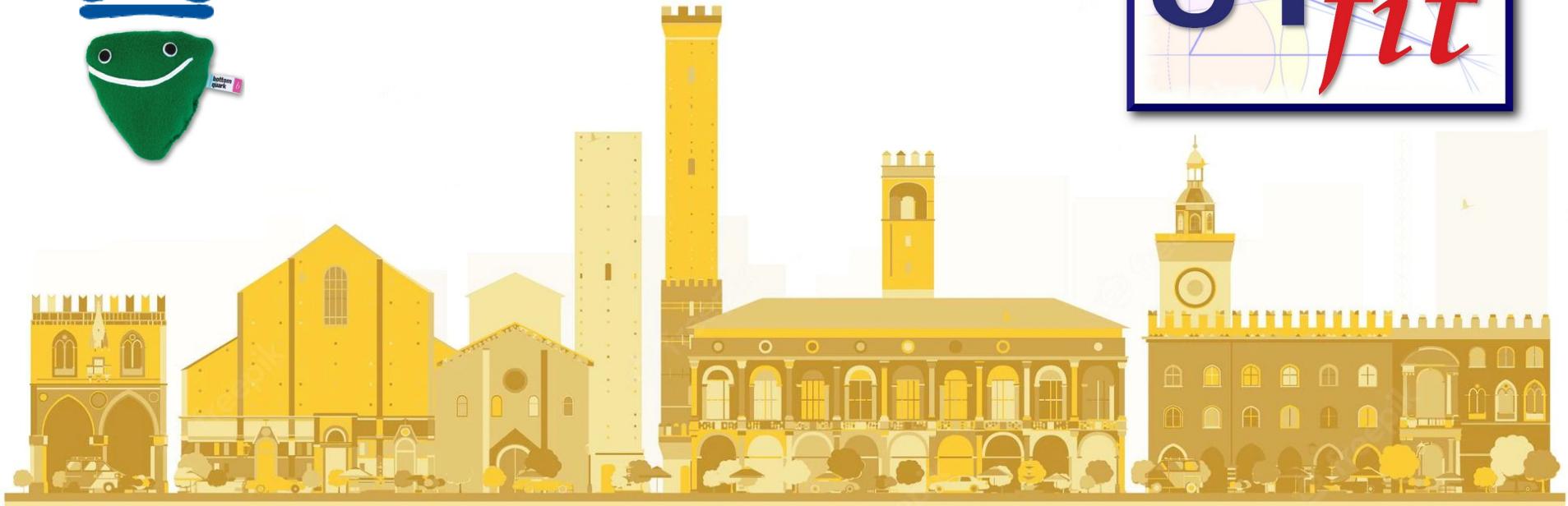


Status of the Unitarity Triangle

Marcella Bona

Queen Mary University of London
On behalf of the
UTfit collaboration



Unitarity Triangle analysis in the SM

SM UT analysis:

- All updated with Summer 2022 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 2022 inputs
- model-independent analysis
- provides limit on the allowed deviations from the SM
- obtain the NP scale



www.utfit.org

RELOADED

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

Plots and numbers in this talk are obtained with updated inputs and labelled “summer22”.

Some changes included with respect to the results presented in May 2022 at LHCP22 and FPCP22:
→ all new plots!

Usual method and inputs:

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

Bayes Theorem

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

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

$(b \rightarrow u)/(b \rightarrow c)$

ϵ_K

Δm_d

$\Delta m_d / \Delta m_s$

$A_{CP}(J/\psi K_S)$

$\bar{\rho}^2 + \bar{\eta}^2$

$\bar{\eta}[(1 - \bar{\rho}) + P]$

$(1 - \bar{\rho})^2 + \bar{\eta}^2$

$(1 - \bar{\rho})^2 + \bar{\eta}^2$

$\sin 2\beta$

$\bar{\Lambda}, \lambda_1, F(1), \dots$

B_K

$f_B^2 B_B$

ξ

Standard Model +
OPE/HQET/
Lattice QCD
to go

m_t 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 UTfit (coming soon)

$$|V_{cb}| \text{ (excl)} = (39.44 \pm 0.63) 10^{-3}$$

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

from Bordone et al.
arXiv:2107.00604

$\sim 3.3\sigma$ discrepancy

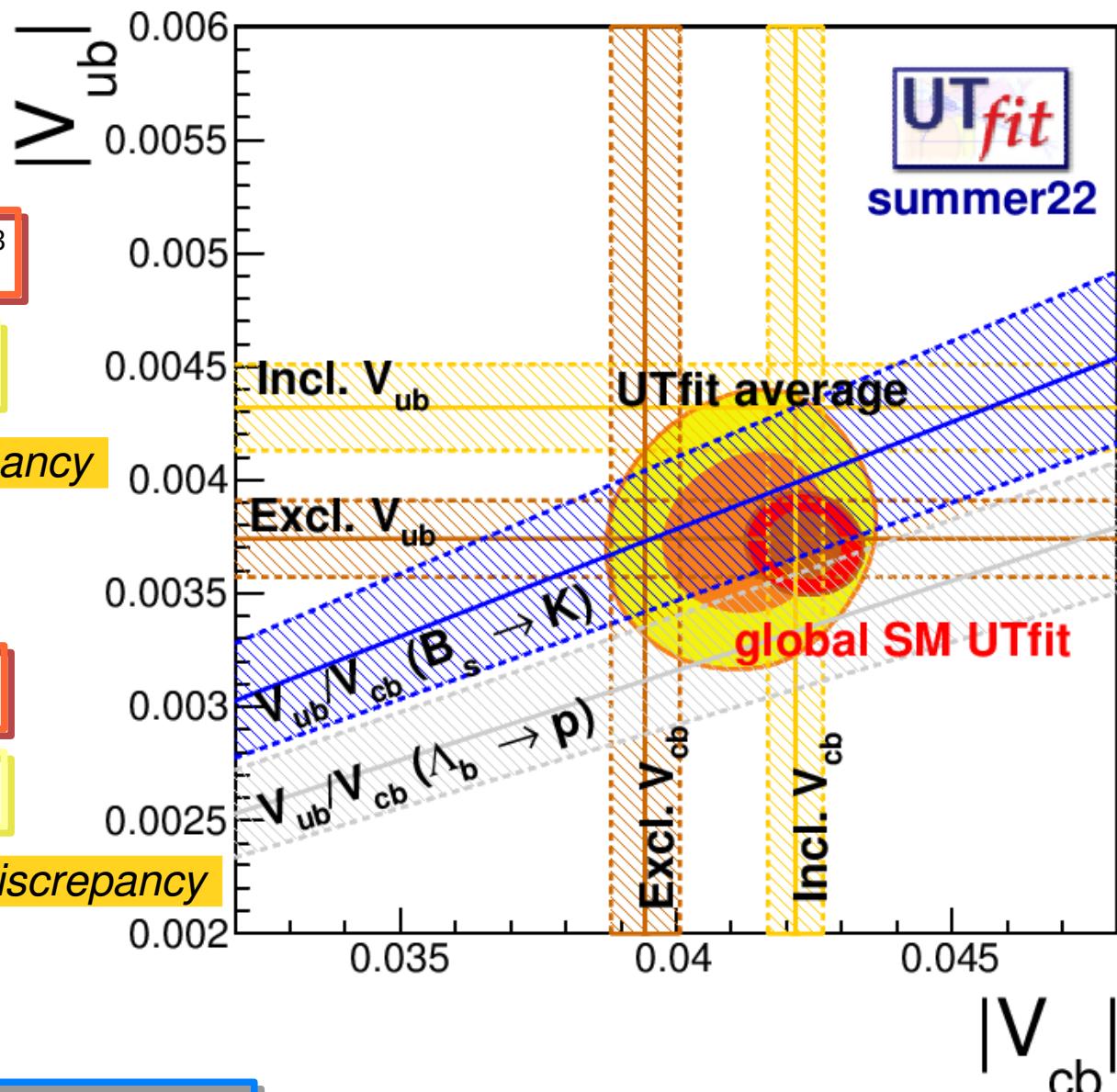
from UTfit (coming soon)

$$|V_{ub}| \text{ (excl)} = (3.74 \pm 0.17) 10^{-3}$$

$$|V_{ub}| \text{ (incl)} = (4.32 \pm 0.29) 10^{-3}$$

from UTfit (coming soon)

$\sim 1.7\sigma$ discrepancy



$$|V_{ub} / V_{cb}| \text{ (LHCb)} = (9.46 \pm 0.79) 10^{-2}$$

From B_s to K at high q^2

$$|V_{ub} / V_{cb}| \text{ (LHCb)} = (7.9 \pm 0.6) 10^{-2}$$

From Λ_b , excluded following FLAG guidelines

V_{cb} and V_{ub}

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

$$|V_{cb}| = (41.25 \pm 0.95) 10^{-3}$$

uncertainty $\sim 2.3\%$

$$|V_{ub}| = (3.77 \pm 0.24) 10^{-3}$$

uncertainty $\sim 6.4\%$

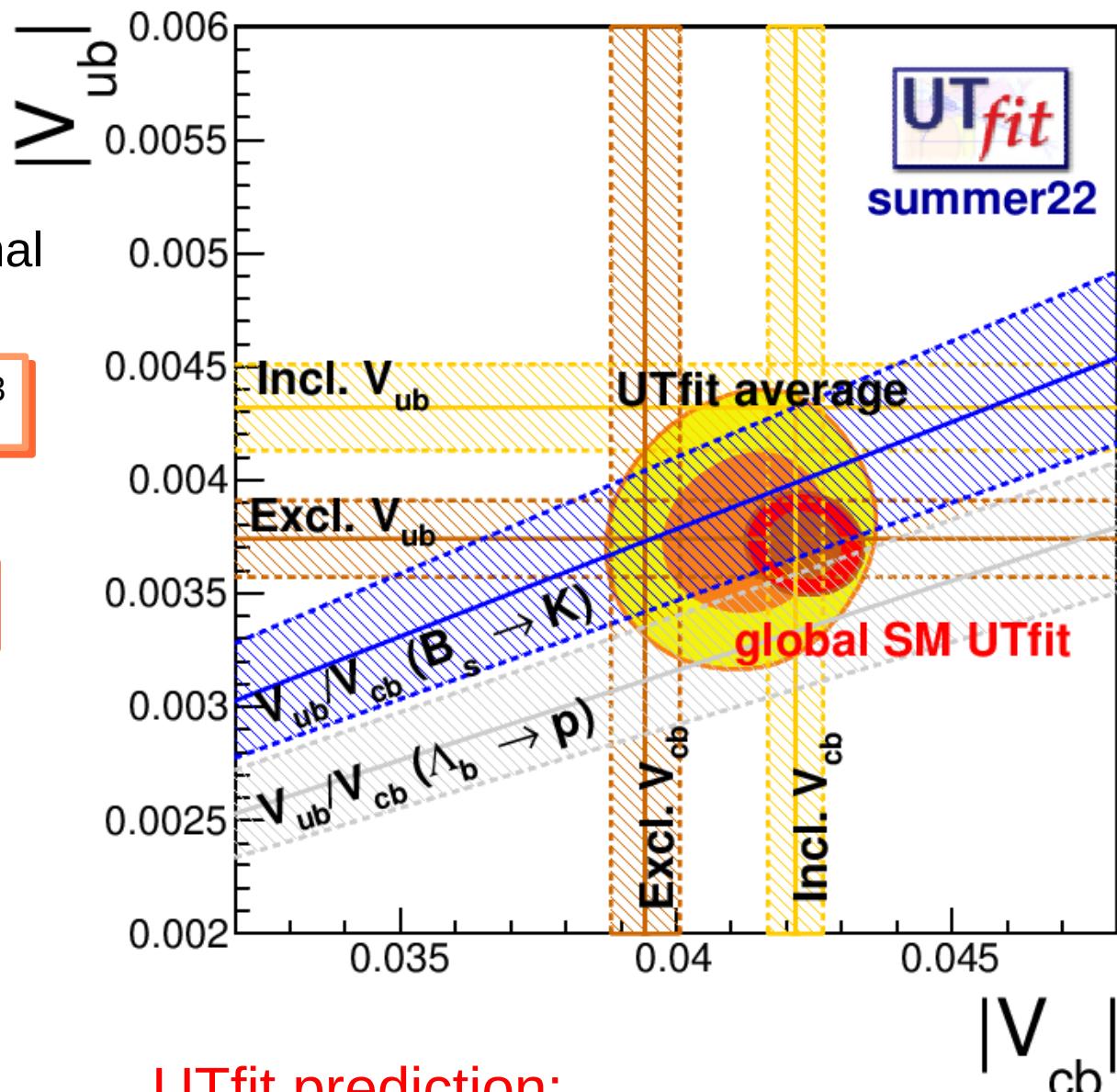
Correlation $\rho = 0.11$

Updated averages
including correlation

From global SM fit

$$|V_{cb}| = (42.3 \pm 0.4) 10^{-3}$$

$$|V_{ub}| = (3.72 \pm 0.09) 10^{-3}$$



UTfit prediction:

