Unitarity Triangle analysis in the Standard Model and beyond from UTfit

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Unitarity Triangle analysis in the SM

- SM UT analysis:
  - provide the best determination of CKM parameters
  - test the consistency of the SM ("*direct*" vs "*indirect*" determinations)
  - provide predictions (from data..) for SM observables

.. and beyond

- NP UT analysis:
  - model-independent analysis
  - provides limit on the allowed deviations from the SM
  - obtain the NP scale

www.utfit.org

C. Alpigiani, A. Bevan, M.B., M. Ciuchini,
D. Derkach, E. Franco, V. Lubicz, G. Martinelli,
F. Parodi, M. Pierini, C. Schiavi, L. Silvestrini,
A. Stocchi, V. Sordini, C. Tarantino and V. Vagnoni

Other UT analyses exist, by:

CKMfitter (http://ckmfitter.in2p3.fr/),
Laiho&Lunghi&Van de Water (http://latticeaverages.org/)
Lunghi&Soni (1010.6069)

the method and the inputs:

$$f(\bar\rho,\bar\eta,X|c_1,...,c_m) \sim \prod_{j=1,m} f_j(\mathcal{C}|\bar\rho,\bar\eta,X) * \prod_{i=1,N} f_i(x_i) f_0(\bar\rho,\bar\eta)$$

Bayes Theorem

$$X \equiv x_1,...,x_n = m_t, B_K, F_B, ...$$

$$\mathcal{C} \equiv c_1,...,c_m = \epsilon, \Delta m_d/\Delta m_s, A_{CP}(J/\psi K_S), ...$$

$(b \to u)/(b \to c)$	$\bar\rho^2 + \bar\eta^2$	$\bar\Lambda, \lambda_1, F(1), ...$
ϵ_K	$\bar\eta[(1-\bar\rho) + P]$	B_K }
Δm_d	$(1-\bar\rho)^2 + \bar\eta^2$	$f_B^2 B_B$
$\Delta m_d/\Delta m_s$	$(1-\bar\rho)^2 + \bar\eta^2$	ξ
$A_{CP}(J/\psi K_S)$	$\sin 2\beta$	

, $\mathbf{m_t}$

Standard Model + OPE/HQET/ Lattice QCD to go from quarks to hadrons

M. Bona *et al*. (UTfit Collaboration) JHEP 0507:028,2005 hep-ph/0501199
M. Bona *et al*. (UTfit Collaboration) JHEP 0603:080,2006 hep-ph/0509219

V_{cb} and V_{ub}

$|V_{cb}|$ *(excl)* = (38.9 ± 0.6) 10^{-3}

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

~3.3σ discrepancy

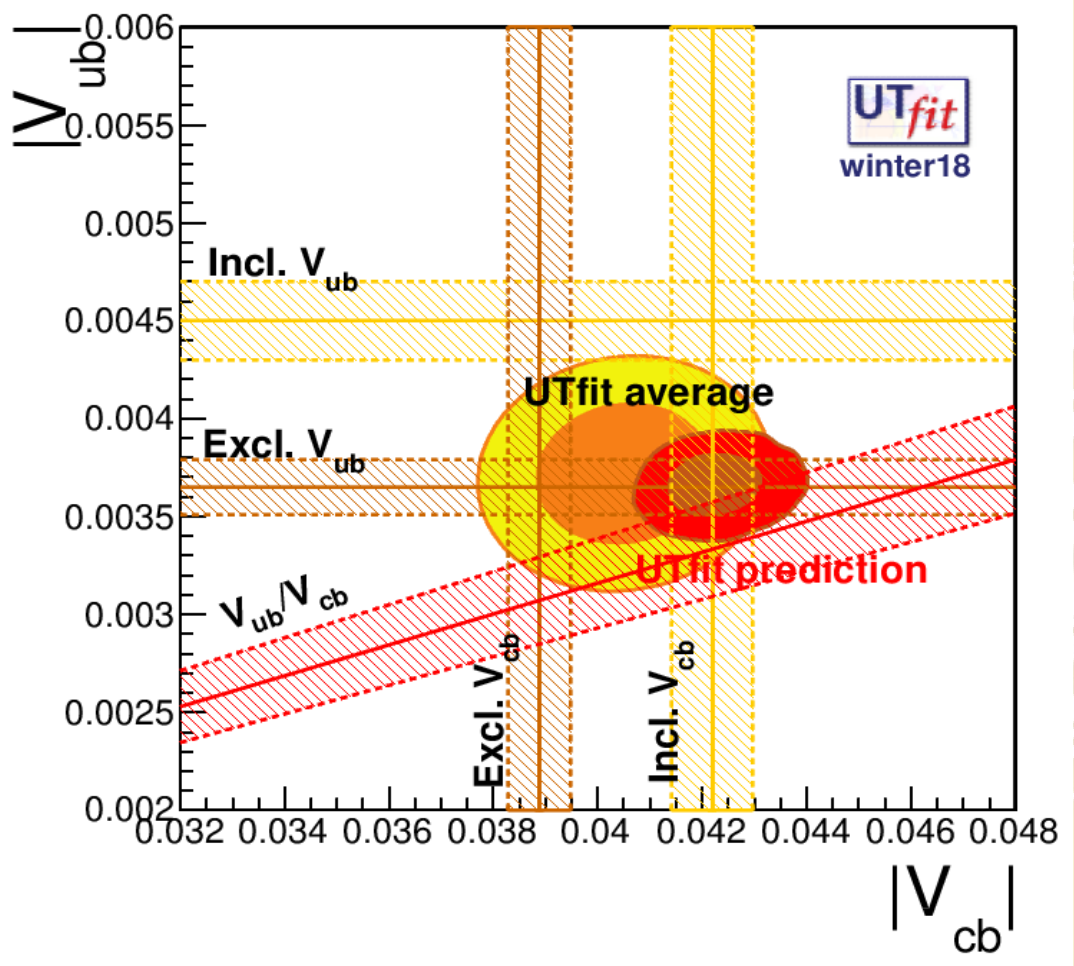
$|V_{ub}|$ *(excl)* = (3.65 ± 0.14) 10^{-3}

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

~3.4σ discrepancy

$|V_{ub} / V_{cb}|$ *(LHCb)* = (7.9 ± 0.6) 10^{-2}

updated for Winter18



V_{cb} and V_{ub}

updated for Winter18

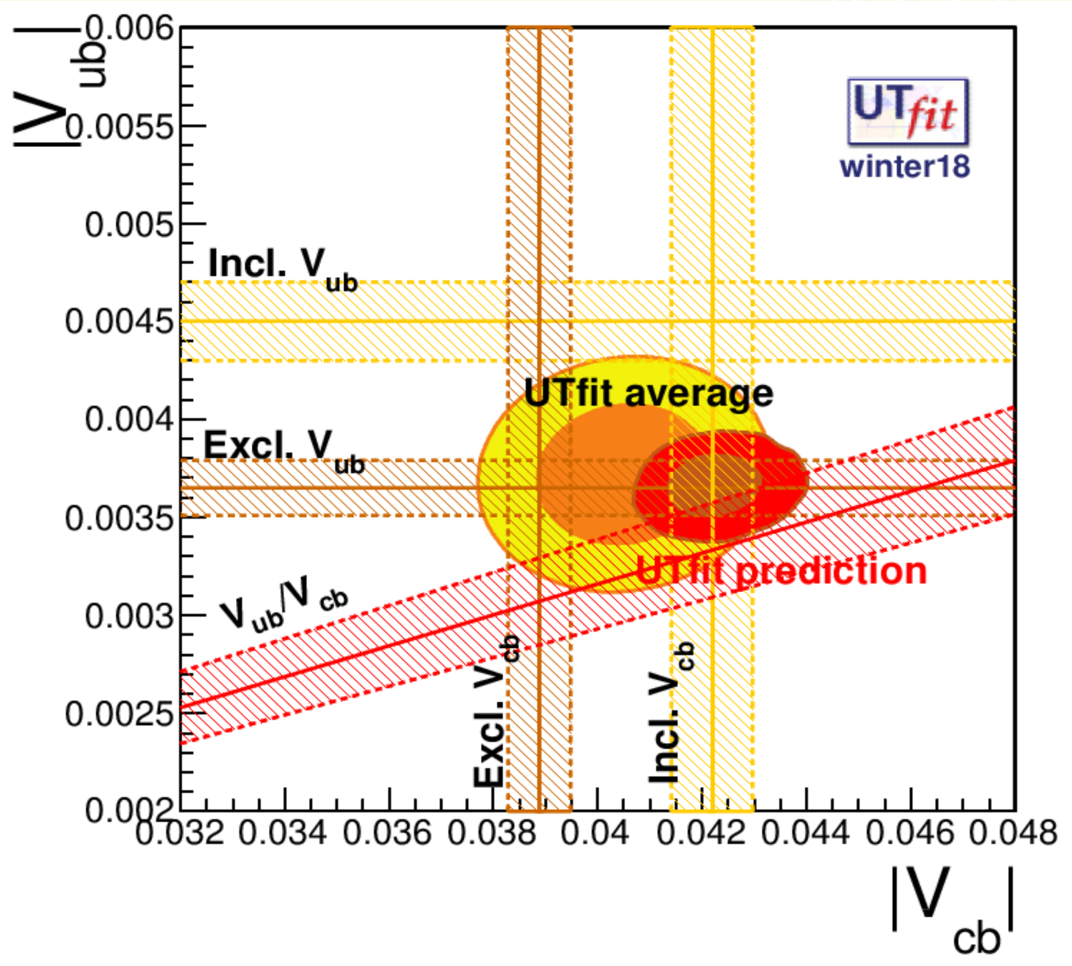
2D average inspired by D'Agostini skeptical procedure (hep-ex/9910036) with σ=1.
Very similar results obtained from a 2D a la PDG procedure.

