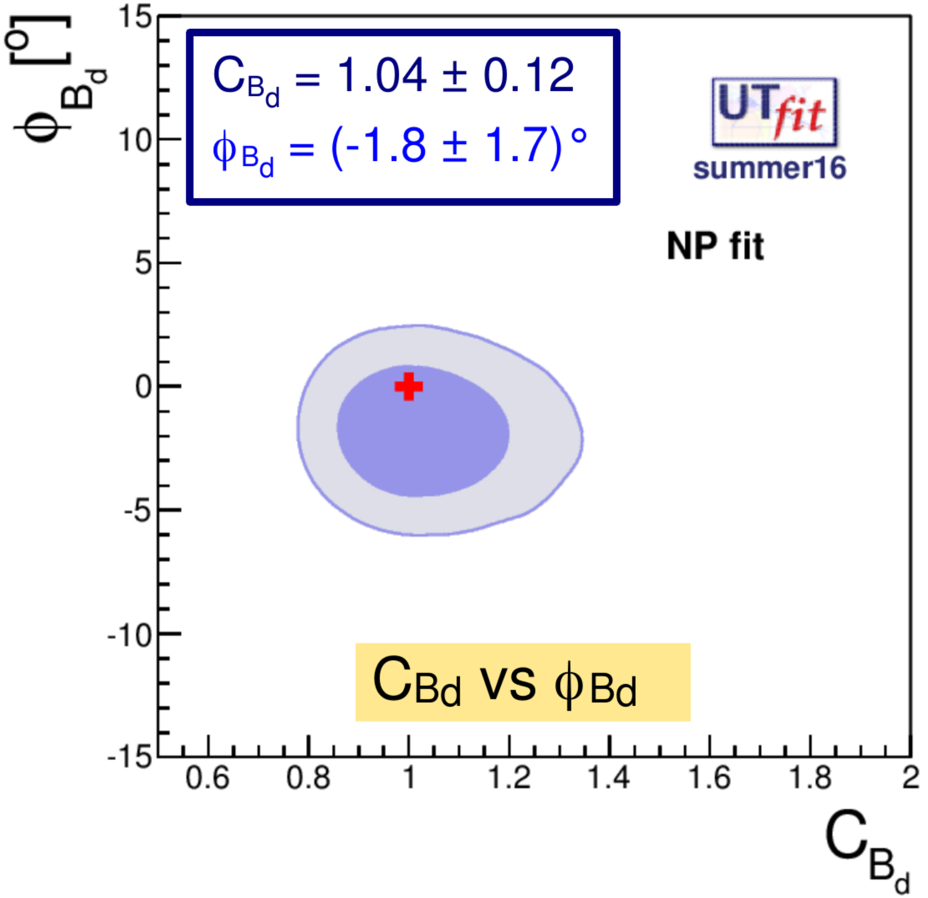
NP parameter results

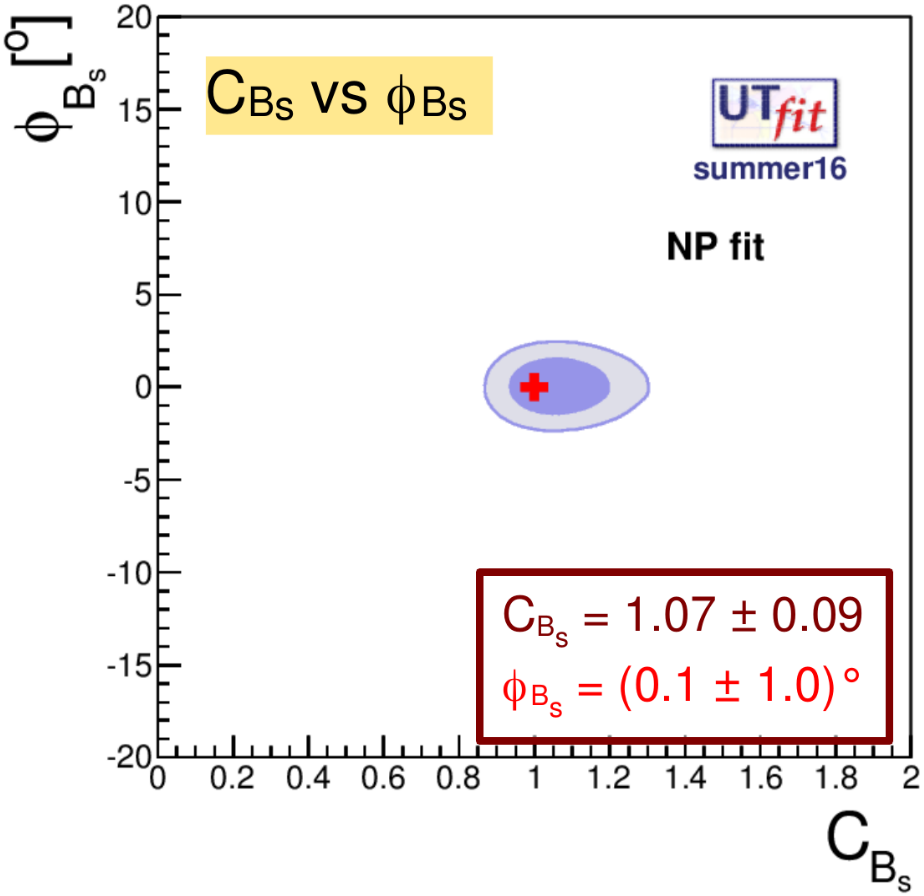
dark: 68%
light: 95%
SM: red cross

K system

$C_{\varepsilon_K} = 1.05 \pm 0.11$

$$A_q = C_{B_q} e^{2i\phi_{B_q}} A_q^{SM} e^{2i\phi_q^{SM}}$$

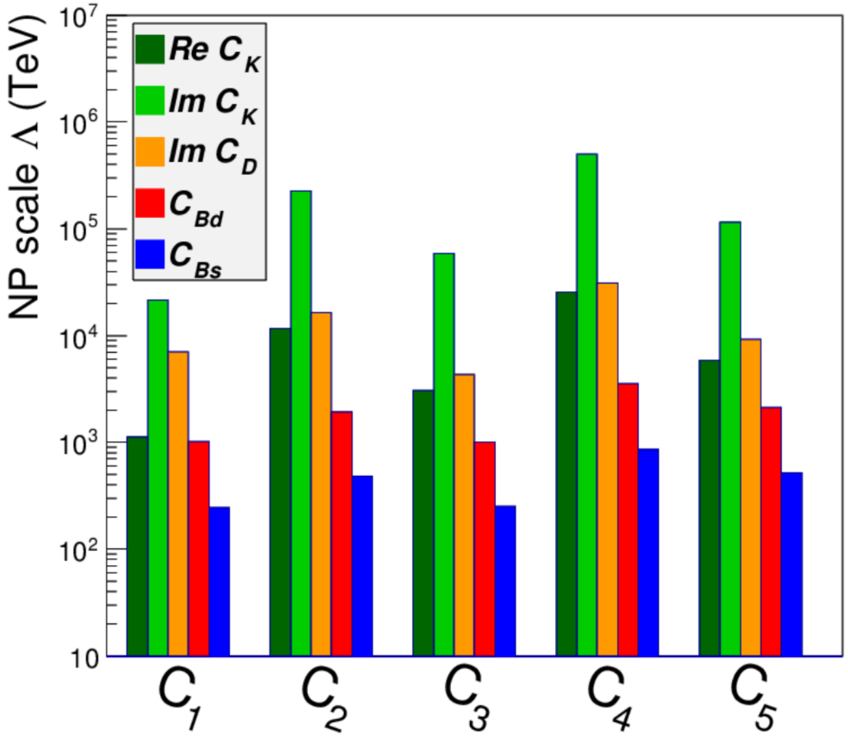




results from the Wilson coefficients

Generic: $C(\Lambda) = \alpha/\Lambda^2$, $F_i \sim 1$, arbitrary phase

$\alpha \sim 1$ for strongly coupled NP



Lower bounds on NP scale (in TeV at 95% prob.)