$$|V_{cb}| = (42.6 \pm 0.5) 10^{-3}$$

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

V_{cb} and V_{ub}

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

$$|V_{cb}| = (41.25 \pm 0.95) 10^{-3}$$

uncertainty $\sim 2.3\%$

$$|V_{ub}| = (3.77 \pm 0.24) 10^{-3}$$

uncertainty $\sim 6.4\%$

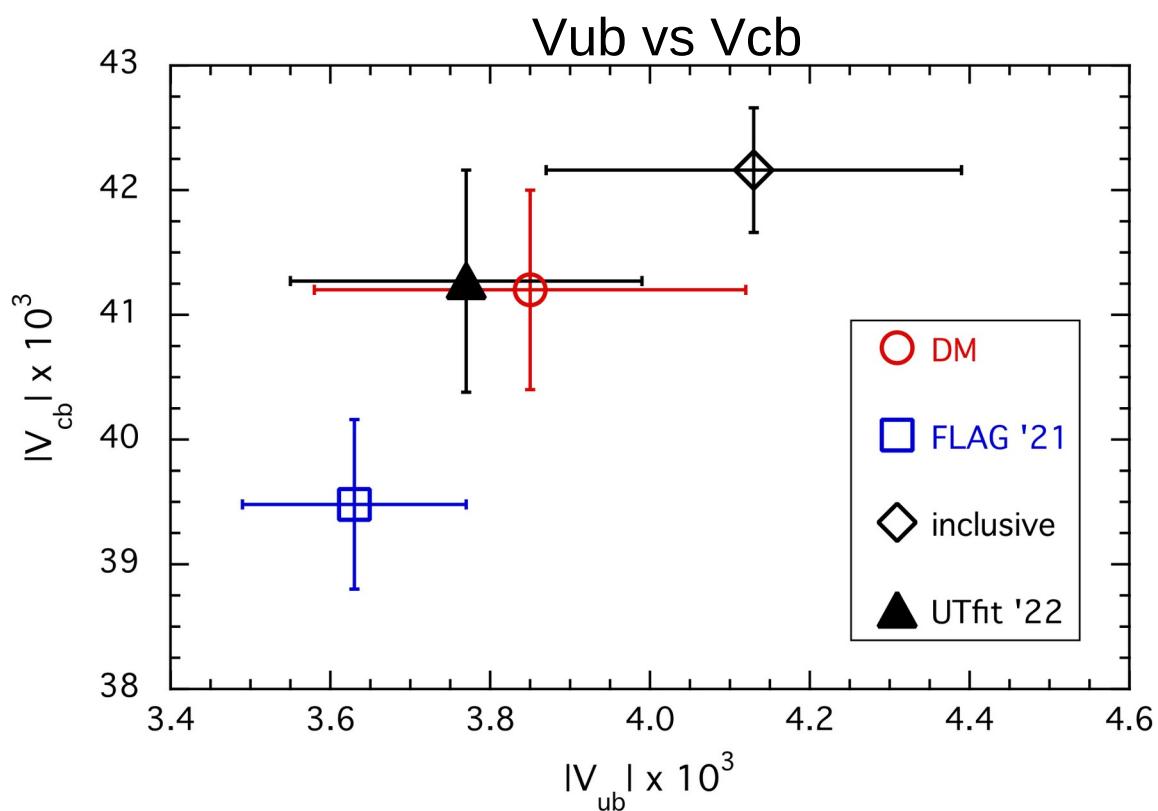
Correlation $\rho = 0.11$

Updated averages
including correlation

From global SM fit

$$|V_{cb}| = (42.3 \pm 0.4) 10^{-3}$$

$$|V_{ub}| = (3.72 \pm 0.09) 10^{-3}$$



See talks from Ludovico Vittorio and Manuel Naviglio (with G.Martinelli, and S. Simula)

UTfit prediction:

$$|V_{cb}| = (42.6 \pm 0.5) 10^{-3}$$

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

Some updated inputs

lattice inputs updated for this summer

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}	1.015 ± 0.021
B_{Bs}	1.284 ± 0.059

We quote, instead, the weighted average of the $N_f=2+1+1$ and $N_f=2+1$ results with the error rescaled when $\text{chi}^2/\text{dof} > 1$, as done by FLAG for the $N_f=2+1+1$ and $N_f=2+1$ averages separately
[new HPQCD (2+1+1) result 1907.01025]

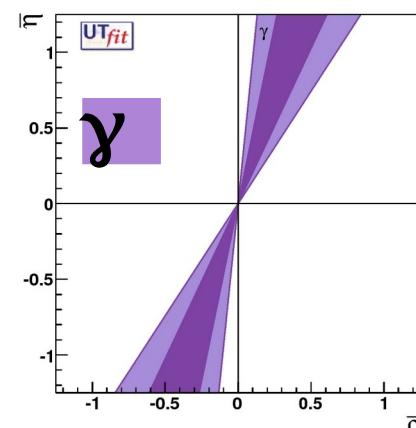
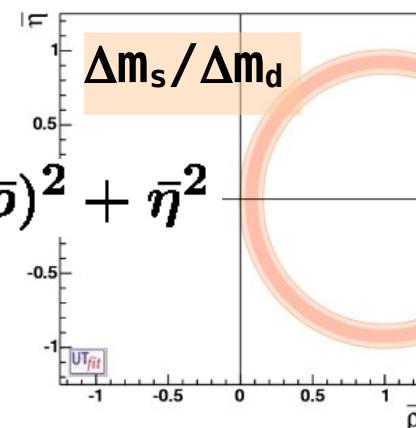
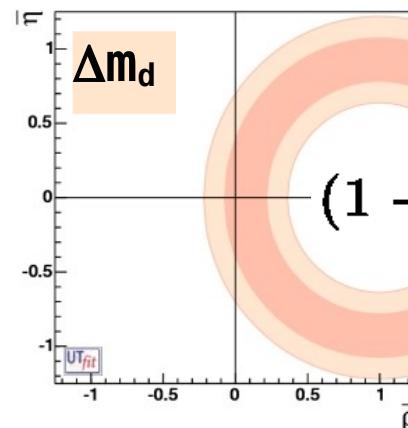
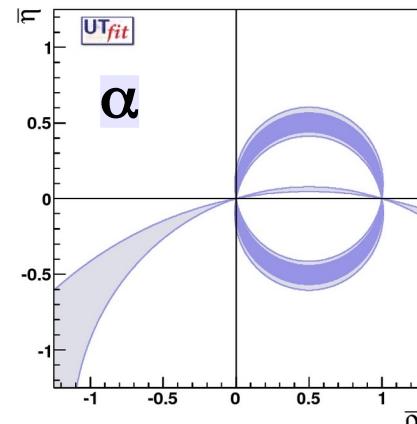
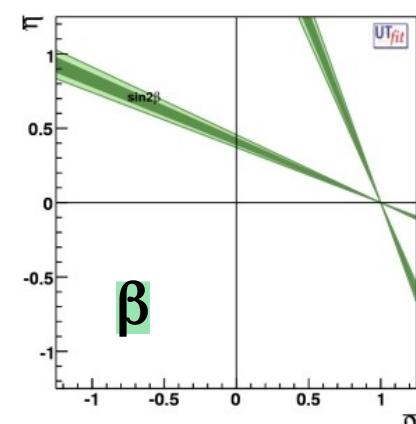
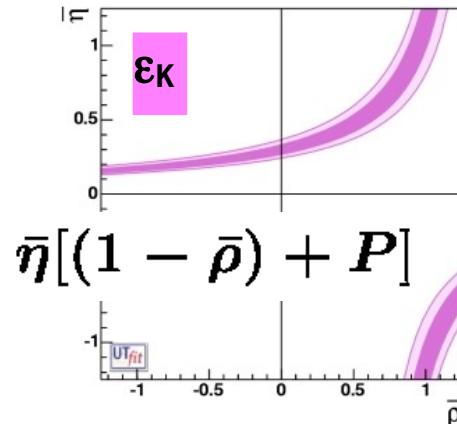
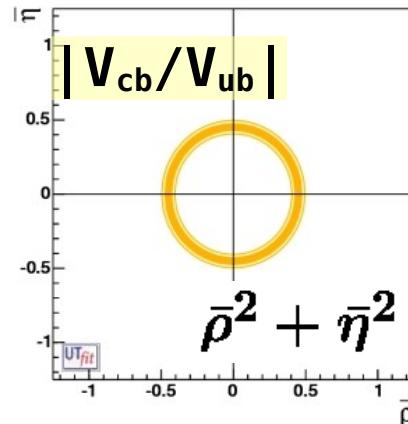
V_{ud} and V_{us} updated for this summer

Observables	Measurement
V_{ud}	0.97433 ± 0.00019
V_{us}	$0.2249 (\pm 0.0004)$

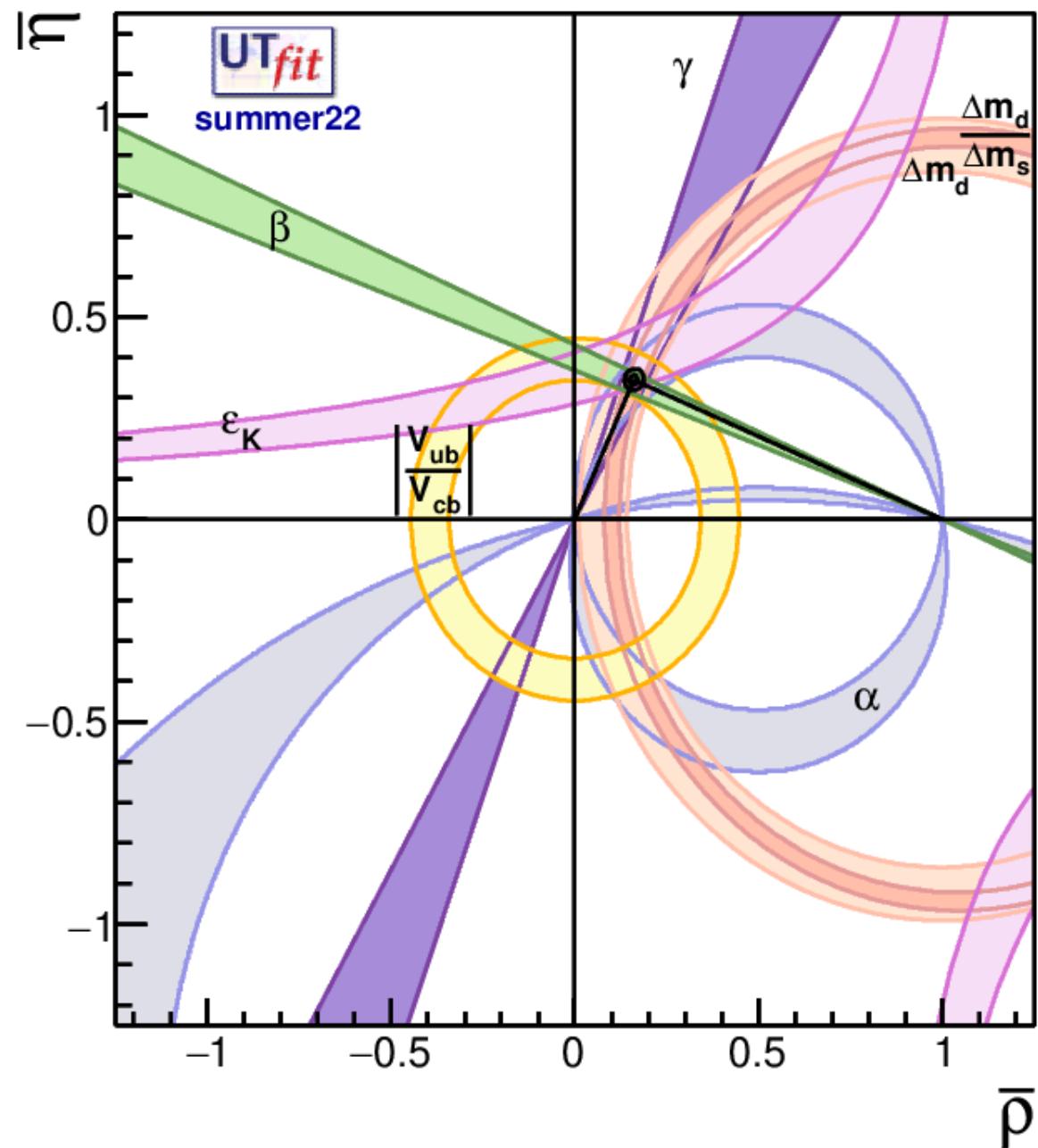
V_{ud} is taken from the PDG average of V_{ud} FLAG numbers (for 2+1+1 and 2+1) and superallowed beta decays value. PDG scale factor S=2.0

V_{us} is not used in the fit

Unitarity Triangle analysis in the SM:



Unitarity Triangle analysis in the SM:



levels @
95% Prob

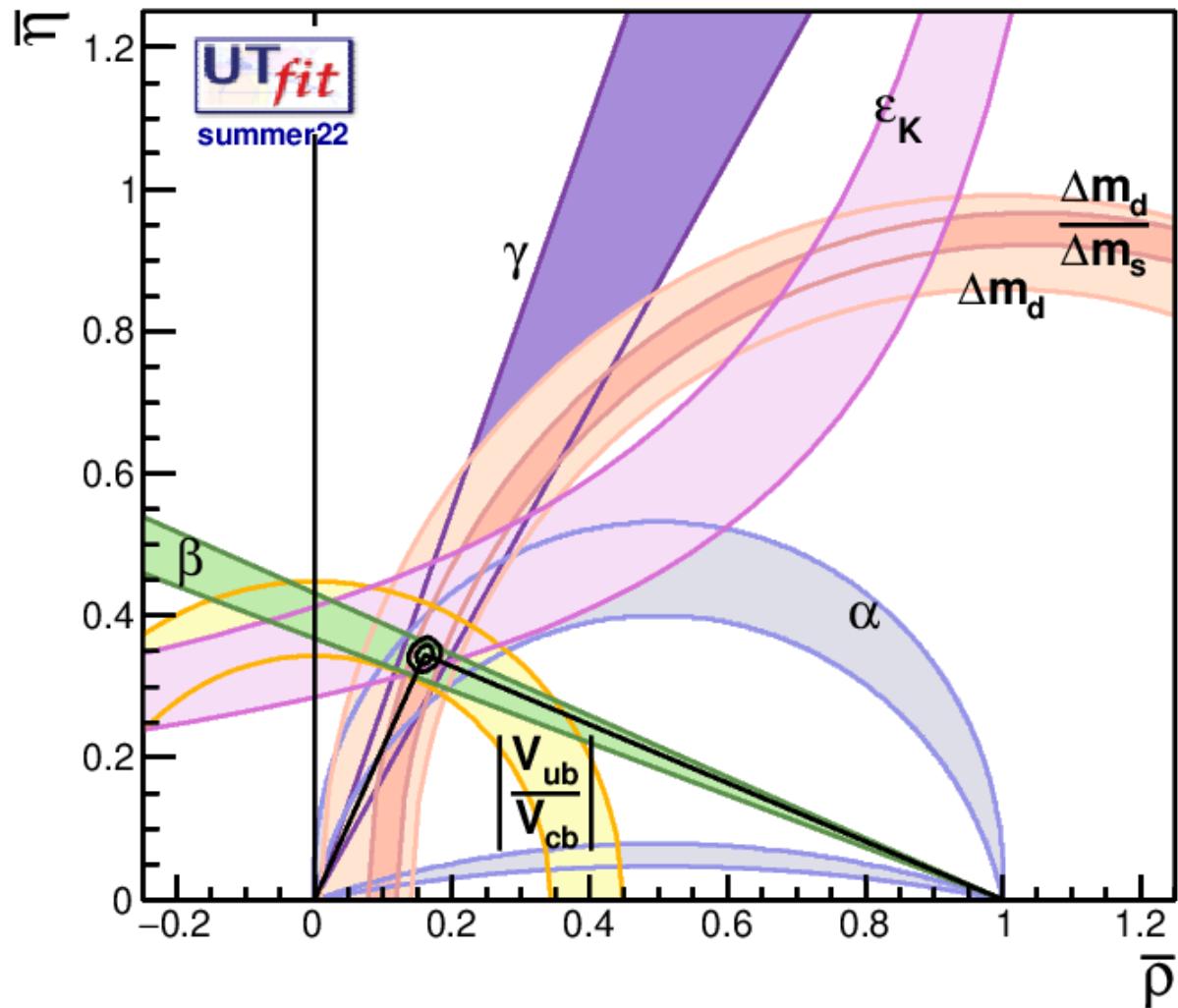
~6%

$$\begin{aligned}\bar{\rho} &= 0.160 \pm 0.009 \\ \bar{\eta} &= 0.345 \pm 0.009\end{aligned}$$

~3%

Unitarity Triangle analysis in the SM:

zoomed in..



levels @
95% Prob

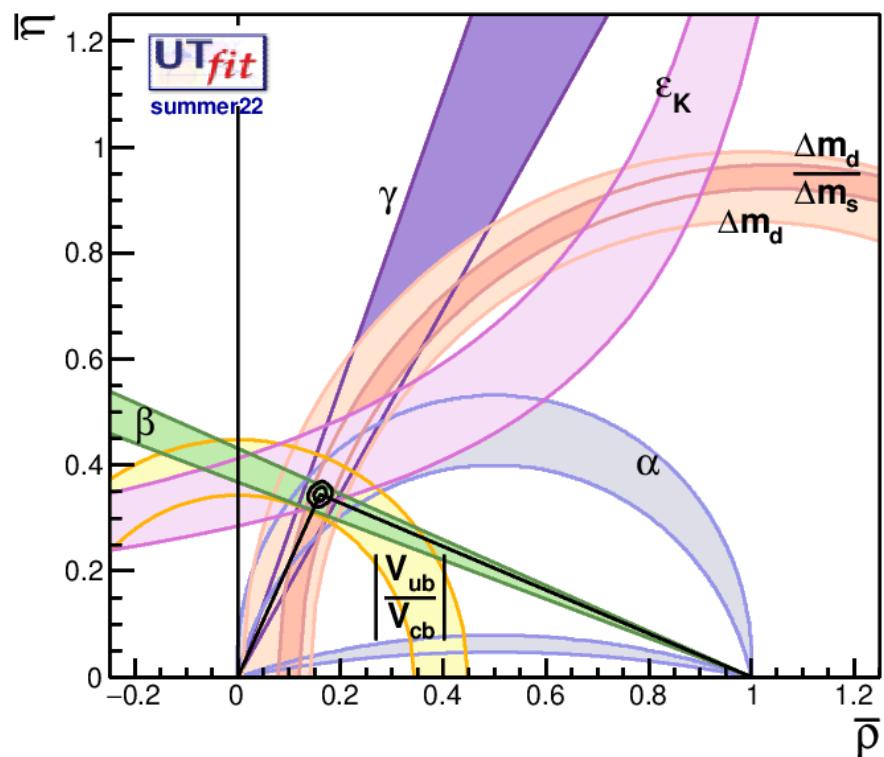
~6%

$$\begin{aligned}\bar{\rho} &= 0.160 \pm 0.009 \\ \bar{\eta} &= 0.345 \pm 0.009\end{aligned}$$

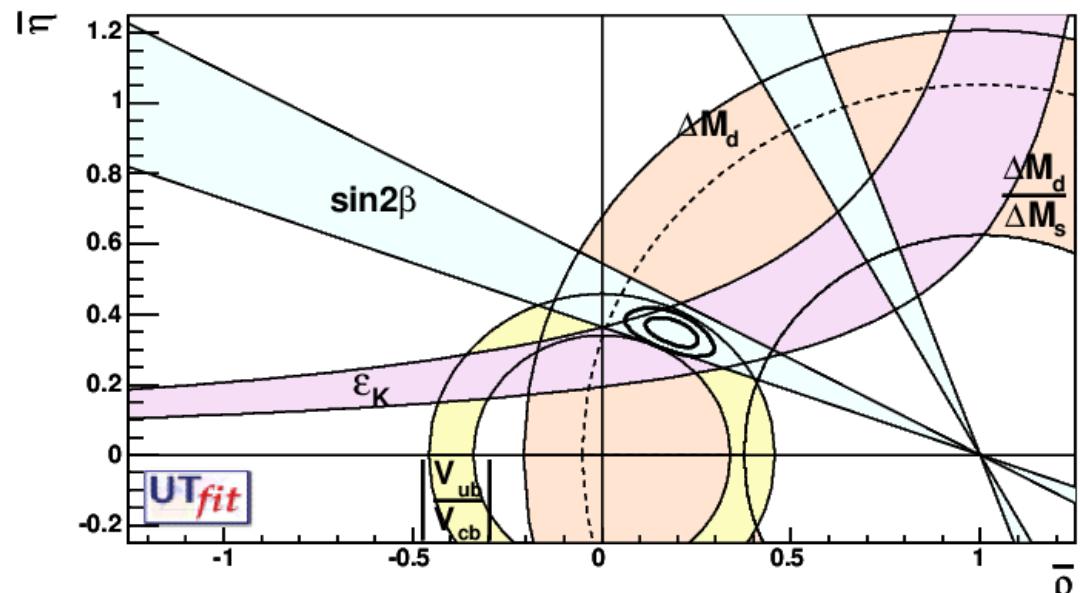
~3%

Unitarity Triangle analysis in the SM:

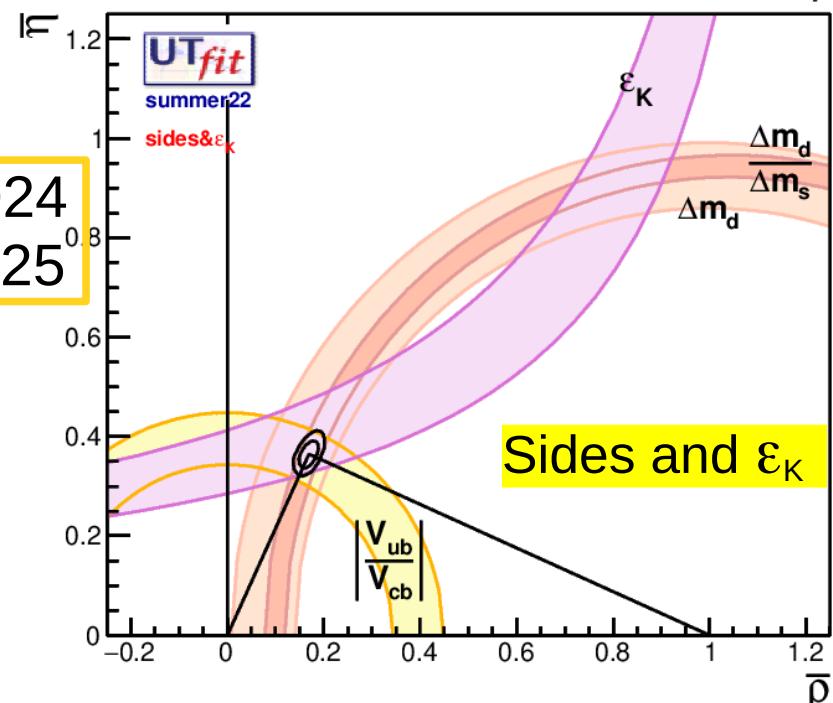
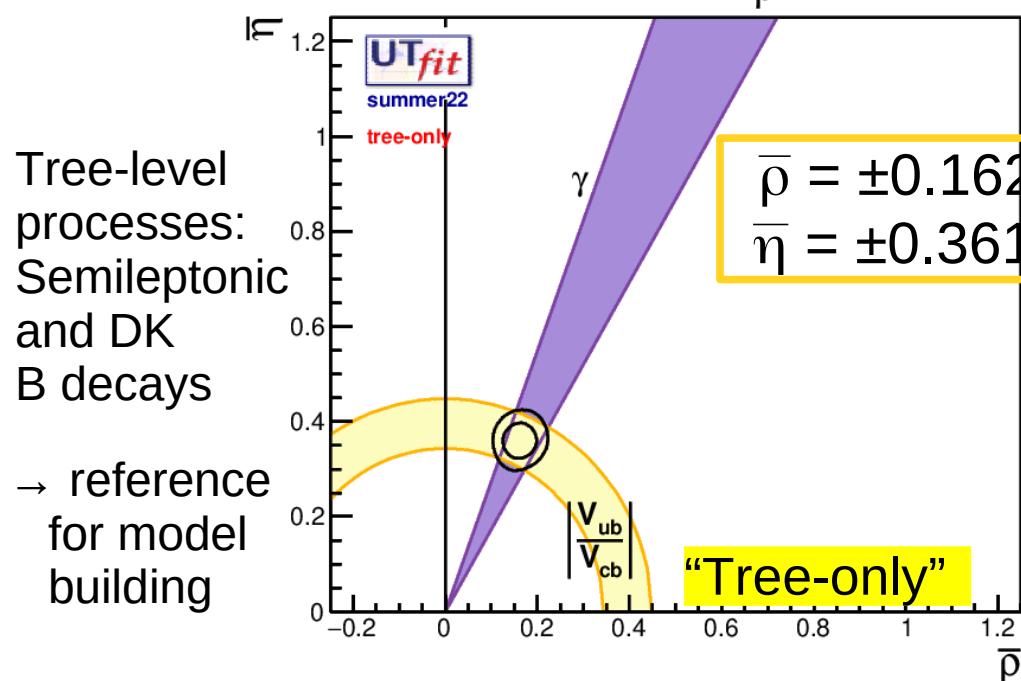
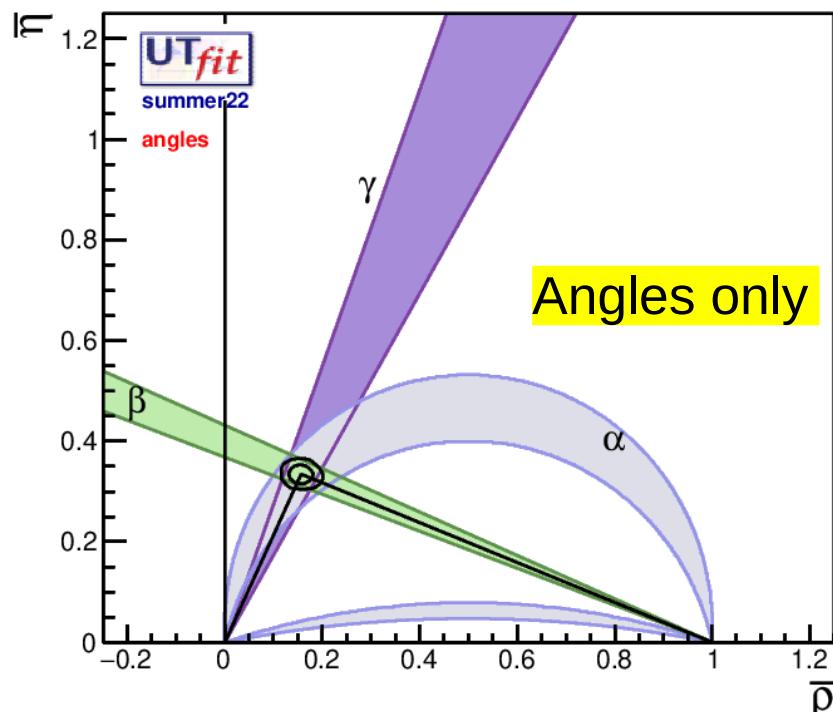
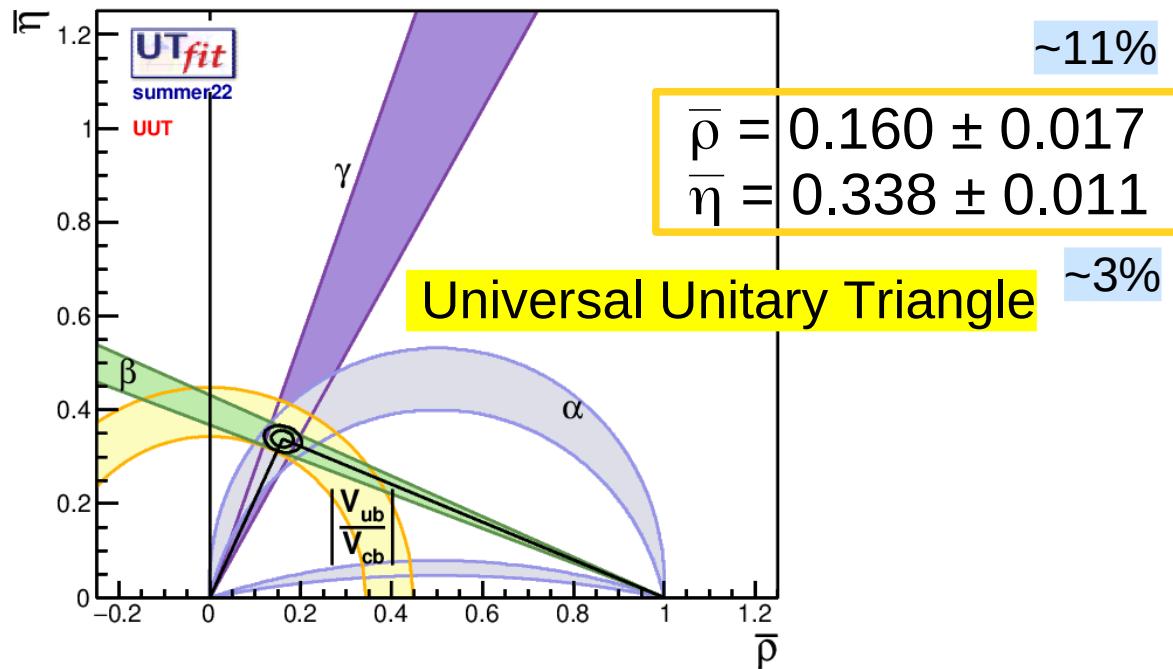
2022