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

uncertainty ~ 2.7%

$|V_{ub}| = (3.72 \pm 0.23)\ 10^{-3}$

uncertainty ~ 6.2%



$|V_{cb}| = (42.4 \pm 0.7)\ 10^{-3}$

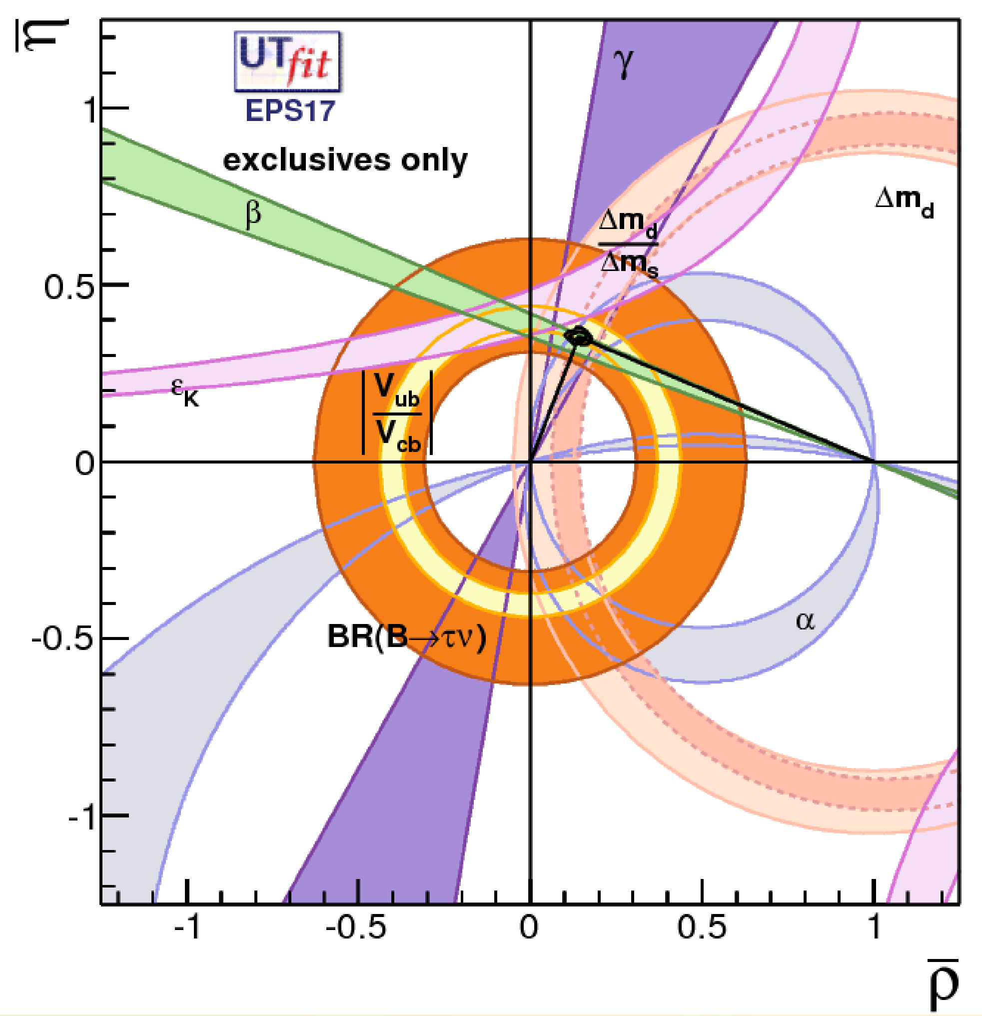
$|V_{ub}| = (3.66 \pm 0.11)\ 10^{-3}$

UTfit predictions

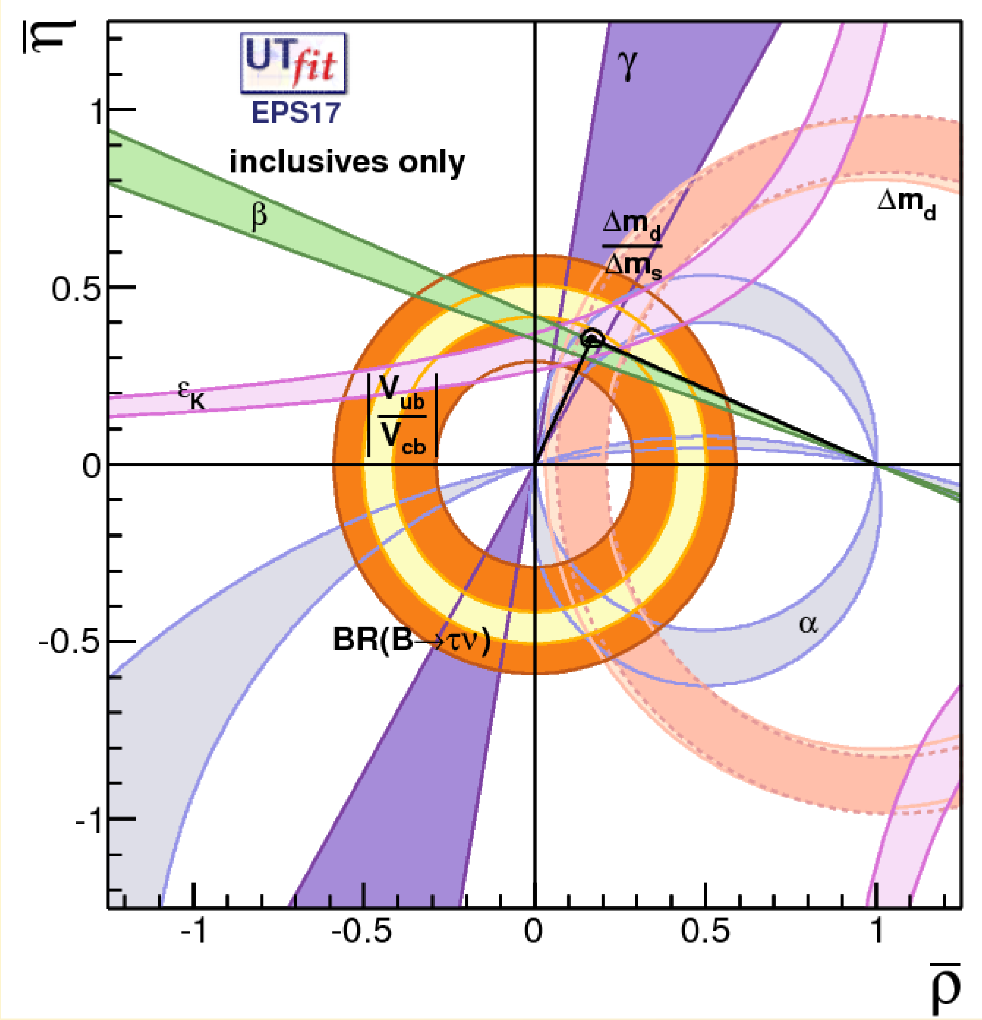
EPS17

exclusives vs inclusives

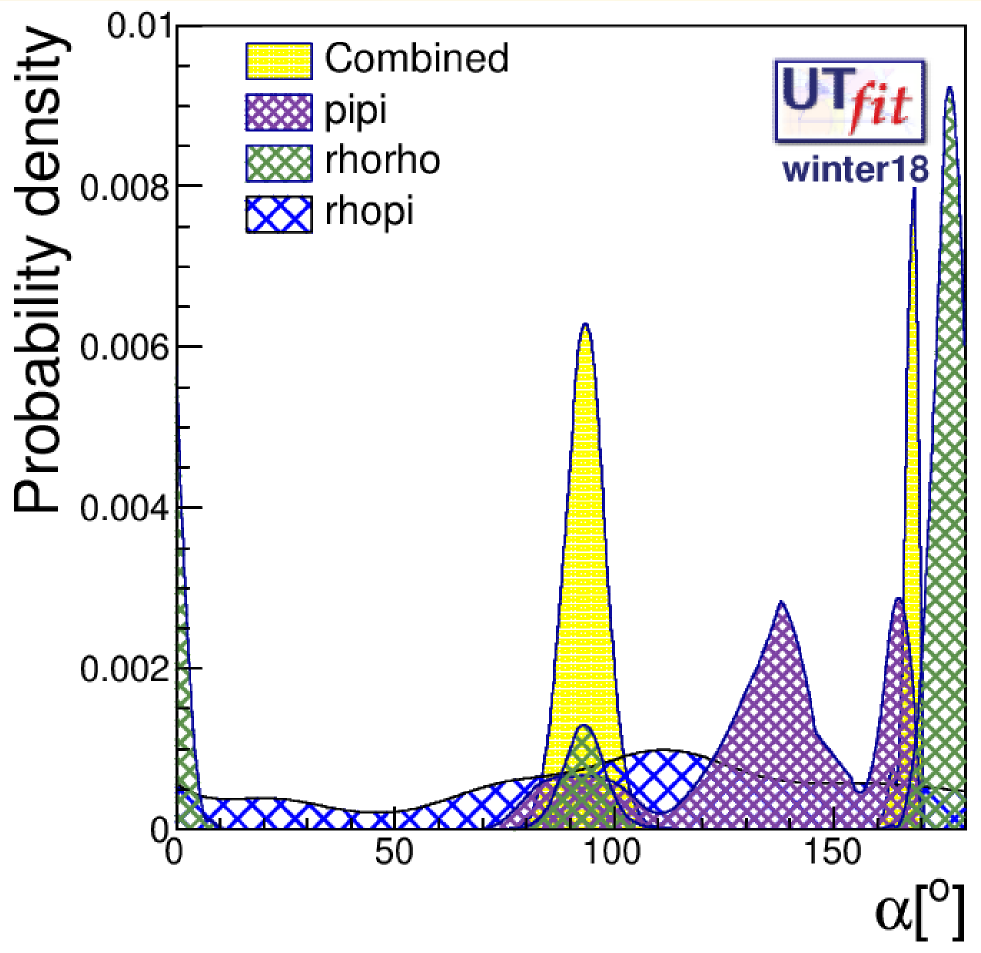
only exclusive values

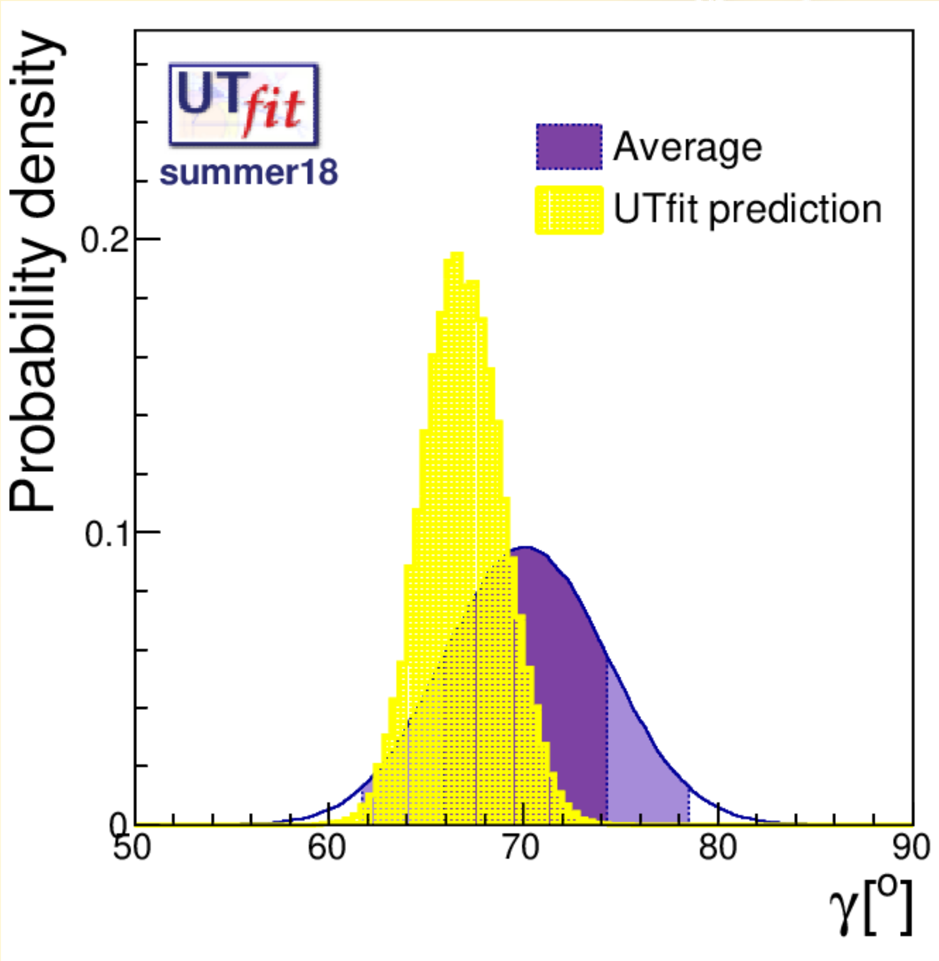


only inclusive values



sin2α (ϕ_2) and γ (ϕ_3)





