Updates in the Unitarity Triangle fits with UTfit

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on behalf of the UTfit collaboration

The European Physical Society Conference on High Energy Physics (EPS-HEP)
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Unitarity Triangle analysis in the SM

- SM UT analysis:
  - All updated with Summer 2021 inputs
  - 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:
  - Also all updated with Summer 2021 inputs
  - model-independent analysis
  - provides limit on the allowed deviations from the SM
  - obtain the NP scale

UTfit

www.utfit.org

RELOADED

M.Bona, M. Ciuchini, D. Derkach, F. Ferrari, E. Franco, V. Lubicz, G. Martinelli, M. Pierini, L. Silvestrini, C. Tarantino, V. Vagnoni, M. Valli, and L.Vittorio

Plots and numbers in this talk are hot-off-the-press for this conference

Usual method and 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}

from FLAG 2019 arXiv:1902.08191

$|V_{cb}|$ *(excl)* = (39.09 ± 0.68) 10^{-3}

$|V_{cb}|$ *(incl)* = (42.16 ± 0.50) 10^{-3}

from Bordone et al. arXiv:2107.00604

~2.8σ discrepancy

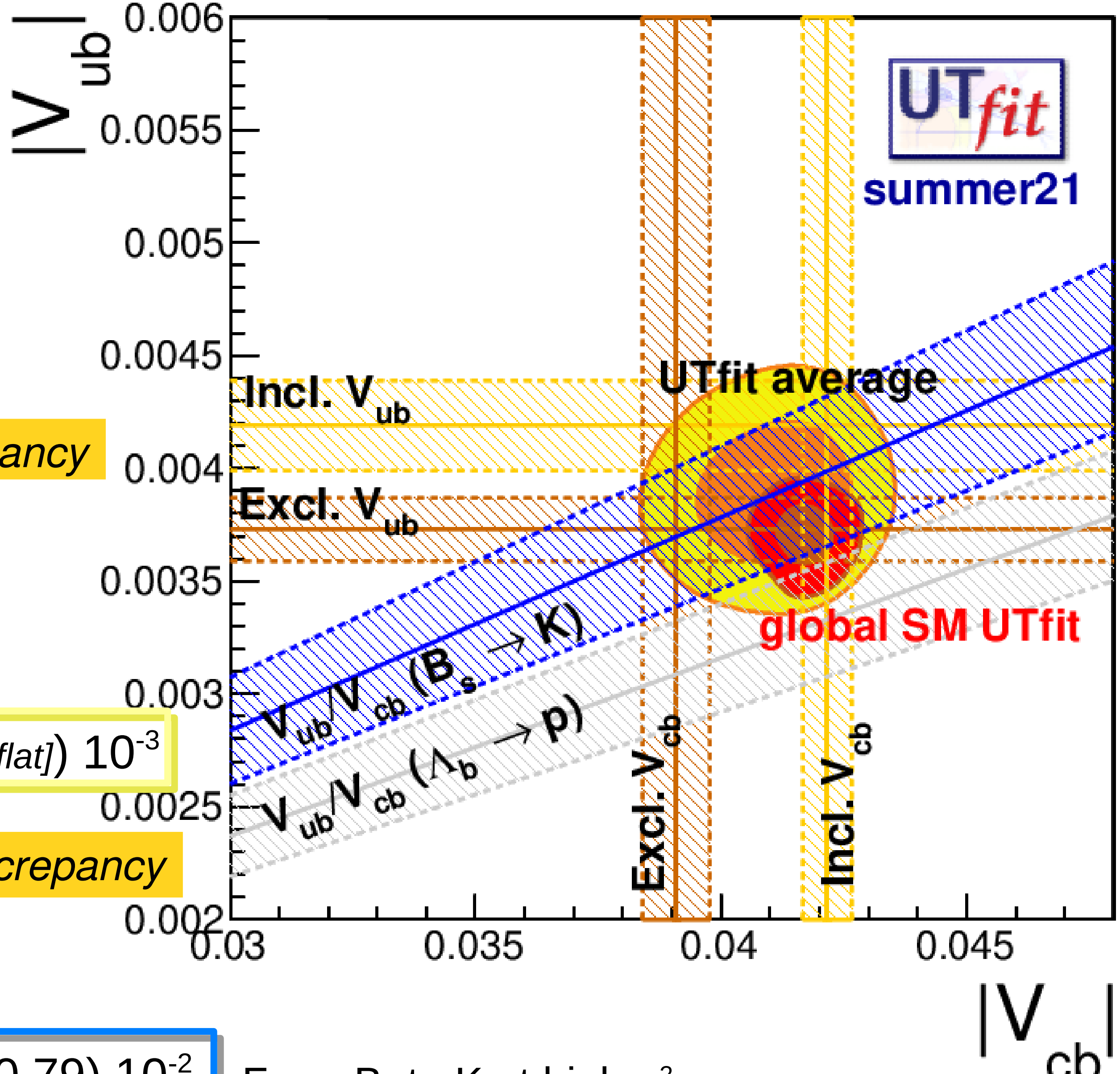
from FLAG 2019 arXiv:1902.08191

$|V_{ub}|$ *(excl)* = (3.73 ± 0.14) 10^{-3}

$|V_{ub}|$ *(incl)* = (4.19 ± 0.17 ± 0.18 *[flat]*) 10^{-3}

from GGOU HFLAV 2021 adding a flat uncertainty covering the spread of central values

~1.5σ discrepancy



$|V_{ub} / V_{cb}|$ *(LHCb)* = (9.46 ± 0.79) 10^{-2} — From B_s to K at high q^2

$|V_{ub} / V_{cb}|$ *(LHCb)* = (7.9 ± 0.6) 10^{-2} — From Λ_b, excluded following FLAG guidelines

V_{cb} and V_{ub}

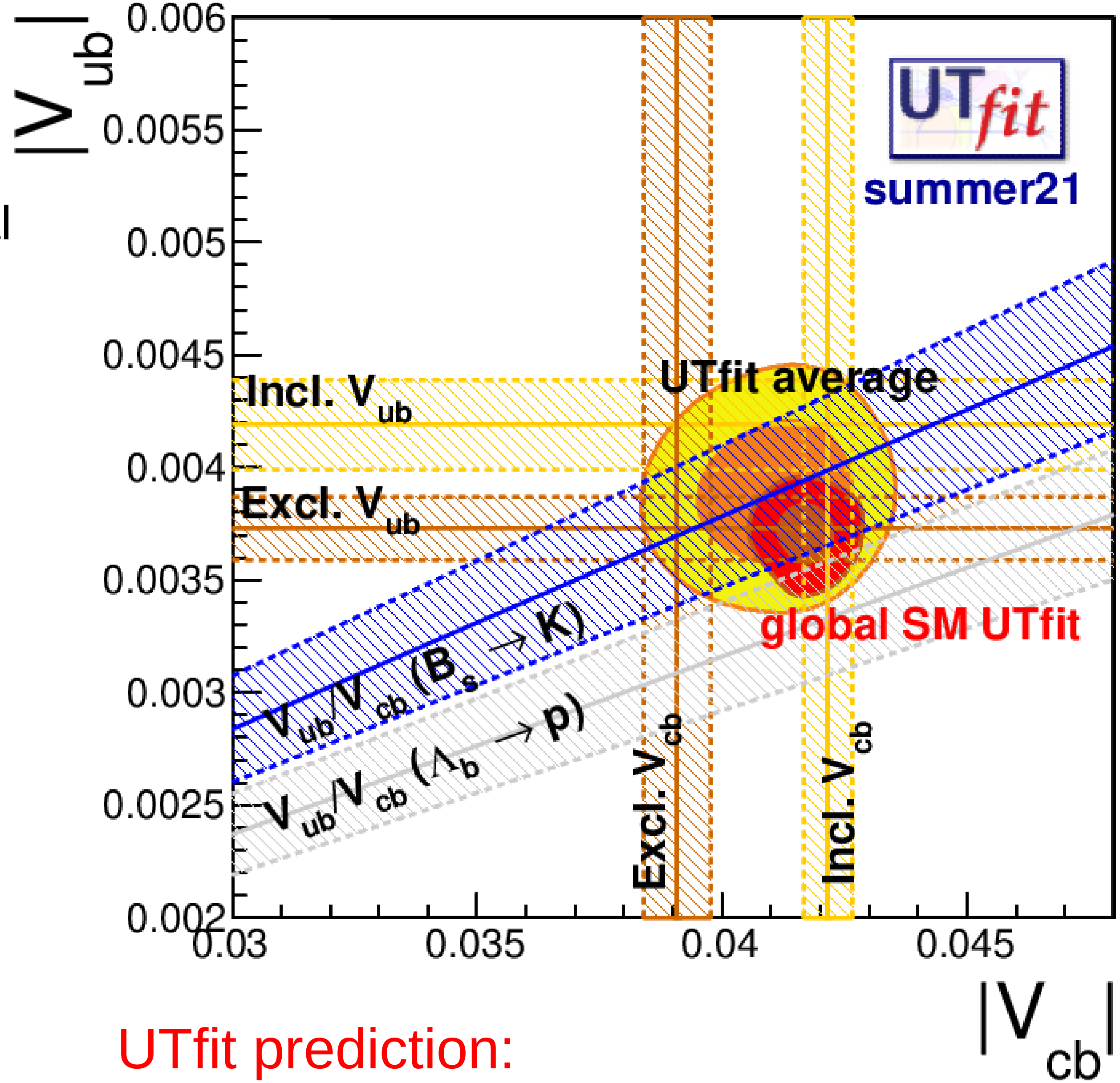
A-la-D'Agostini two-dimensional average procedure:

$|V_{cb}| = (41.1 \pm 1.0)\ 10^{-3}$

uncertainty ~ 2.4%

$|V_{ub}| = (3.89 \pm 0.21)\ 10^{-3}$

uncertainty ~ 5.4%



From global SM fit

$|V_{cb}| = (41.7 \pm 0.4)\ 10^{-3}$

$|V_{ub}| = (3.70 \pm 0.10)\ 10^{-3}$

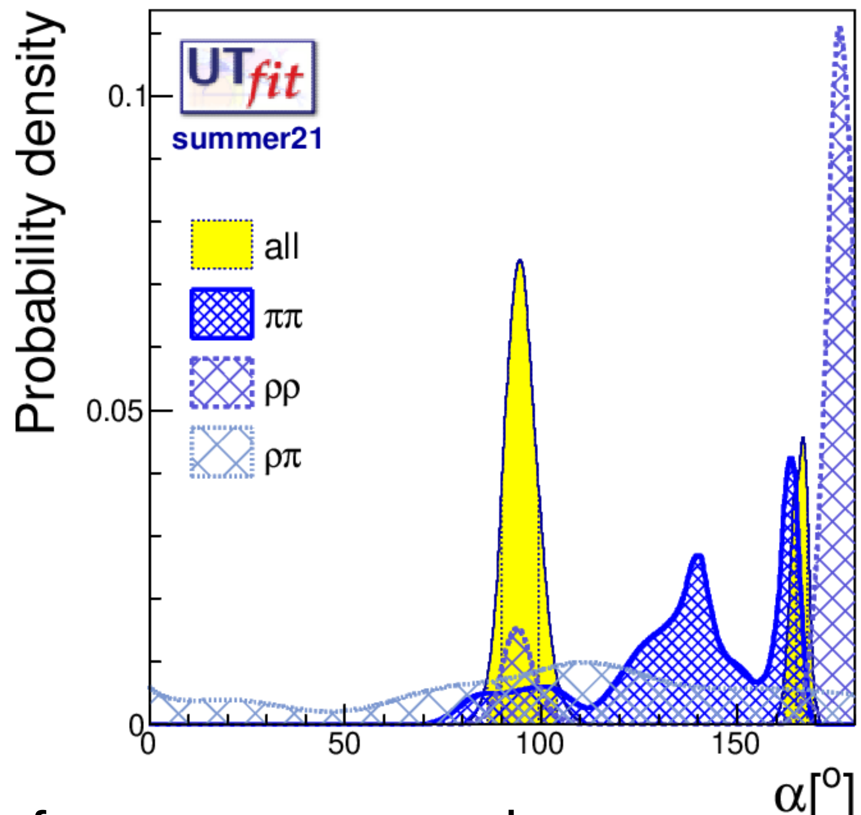
UTfit prediction:

$|V_{cb}| = (41.9 \pm 0.5)\ 10^{-3}$

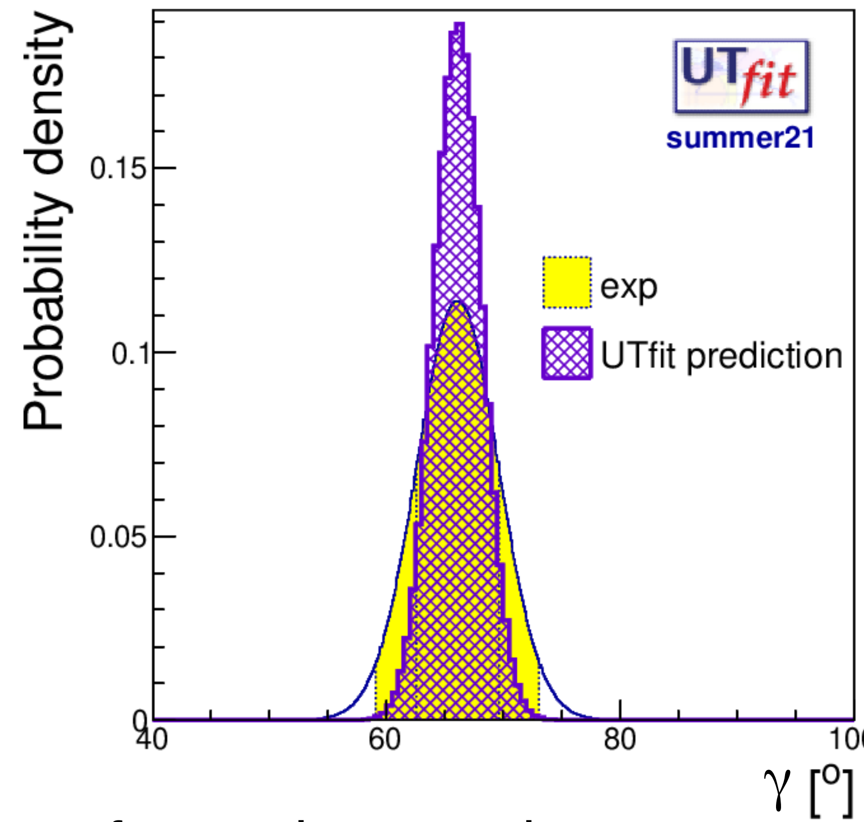
$|V_{ub}| = (3.68 \pm 0.10)\ 10^{-3}$

sin2α (ϕ_2) and γ (ϕ_3)

α updated with latest ππ/ρρ BR and C/S results



γ updated with all the latest results (LHCb)

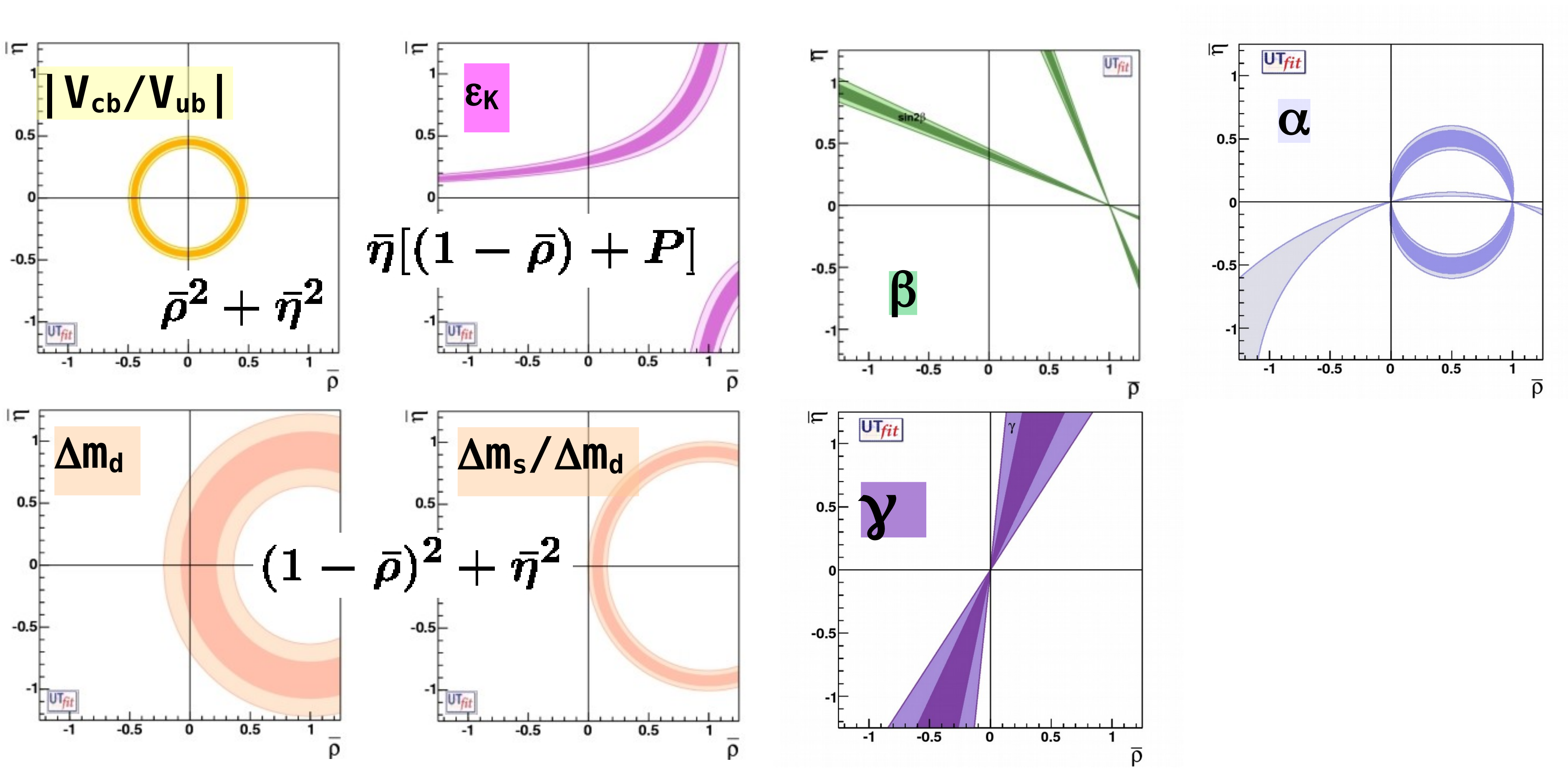


α from ππ, ρρ, πρ decays:
combined SM: (93.6 ± 4.2)°
UTfit prediction: (90.5 ± 2.1)°

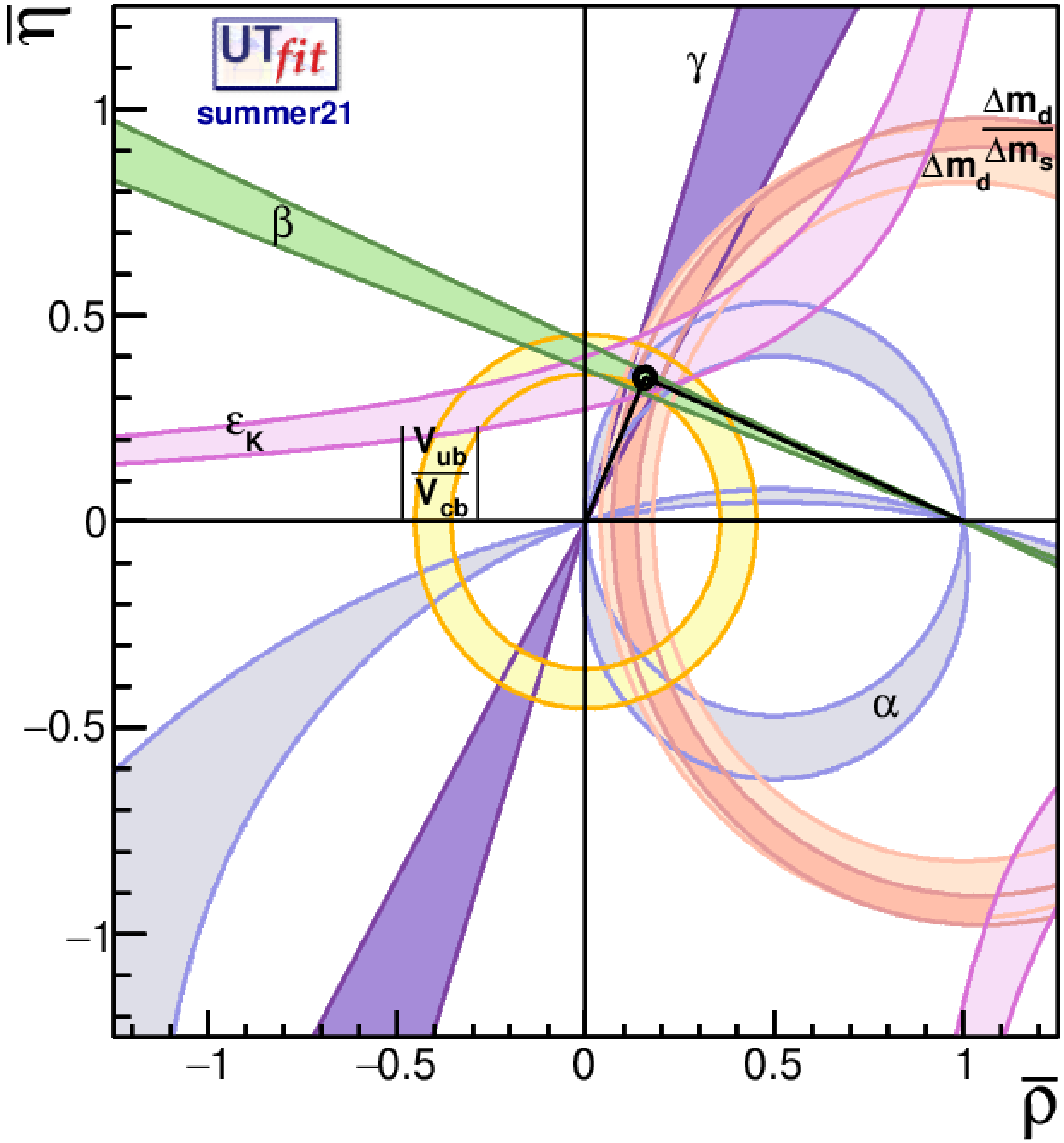
γ from B into DK decays:
HFLAV: (66.1 ± 3.5)°
UTfit prediction: (66.1 ± 2.1)°