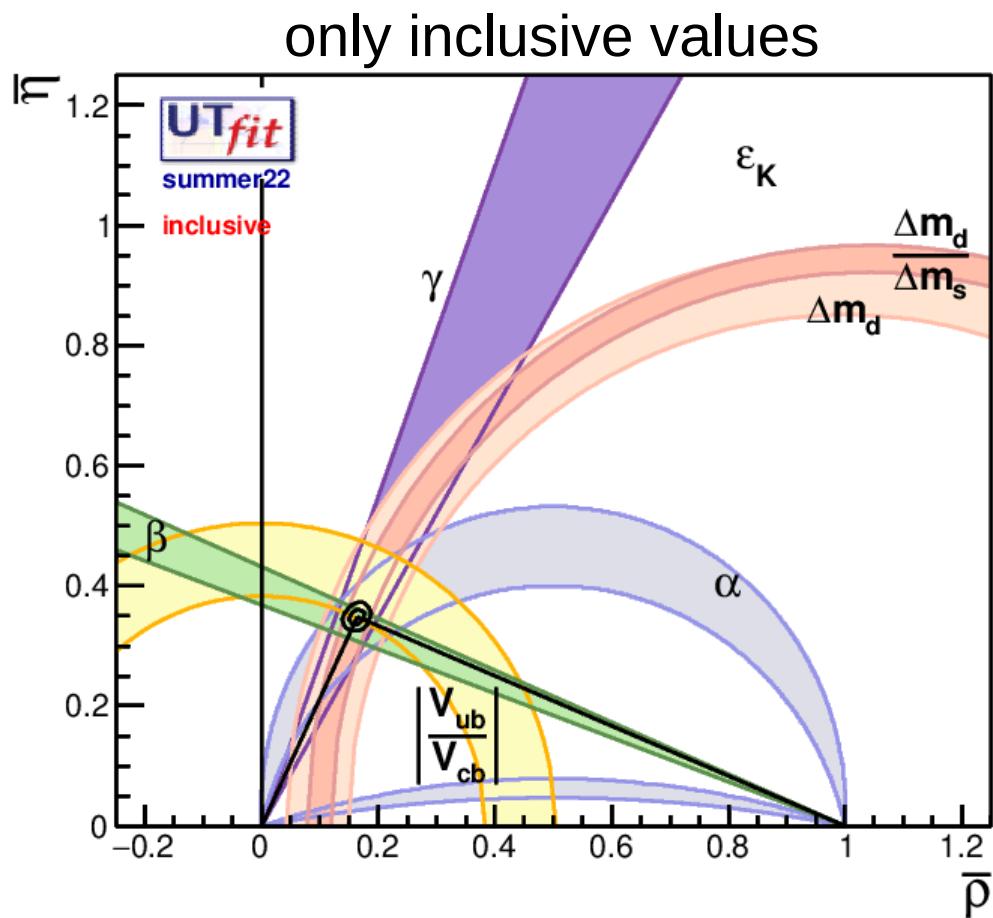
2004



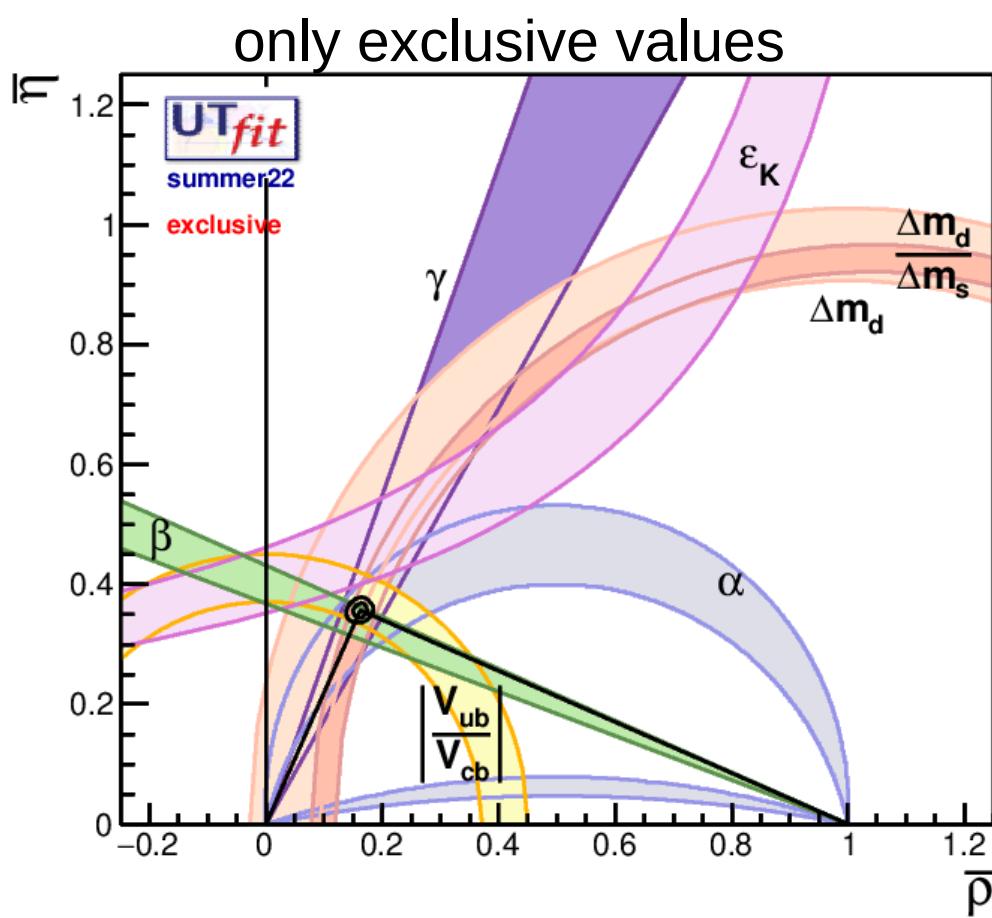
Some interesting configurations



Inclusive vs Exclusive



$$\begin{aligned}\bar{\rho} &= 0.164 \pm 0.009 \\ \bar{\eta} &= 0.348 \pm 0.009 \\ \sin 2\beta &= 0.753 \pm 0.028\end{aligned}$$

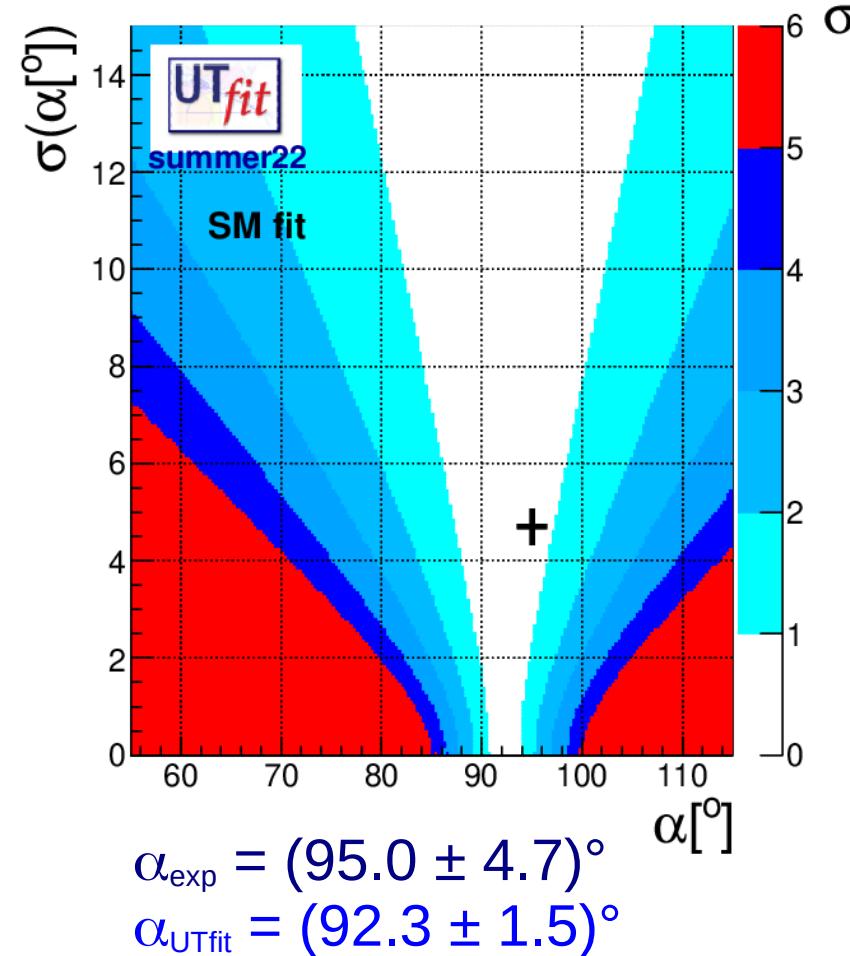


$$\begin{aligned}\bar{\rho} &= 0.162 \pm 0.009 \\ \bar{\eta} &= 0.356 \pm 0.009 \\ \sin 2\beta &= 0.755 \pm 0.020\end{aligned}$$