α from $\pi\pi$, $\rho\rho$, $\pi\rho$ decays:

combined SM: (93.3 ± 5.6)°

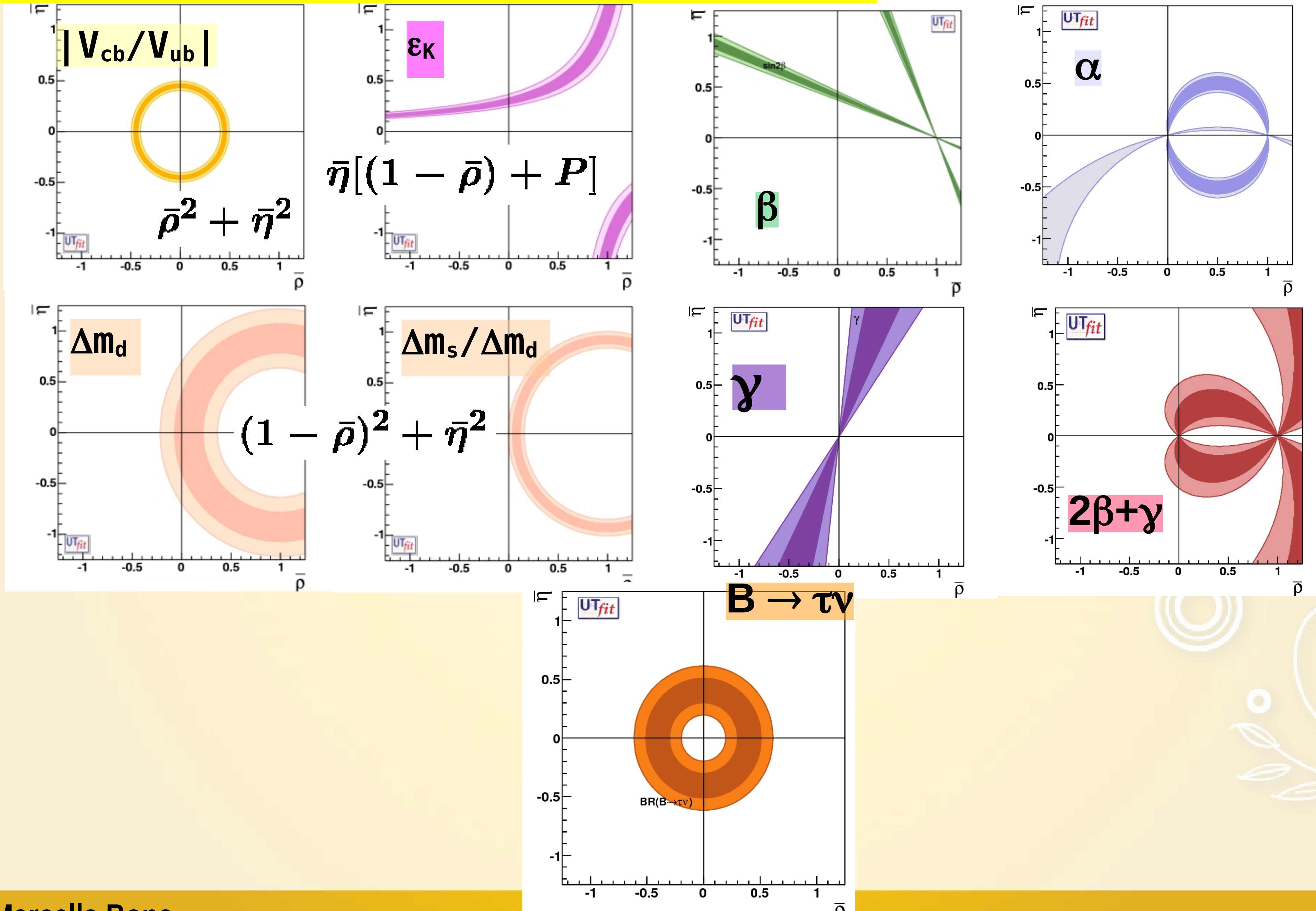
UTfit prediction: (90.1 ± 2.2)°

γ from B into DK decays:

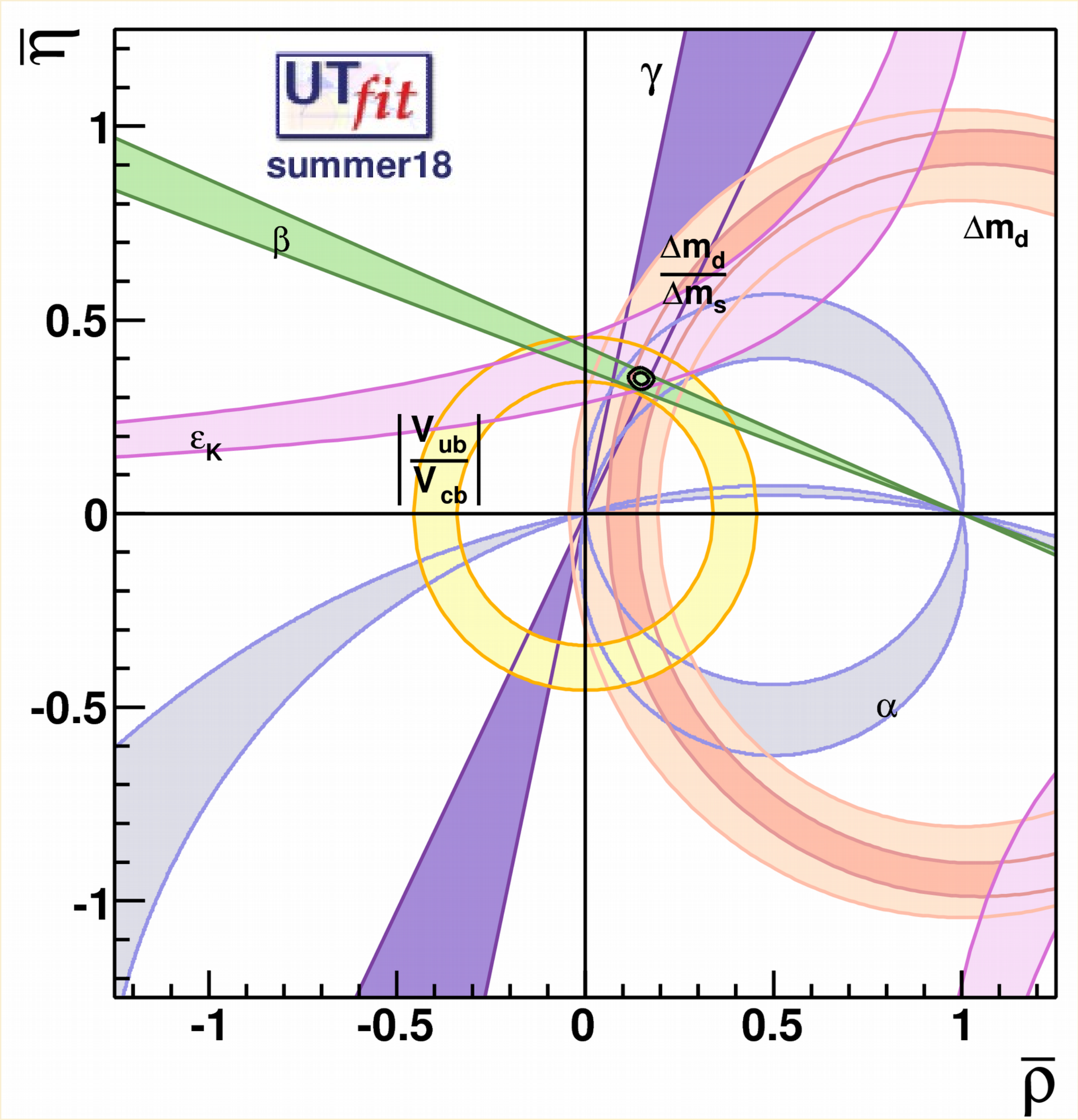
combined: (73.4 ± 4.4)°

UTfit prediction: (65.8 ± 2.2)°

Unitarity Triangle analysis in the SM:



Unitarity Triangle analysis in the SM:



levels @ 95% Prob

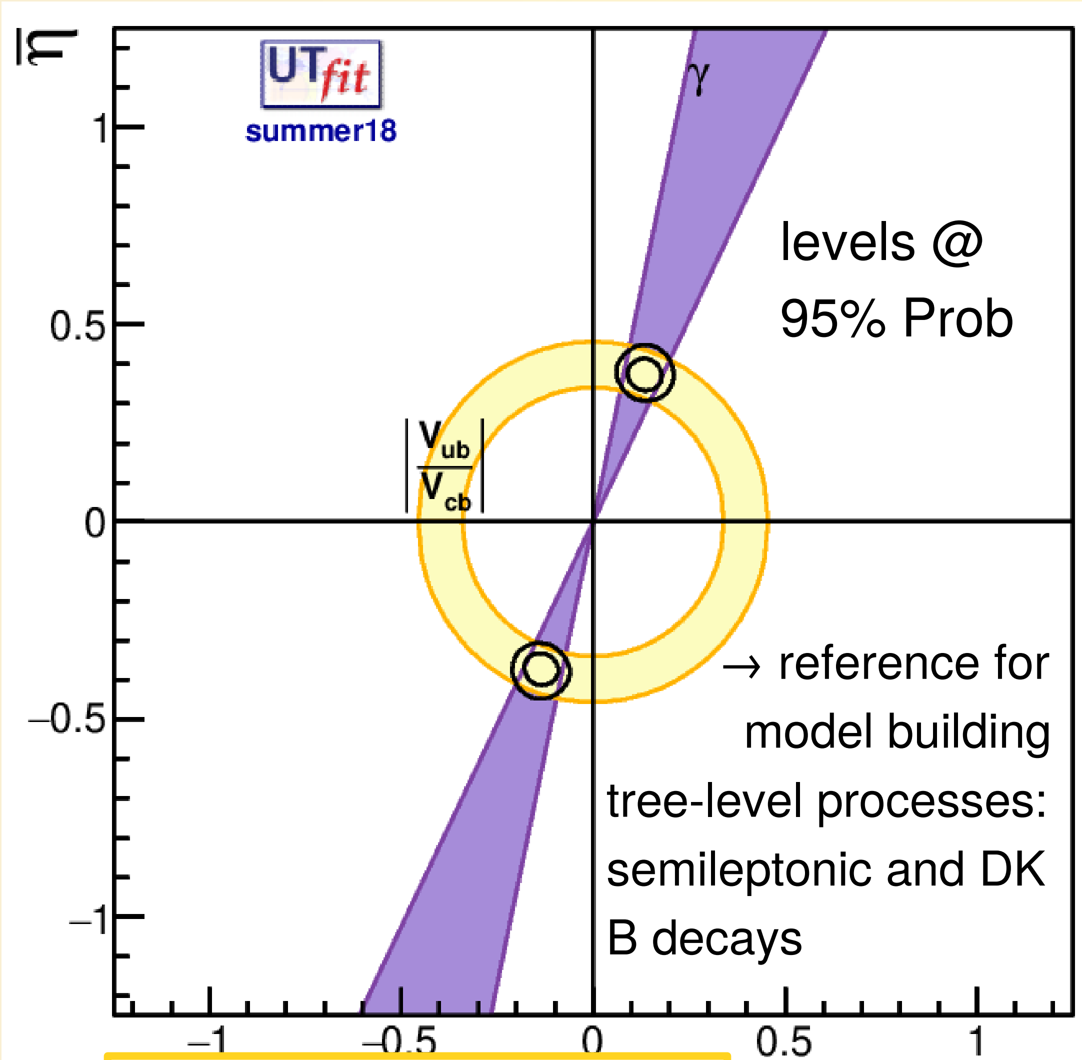
~9%

$\bar{\rho} = 0.148 \pm 0.013$

$\bar{\eta} = 0.348 \pm 0.010$

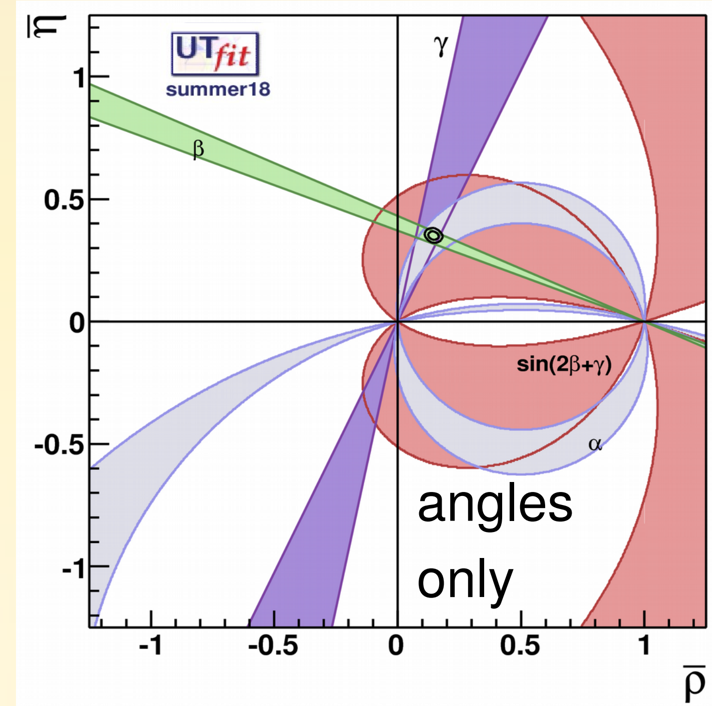
~3%

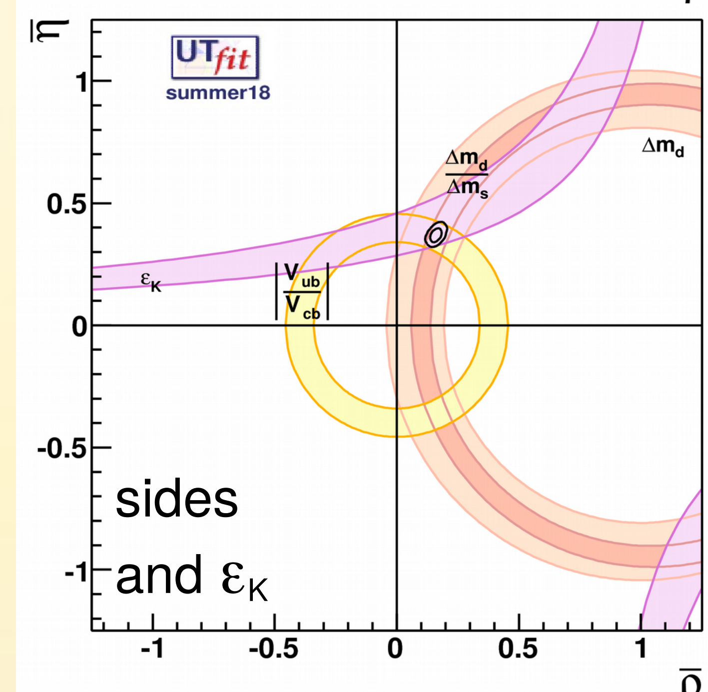
tree only, angles & sides (and ε_K)



$\bar{\rho} = 0.135 \pm 0.029$ ~21%

$\bar{\eta} = 0.372 \pm 0.027$ ~7%



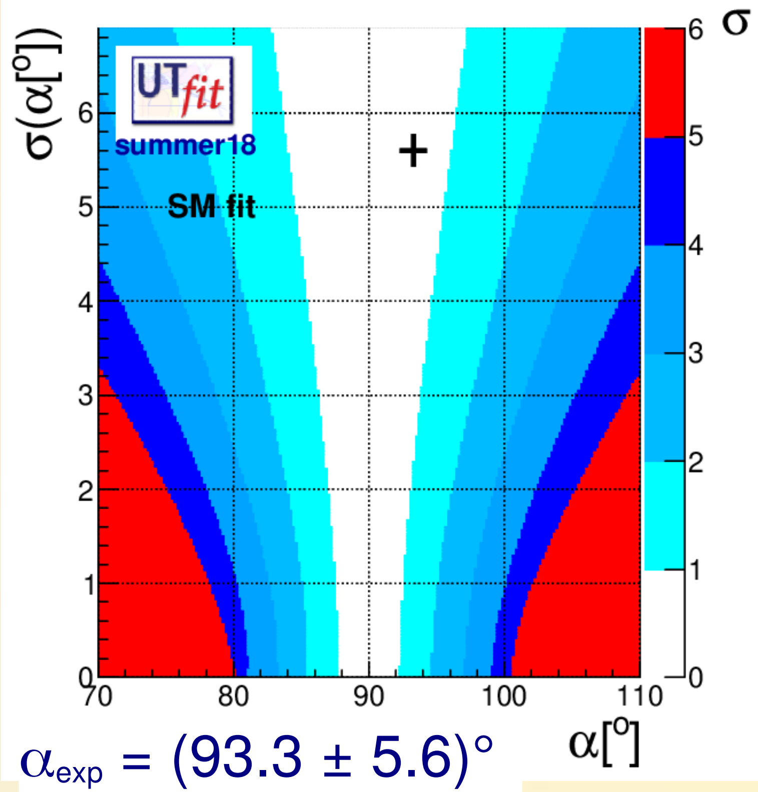


compatibility plots

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

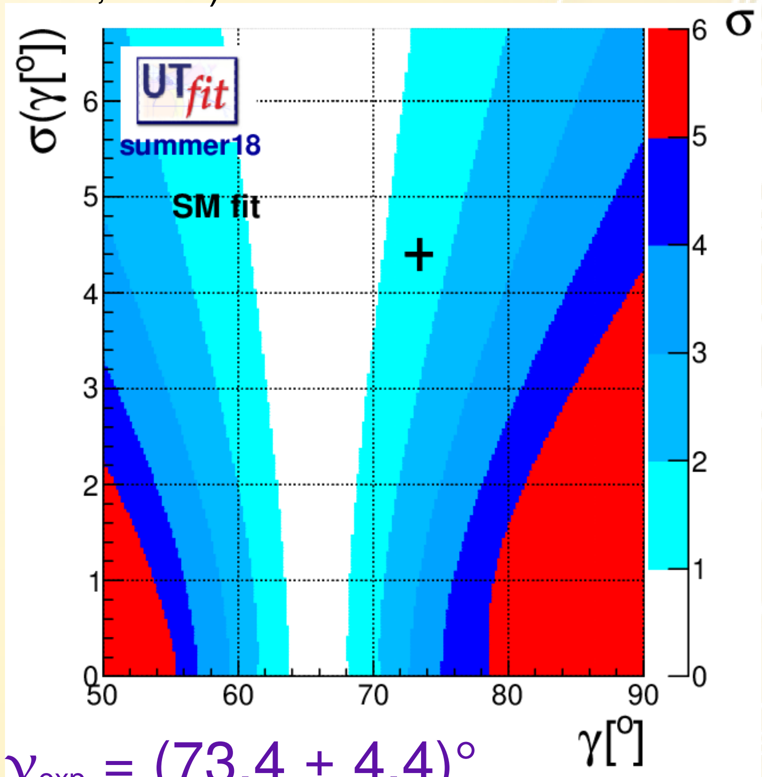
Color code: agreement between the predicted values and the measurements at better than 1, 2, ...nσ