Non-perturbative NP

$\Lambda > 5.0\ 10^5$ TeV

To obtain the lower bound for loop-mediated contributions, one simply multiplies the bounds by α_s (~ 0.1) or by α_W (~ 0.03).

$\alpha \sim \alpha_W$ in case of loop coupling through weak interactions

NP in α_W loops

$\Lambda > 1.5\ 10^4$ TeV

Best bound from ε_K
- dominated by CKM error

CPV in charm mixing follows,
- exp error dominant

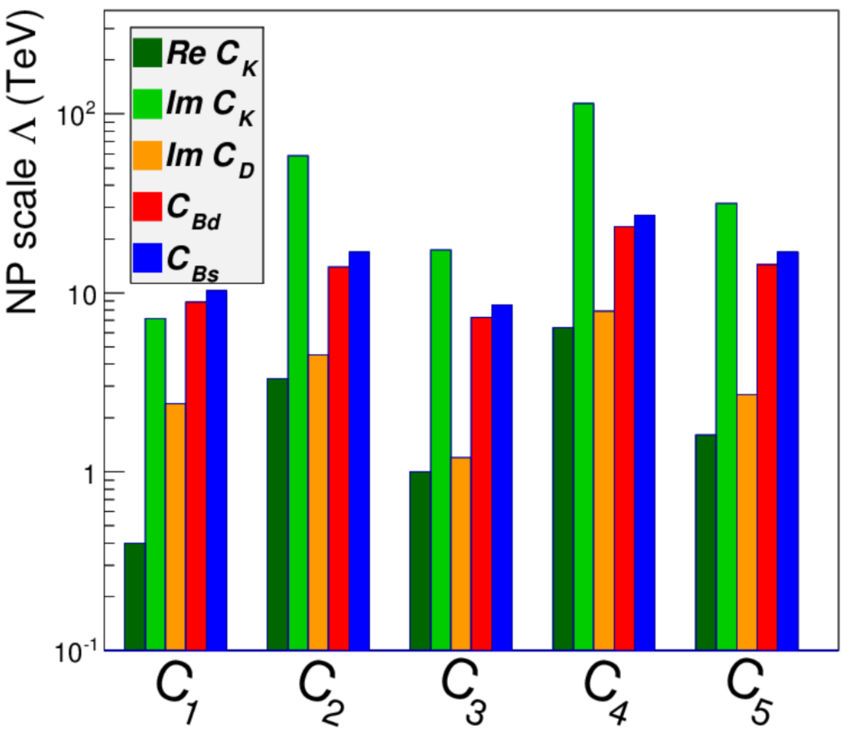
Best CP conserving from Δm_K,
- dominated by long distance