α from HFLAV: 85.5 ± 4.6

Unitarity Triangle analysis in the SM:



Unitarity Triangle analysis in the SM:



levels @
95% Prob

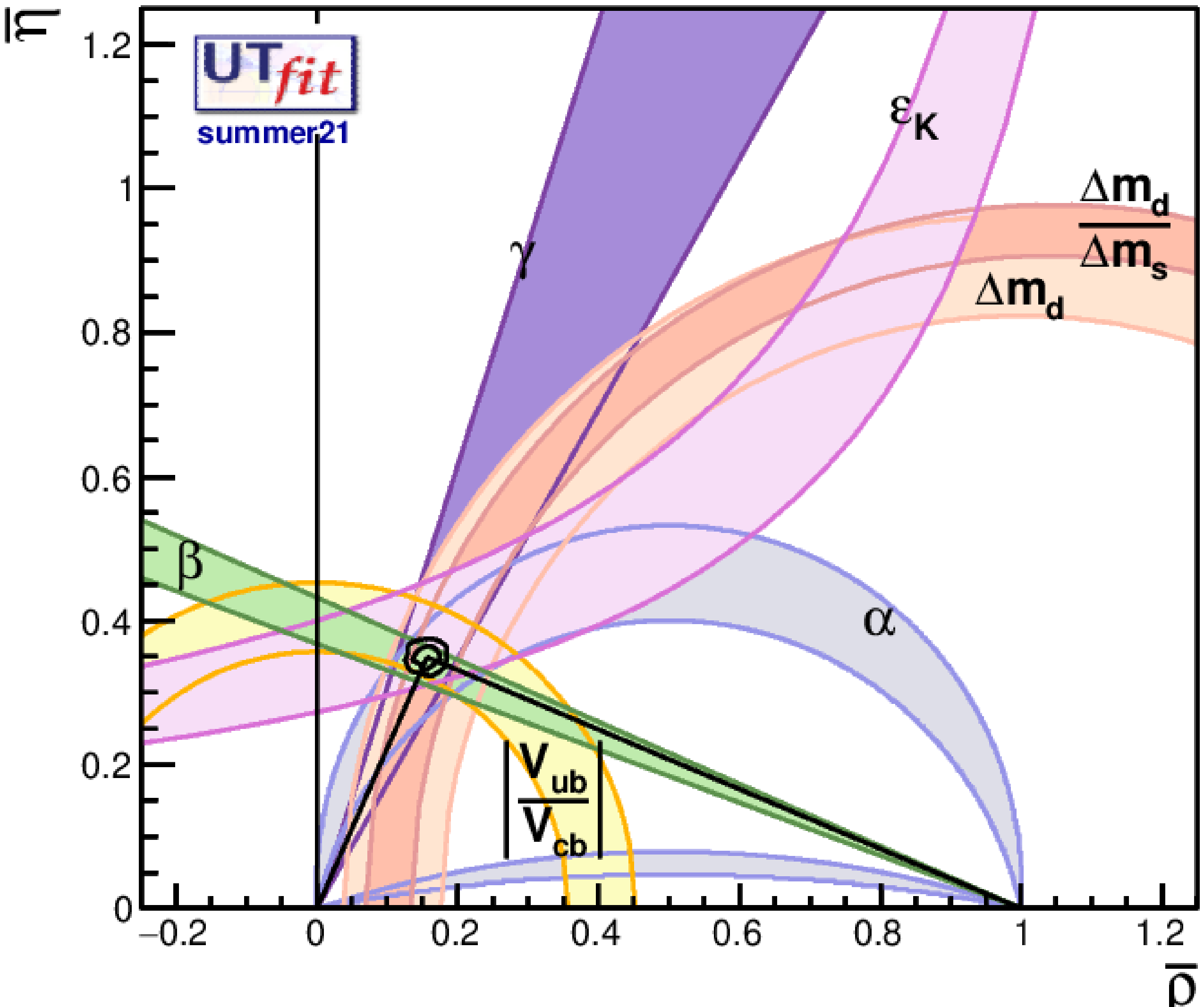
~8%

$\bar{\rho}$ = 0.157 ± 0.012
$\bar{\eta}$ = 0.350 ± 0.010

~3%

Unitarity Triangle analysis in the SM:

zoomed in..



