Updates on CKM phenomenology

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Workshop on status and perspectives of physics
at high intensity,
INFN - Laboratori Nazionali di Frascati,

10 November 2022

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

UTfit

www.utfit.org

RELOADED

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

Plots and numbers updated for Summer 2022:
paper in preparation, coming soon!

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
$A_{CP}(J/\psi K_S)$	$\sin 2\beta$	

, 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 UTfit (coming soon)

$|V_{cb}|$ *(excl)* = (39.44 ± 0.63) 10^{-3}

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

from Bordone et al.
arXiv:2107.00604

~3.3σ discrepancy

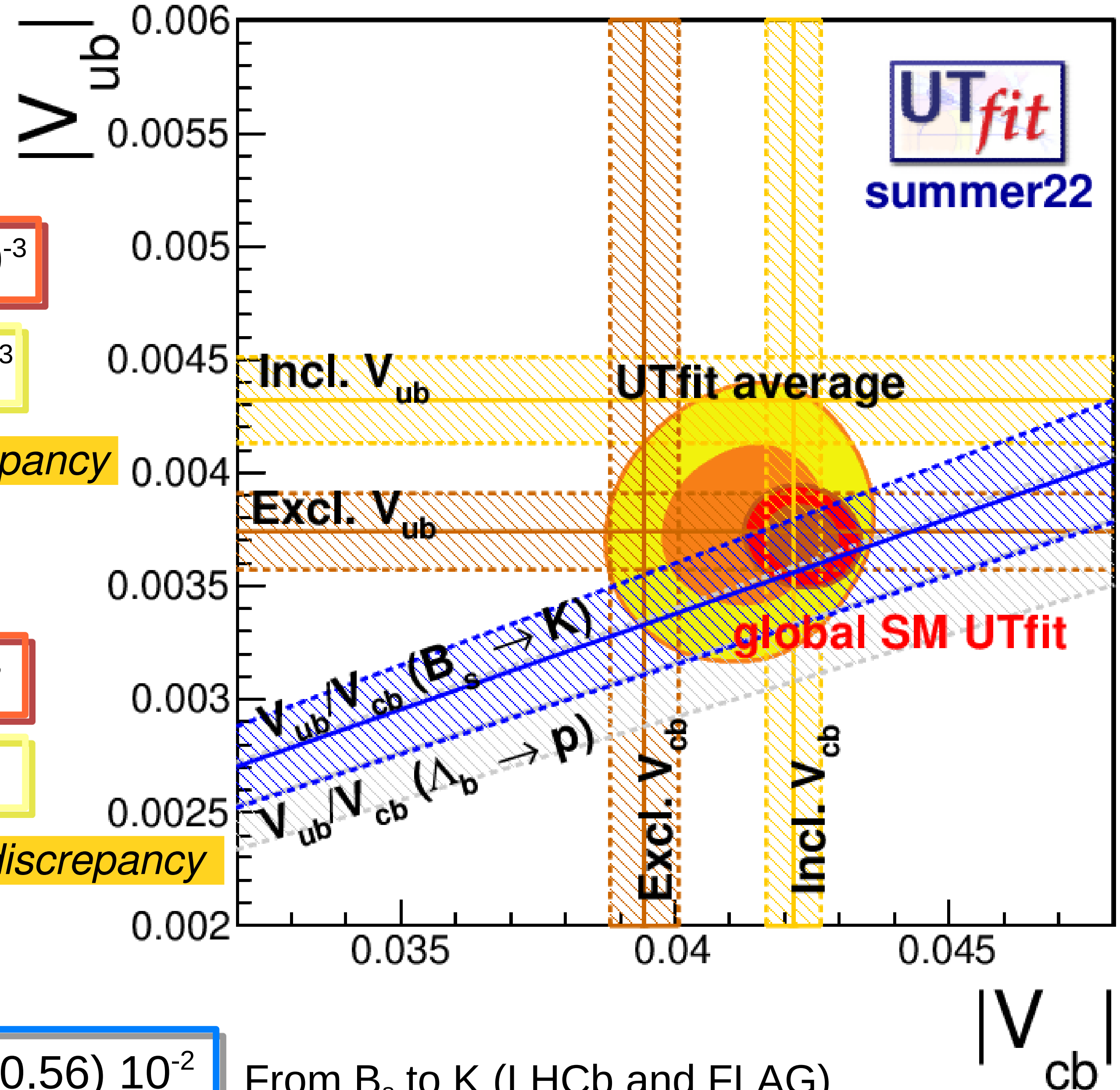
from UTfit (coming soon)

$|V_{ub}|$ *(excl)* = (3.74 ± 0.17) 10^{-3}

$|V_{ub}|$ *(incl)* = (4.32 ± 0.29) 10^{-3}

from UTfit (coming soon)

~1.7σ discrepancy



$|V_{ub} / V_{cb}|$ *(LHCb)* = (8.44 ± 0.56) 10^{-2} From B_s to K (LHCb and FLAG)

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

V_{cb} and V_{ub}

A-la-PDG two-dimensional average procedure:

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

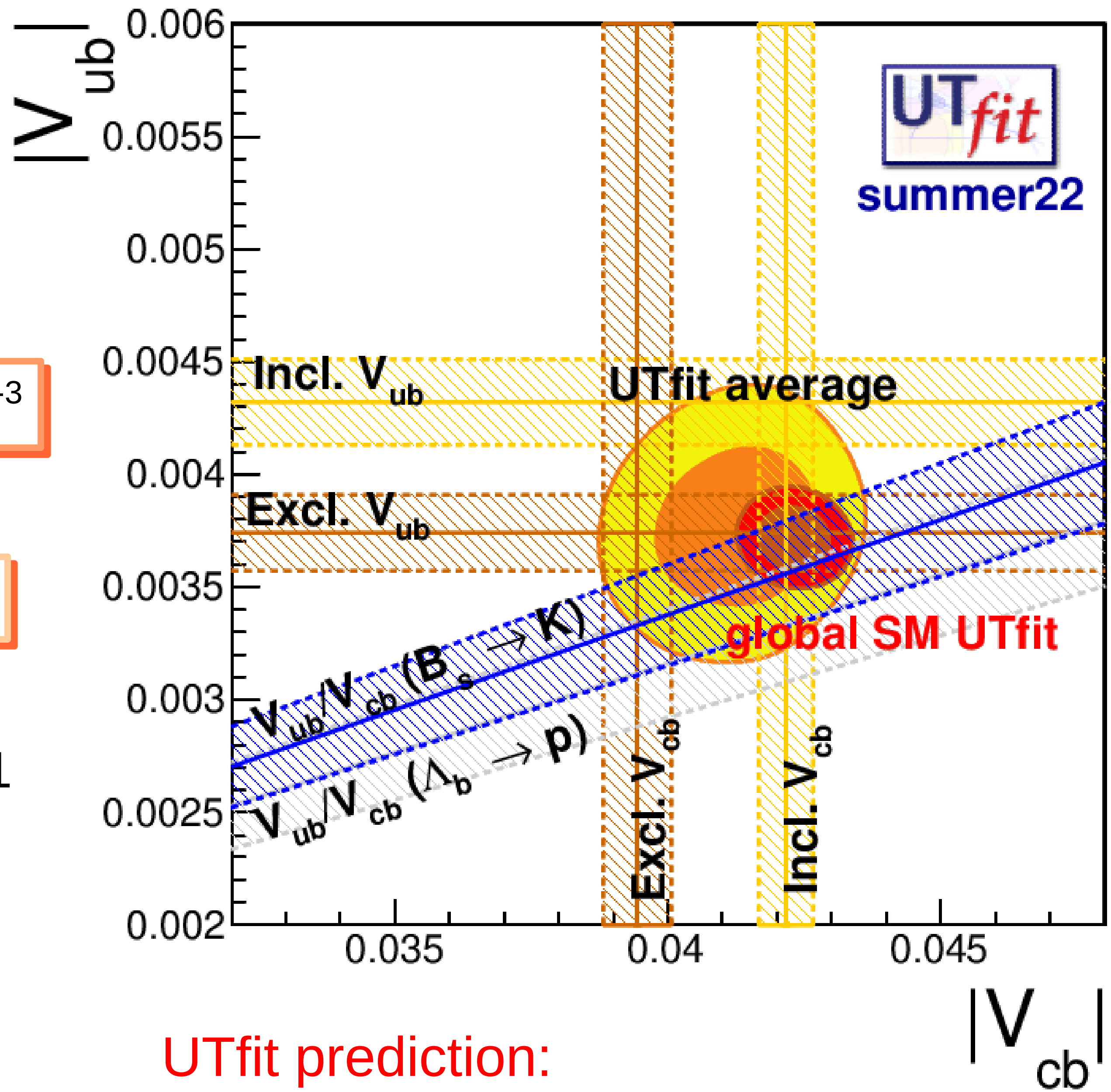
uncertainty ~ 2.3%

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

uncertainty ~ 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:

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

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

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 chi2/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]

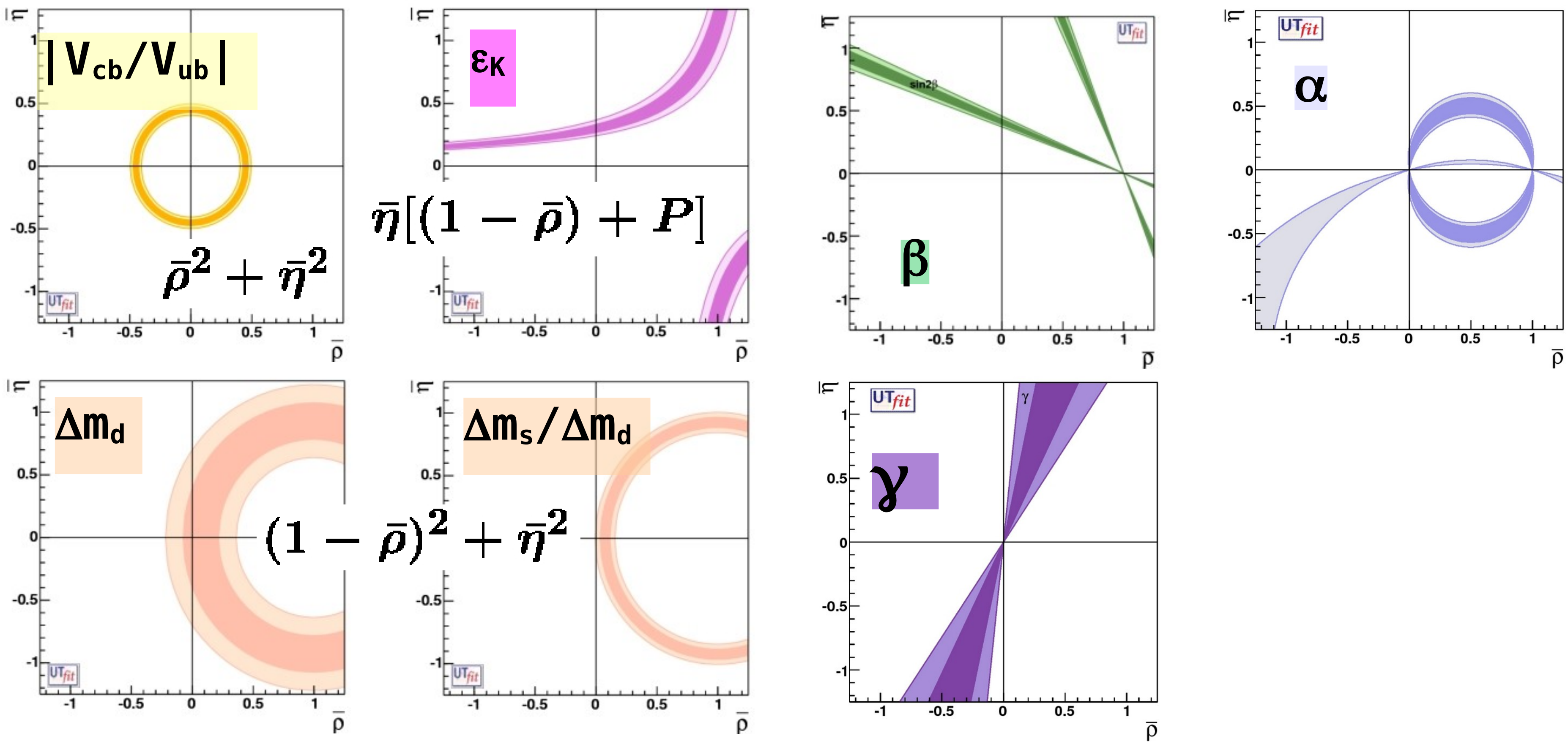
V_{ud} and V_{us} updated for this Summer

Observables	**Measurement**
V_{ud}	**0.97433 ± 0.00019**
V_{us}	**0.2249 (± 0.0004)**