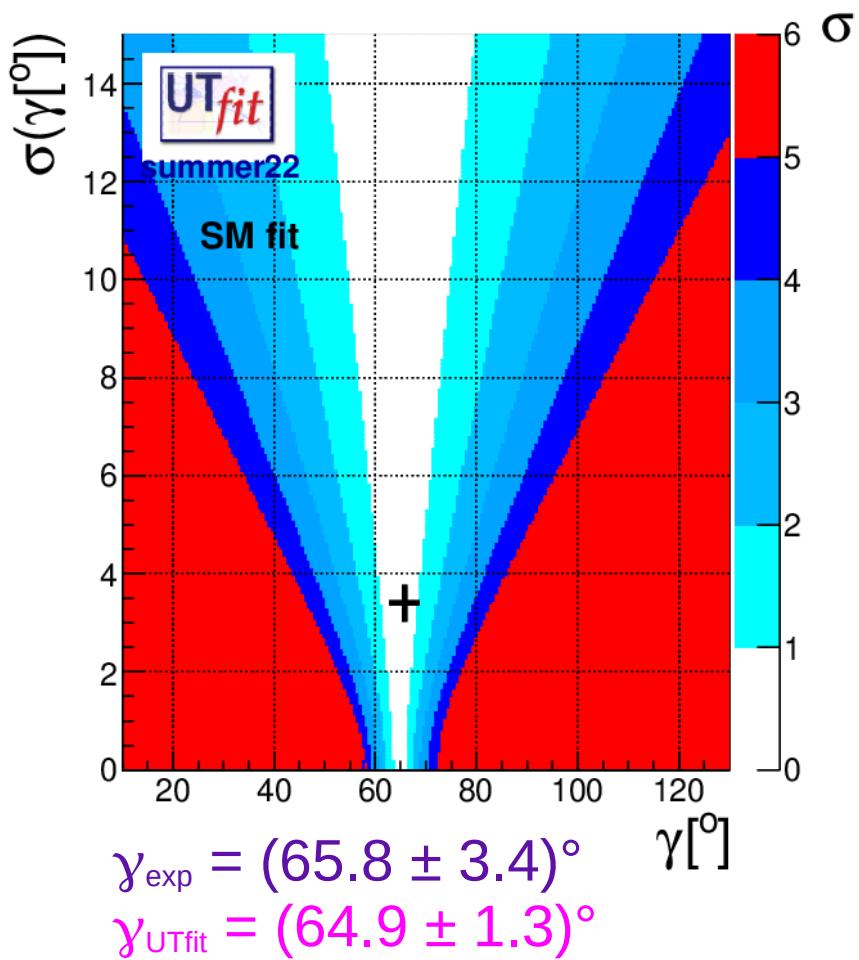
compatibility plots

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, ... $n\sigma$



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

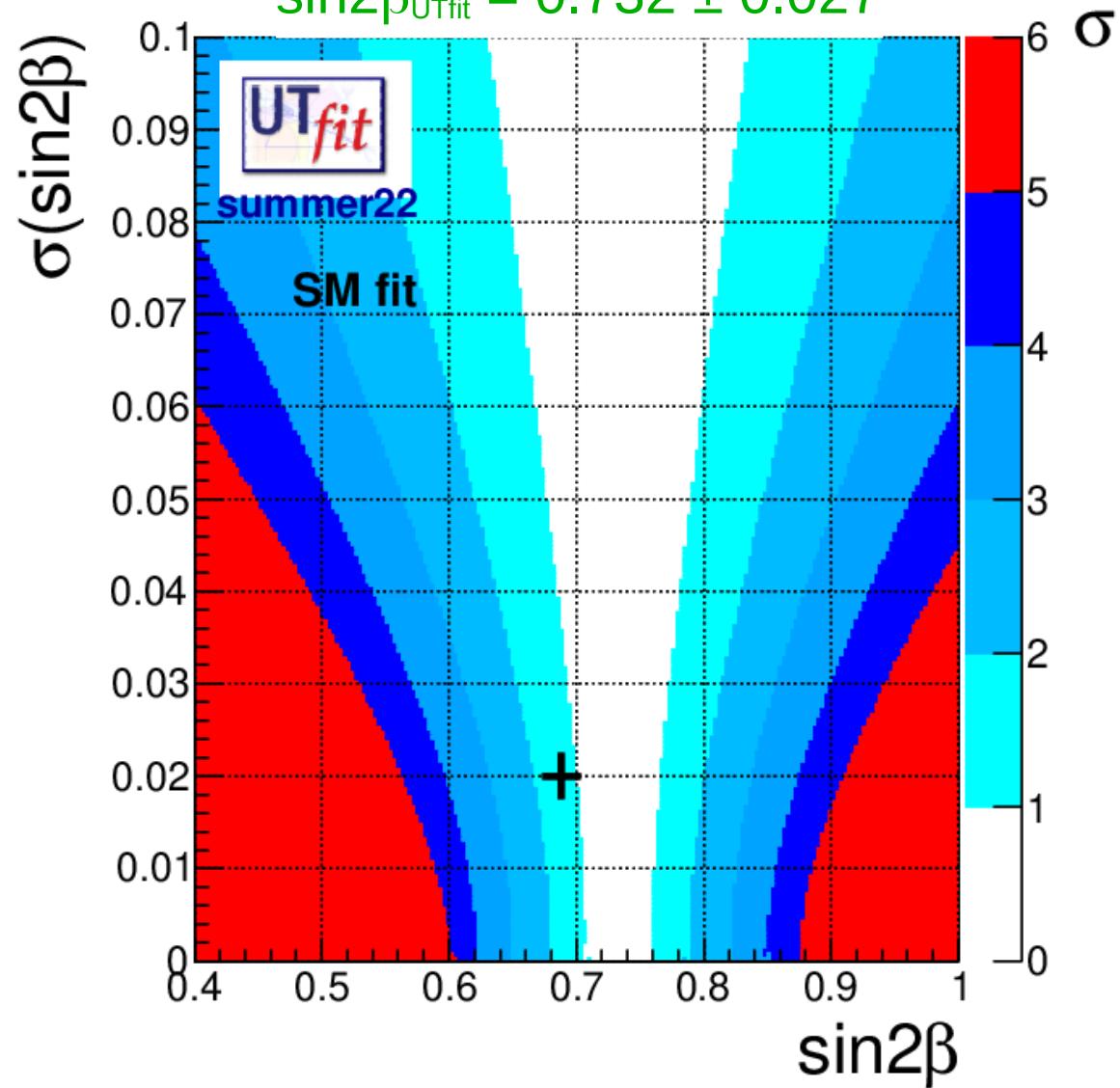


Checking the usual *tensions*..

$\sim 1.3\sigma$

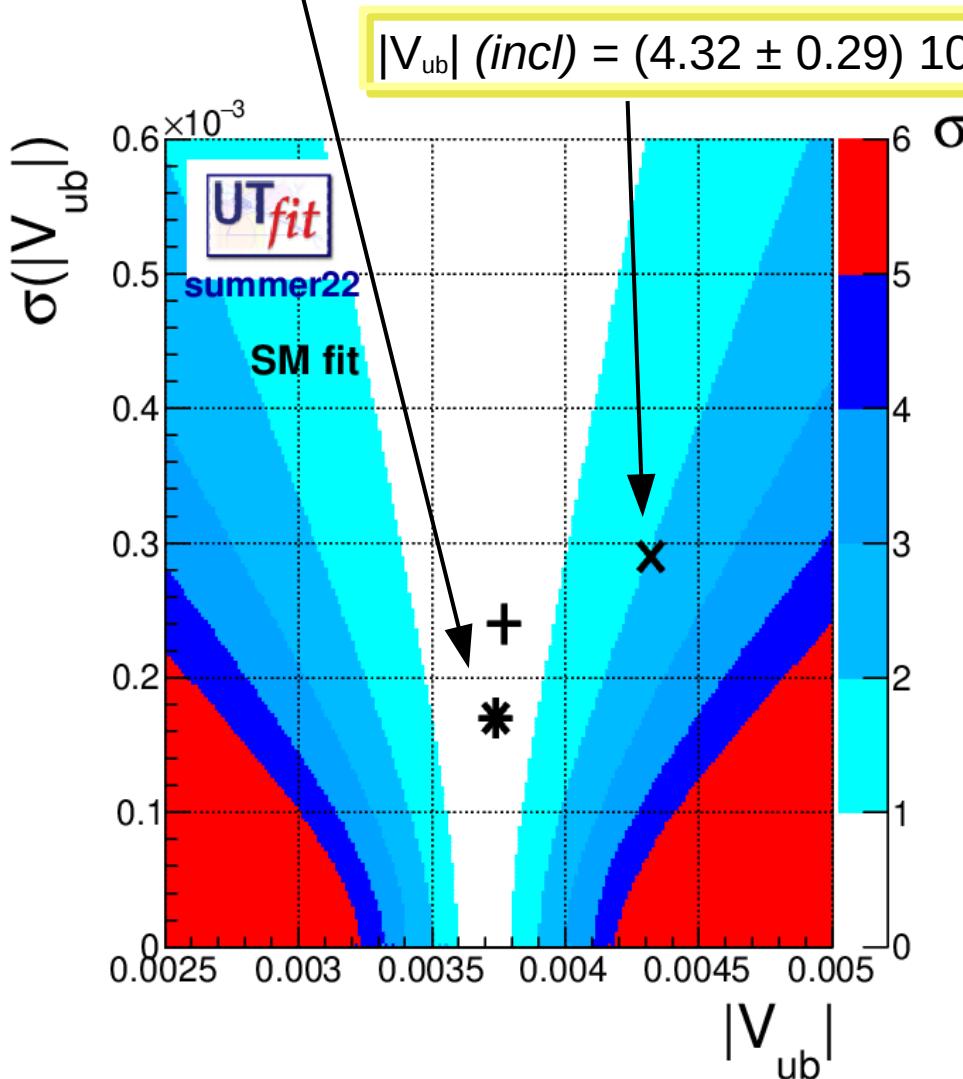
$$\sin 2\beta_{\text{exp}} = 0.688 \pm 0.020$$

$$\sin 2\beta_{\text{UTfit}} = 0.732 \pm 0.027$$



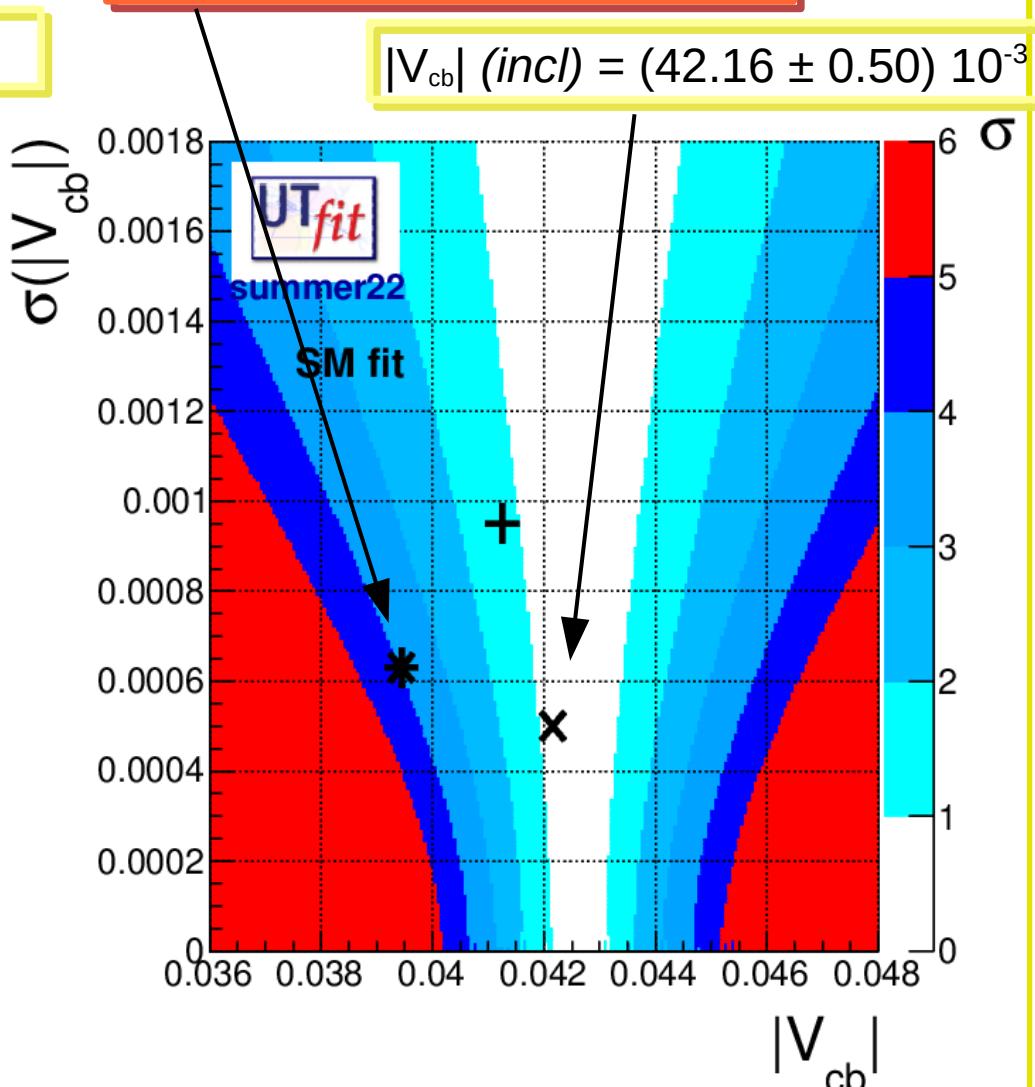
Checking the usual *tensions*..