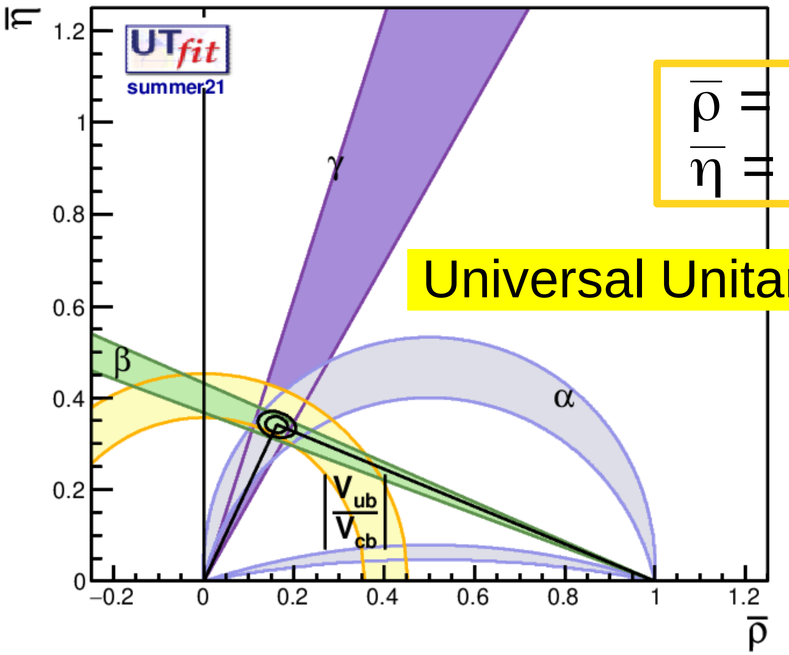
levels @
95% Prob

~8%

$\bar{\rho} = 0.157 \pm 0.012$
$\bar{\eta} = 0.350 \pm 0.010$

~3%

Some interesting configurations

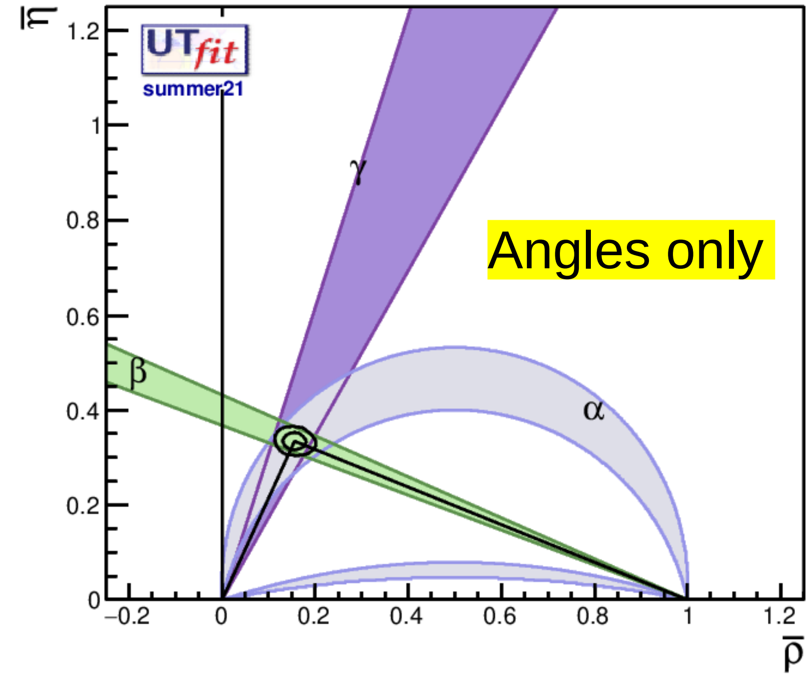


~10%

$\bar{\rho} = 0.162 \pm 0.017$
$\bar{\eta} = 0.341 \pm 0.011$

~3%

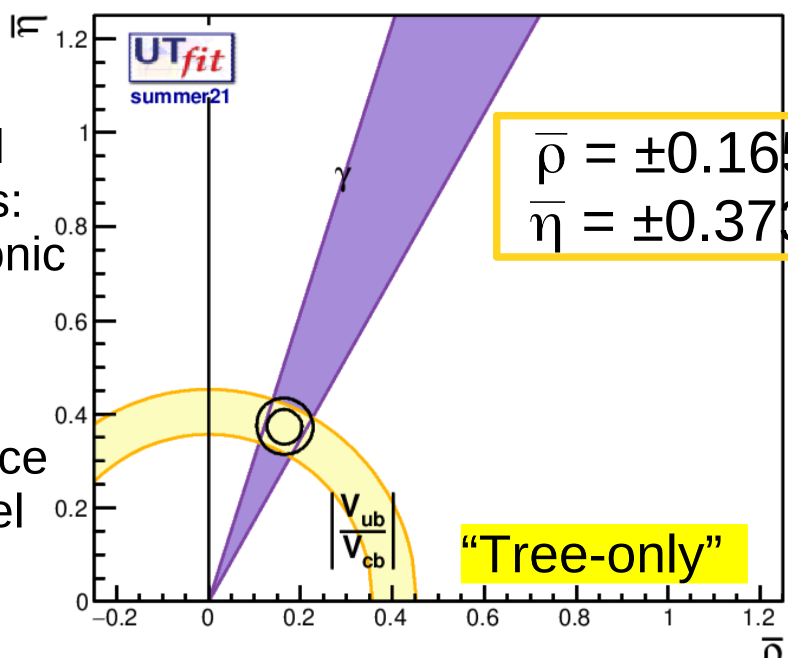
Universal Unitary Triangle



Angles only

Tree-level processes: Semileptonic and DK B decays

→ reference for model building

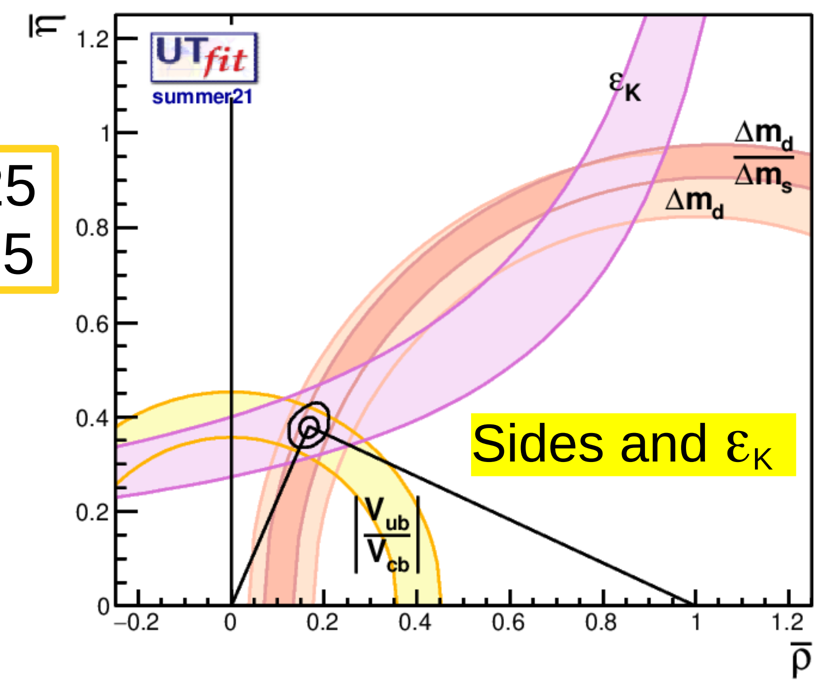


~15%

$\bar{\rho} = \pm 0.165 \pm 0.025$
$\bar{\eta} = \pm 0.373 \pm 0.025$

~7%

"Tree-only"



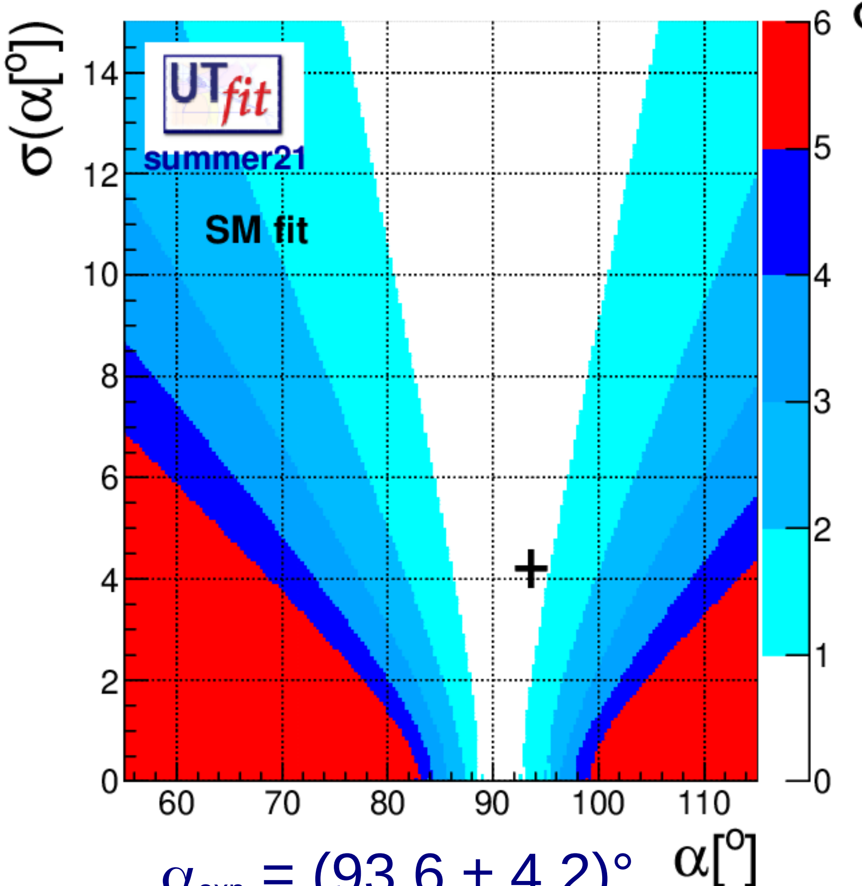
Sides and ε_K

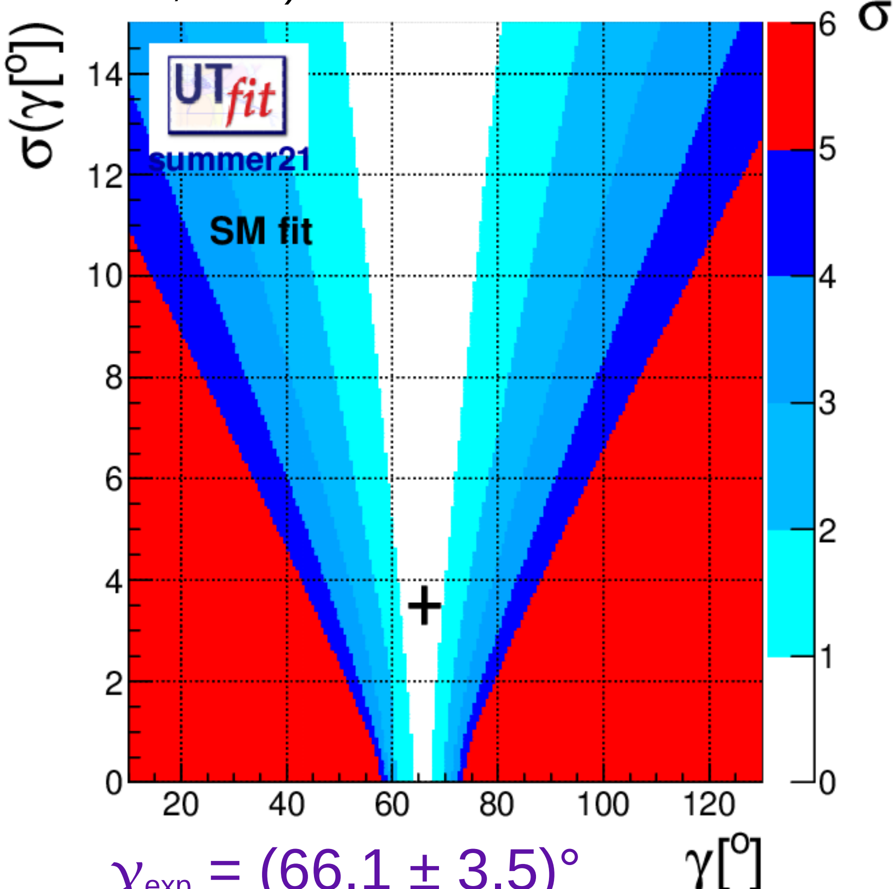
compatibility plots

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





$\alpha_{exp} = (93.6 \pm 4.2)°$

$\alpha_{UTfit} = (90.5 \pm 2.1)°$

$\gamma_{exp} = (66.1 \pm 3.5)°$

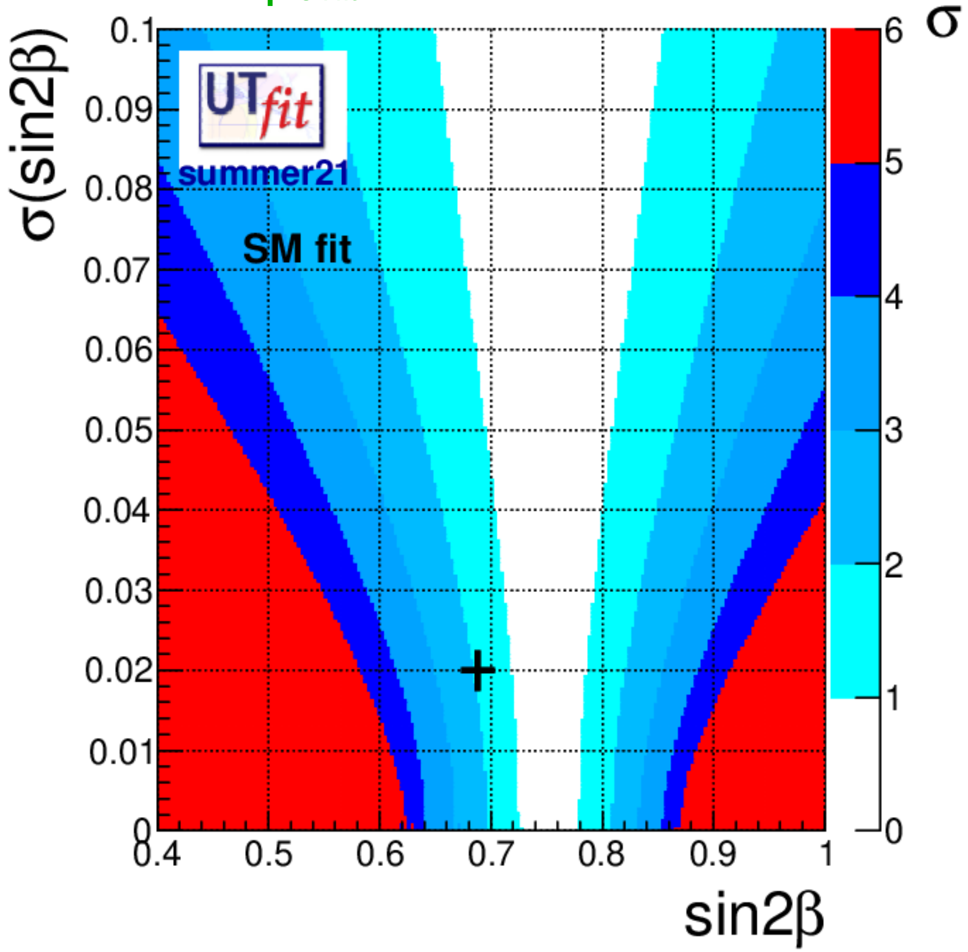
$\gamma_{UTfit} = (66.1 \pm 2.1)°$

Checking the usual *tensions*..