B_d and B_s behind,
- errors from both CKM and B-parameters

results from the Wilson coefficients

NMFV: $C(\Lambda) = \alpha \times |F_{SM}|/\Lambda^2$, $F_i \sim |F_{SM}|$, arbitrary phase

$\alpha \sim 1$ for strongly coupled NP



Lower bounds on NP scale (in TeV at 95% prob.)

Non-perturbative NP
$\Lambda > 114$ TeV

To obtain the lower bound for loop-mediated contributions, one simply multiplies the bounds by α_s (~ 0.1) or by α_W (~ 0.03).

$\alpha \sim \alpha_W$ in case of loop coupling through weak interactions

NP in α_W loops
$\Lambda > 3.4$ TeV

If new chiral structures present, ε_K still leading

$B_{(s)}$ mixing provides very stringent constraints, especially if no new chiral structures are present

Constraining power of the various sectors depends on unknown NP flavour structure.

THEORETICAL PROSPECTS: ANGLE MEASUREMENTS

- γ from $B \to DK$ theoretically clean (up to 10^{-7})

Brod & Zupan '14

- $\sin 2\beta$ from $B \to J/\psi K_S$: theoretical uncertainty comes from $V_{ub}V_{us}$ contribution

$$A(B^0 \to J/\psi K^0) = V_{cb}^* V_{cs} (E_2 - P_2) + V_{ub}^* V_{us} (P_2^{\rm GIM} - P_2)$$

  - estimate it using SU(3)-related $b \to d$ transitions $B_S \to J/\psi K_S$ and $B \to J/\psi \pi^0$ where the second term is not doubly Cabibbo suppressed

Fleischer '99; Ciuchini, Pierini & LS '05; ...

  - th error scales with the uncertainty on control channels
  - under control (Belle II can help here)

De Bruyn & Fleischer '15

THEORETICAL PROSPECTS: ANGLE MEASUREMENTS

- LHCb can contribute to the extraction of α with the combined analysis of $B \to \pi\pi$, $B_s \to KK$ decays

Fleischer '99, '07; Franco et al. '12; LHCb '15; Fleischer et al. '16

- β_s from $B_s \to J/\psi\phi$: theoretical uncertainty comes again from $V_{ub}V_{us}$ contribution
  - estimate using SU(3)-related $b \to d$ transitions more difficult since ϕ not pure flavour octet
  - in the literature small th uncertainty found

    De Bruyn & Fleischer '15
  - probably under control, but to be studied in more detail

THEORETICAL PROSPECTS: SIDE MEASUREMENTS

- Exclusive V_{ub} and V_{cb}: expect LQCD $F_{D^*}(1)$ @ 0.5% and $B\to\pi$ ~ 1% in 2025 Tarantino @ What Next, based on SuperB
- Recently raised caveats on parameterization of q^2-dependence in V_{cb}^{excl} can be avoided with lattice + data Bigi, Gambino & Schacht '17; Grinstein & Kobach '17
- Expect V_{cb} @ ~ 1% and V_{ub} @ ~ 2% from Belle II - LHCb contributes with ratio
- LQCD will provide f_{Bs}, B_{Bs} and B_s/B_d ratios @ 0.5% - excellent prospects for the mixings

Tarantino @ What Next, based on SuperB

Parameter	Error				
	Now	50/fb	300/fb	1000/fb	3000/fb
ΔM_d [ps^{-1}]	0.002	0.0005	0.0002	0.0001	0.00006
ΔM_s [ps^{-1}]	0.021	0.005	0.002	0.001	0.0006
$\sin 2\beta$	0.022	0.008	0.0026	0.0018	0.001
γ [°]	6.5	0.9	0.4	0.2	0.09
α [°]	5.5	1	Belle II		
β_s [°]	4	0.26	0.11	0.06	0.034
V_{us}	$1 \cdot 10^{-4}$	$1 \cdot 10^{-4}$			
V_{cb}	2.7%	1%	Belle II		
V_{ub}	10%	1%	Belle II		
x		$1.5 \cdot 10^{-4}$	$4.5 \cdot 10^{-5}$	$3 \cdot 10^{-5}$	$1.5 \cdot 10^{-5}$
y		10^{-4}	$3 \cdot 10^{-5}$	$2 \cdot 10^{-5}$	10^{-5}
$\lvert q/p \rvert$		0.01	0.003	0.002	0.001
ϕ [°]		3	0.9	0.6	0.3
A_Γ		$4 \cdot 10^{-5}$	$12 \cdot 10^{-6}$	$8 \cdot 10^{-6}$	$4 \cdot 10^{-6}$
$\alpha_s(M_Z)$	0.0005	0.0002			
m_t	760 MeV	250 MeV	theory limited		
m_b	50 MeV	10 MeV			
B_K	1.3%	0.1%			
F_{B_s}	5 MeV	1 MeV			
F_{B_s}/F_{B_d}	1.4%	0.5%			
$F_{B_s}\sqrt{B_{B_s}}$	3.8%	3%			
ξ	2.5%	0.5%			