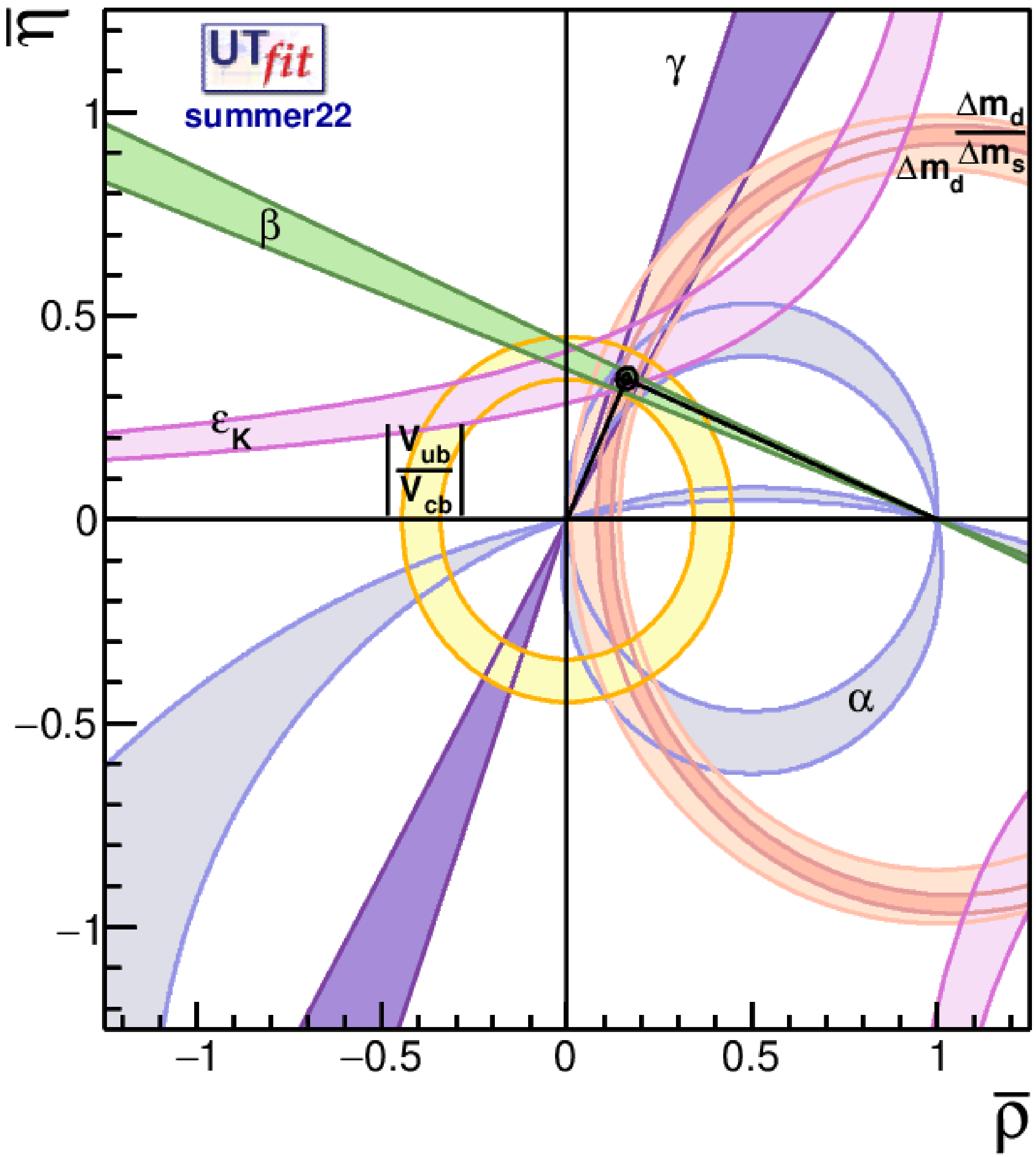
V_{ud} is taken from the PDG average of V_{ud} FLAG numbers (for 2+1+1 and 2+1) and superallowed beta decays value. PDG scale factor S=2.0

V_{us} is not used in the fit

Unitarity Triangle analysis in the SM:



Unitarity Triangle analysis in the SM:



levels @
95% Prob

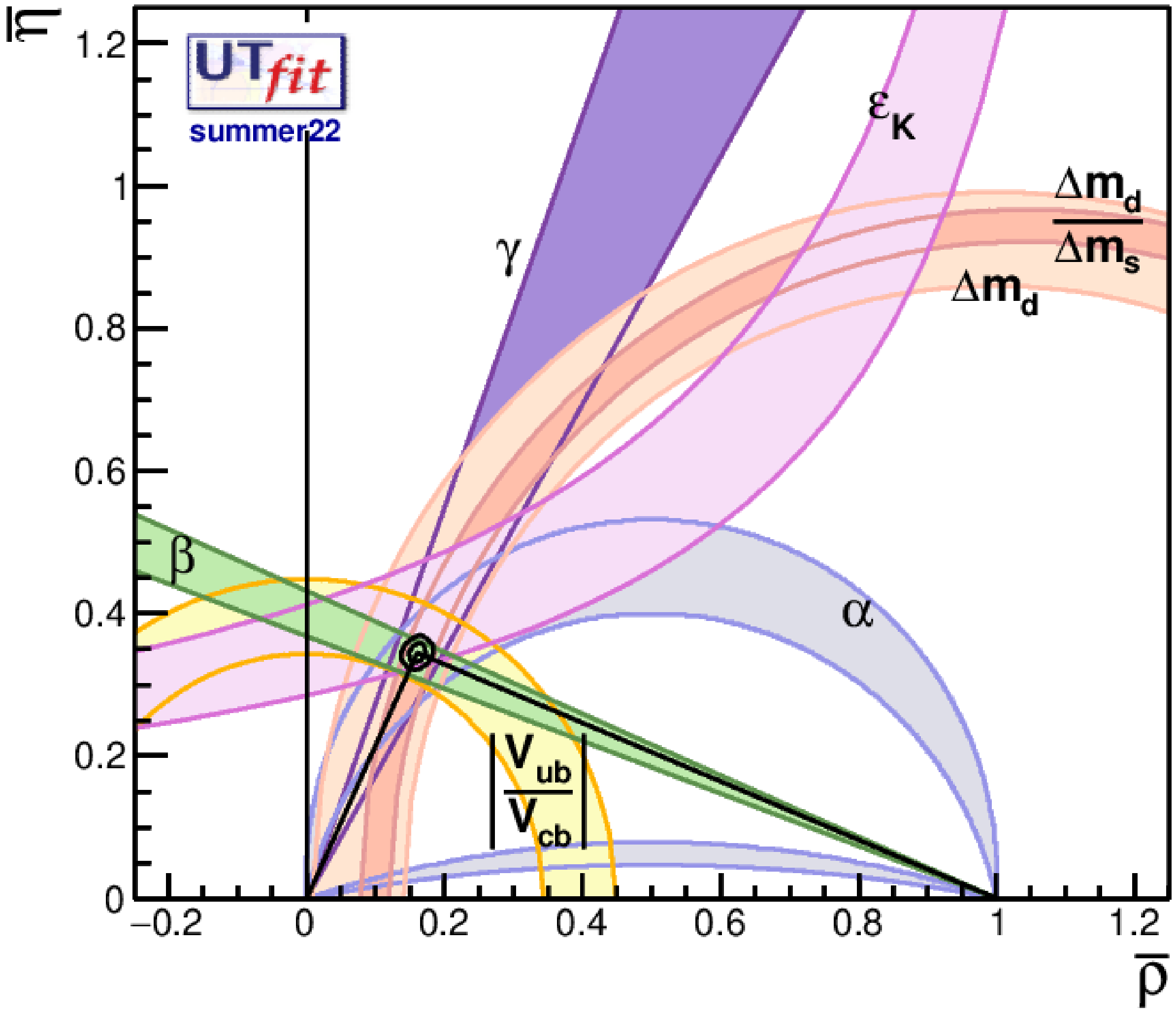
~6%

$\bar{\rho} = 0.160 \pm 0.009$
$\bar{\eta} = 0.345 \pm 0.009$

~3%

Unitarity Triangle analysis in the SM:

zoomed in..