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



α_{exp} = (93.3 ± 5.6)°

α_{UTfit} = (90.1 ± 2.2)°



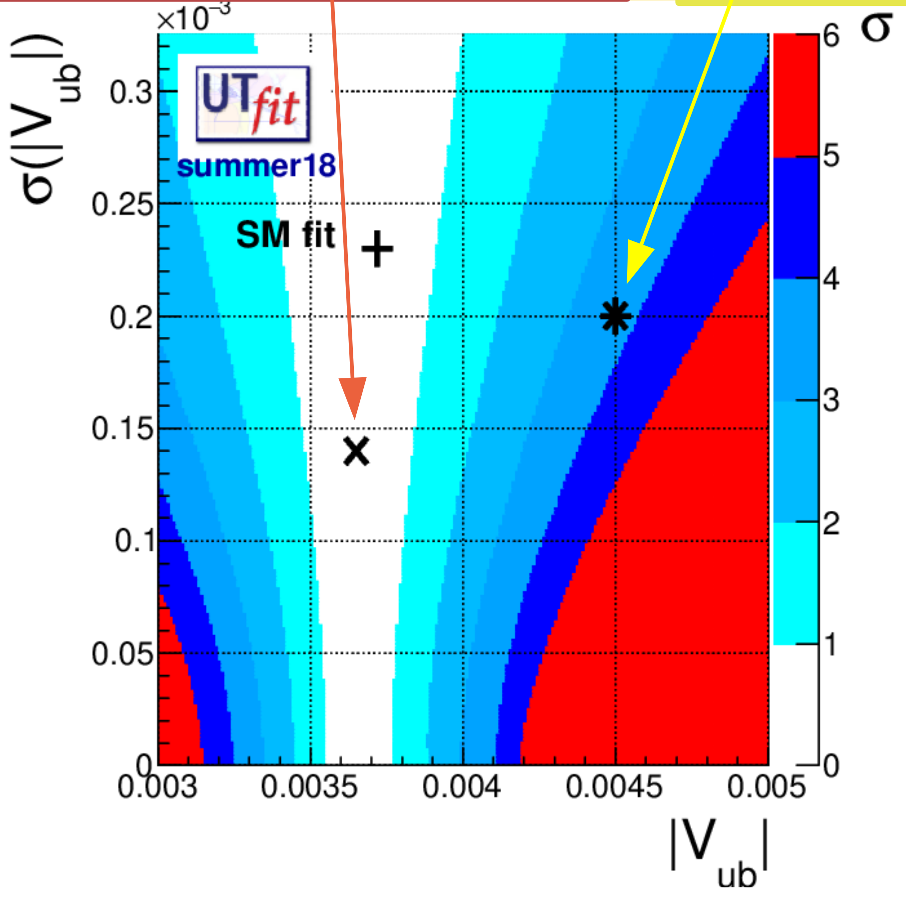
γ_{exp} = (73.4 ± 4.4)°

γ_{UTfit} = (65.8 ± 2.2)°

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

V_{ub} *(excl)* = (3.65 ± 0.14) 10^{-3}

Vub (incl) = (4.50 ± 0.20) 10-3



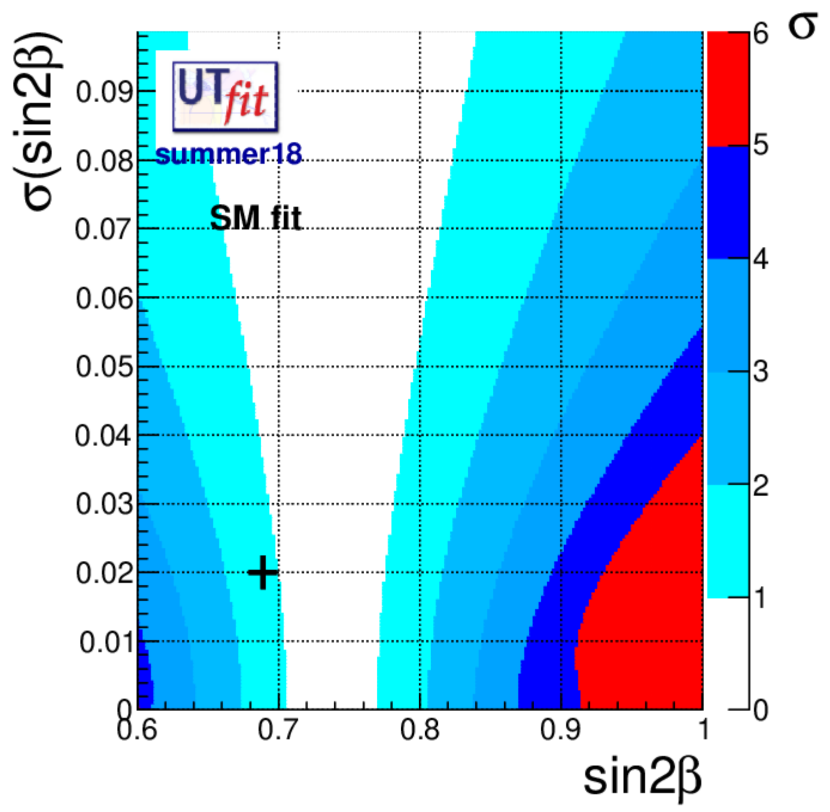
Vub_{exp} = (3.72 ± 0.23) · 10^{-3}

Vub_{UTfit} = (3.66 ± 0.11) · 10^{-3}

~1.2σ

$\sin 2\beta_{exp} = 0.689 \pm 0.018$

$\sin 2\beta_{UTfit} = 0.738 \pm 0.033$



Unitarity Triangle analysis in the SM:

obtained excluding the given constraint from the fit

Observables	Measurement	Prediction	Pull (#σ)
$\sin 2\beta$	0.689 ± 0.018	0.738 ± 0.033	~ 1.2
γ	73.4 ± 4.4	65.8 ± 2.2	< 1
α	93.3 ± 5.6	90.1 ± 2.2	< 1
$\lvert V_{ub}\rvert \cdot 10^3$	3.72 ± 0.23	3.66 ± 0.11	< 1
$\lvert V_{ub}\rvert \cdot 10^3$ (incl)	4.50 ± 0.20	-	~ 3.8
$\lvert V_{ub}\rvert \cdot 10^3$ (excl)	3.65 ± 0.14	-	< 1
$\lvert V_{cb}\rvert \cdot 10^3$	40.5 ± 1.1	42.4 ± 0.7	~ 1.4
$BR(B \to \tau\nu)[10^{-4}]$	1.09 ± 0.24	0.81 ± 0.05	~ 1.2
$A_{SL}^{d} \cdot 10^3$	-2.1 ± 1.7	-0.292 ± 0.026	~ 1
$A_{SL}^{s} \cdot 10^3$	-0.6 ± 2.8	0.013 ± 0.001	< 1

UT analysis including new physics

fit simultaneously for the CKM and the NP parameters (generalized UT fit)

- add most general loop NP to all sectors
- use all available experimental info
- find out NP contributions to ΔF=2 transitions

B_d and B_s mixing amplitudes (2+2 real parameters):

$$A_q = C_{B_q} e^{2i\phi_{B_q}} A_q^{SM} e^{2i\phi_q^{SM}} = \left(1 + \frac{A_q^{NP}}{A_q^{SM}} e^{2i(\phi_q^{NP} - \phi_q^{SM})}\right) A_q^{SM} e^{2i\phi_q^{SM}}$$

$$\Delta m_{q/K} = C_{B_q/\Delta m_K} (\Delta m_{q/K})^{SM}$$

$$A_{CP}^{B_d \to J/\psi K_s} = \sin 2(\beta + \phi_{B_d})$$

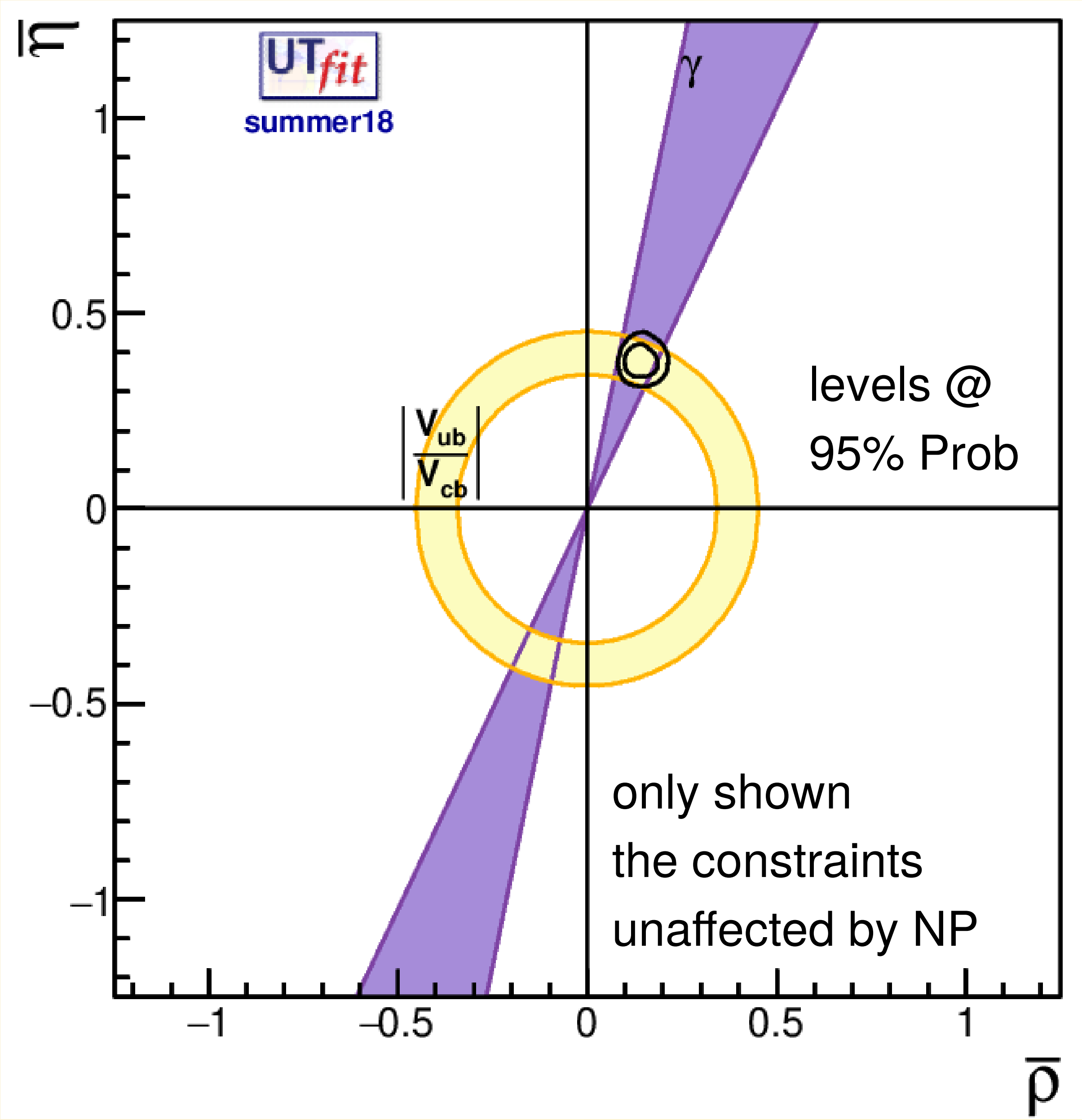
$$A_{SL}^q = \mathrm{Im}\left(\Gamma_{12}^q / A_q\right)$$