Parameter	Error				
	Now	50/fb	300/fb	1000/fb	3000/fb
$\bar{\rho}$ (SM fit)	0.002	0.0039	0.0023	0.0013	0.00064
$\bar{\eta}$ (SM fit)	0.021	0.0037	0.0019	0.0013	0.00068
γ [°] (SM fit)	6.5	0.6	0.35	0.2	0.09
α [°] (SM fit)	5.5	0.6	0.37	0.2	0.1
β [°] (SM fit)	4	0.2	0.10	0.07	0.04
β_s [°] (SM fit)	4	0.011	0.057	0.004	0.0023
$\bar{\rho}$ (NP fit)	0.002	0.006	0.0034	0.0028	0.0022
$\bar{\eta}$ (NP fit)	0.021	0.006	0.0053	0.0061	0.0052
γ [°] (NP fit)	6.5	0.9	0.4	0.2	0.09
α [°] (NP fit)	5.5	1	0.5	0.45	0.36
β [°] (NP fit)	4	0.8	0.7	0.7	0.7
β_s [°] (NP fit)	4	0.017	0.016	0.016	0.016
C_{ε_K}	0.14	0.065	0.065	0.065	0.064
C_{B_d}	0.15	0.024	0.024	0.024	0.022
Φ_{B_d}	2.8	0.48	0.36	0.36	0.35
C_{B_s}	0.087	0.02	0.02	0.02	0.02
Φ_{B_s}	0.96	0.26	0.11	0.063	0.038
$\Phi_{M_{12}}$ [°]	2.5	0.4	0.1	0.08	0.04
$\Phi_{\Gamma_{12}}$ [°]	–	1.2	0.4	0.24	0.12

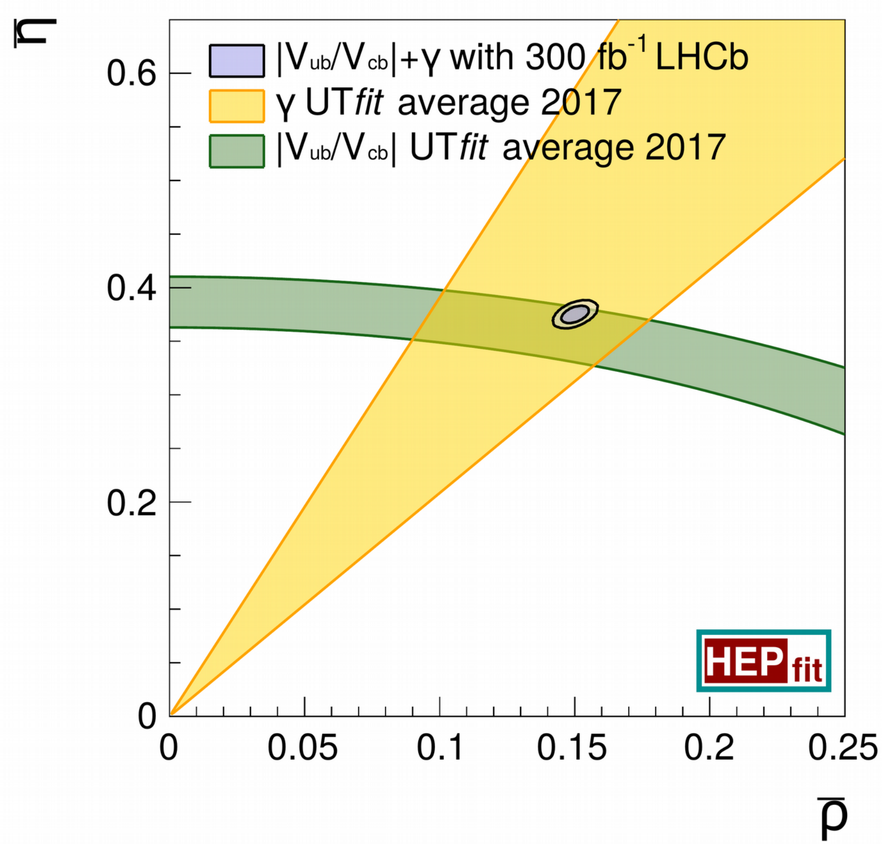
Crucial to improve SM predictions of rare decays!