levels @
95% Prob

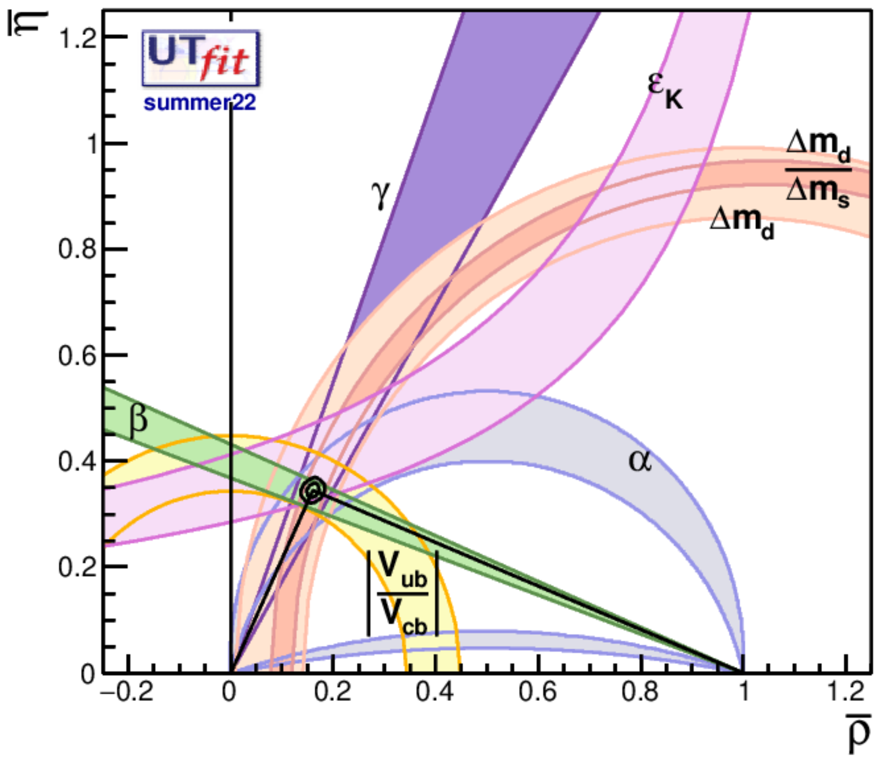
~6%

$\bar{\rho}$ = 0.160 ± 0.009
$\bar{\eta}$ = 0.345 ± 0.009

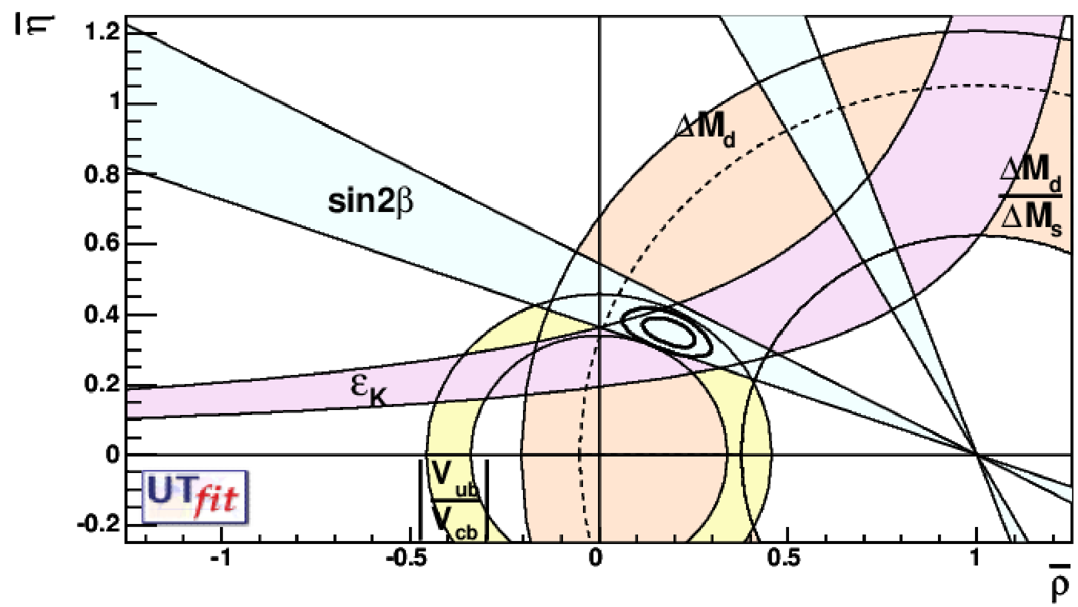
~3%

Unitarity Triangle analysis in the SM:

2022



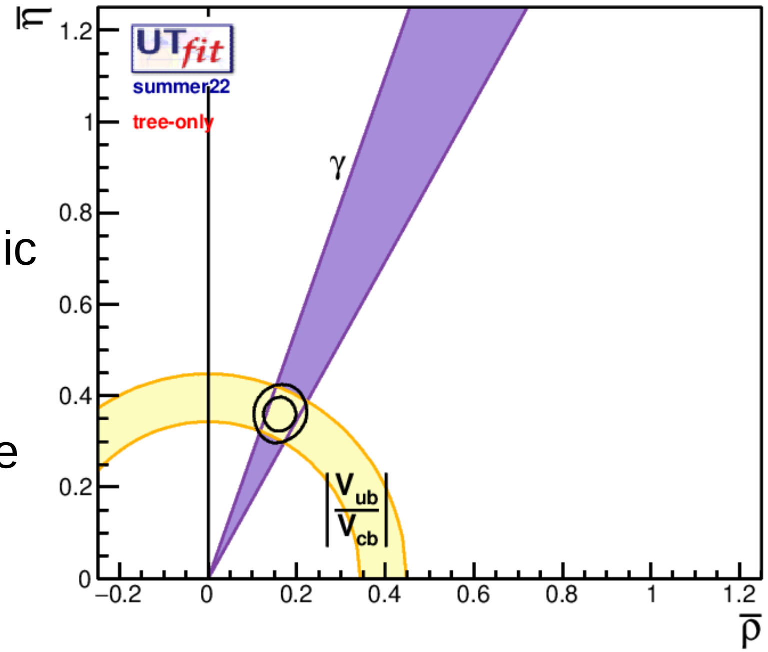
2004



Some interesting configurations

Tree-level processes: Semileptonic and DK B decays

→ reference for model building

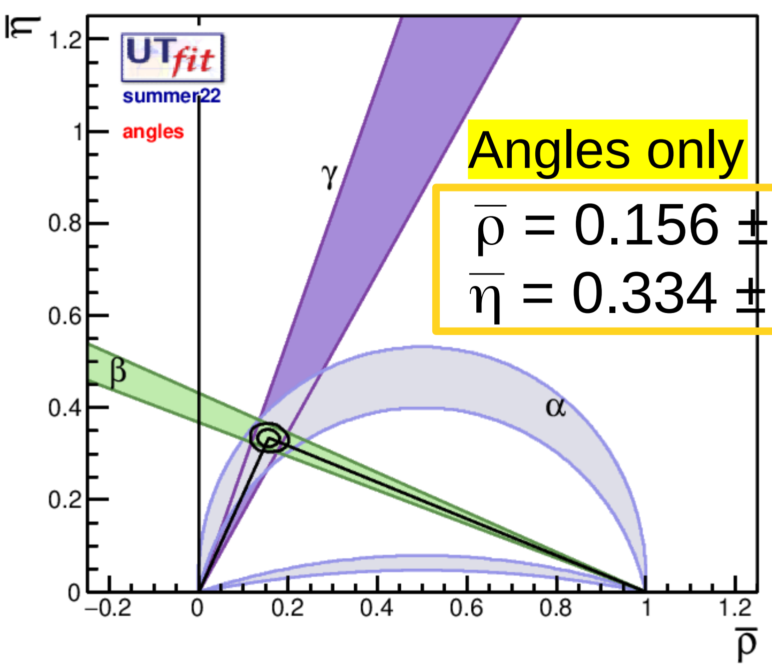


"Tree-only" ~15%

$\bar{\rho}$ = ±0.162 ± 0.024

$\bar{\eta}$ = ±0.361 ± 0.025

~7%

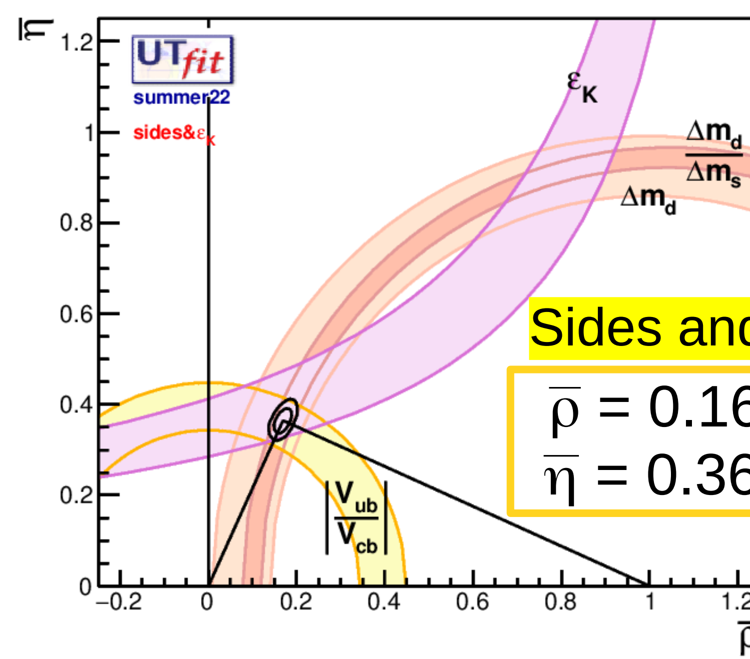


Angles only ~11%

$\bar{\rho}$ = 0.156 ± 0.017

$\bar{\eta}$ = 0.334 ± 0.012

~4%



Sides and ε_K ~8%

$\bar{\rho}$ = 0.169 ± 0.013

$\bar{\eta}$ = 0.363 ± 0.019