$$|V_{ub}| \text{ (excl)} = (3.74 \pm 0.17) \cdot 10^{-3}$$



$$\begin{aligned} V_{ub\text{exp}} &= (3.77 \pm 0.24) \cdot 10^{-3} \\ V_{ub\text{UTfit}} &= (3.70 \pm 0.10) \cdot 10^{-3} \end{aligned}$$

$$|V_{cb}| \text{ (excl)} = (39.44 \pm 0.63) \cdot 10^{-3}$$



$$\begin{aligned} V_{cb\text{exp}} &= (41.25 \pm 0.95) \cdot 10^{-3} \\ V_{cb\text{UTfit}} &= (42.6 \pm 0.5) \cdot 10^{-3} \end{aligned}$$

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	0.732 ± 0.027	~ 1.3
γ	65.8 ± 3.4	64.9 ± 1.3	< 1
α	95.0 ± 4.7	92.3 ± 1.5	< 1
$\varepsilon_K \cdot 10^3$	2.228 ± 0.001	2.04 ± 0.14	< 1
$ V_{cb} \cdot 10^3$	41.25 ± 0.95	42.6 ± 0.5	< 1
$ V_{cb} \cdot 10^3$ (incl)	42.16 ± 0.50		< 1
$ V_{cb} \cdot 10^3$ (excl)	39.44 ± 0.63		~ 4.0
$ V_{ub} \cdot 10^3$	3.77 ± 0.24	3.70 ± 0.10	< 1
$ V_{ub} \cdot 10^3$ (incl)	4.32 ± 0.29	-	~ 2.0
$ V_{ub} \cdot 10^3$ (excl)	3.74 ± 0.17	-	< 1
$\text{BR}(B \rightarrow \tau\nu)[10^{-4}]$	1.09 ± 0.24	0.88 ± 0.05	< 1
$A_{SL}^d \cdot 10^3$	-2.1 ± 1.7	-0.33 ± 0.02	< 1
$A_{SL}^s \cdot 10^3$	-0.6 ± 2.8	0.014 ± 0.001	< 1

Unitarity Triangle analysis in the SM:

We obtain the predictions for the lattice parameters in different configurations in the fit:

- only lattice parameters ratios
 - $(F_{Bs}/F_B, B_{Bs}/B_{Bd} \text{ used})$
- only B parameters
 - $(B_{Bs}^{-1}, B_{Bs}/B_{Bd} \text{ used})$
- only decay constants f
 - $(f_{Bs}, f_{Bs}/f_B \text{ included})$

Observables	Measurement	Prediction
B_K	0.756 ± 0.016	0.832 ± 0.054
No B lattice		
$f_B \sqrt{B_{Bd}}$	(0.2142 ± 0.0056)	0.212 ± 0.010
$f_{Bs} \sqrt{B_{Bs}}$	(0.2607 ± 0.0061)	0.259 ± 0.010
ξ	(1.217 ± 0.014)	1.225 ± 0.033
Ratios only		
f_{Bs}	0.2301 ± 0.0012	0.227 ± 0.009
B_{Bs}	1.284 ± 0.059	1.30 ± 0.10
B pars only		
f_{Bs}/f_{Bd}	1.208 ± 0.005	1.215 ± 0.028
f_{Bs}	0.2301 ± 0.0012	0.228 ± 0.008
f pars only		
B_{Bs}/B_{Bd}	1.015 ± 0.021	1.017 ± 0.028
B_{Bs}	1.284 ± 0.059	1.290 ± 0.065

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):

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

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

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

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

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

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

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

new-physics-specific constraints

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

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

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

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

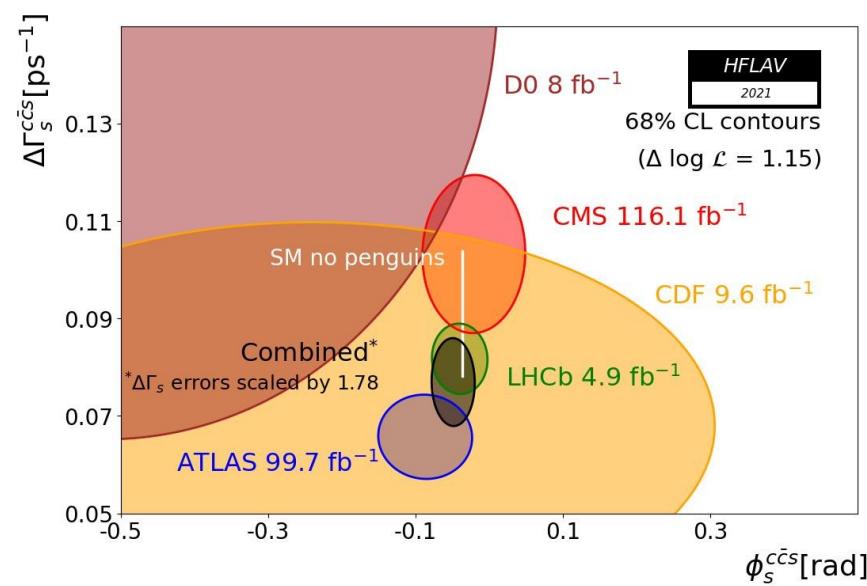
$$\tau^{\text{FS}}(B_s) = 1.527 \pm 0.011 \text{ ps}$$

HFLAV

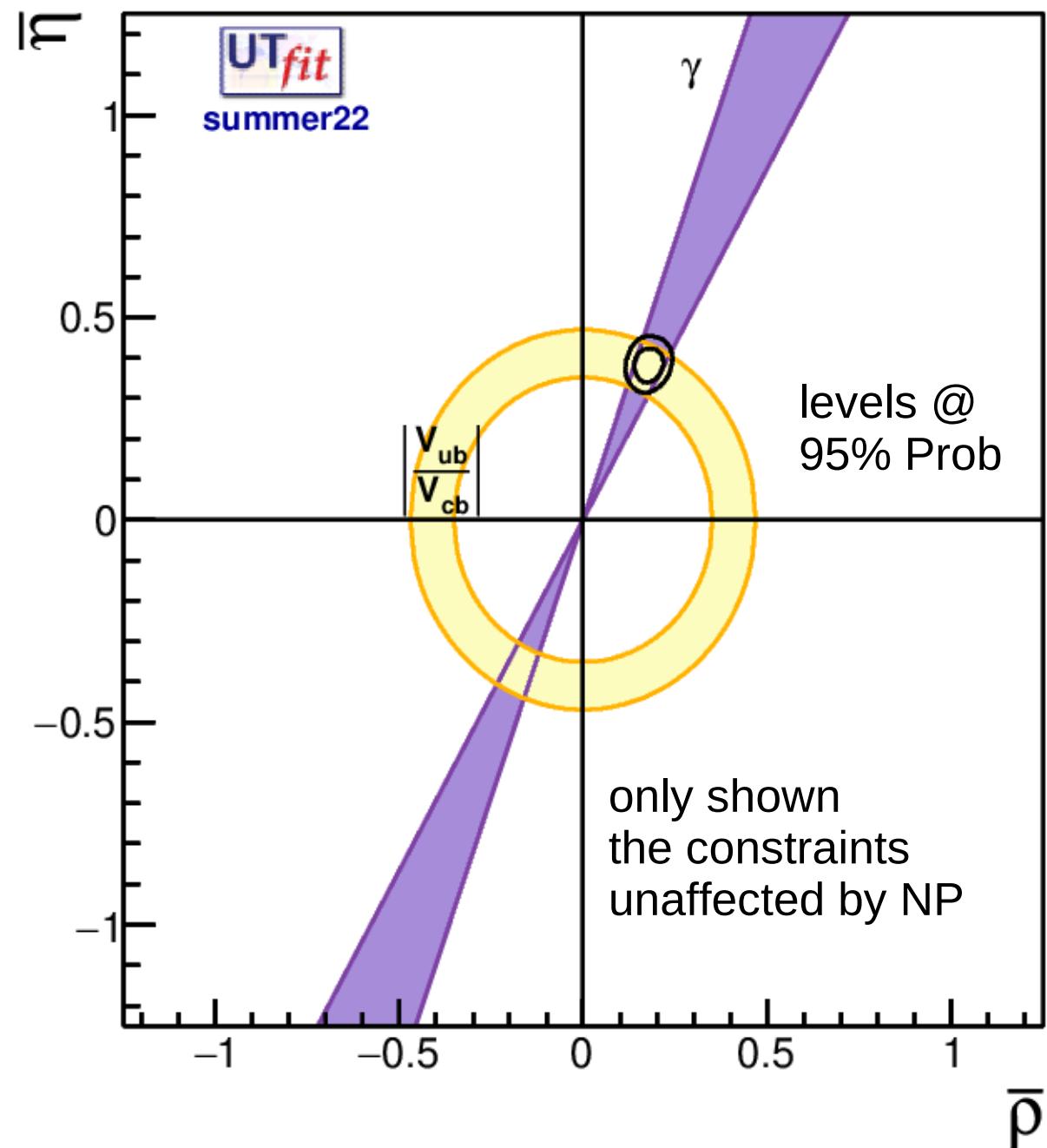
$\phi_s = 2\beta_s$ vs $\Delta\Gamma_s$ from $B_s \rightarrow J/\psi\phi$
angular analysis as a function
of proper time and b-tagging

$$\phi_s = -0.049 \pm 0.019 \text{ rad}$$

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



NP analysis results



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

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

SM is

$$\bar{p} = 0.160 \pm 0.009$$

$$\bar{\eta} = 0.345 \pm 0.009$$

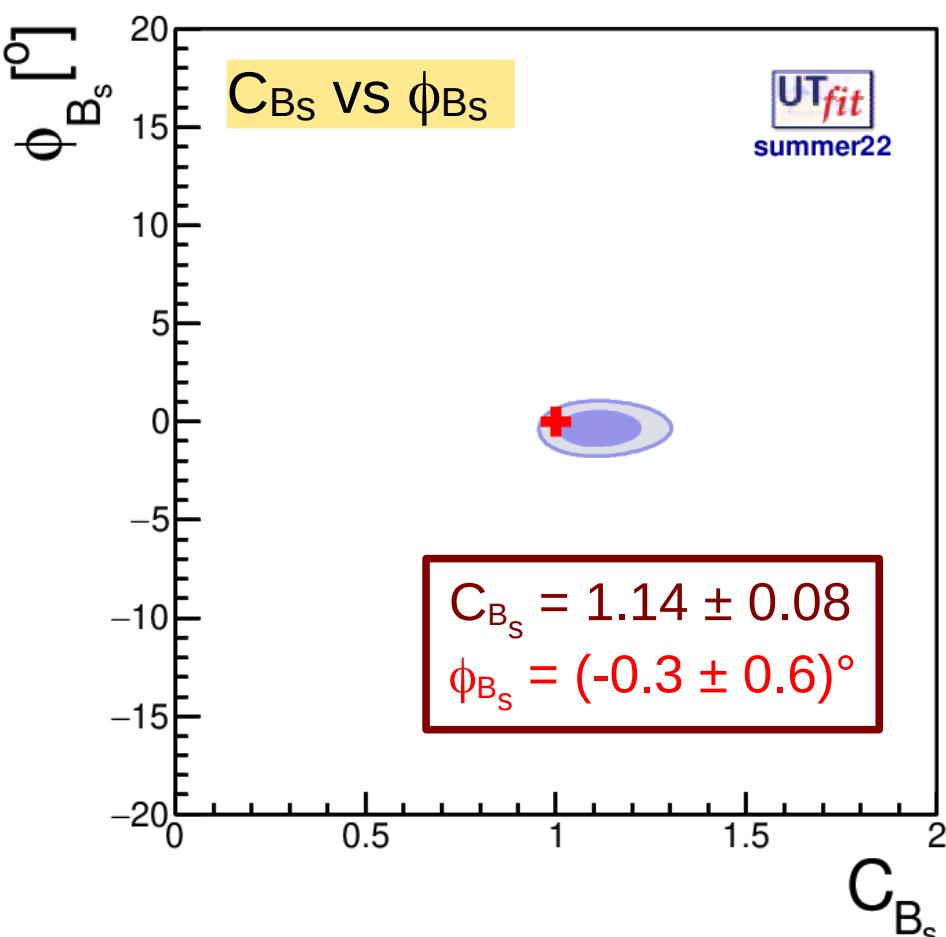
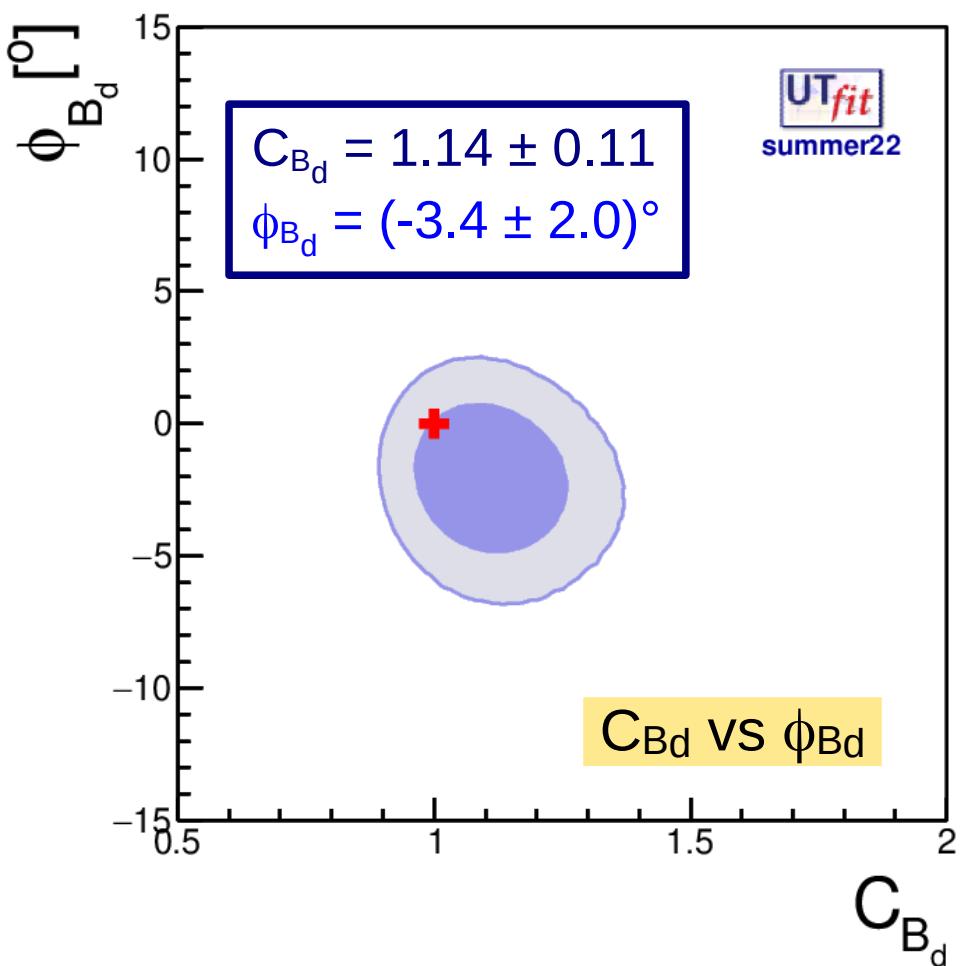
NP parameter results