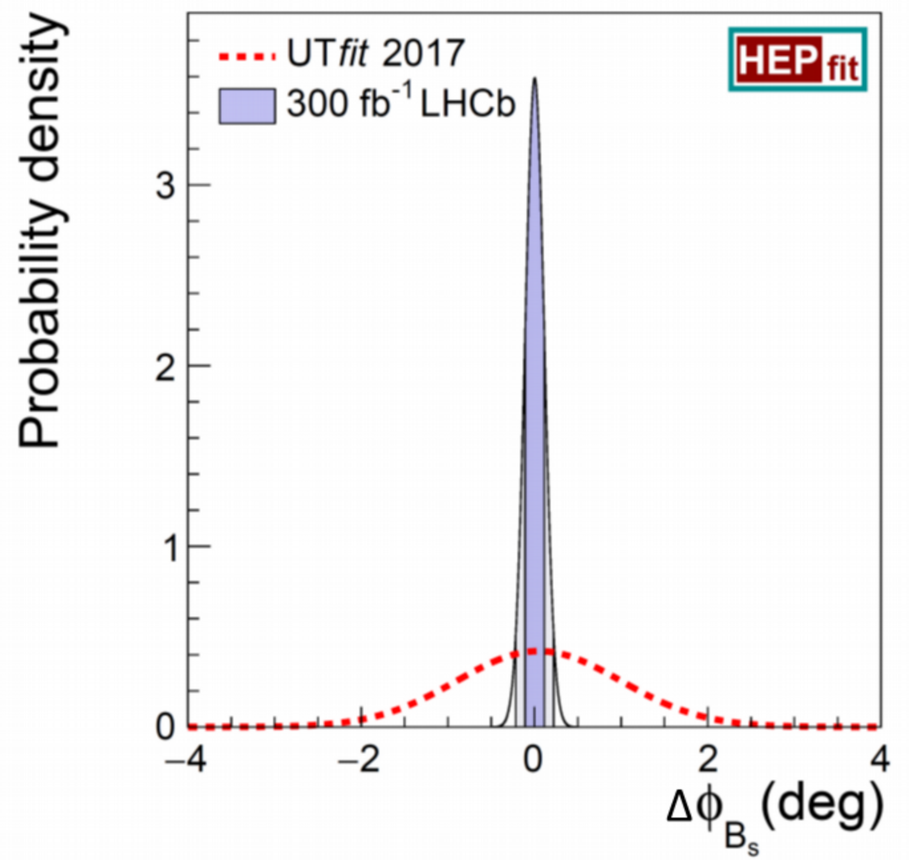
Need progress in $|V_{ub}|$, $|V_{cb}|$ and lattice

Steady improvement

Very preliminary!!!

TREE-LEVEL UT & NP WITH 300/fb





Plus improved measurements of $A^{SL}_{d,s}$

CP VIOLATION IN D MIXING

- D mixing is described by:
  - Dispersive D→D amplitude M_{12}
    - SM: long-distance dominated, not calculable
    - NP: short distance, calculable w. lattice
  - Absorptive D→D amplitude Γ_{12}
    - SM: long-distance, not calculable
    - NP: negligible
  - Observables: $|M_{12}|$, $|\Gamma_{12}|$, $\Phi_{12}=\arg(\Gamma_{12}/M_{12})$

discussion based on Grossman, Kagan, Ligeti, Perez, Petrov & LS, eternally in preparation

- $V_{cd}V_{ud}^* + V_{cs}V_{us}^* + V_{cb}V_{ub}^* = \lambda_d + \lambda_s + \lambda_b = 0$
- eliminate λ_d and take λ_s real (all physical results convention independent)
- imaginary parts suppr. by $r = \mathrm{Im}\,\lambda_b/\lambda_s = 6.5\ 10^{-4}$
- M_{12}, Γ_{12} have the following structure:

  $\lambda_s^2\,(f_{dd}+f_{ss}-2f_{ds}) + 2\lambda_s\lambda_b\,(f_{dd}-f_{ds}-f_{db}+f_{sb}) + O(\lambda_b^2)$

  - GIM mechanism $\Leftrightarrow$ SU(3)
  - $\lambda_s^2\,\varepsilon^2 + \lambda_s\lambda_b\varepsilon$
- CPV effects at the level of $r/\varepsilon \sim 2\ 10^{-3} \sim 1/8°$ for "nominal" SU(3) breaking $\varepsilon \sim 30\%$