$$\varepsilon_K = C_\varepsilon \varepsilon_K^{SM}$$

$$A_{CP}^{B_s \to J/\psi \phi} \sim \sin 2(-\beta_s + \phi_{B_s})$$

$$\Delta\Gamma^q / \Delta m_q = \mathrm{Re}\left(\Gamma_{12}^q / A_q\right)$$

NP analysis results



$\bar{\rho} = 0.144 \pm 0.028$

$\bar{\eta} = 0.378 \pm 0.027$

SM is

$\bar{\rho} = 0.148 \pm 0.013$

$\bar{\eta} = 0.348 \pm 0.010$

NP parameter results

dark: 68%

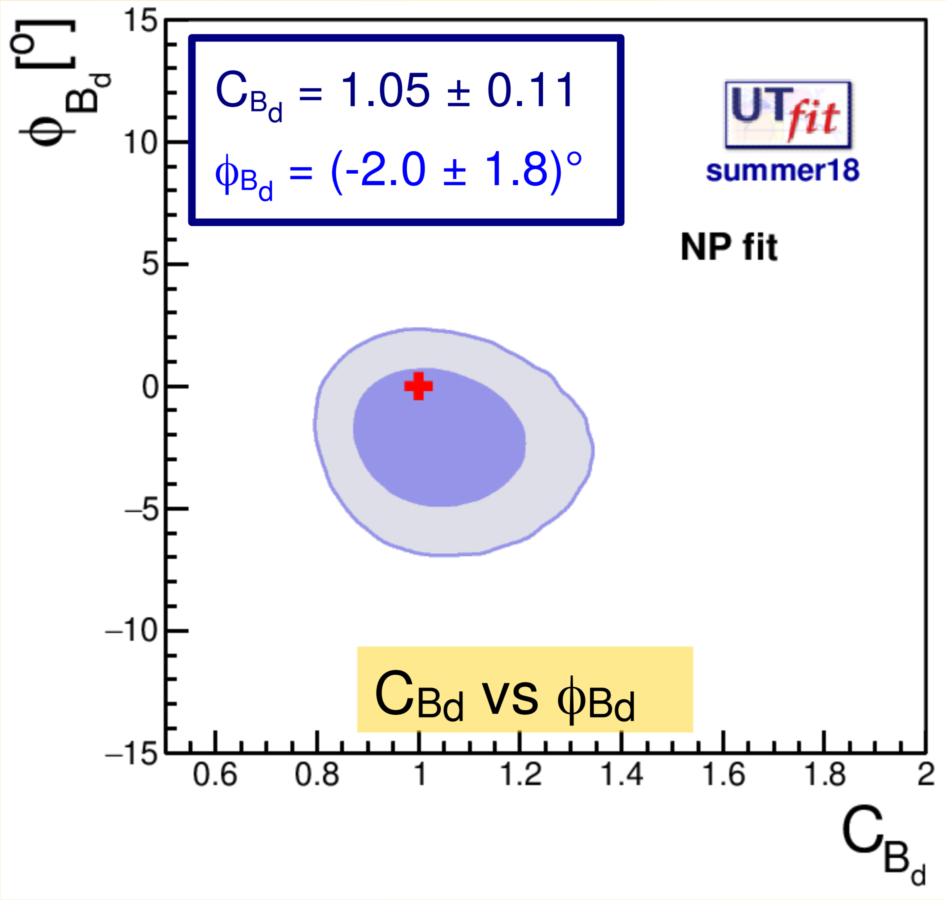
light: 95%

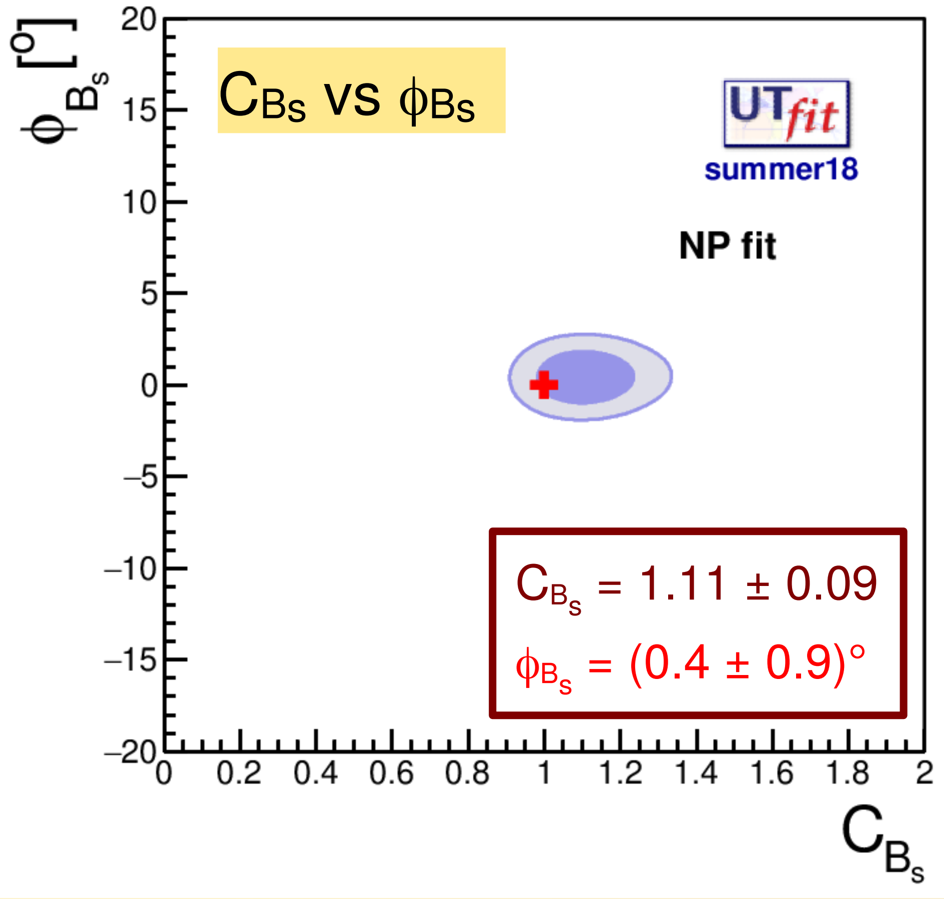
SM: red cross

K system

$C_{\varepsilon_K} = 1.11 \pm 0.12$

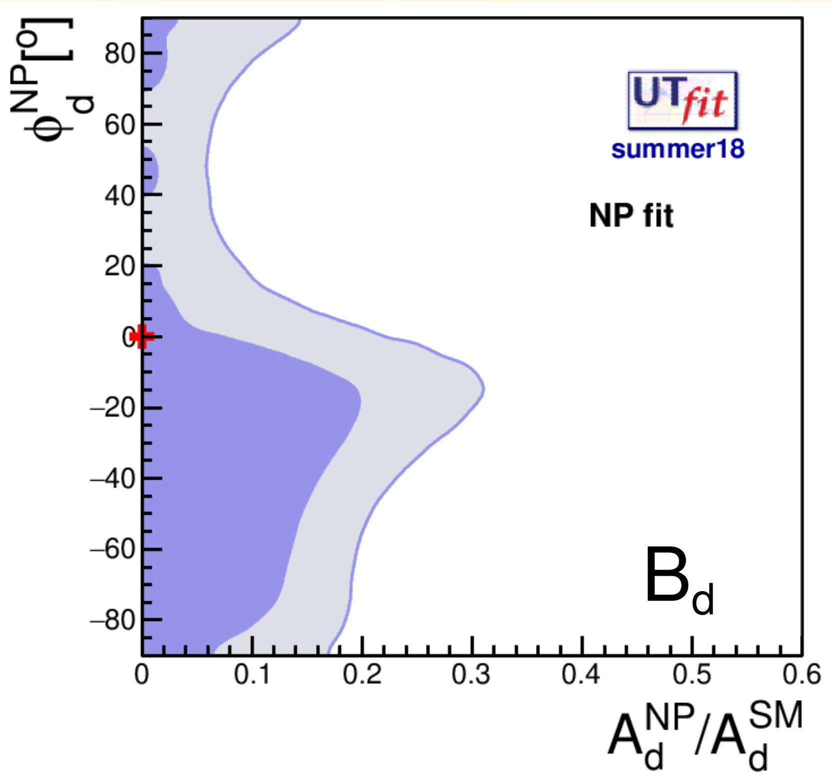
$$A_q = C_{B_q} e^{2i\phi_{B_q}} A_q^{SM} e^{2i\phi_q^{SM}}$$

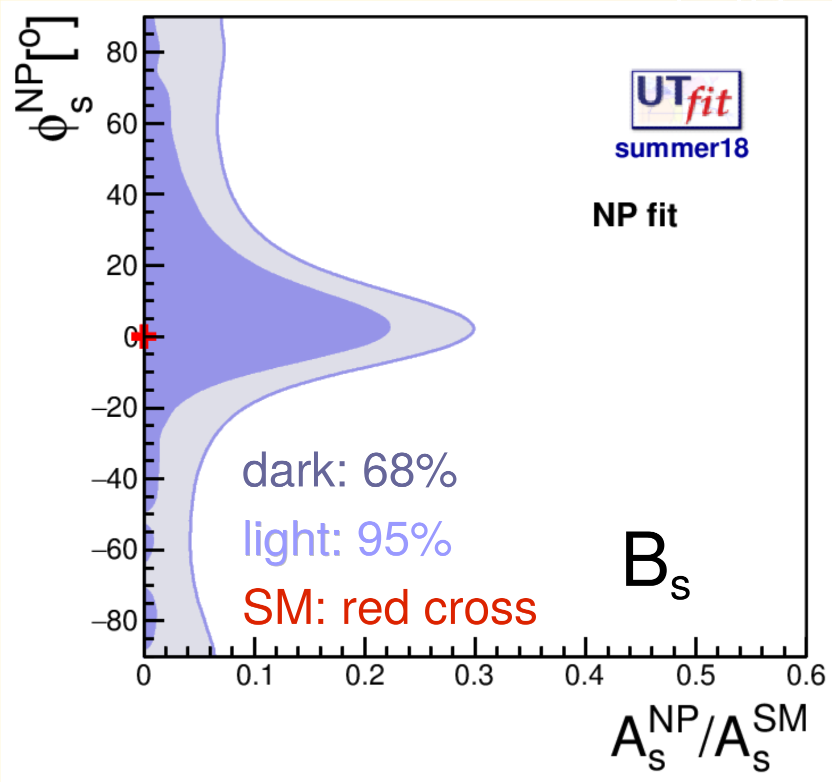




NP parameter results

$$A_q = \left(1 + \frac{A_q^{NP}}{A_q^{SM}} e^{2i(\phi_q^{NP} - \phi_q^{SM})}\right) A_q^{SM} e^{2i\phi_q^{SM}}$$