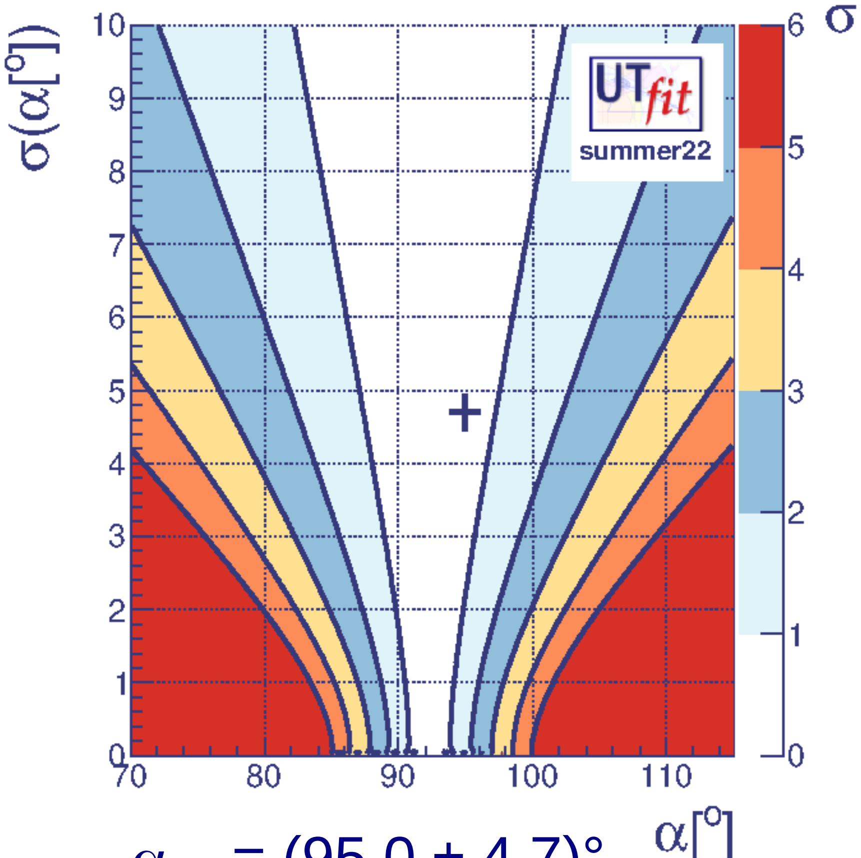
~5%

compatibility plots

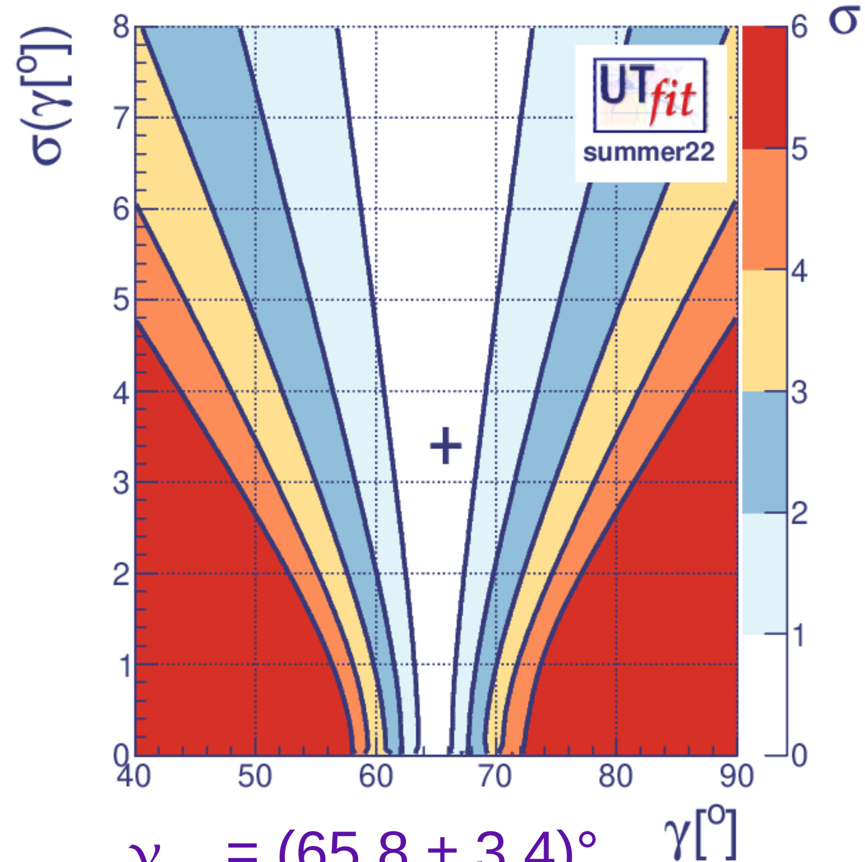
A way to “measure” the agreement of a single measurement with the indirect determination from the fit using all the other inputs: test for the SM description of the flavour physics

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



$\alpha_{exp} = (95.0 \pm 4.7)°$
$\alpha_{UTfit} = (92.3 \pm 1.5)°$



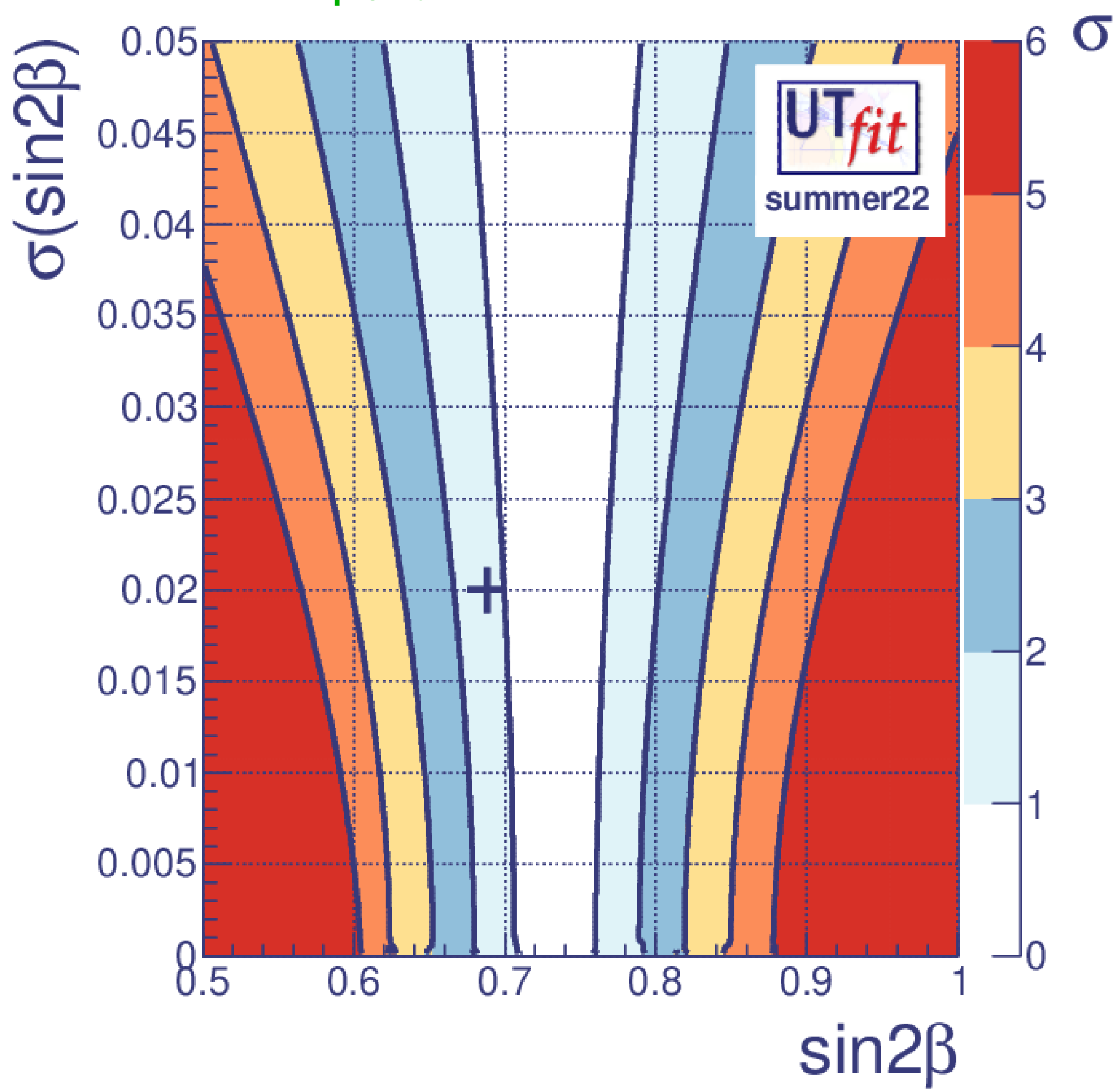
$\gamma_{exp} = (65.8 \pm 3.4)°$
$\gamma_{UTfit} = (64.9 \pm 1.3)°$