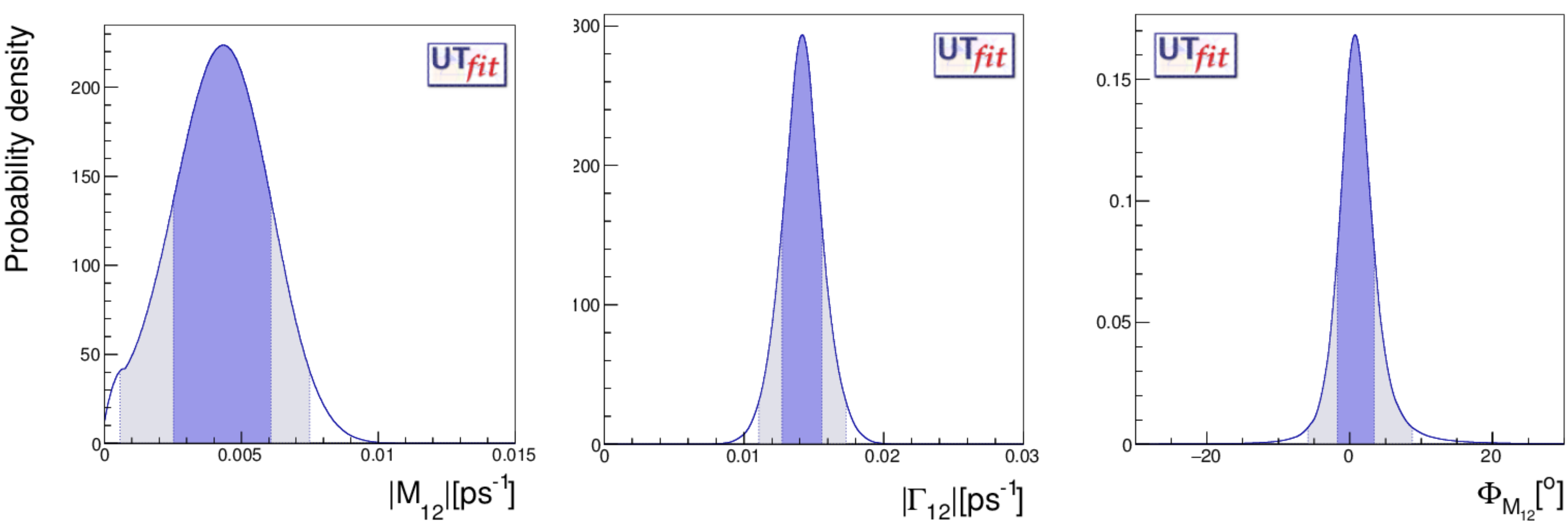
"REAL SM" APPROXIMATION

- Given present experimental errors, it is perfectly adequate to assume that SM contributions to both M_{12} and Γ_{12} are real
- all decay amplitudes relevant for the mixing analysis can also be taken real
- NP could generate a nonvanishing phase for M_{12}

CPV IN MIXING TODAY

- From a global analysis of D mixing data we extract the mixing parameters:

$|M_{12}| = (4 \pm 2)/\mathrm{fs}$, $|\Gamma_{12}| = (14 \pm 1)/\mathrm{fs}$
and $\Phi_{12} = (0 \pm 3)^\circ$ ($[-6,9]^\circ$ @ 95% prob.)



BEYOND THE "REAL SM"

- Foreseen precision with 300/fb may clash with the "real SM" approximation
  - Relax the assumption of real decay amplitudes
  - In principle, if decay amplitudes are not real, they affect the extraction of ϕ:

    $\phi \to \phi + \delta\phi_f$, with $\delta\phi_f = \arg(\overline{A}_f/A_f)$ (f CP eig.)
  - for CA and DCS decays, $\delta\phi_f$ negligible
  - for SCS decays, $\delta\phi_f = A_{CP}^{dir}(D \to f) \cot \delta_f$

    (δ_f O(1) strong phase difference)
  - current data on direct CPV imply $\delta\phi_f \sim 10^{-3}$

BEYOND THE "REAL SM" II

- CPV contributions to Γ_{12} enhanced by $1/\varepsilon$:

  $\lambda_s^2\ \varepsilon^2 + \lambda_s \lambda_b \varepsilon$

  while this is not the case for $\delta\phi_f$

- can go beyond the "real SM" approximation by adding one universal phase $\phi_{\Gamma 12}$ and fitting for ϕ_{M12} and $\phi_{\Gamma 12}$

CPV IN D MIXING W. 300/fb

- Expected uncertainties with 300/fb:
  - $\delta x=1\ 10^{-4}$, $\delta y=0.5\ 10^{-4}$, $\delta|q/p|=5\ 10^{-3}$, $\delta\phi=1°$ (from $K_s\pi\pi$); $\delta y_{CP}=\delta A_\Gamma=2\ 10^{-6}$ (from K^+K^-)
- Allow to determine $\phi_{\Gamma 12}$ with a reach on CPV well below the degree:
  - $\delta\phi_\Gamma=0.4°$ (7 mrad) and
  - $\delta\phi_{M12}=0.1°$ (2 mrad)

  with a sensitivity to NP above 10^5 TeV

CONCLUSIONS

- LHCb upgrade with 300/fb will allow to improve constraints on NP from the UT analysis without hitting the theoretical uncertainties wall
- Theoretical progress on long-distance contributions in D mixing might further improve the NP sensitivity

CONCLUSIONS

- CP violation in penguin-dominated B decays also very interesting, but requires theoretical breakthrough
- Lattice might help with CP violation in SCS D decays on the 300/fb time scale
- Broad spectrum of measurements with 300/fb makes it a wonderful opportunity to test the SM and look for NP