~1.4σ

$\sin 2\beta_{exp} = 0.688 \pm 0.020$

$\sin 2\beta_{UTfit} = 0.751 \pm 0.027$



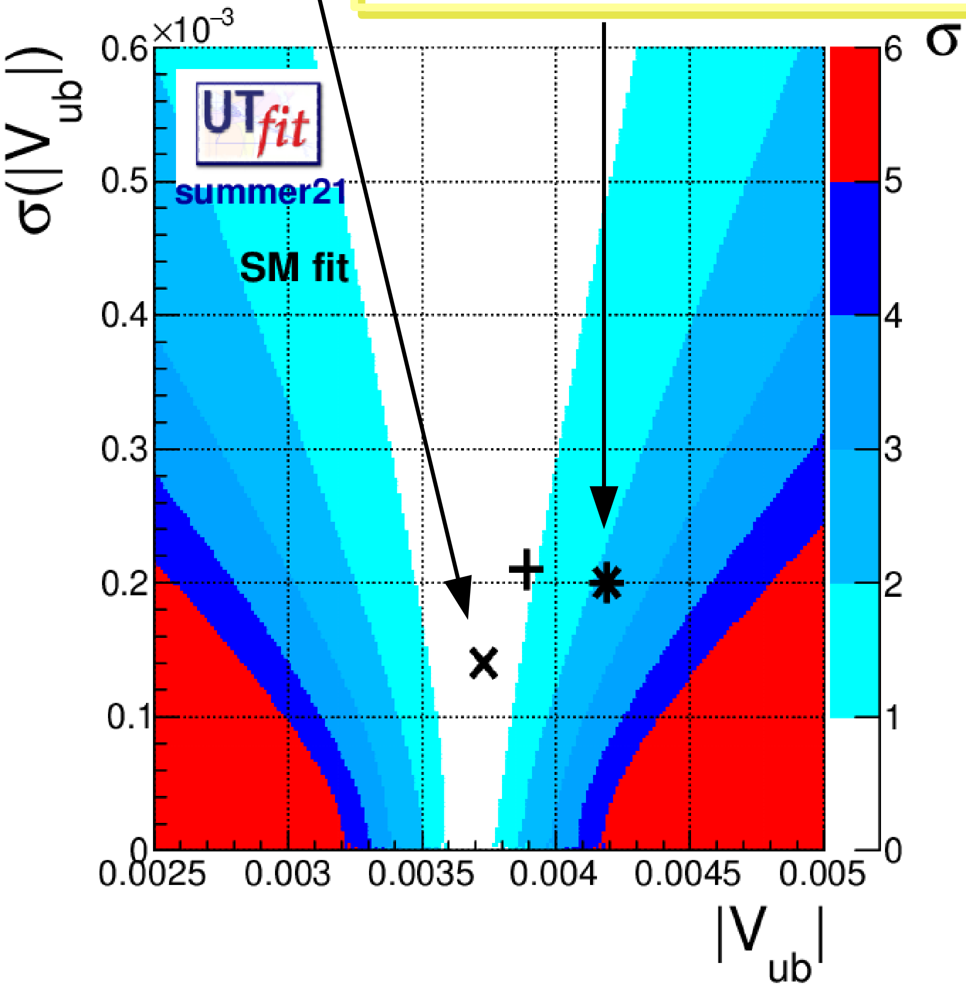
Checking the usual *tensions*..

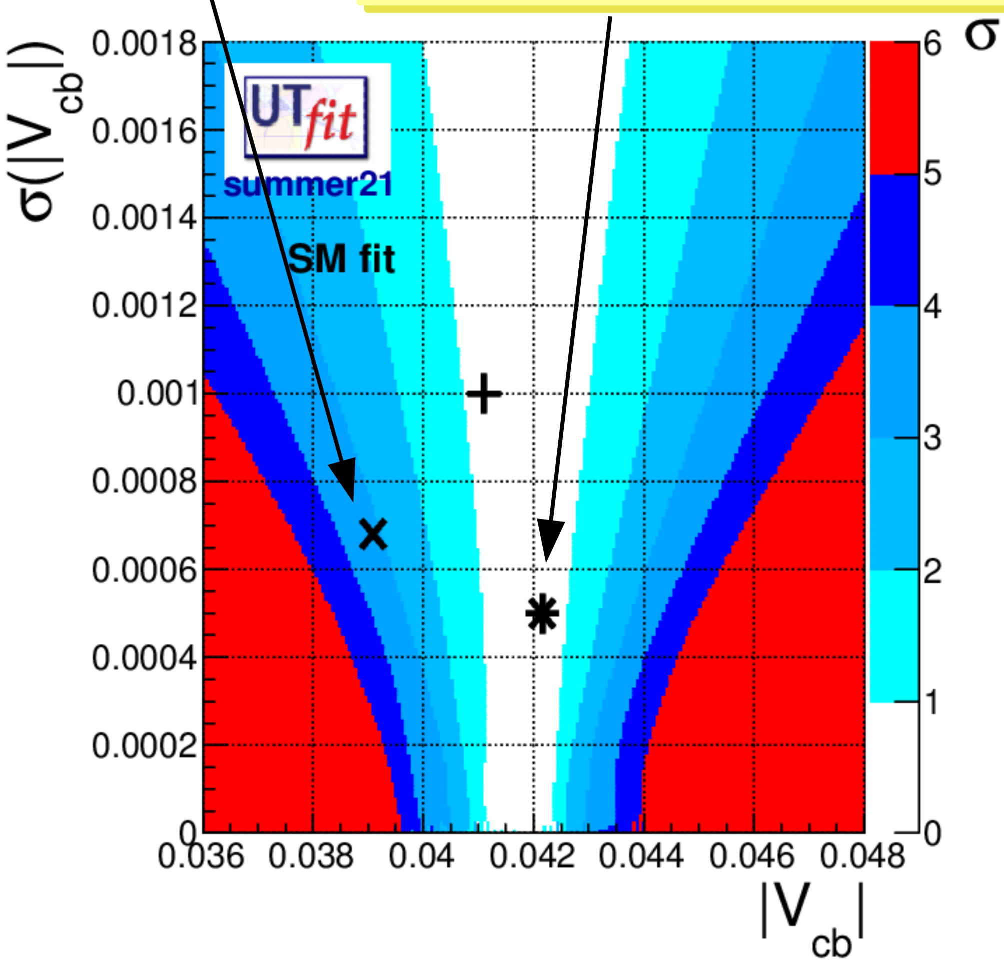
$|V_{ub}|$ *(excl)* = $(3.73 \pm 0.14)\ 10^{-3}$

$|V_{ub}|$ *(incl)* = $(4.19 \pm 0.20)\ 10^{-3}$

$|V_{cb}|$ *(excl)* = $(39.09 \pm 0.68)\ 10^{-3}$

$|V_{cb}|$ *(incl)* = $(42.16 \pm 0.50)\ 10^{-3}$





$Vub_{exp} = (3.89 \pm 0.21) \cdot 10^{-3}$

$Vub_{UTfit} = (3.68 \pm 0.10) \cdot 10^{-3}$

$Vcb_{exp} = (41.1 \pm 1.0) \cdot 10^{-3}$

$Vcb_{UTfit} = (41.9 \pm 0.5) \cdot 10^{-3}$

Unitarity Triangle analysis in the SM:

obtained excluding the given constraint from the fit

Observables	Measurement	Prediction	Pull (#σ)
$\sin 2\beta$	0.688 ± 0.020	0.751 ± 0.027	~ 1.4
γ	66.1 ± 3.5	66.1 ± 2.1	< 1
α	93.6 ± 4.2	90.5 ± 2.1	< 1
$\varepsilon_K \cdot 10^3$	2.228 ± 0.001	2.05 ± 0.13	~ 1.4
$\|V_{cb}\| \cdot 10^3$	40.4 ± 1.3	41.9 ± 0.5	< 1
$\|V_{cb}\| \cdot 10^3$ (incl)	42.16 0.50		< 1
$\|V_{cb}\| \cdot 10^3$ (excl)	39.09 0.68		~ 2.4
$\|V_{ub}\| \cdot 10^3$	3.89 ± 0.21	3.68 ± 0.10	< 1
$\|V_{ub}\| \cdot 10^3$ (incl)	4.19 ± 0.20	-	~ 1.7
$\|V_{ub}\| \cdot 10^3$ (excl)	3.73 ± 0.14	-	< 1
$BR(B \to \tau\nu)[10^{-4}]$	1.09 ± 0.24	0.87 ± 0.05	< 1
$A_{SL}^d \cdot 10^3$	-2.1 ± 1.7	-0.32 ± 0.03	< 1
$A_{SL}^s \cdot 10^3$	-0.6 ± 2.8	0.014 ± 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 $\Delta F=2$ transitions

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

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

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

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

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

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

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

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

new-physics-specific constraints

$$A_{\rm SL}^s \equiv \frac{\Gamma(\bar{B}_s \to \ell^+ X) - \Gamma(B_s \to \ell^- X)}{\Gamma(\bar{B}_s \to \ell^+ X) + \Gamma(B_s \to \ell^- X)} = {\rm Im}\left(\frac{\Gamma_{12}^s}{A_s^{\rm full}}\right)$$

semileptonic asymmetries in B^0 and B_s: sensitive to NP effects in both size and phase. Taken from the latest HFLAV.

Cleo, BaBar, Belle, D0 and LHCb

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

D0 arXiv:1106.6308

$$A_{\rm SL}^{\mu\mu} \times 10^3 = -7.9 \pm 2.0$$

$$A_{\rm SL}^{\mu\mu} = \frac{f_d \chi_{d0} A_{\rm SL}^d + f_s \chi_{s0} A_{\rm SL}^s}{f_d \chi_{d0} + f_s \chi_{s0}}$$