Checking the usual *tensions..*

~1.3σ

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

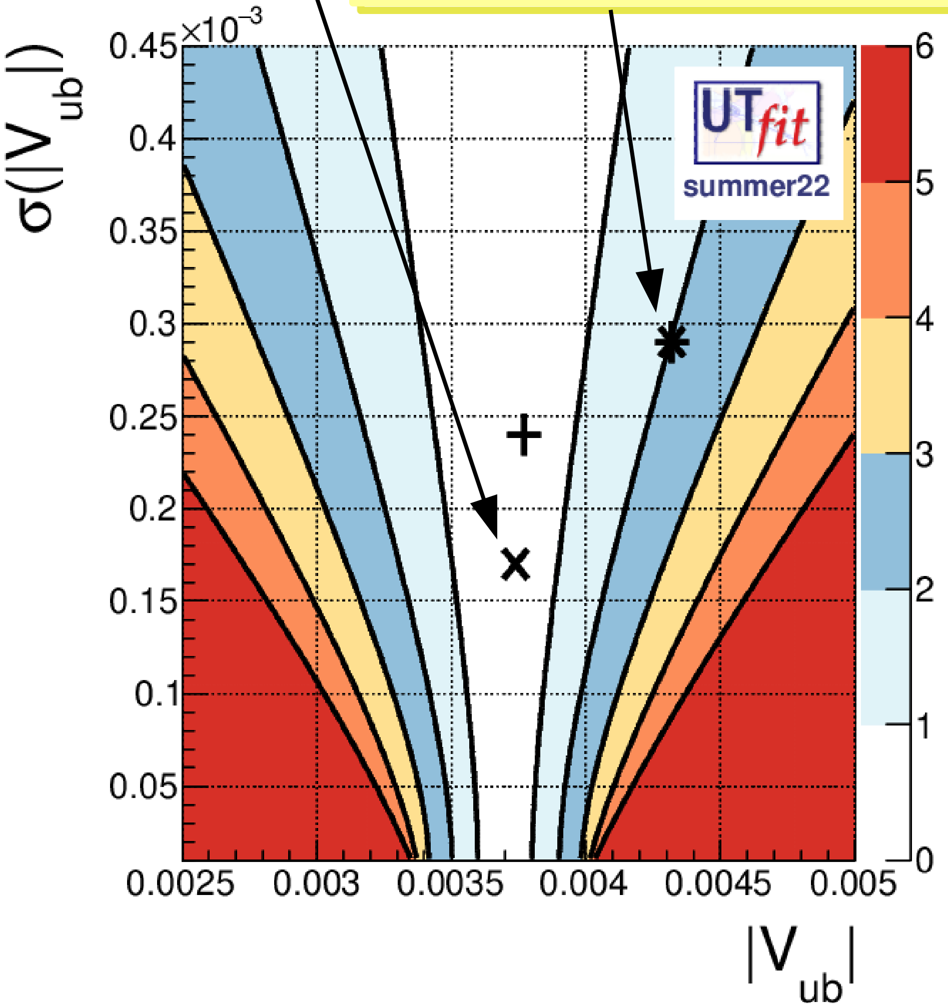
$\sin 2\beta_{UTfit} = 0.732 \pm 0.027$



Checking the usual *tensions*..

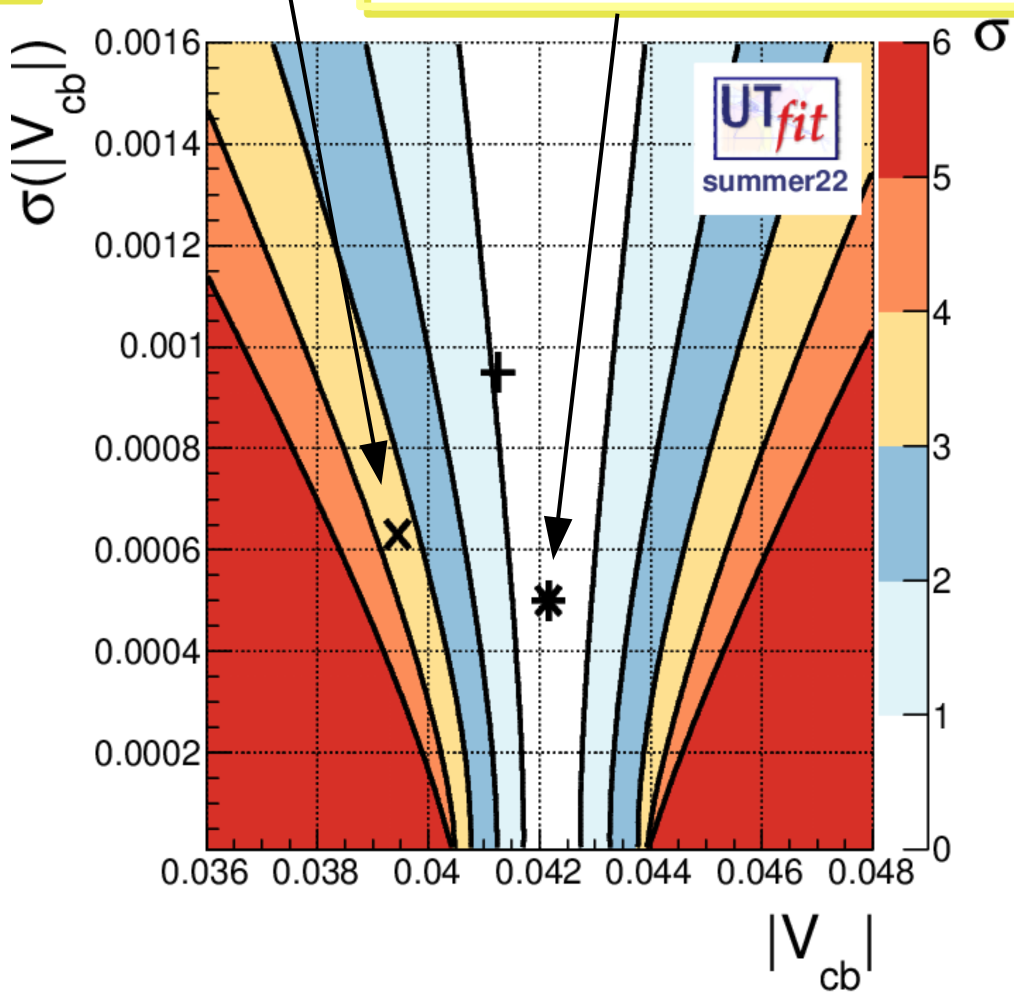
$|V_{ub}|$ *(excl)* = (3.74 ± 0.17) 10^{-3}

$|V_{ub}|$ *(incl)* = (4.32 ± 0.29) 10^{-3}



$|V_{cb}|$ *(excl)* = (39.44 ± 0.63) 10^{-3}

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



Vub_{exp} = (3.77 ± 0.24) · 10^{-3}

Vub_{UTfit} = (3.70 ± 0.10) · 10^{-3}

Vcb_{exp} = (41.25 ± 0.95) · 10^{-3}

Vcb_{UTfit} = (42.6 ± 0.5) · 10^{-3}

Unitarity Triangle analysis in the SM:

obtained excluding the given constraint from the fit

Observables	Measurement	Prediction	Pull (#σ)
sin2β	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
$\lvert V_{cb}\rvert \cdot 10^3$	41.25 ± 0.95	42.6 ± 0.5	< 1
$\lvert V_{cb}\rvert \cdot 10^3$ (incl)	42.16 0.50		< 1
$\lvert V_{cb}\rvert \cdot 10^3$ (excl)	39.44 0.63		~ 4.0
$\lvert V_{ub}\rvert \cdot 10^3$	3.77 ± 0.24	3.70 ± 0.10	< 1
$\lvert V_{ub}\rvert \cdot 10^3$ (incl)	4.32 ± 0.29	-	~ 2.0
$\lvert V_{ub}\rvert \cdot 10^3$ (excl)	3.74 ± 0.17	-	< 1
$BR(B \to \tau\nu)[10^{-4}]$	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} used)
- only B parameters
  - (B_{Bs}^1, B_{Bs}/B_{Bd} used)
- only decay constants f
  - (f_{Bs}, f_{Bs}/f_B included)