BACKUP SLIDES

V_{cb} and V_{ub}

New HFAG (HFLAV) @CKM16

$|V_{cb}|$ *(excl)* = $(38.88 \pm 0.60)\ 10^{-3}$

$|V_{cb}|$ *(incl)* = $(42.19 \pm 0.78)\ 10^{-3}$

New HFAG @CKM16

~3.3σ discrepancy

New HFAG @CKM16

$|V_{ub}|$ *(excl)* = $(3.65 \pm 0.14)\ 10^{-3}$

$|V_{ub}|$ *(incl)* = $(4.50 \pm 0.20)\ 10^{-3}$

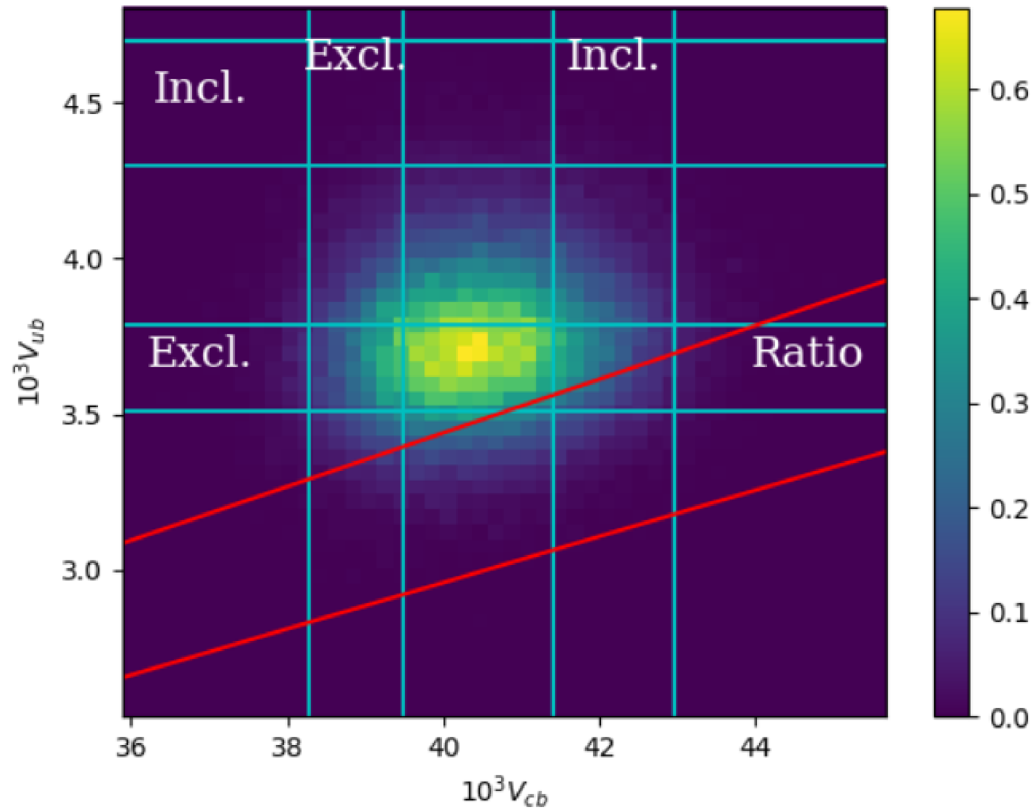
New HFAG @CKM16

~3.4σ discrepancy

$|V_{ub} / V_{cb}|$ *(LHCb)* = $(8.0 \pm 0.6)\ 10^{-2}$

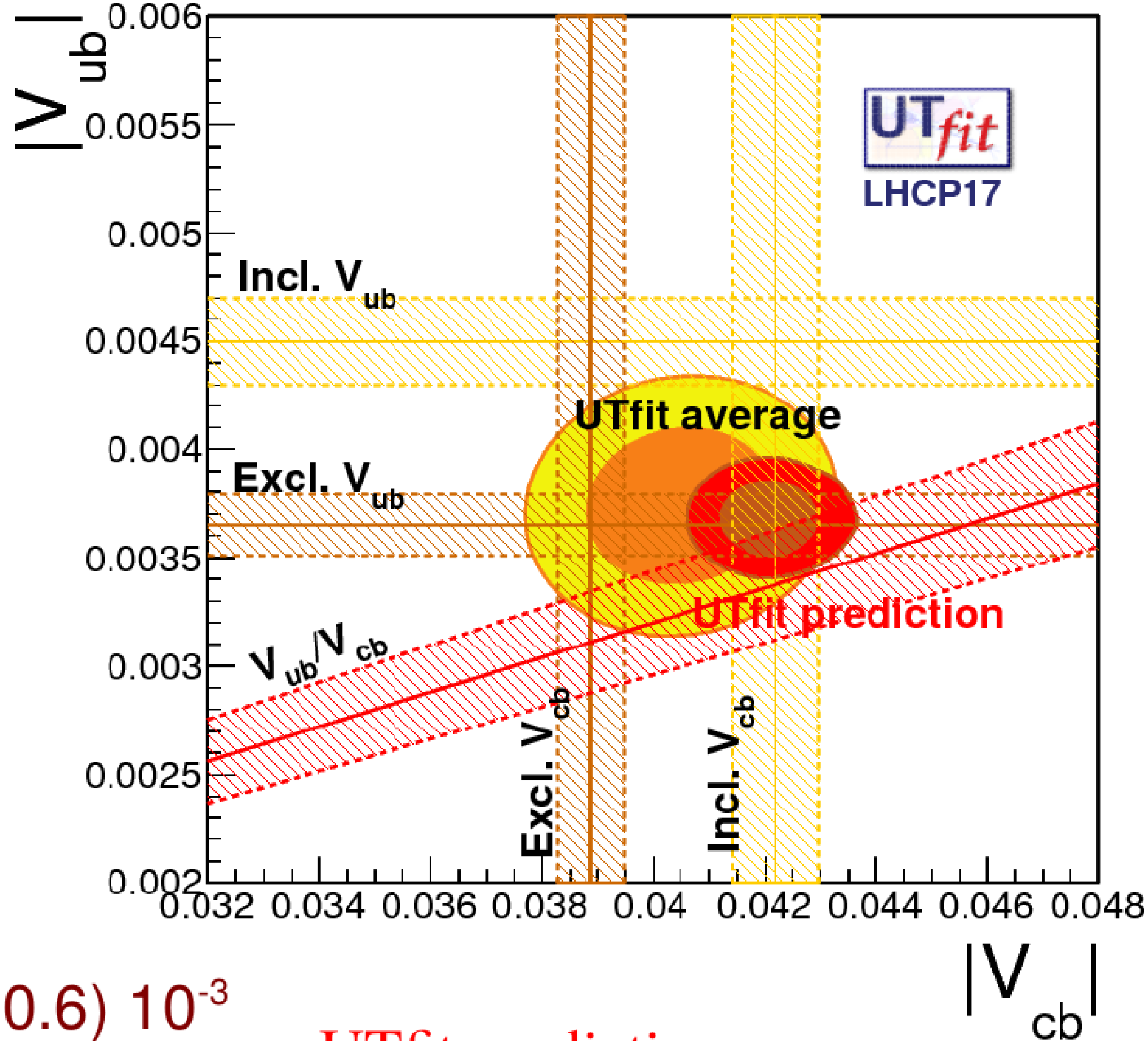
Updated value

updated for LHCP17



V_{cb} and V_{ub}

updated for LHPC17