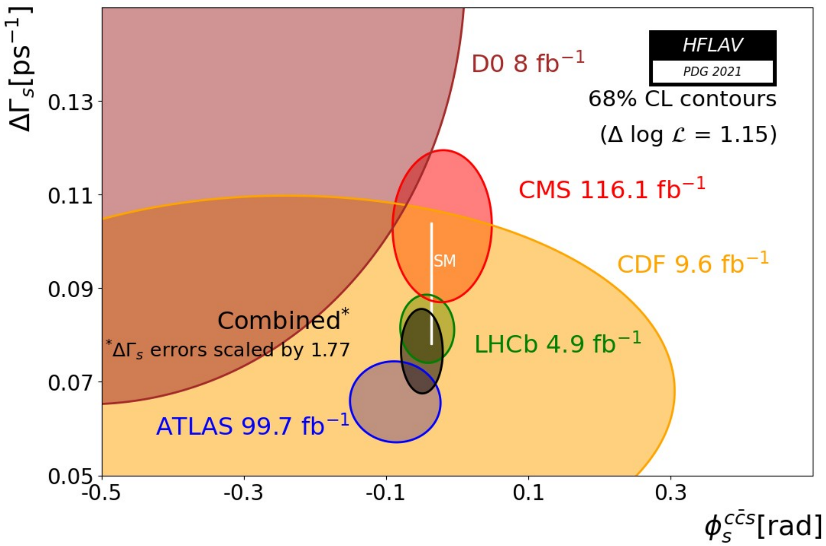
lifetime τ^{FS} in flavour-specific final states: average lifetime is a function to the width and the width difference

$$\tau^{FS}(B_s) = 1.527 \pm 0.011 \text{ ps}$$ **HFLAV**

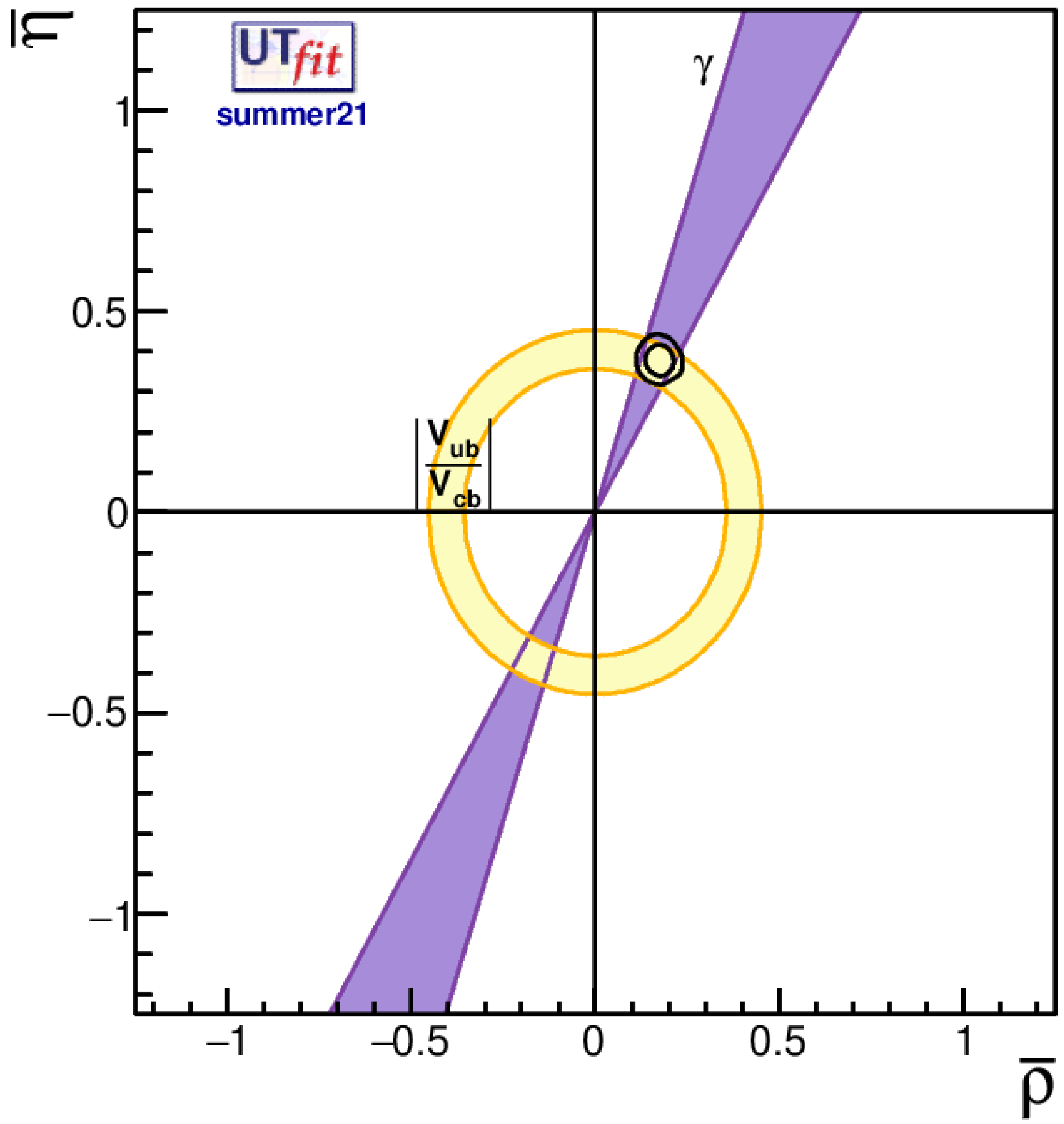
$\phi_s=2\beta_s$ vs $\Delta\Gamma_s$ from $B_s \to J/\psi\phi$

angular analysis as a function of proper time and b-tagging

$$\phi_s = -0.050 \pm 0.019 \text{ rad}$$



NP analysis results



$\bar{\rho} = 0.175 \pm 0.027$
$\bar{\eta} = 0.380 \pm 0.026$

SM is

$\bar{\rho} = 0.157 \pm 0.012$
$\bar{\eta} = 0.350 \pm 0.010$

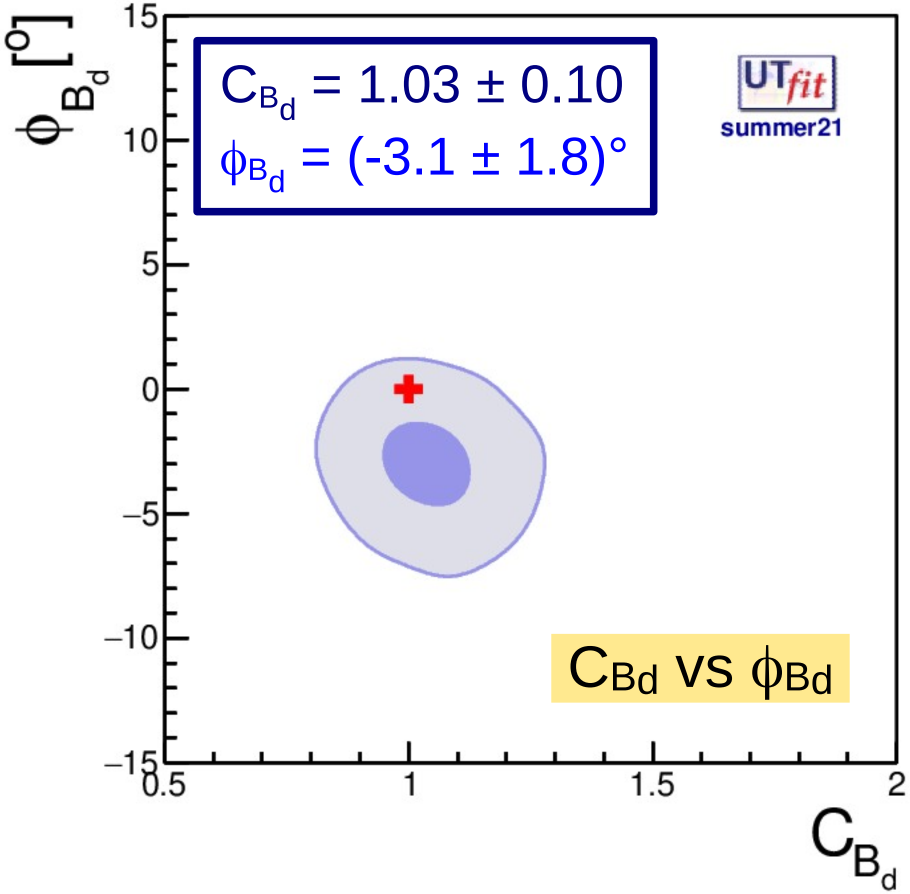
NP parameter results

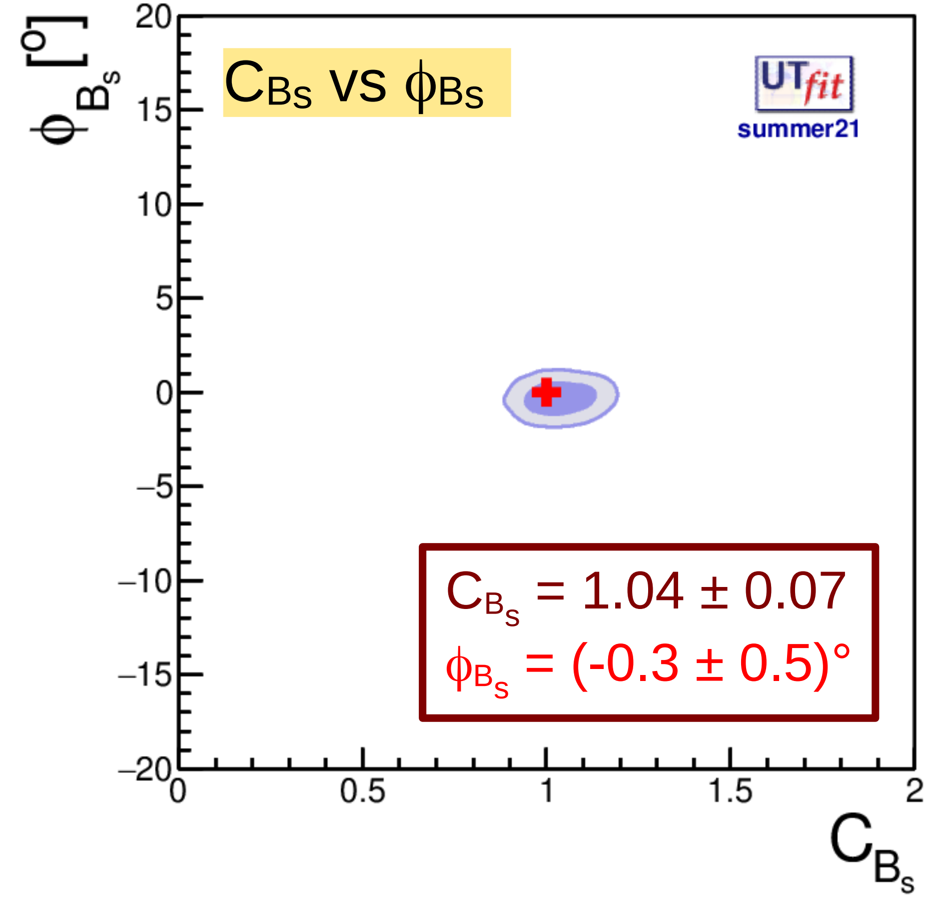
$$A_q = C_{B_q} e^{2i\phi_{B_q}} A_q^{SM} e^{2i\phi_q^{SM}}$$