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

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

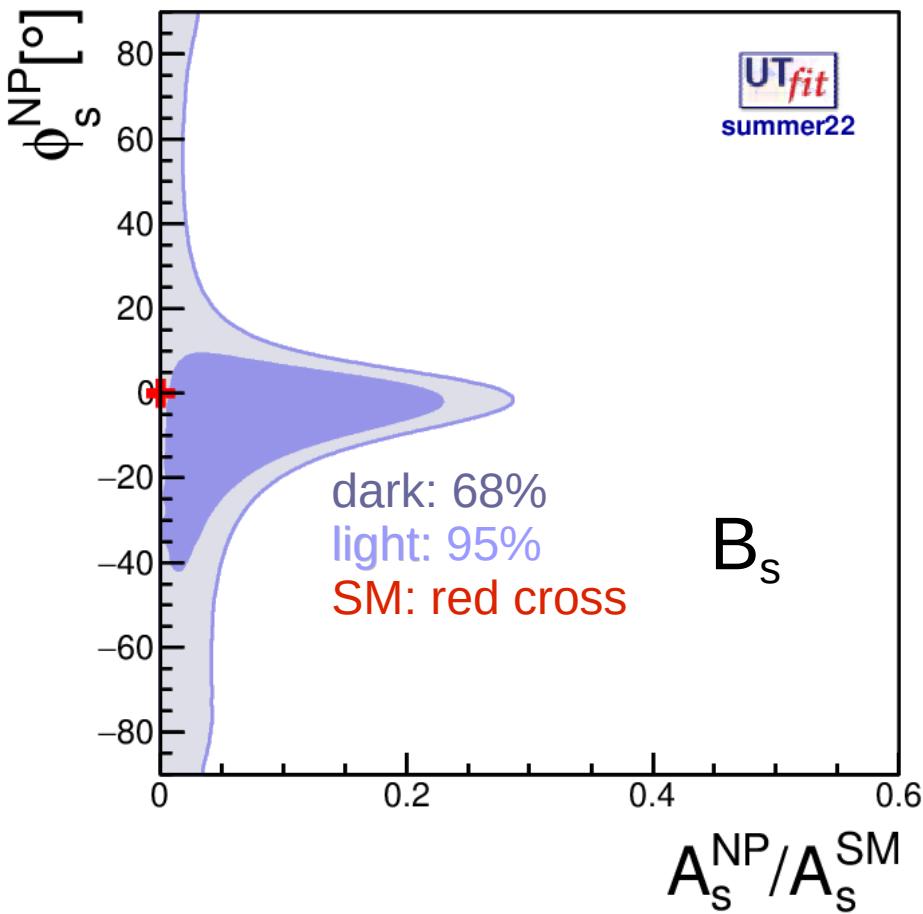
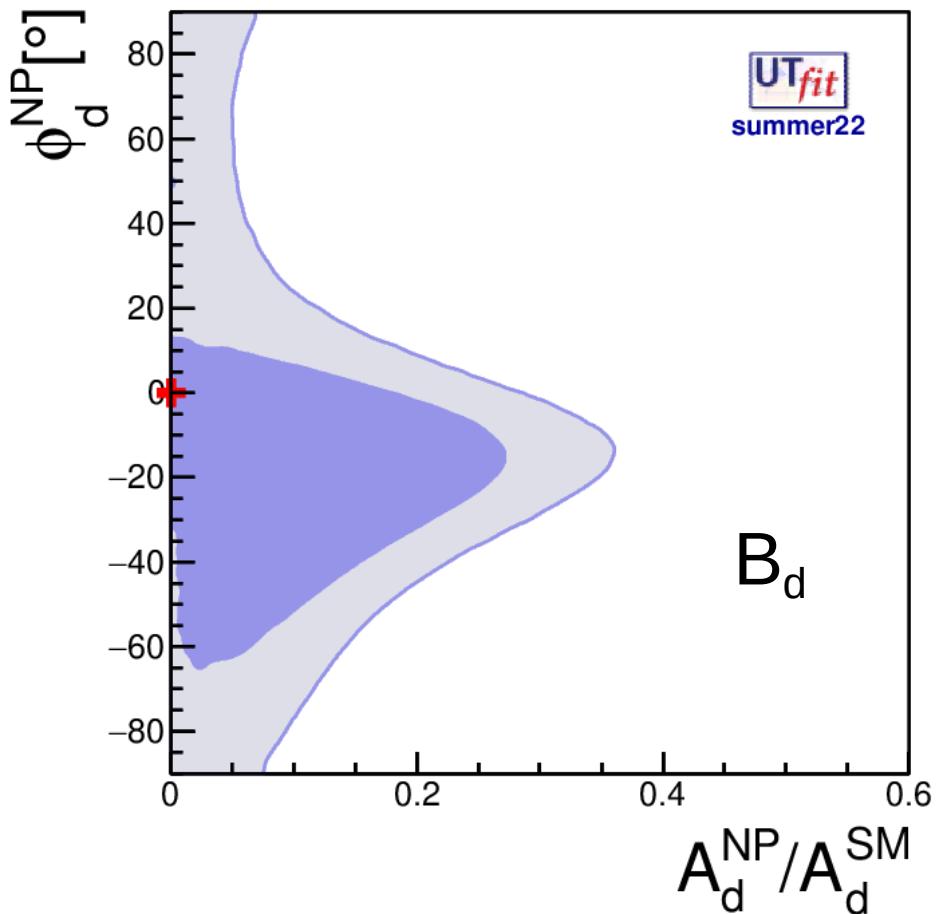
K system

$$C_{e_K} = 1.12 \pm 0.12$$



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:

- < 25% @68% prob. (35% @95%) in B_d mixing
- < 25% @68% prob. (30% @95%) in B_s mixing

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

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

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)

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

$$Q_1^{q_i q_j} = \bar{q}_j^{\alpha} \gamma_{\mu} q_{iL}^{\alpha} \bar{q}_j^{\beta} \gamma^{\mu} q_{iL}^{\beta},$$

$$Q_2^{q_i q_j} = \bar{q}_j^{\alpha} q_{iL}^{\alpha} \bar{q}_j^{\beta} q_{iL}^{\beta},$$

$$Q_3^{q_i q_j} = \bar{q}_j^{\alpha} q_{iL}^{\beta} \bar{q}_j^{\beta} q_{iL}^{\alpha},$$

$$Q_4^{q_i q_j} = \bar{q}_j^{\alpha} q_{iL}^{\alpha} \bar{q}_j^{\beta} q_{iR}^{\beta},$$

$$Q_5^{q_i q_j} = \bar{q}_j^{\alpha} q_{iL}^{\beta} \bar{q}_j^{\beta} q_{iR}^{\alpha}.$$

testing the TeV scale

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

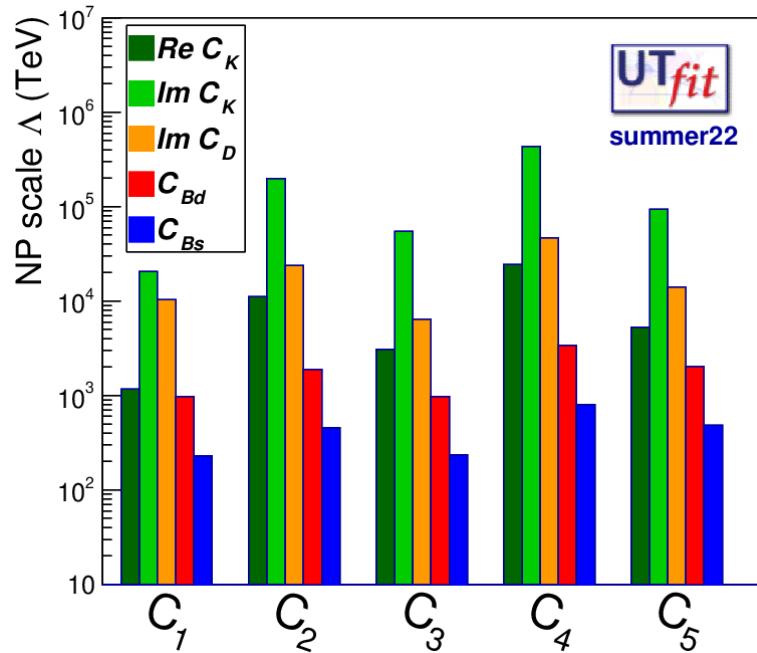
F is the flavour coupling and so F_{SM} is the combination of CKM factors for the considered process