The ratio of NP/SM amplitudes is:

- < 18% @68% prob. (30% @95%) in B_d mixing
- < 20% @68% prob. (30% @95%) in B_s mixing

see also Lunghi & Soni, Buras et al., Ligeti et al.

testing the new-physics scale

M. Bona *et al.* (UTfit)
JHEP 0803:049,2008
arXiv:0707.0636

R G E

At the high scale

new physics enters according to its specific features

At the low scale

use OPE to write the most general effective Hamiltonian. the operators have different chiralities than the SM

NP effects are in the Wilson Coefficients C

$$C_i(\Lambda) = F_i \frac{L_i}{\Lambda^2}$$

$$\mathcal{H}_{\rm eff}^{\Delta B=2} = \sum_{i=1}^{5} C_i Q_i^{bq} + \sum_{i=1}^{3} \tilde{C}_i \tilde{Q}_i^{bq}$$

$$\begin{aligned}
Q_1^{q_i q_j} &= \bar{q}_{jL}^{\alpha} \gamma_\mu q_{iL}^{\alpha} \bar{q}_{jL}^{\beta} \gamma^\mu q_{iL}^{\beta} \,, \\
Q_2^{q_i q_j} &= \bar{q}_{jR}^{\alpha} q_{iL}^{\alpha} \bar{q}_{jR}^{\beta} q_{iL}^{\beta} \,, \\
Q_3^{q_i q_j} &= \bar{q}_{jR}^{\alpha} q_{iL}^{\beta} \bar{q}_{jR}^{\beta} q_{iL}^{\alpha} \,, \\
Q_4^{q_i q_j} &= \bar{q}_{jR}^{\alpha} q_{iL}^{\alpha} \bar{q}_{jL}^{\beta} q_{iR}^{\beta} \,, \\
Q_5^{q_i q_j} &= \bar{q}_{jR}^{\alpha} q_{iL}^{\beta} \bar{q}_{jL}^{\beta} q_{iR}^{\alpha} \,.
\end{aligned}$$

F_i: function of the NP flavour couplings

L_i: loop factor (in NP models with no tree-level FCNC)

Λ: NP scale (typical mass of new particles mediating $\Delta F=2$ processes)

testing the TeV scale

$$C_i(\Lambda) = F_i \frac{L_i}{\Lambda^2}$$

The dependence of C on Λ changes depending on the flavour structure.
We can consider different flavour scenarios:

- Generic: $C(\Lambda) = \alpha/\Lambda^2$ $F_i \sim 1$, arbitrary phase
- NMFV: $C(\Lambda) = \alpha \times |F_{SM}|/\Lambda^2$ $F_i \sim |F_{SM}|$, arbitrary phase
- MFV: $C(\Lambda) = \alpha \times |F_{SM}|/\Lambda^2$ $F_1 \sim |F_{SM}|$, $F_{i\neq 1} \sim 0$, SM phase

α (L_i) is the coupling among NP and SM
- $\alpha \sim 1$ for strongly coupled NP
- $\alpha \sim \alpha_W$ (α_S) in case of loop coupling through weak (strong) interactions

If no NP effect is seen lower bound on NP scale Λ

F is the flavour coupling and so
F_{SM} is the combination of CKM factors for the considered process

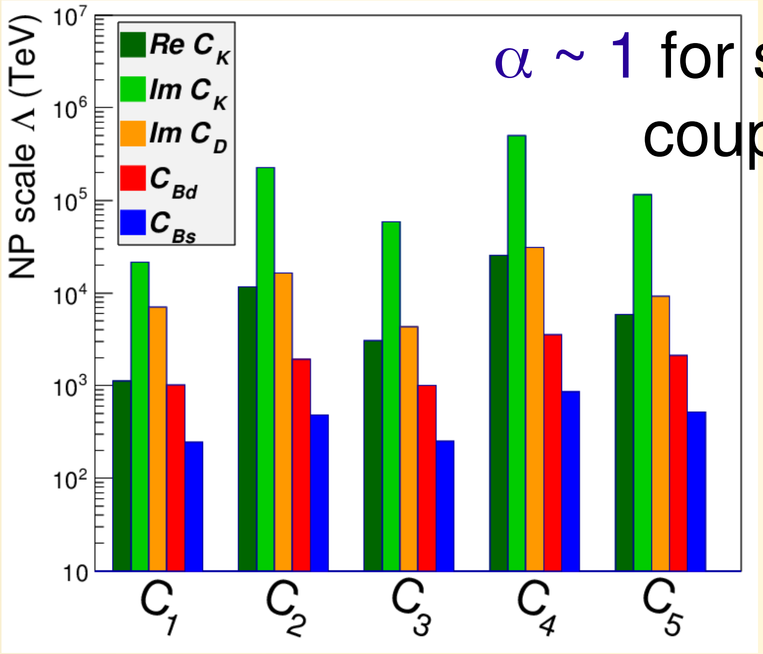
EPS17

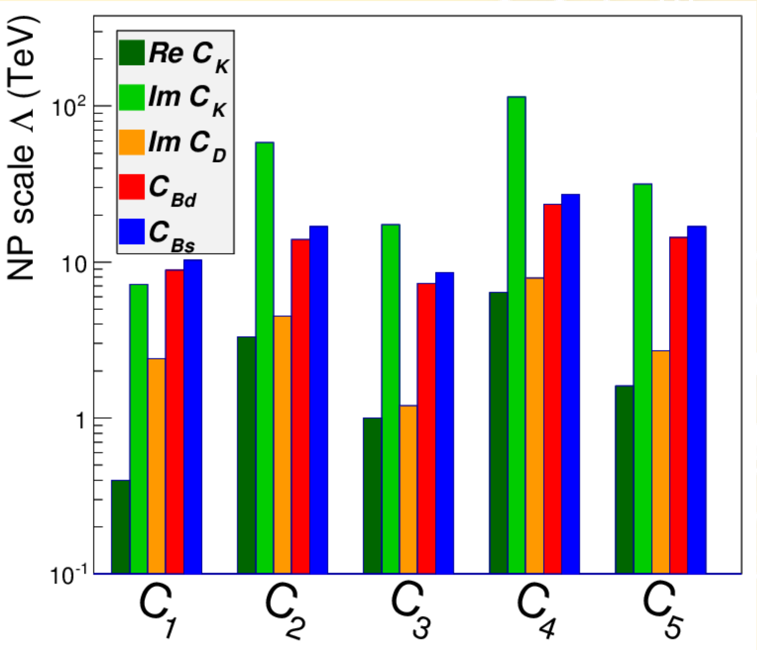
results from the Wilson coefficients

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

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

$\alpha \sim 1$ for strongly coupled NP





$\Lambda > 5.0\ 10^5$ TeV

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

$\Lambda > 114$ TeV

$\alpha \sim \alpha_W$ in case of loop coupling through weak interactions
$\Lambda > 1.5\ 10^4$ TeV

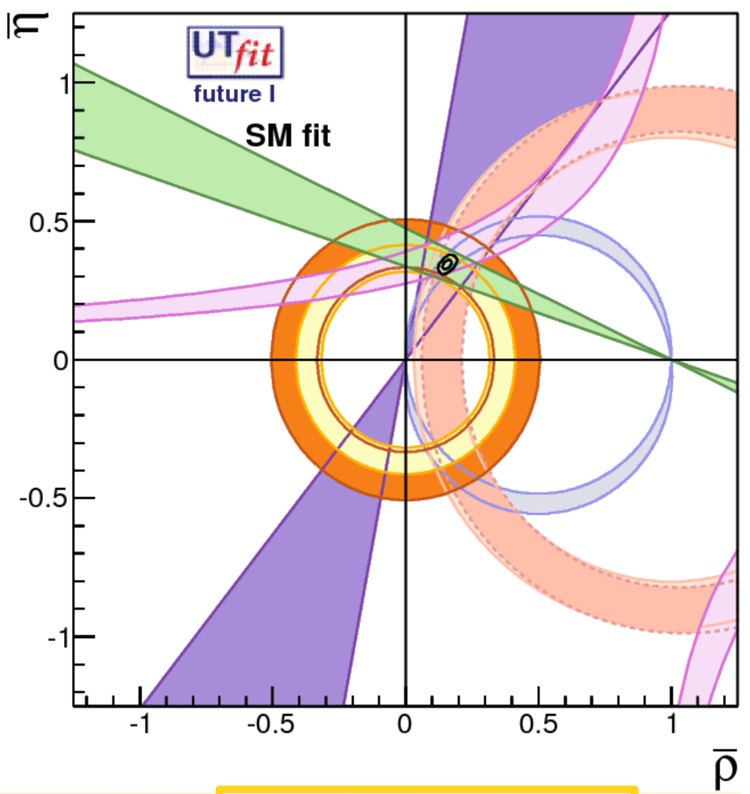
$\alpha \sim \alpha_W$ in case of loop coupling through weak interactions
$\Lambda > 3.4$ TeV

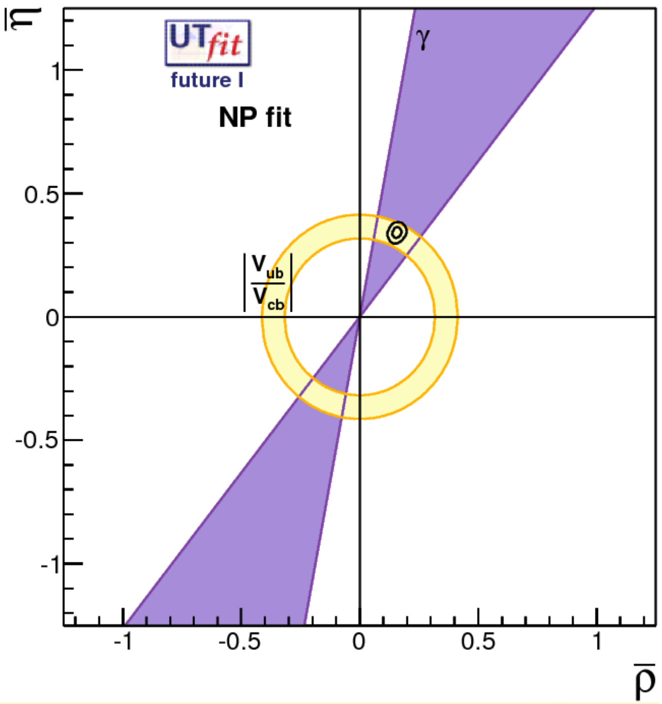
for lower bound for loop-mediated contributions, simply multiply by α_s (~ 0.1) or by α_W (~ 0.03).