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

K system

$C_{\epsilon_K} = 1.05 \pm 0.10$





The ratio of NP/SM amplitudes is:
< 30% @95% in B_d mixing
< 20% @95% in B_s mixing

testing the new-physics scale

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

RGE

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

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

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

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

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

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

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

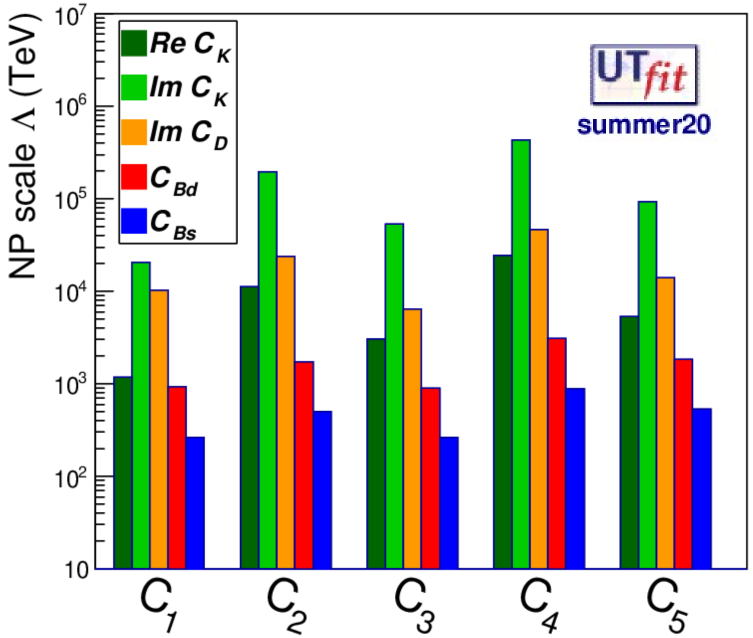
If no NP effect is seen lower bound on NP scale Λ

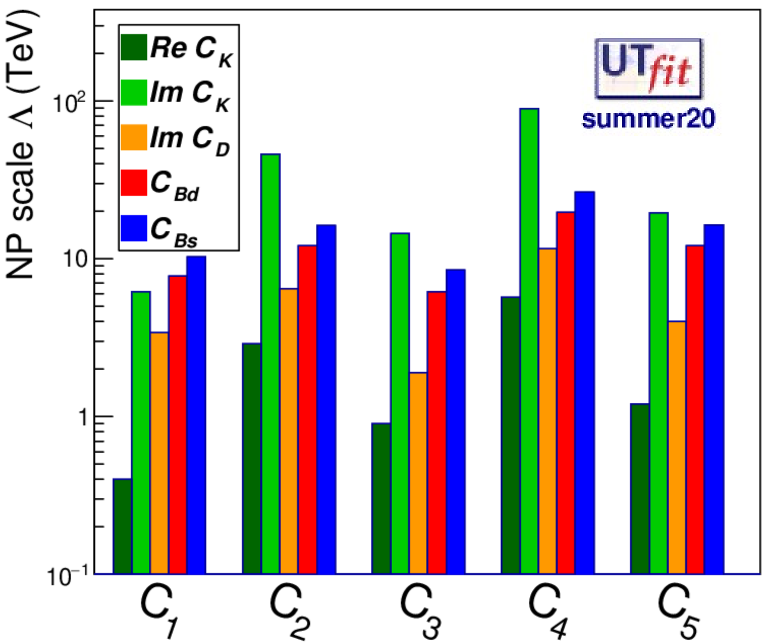
F is the flavour coupling and so
F_{SM} is the combination of CKM factors for the considered process

results from the Wilson coefficients

Generic: $C(\Lambda) = \alpha/\Lambda^2$,
F_i~1, arbitrary phase
α ~ 1 for strongly coupled NP

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





$\Lambda > 4.3\ 10^5$ TeV

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

$\Lambda > 89$ TeV

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

$\Lambda > 1.3\ 10^4$ TeV

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

$\Lambda > 2.7$ TeV

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

conclusions

- SM analysis displays very good (improved) overall consistency
- Still open discussion on semileptonic inclusive vs exclusive: exclusive fit shows tension, V_{cb} now showing the biggest discrepancy..
- UTA provides determination of NP contributions to $\Delta F=2$ amplitudes. It currently leaves space for NP at the level of 20-25%
- 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 not only complementary to direct searches, but they might be the main way to glimpse at new physics.

Back up slides

lattice QCD inputs

updated in early 2020

Observables	**Measurement**
B_K	**0.756 ± 0.016**
f_{Bs}	**0.2301 ± 0.0012**
f_{Bs}/f_{Bd}	**1.208 ± 0.005**
B_{Bs}/B_{Bd}	**1.032 ± 0.038**
B_{Bs}	**1.35 ± 0.06**

FLAG 2019 suggests to take the most precise between the Nf=2+1+1 and Nf=2+1 averages.

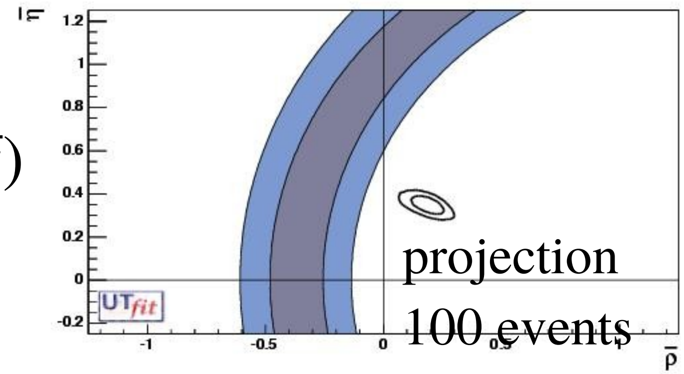
We quote, instead, the weighted average of the Nf=2+1+1 and Nf=2+1 results with the error rescaled when chi2/dof > 1, as done by FLAG for the Nf=2+1+1 and Nf=2+1 averages separately

some old plots coming back to fashion:

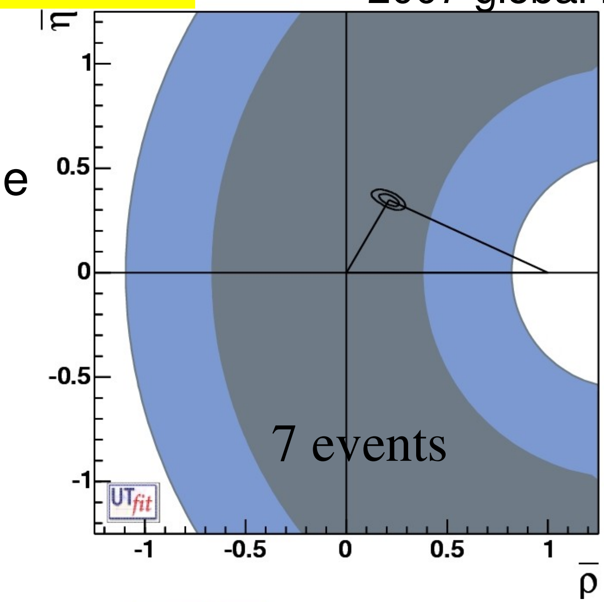
As NA62 and KOTO are analysing data:

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

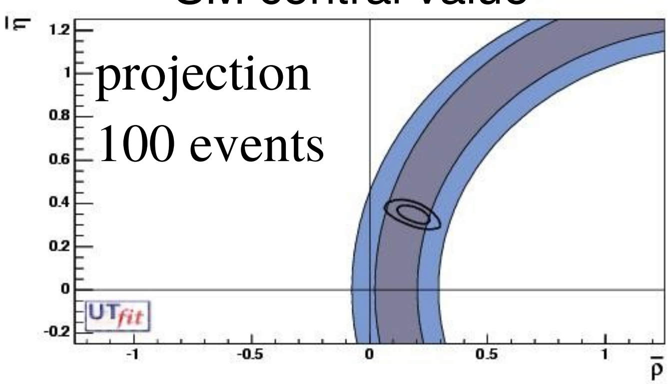
E949 central value

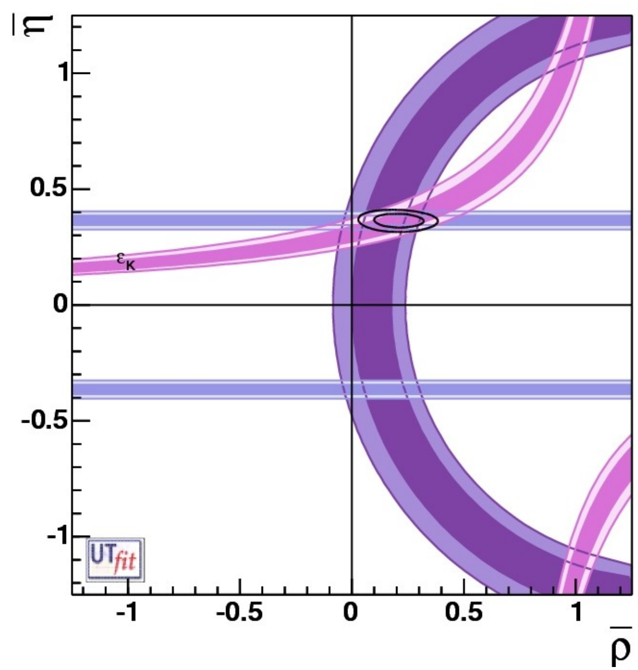


2007 global fit area



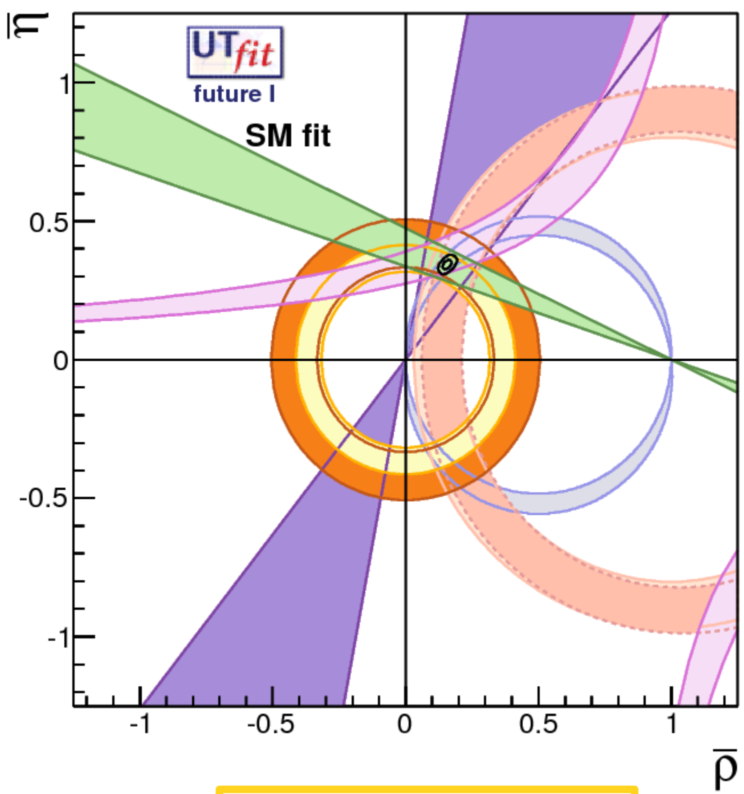
SM central value





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

Look at the near future

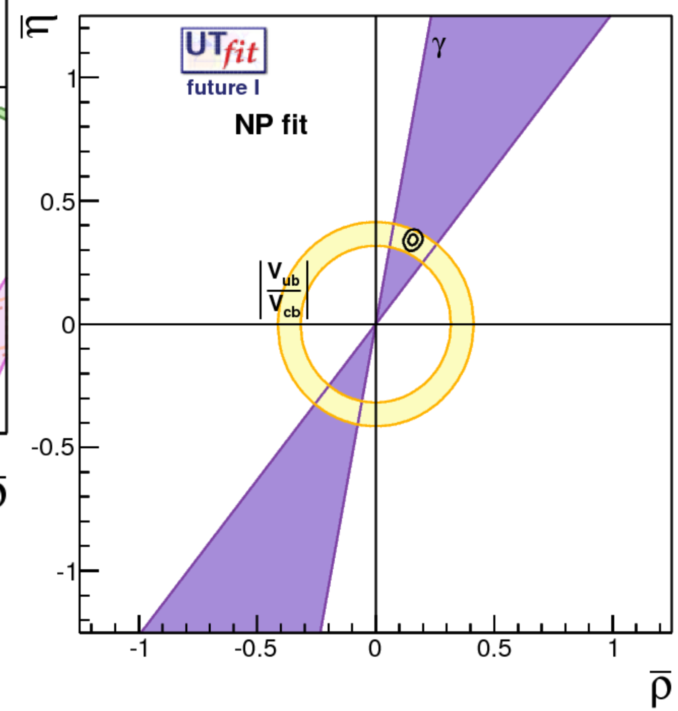


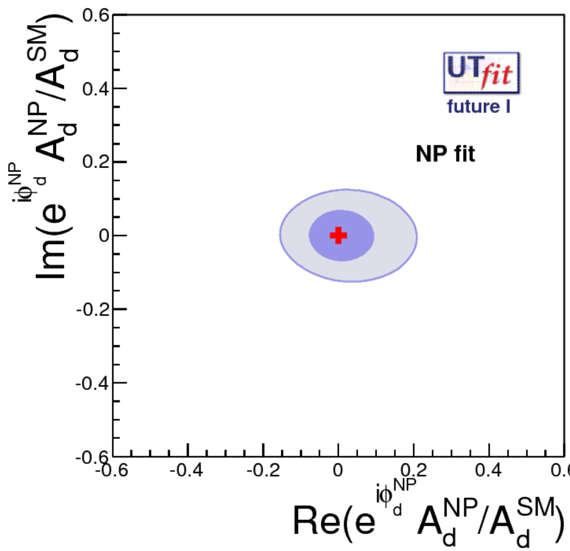
future I scenario:

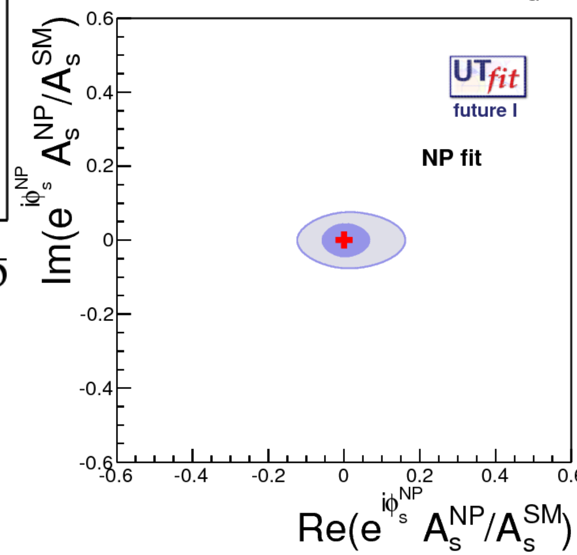
errors from

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

$\bar\rho = 0.150 \pm 0.027$

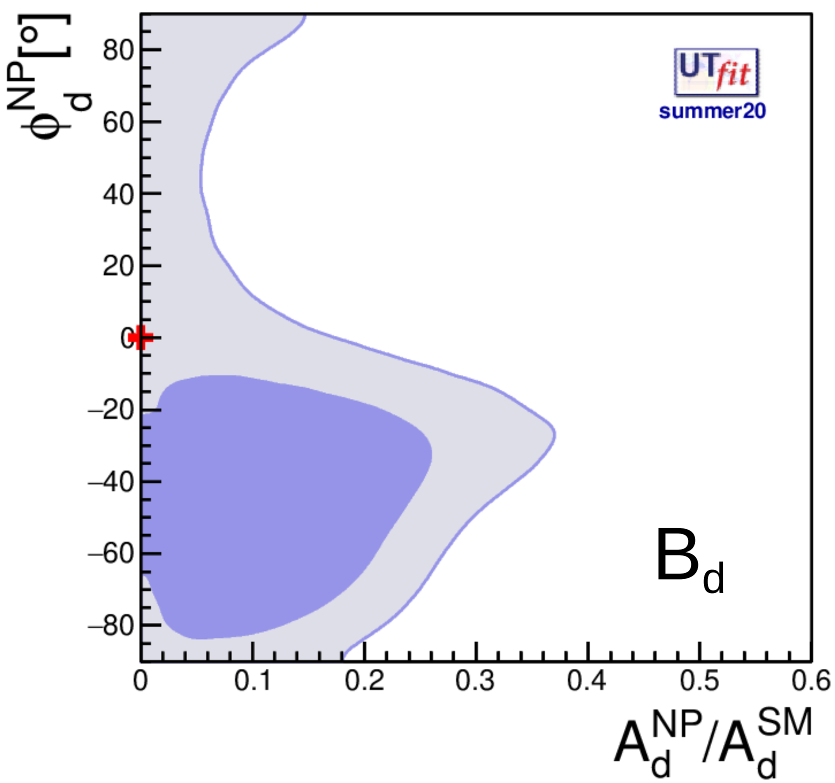
$\bar\eta = 0.363 \pm 0.025$

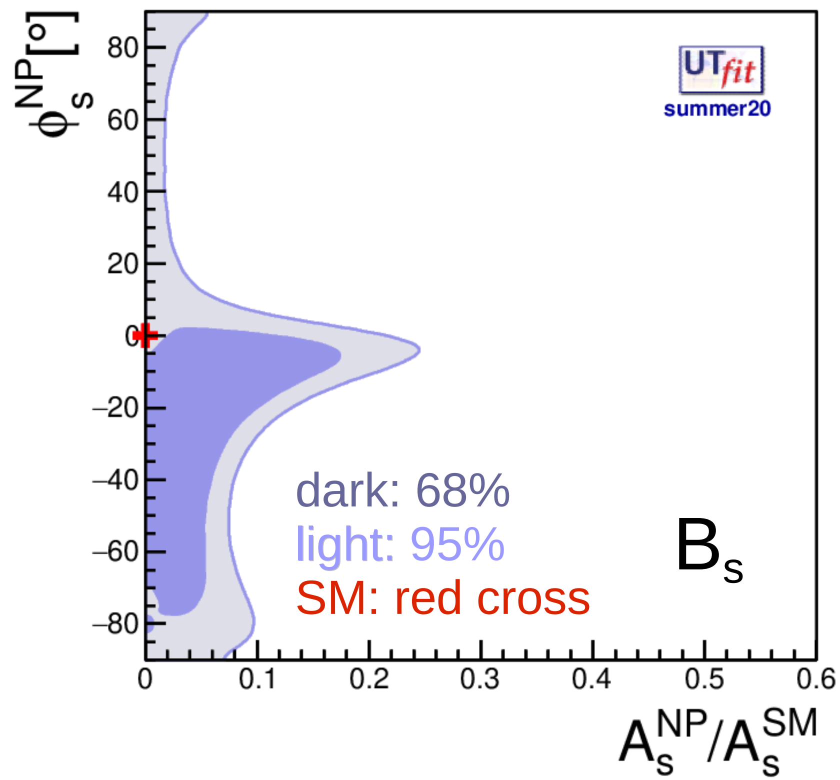
$\rho = \pm\, 0.016$

$\eta = \pm\, 0.019$

NP parameter results

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





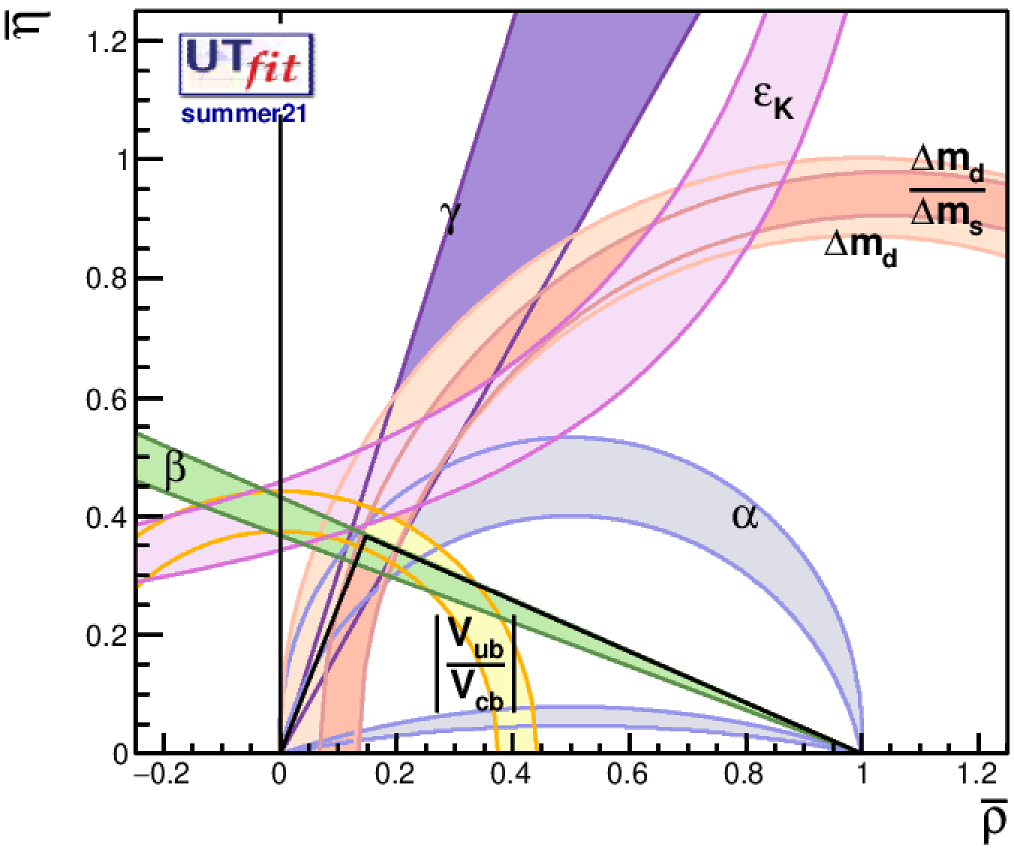
The ratio of NP/SM amplitudes is:

< 26% @68% prob. (37% @95%) in B_d mixing

< 18% @68% prob. (25% @95%) in B_s mixing

exclusives vs inclusives

only exclusive values



only inclusive values