2D average inspired by D'Agostini skeptical procedure (hep-ex/9910036) with σ=1. Very similar results obtained from a 2D a la PDG procedure.

$$|V_{cb}| = (40.5 \pm 1.1)\ 10^{-3}$$

uncertainty ~ 2.4%

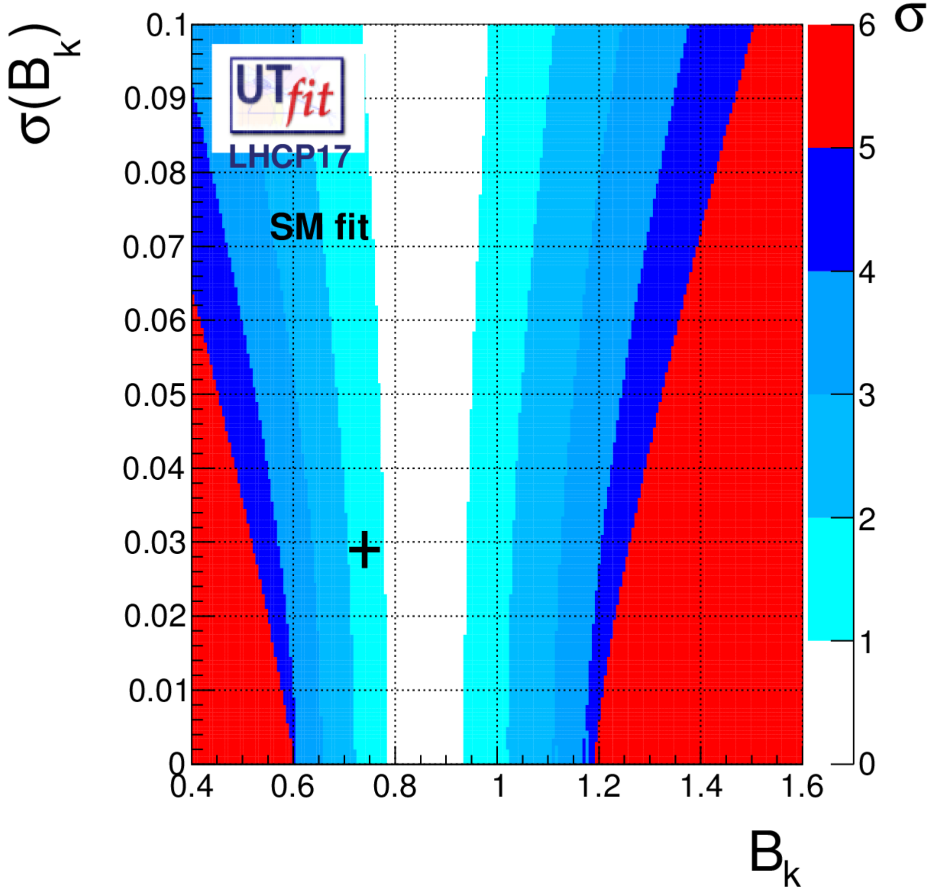
$$|V_{ub}| = (3.74 \pm 0.23)\ 10^{-3}$$

uncertainty ~ 5.6%

$$|V_{cb}| = (42.1 \pm 0.6)\ 10^{-3}$$
$$|V_{ub}| = (3.68 \pm 0.11)\ 10^{-3}$$

UTfit predictions

COMPATIBILITY PLOT FOR ε_K



- Currently no tension in ε_K
- Theoretical improvements needed to fully exploit NP sensitivity: long-distance contributions, B-parameter, D=8 operators...