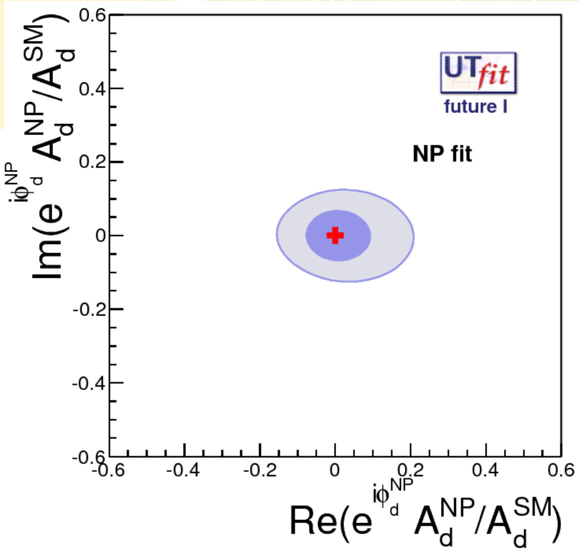
Look at the near future

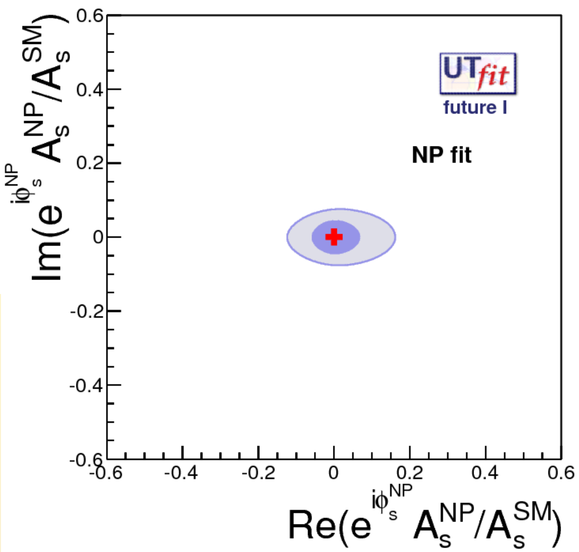
preliminary

future I scenario:
errors from
Belle II at 5/ab
+ **LHCb at 10/fb**









$\rho = \pm\ 0.015$

$\eta = \pm\ 0.015$

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

$\bar{\eta} = 0.344 \pm 0.013$

current sensitivity

$\bar{\rho} = 0.150 \pm 0.027$

$\bar{\eta} = 0.363 \pm 0.025$

$\rho = \pm\ 0.016$

$\eta = \pm\ 0.019$

conclusions

- SM analysis displays very good overall consistency
- Still open discussion on semileptonic inclusive vs exclusive
- UTA provides determination of NP contributions to $\Delta F=2$ amplitudes. It currently leaves space for NP at the level of 25-30%
- So the scale analysis points to high scales for the generic scenario and at the limit of LHC reach for weak coupling. Indirect searches are complementary to direct searches.
- Even if we don't see relevant deviations in the down sector, we might still find them in the up sector.

Back up slides

EPS17

Unitarity Triangle analysis in the SM:

obtained excluding the given constraint from the fit

Observables	Measurement	Prediction	Pull (#σ)
B_K	0.740 ± 0.029	0.81 ± 0.07	< 1
f_{Bs}	0.226 ± 0.005	0.220 ± 0.007	< 1
f_{Bs}/f_{Bd}	1.203 ± 0.013	1.210 ± 0.030	< 1
B_{Bs}/B_{Bd}	1.032 ± 0.036	1.07 ± 0.05	< 1
B_{Bs}	1.35 ± 0.08	1.30 ± 0.07	< 1

in general: average the Nf=2+1+1 and Nf=2+1 FLAG averages, through eq.(28) in arXiv:1403.4504

for Bk, fBs, fBs/fBd:

FLAG Nf=2+1+1 (single result) and Nf=2+1 average

for B_{Bs}, B_{bs}/B_{bd}:

update w.r.t. the Nf=2+1 FLAG average (no Nf=2+1+1 results yet)

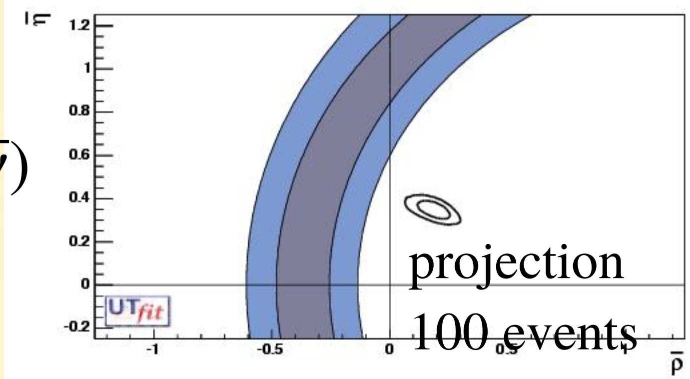
updating the FNAL/MILC result to FNAL/MILC 2016 (1602.03560)

some old plots coming back to fashion:

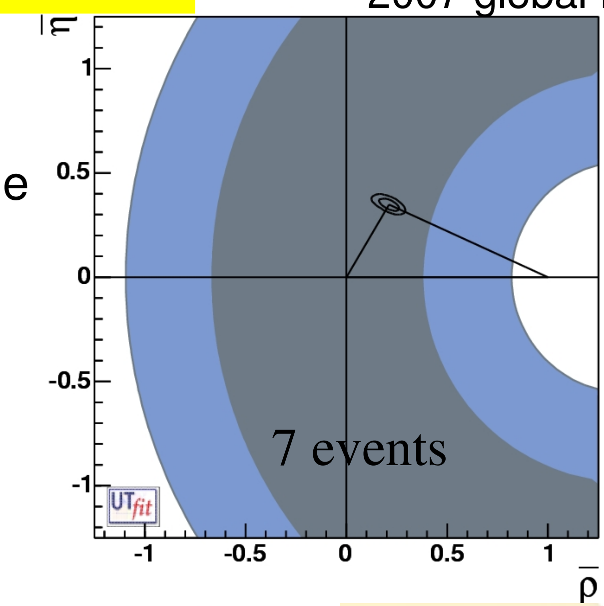
As NA62 and KOTO are analysing data:

$BR(K^+ \to \pi^+ \nu \bar{\nu})$

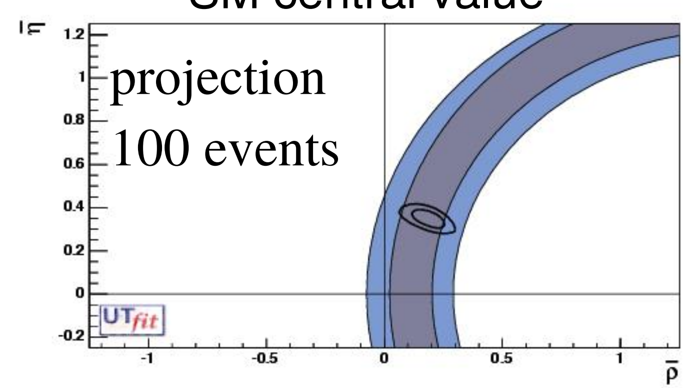
E949 central value

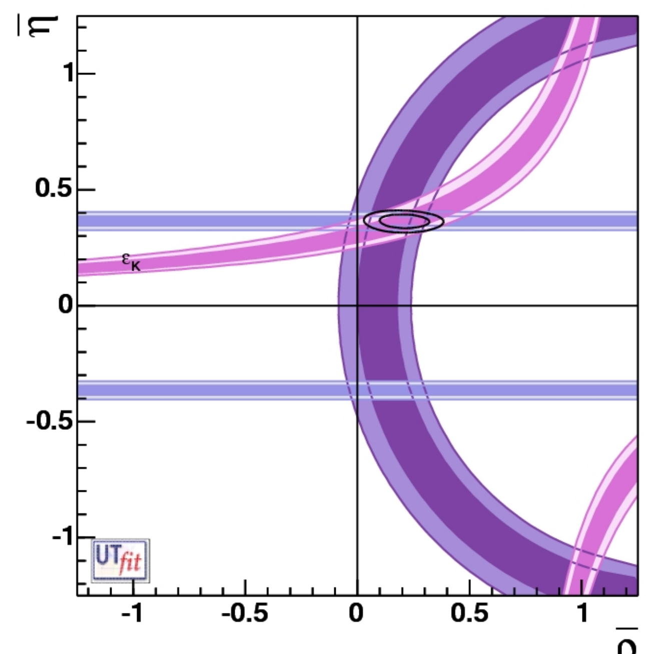


2007 global fit area



SM central value





including
$BR(K^0 \to \pi^0 \nu \bar{\nu})$
SM central value

new-physics-specific constraints

$$A^s_{\mathrm{SL}} \equiv \frac{\Gamma(\bar{B}_s \to \ell^+ X) - \Gamma(B_s \to \ell^- X)}{\Gamma(\bar{B}_s \to \ell^+ X) + \Gamma(B_s \to \ell^- X)} = \mathrm{Im}\left(\frac{\Gamma^s_{12}}{A^{\mathrm{full}}_s}\right)$$

semileptonic asymmetries in B^0 and B_s: sensitive to NP effects in both size and phase. Currently using HFLAV.

BaBar, Belle, D0 + LHCb

same-side dilepton charge asymmetry: admixture of B_s and B_d so sensitive to NP effects in both.

D0 arXiv:1106.6308

$$A^{\mu\mu}_{\mathrm{SL}} = \frac{f_d \chi_{d0} A^d_{\mathrm{SL}} + f_s \chi_{s0} A^s_{\mathrm{SL}}}{f_d \chi_{d0} + f_s \chi_{s0}}$$

$$A^{\mu\mu}_{\mathrm{SL}} \times 10^3 = -7.9 \pm 2.0$$

lifetime τ^{FS} in flavour-specific final states: average lifetime is a function to the width and the width difference

$\tau^{FS}(B_s) = 1.509 \pm 0.004$ ps **HFLAV**

$\phi_s = 2\beta_s$ vs $\Delta\Gamma_s$ from $B_s \to J/\psi\phi$
angular analysis as a function of proper time and b-tagging