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

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

results from the Wilson coefficients

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



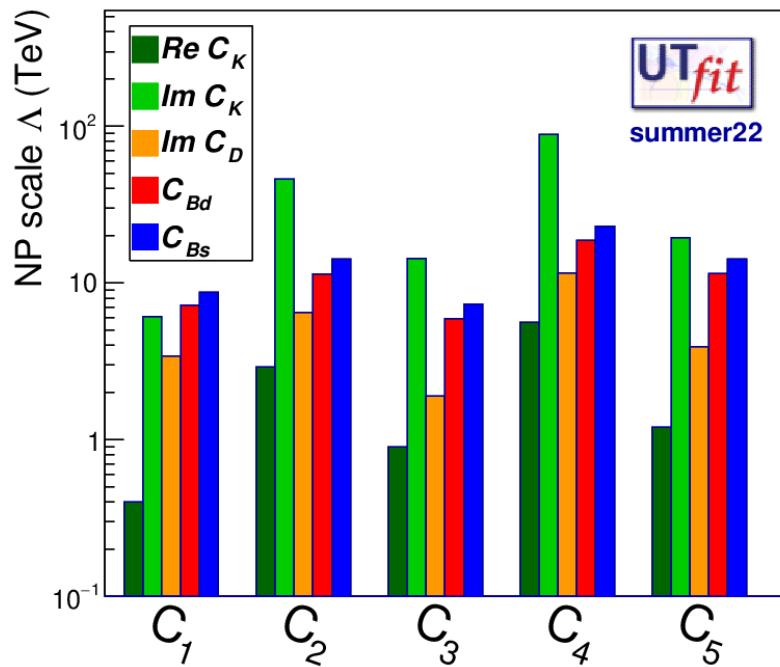
$\Lambda > 4.4 \cdot 10^5$ TeV

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

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

$\Lambda > 1.3 \cdot 10^4$ TeV

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



$\Lambda > 95$ TeV

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

$\Lambda > 2.9$ TeV

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

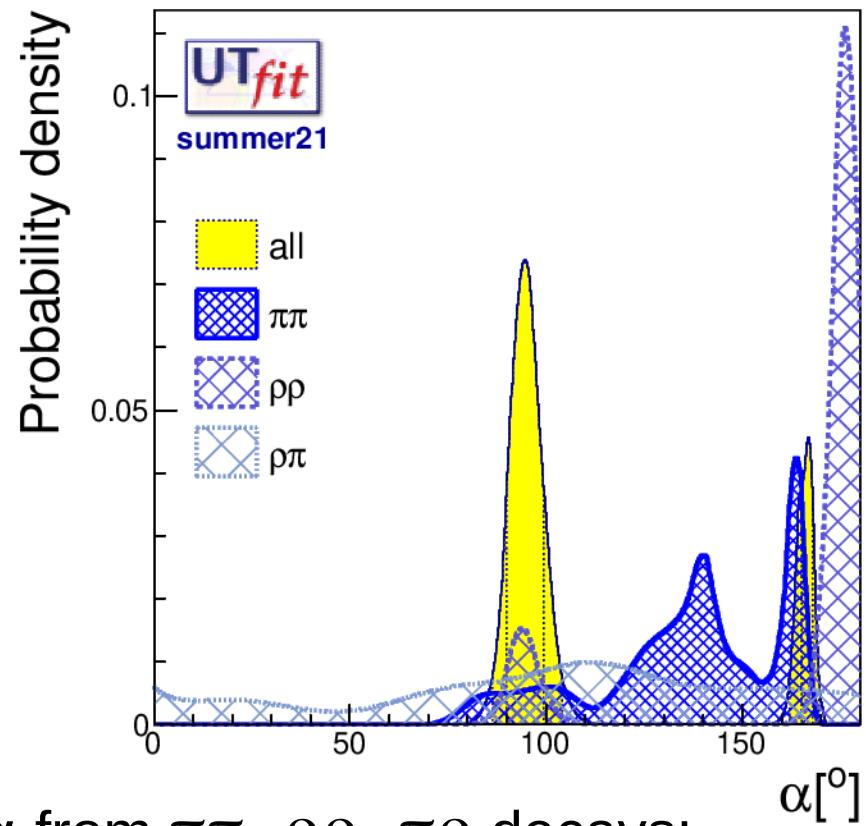
conclusions

- 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

$\sin 2\alpha (\phi_2)$ and $\gamma (\phi_3)$

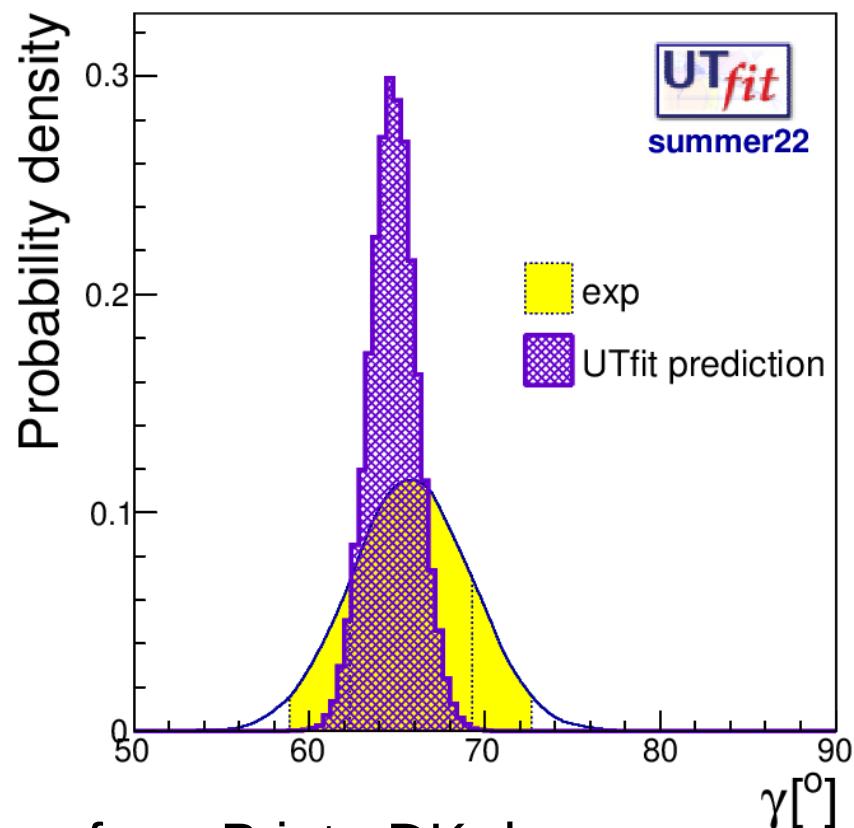
α updated with latest $\pi\pi/\rho\rho$
BR and C/S results



α from $\pi\pi$, $\rho\rho$, $\rho\pi$ decays:
combined SM: $(95.0 \pm 4.7)^\circ$
UTfit prediction: $(92.3 \pm 1.5)^\circ$

α from HFLAV: 85.5 ± 4.6

γ updated with all the
latest results (LHCb)



γ from B into DK decays:
HFLAV: $(65.8 \pm 3.4)^\circ$
UTfit prediction: $(64.9 \pm 1.3)^\circ$

Unitarity Triangle analysis in the SM:

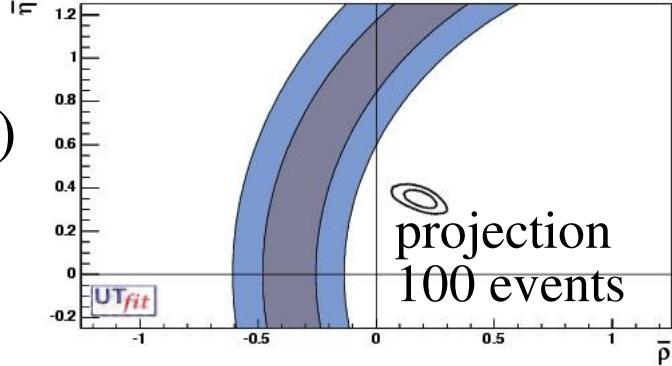
obtained excluding the given constraint from the fit

Observables	Measurement	Prediction	Pull (# σ)
$\epsilon_K \cdot 10^3$	2.228 ± 0.001	2.04 ± 0.14	< 1
$\epsilon_K' / \epsilon_K \cdot 10^3$	(1.66 ± 0.23)	1.38 ± 0.43	
$ V_{cb} \cdot 10^3$	41.25 ± 0.95	42.6 ± 0.5	< 1
$ V_{cb} \cdot 10^3$ (incl)	42.16 ± 0.50		< 1
$ V_{cb} \cdot 10^3$ (excl)	39.44 ± 0.63		~ 4.0
$ V_{ub} \cdot 10^3$	3.77 ± 0.24	3.70 ± 0.10	< 1
$ V_{ub} \cdot 10^3$ (incl)	4.32 ± 0.29	-	~ 2.0
$ V_{ub} \cdot 10^3$ (excl)	3.74 ± 0.17	-	< 1
$BR(B \rightarrow \tau\nu)[10^{-4}]$	1.09 ± 0.24	0.88 ± 0.05	< 1
$BR(B_s \rightarrow \mu\mu)[10^{-9}]$	(2.84 ± 0.33)	3.25 ± 0.12	
$BR(B \rightarrow \mu\mu)[10^{-10}]$	(< 1.9)	0.948 ± 0.038	
$A_{SL}^d \cdot 10^3$	-2.1 ± 1.7	-0.33 ± 0.02	< 1
$A_{SL}^s \cdot 10^3$	-0.6 ± 2.8	0.014 ± 0.001	< 1

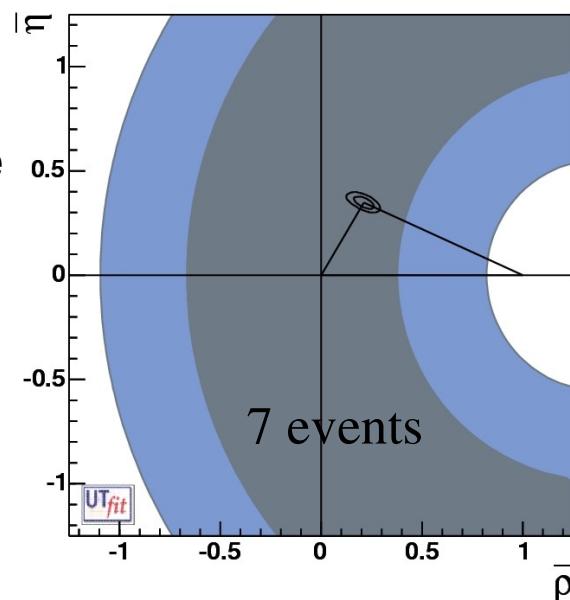
some old plots coming back to fashion:

As NA62 and KOTO are analysing data:

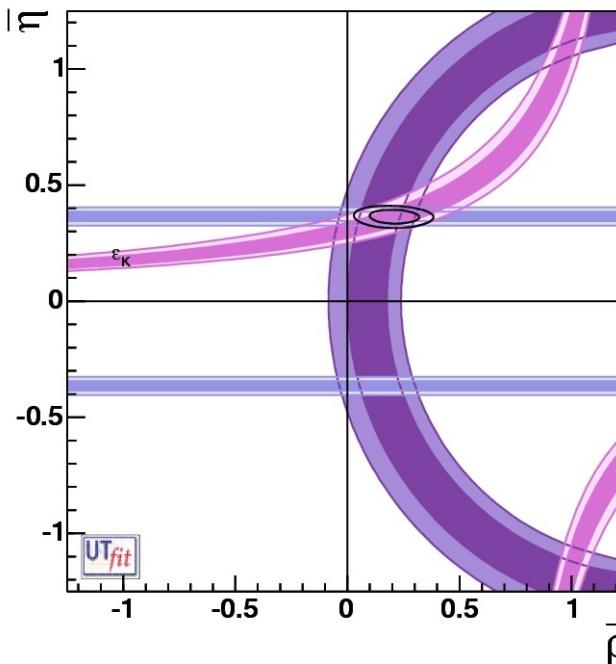
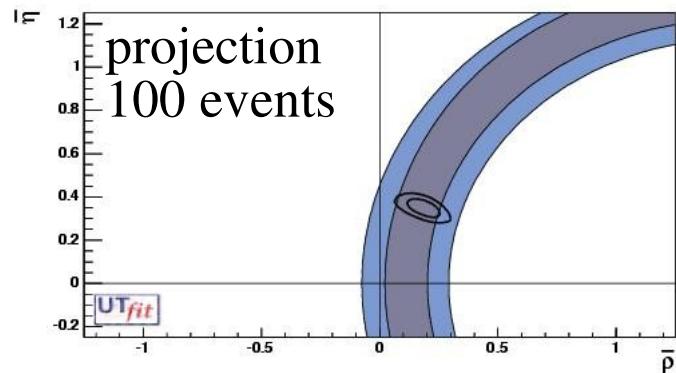
$\text{BR}(K^+ \rightarrow \pi^+ \bar{\nu} \bar{\nu})$



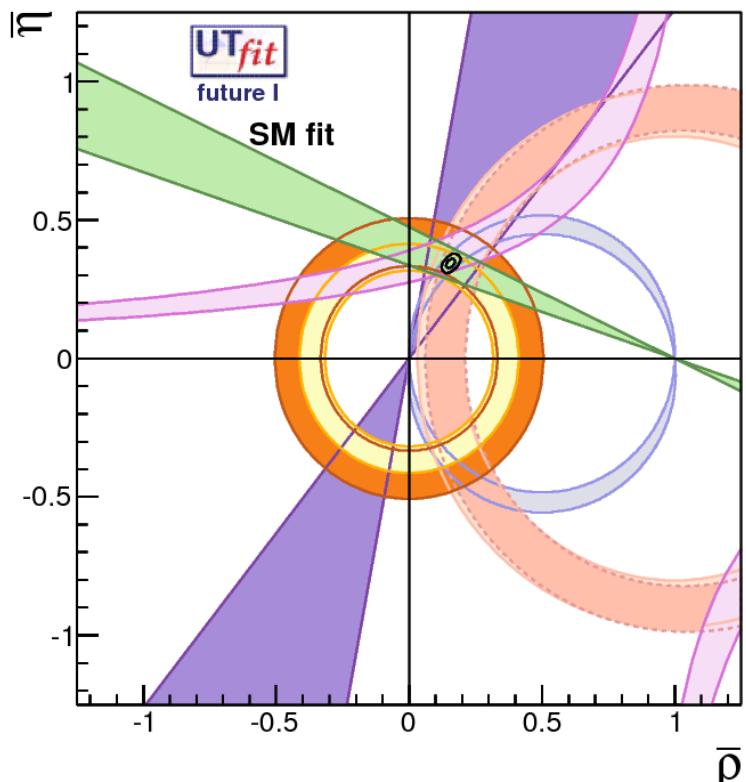
E949 central value



SM central value



Old future predictions..



$$\begin{aligned}\bar{\rho} &= 0.154 \pm 0.015 \\ \bar{\eta} &= 0.344 \pm 0.013\end{aligned}$$

current sensitivity

$$\begin{aligned}\bar{\rho} &= 0.150 \pm 0.027 \\ \bar{\eta} &= 0.363 \pm 0.025\end{aligned}$$

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