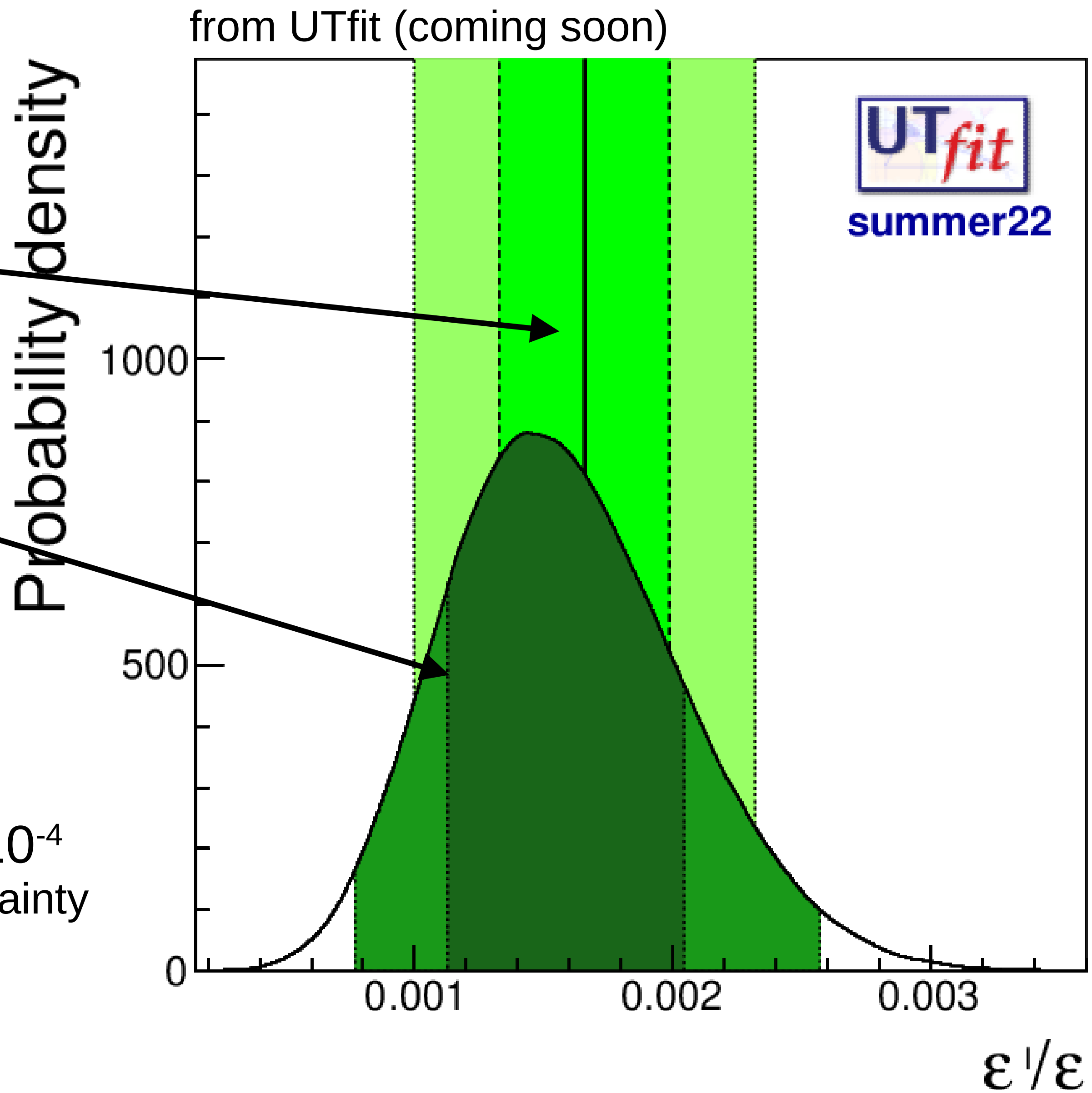
Observables	Measurement	Prediction
B_K	0.756 ± 0.016	0.832 ± 0.054
No B lattice		
$f_B\sqrt{B_{Bd}}$	(0.2142 ± 0.0056)	0.212 ± 0.010
$f_{Bs}\sqrt{B_{Bs}}$	(0.2607 ± 0.0061)	0.259 ± 0.010
ξ	(1.217 ± 0.014)	1.225 ± 0.033
Ratios only		
f_{Bs}	0.2301 ± 0.0012	0.227 ± 0.009
B_{Bs}	1.284 ± 0.059	1.30 ± 0.10
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

New ε'/ε prediction from the Unitarity Triangle fit

Experimental value
$\varepsilon'/\varepsilon = (16.6 \pm 3.3) \cdot 10^{-4}$

New UTfit work:
$\varepsilon'/\varepsilon = (15.2 \pm 4.7) \cdot 10^{-4}$

RBC/UKQCD obtains:
$\varepsilon'/\varepsilon = (21.7 \pm 6.7 \pm 5.0_{IB}) \cdot 10^{-4}$
IB = isospin-breaking uncertainty



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):

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

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

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

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

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

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

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

new-physics-specific constraints

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

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

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

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

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

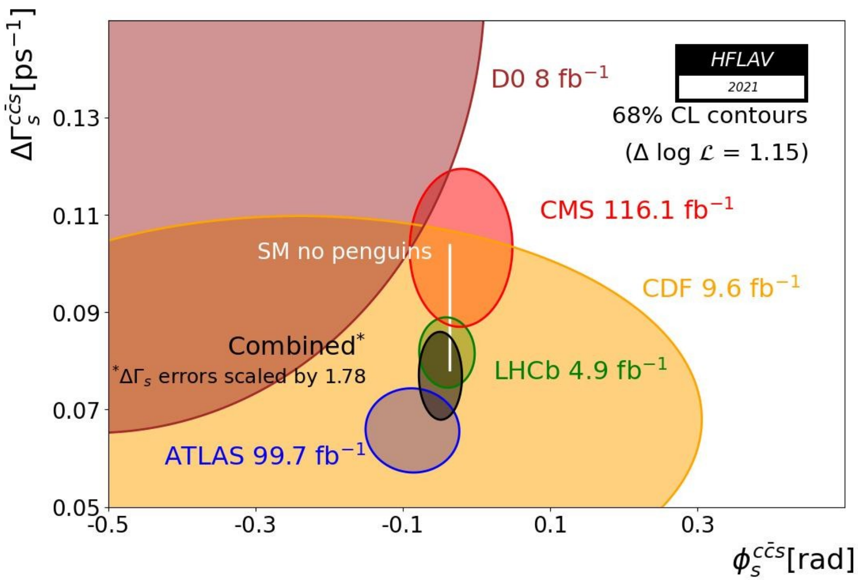
$$\tau^{FS}(B_s) = 1.527 \pm 0.011 \text{ ps}$$

HFLAV

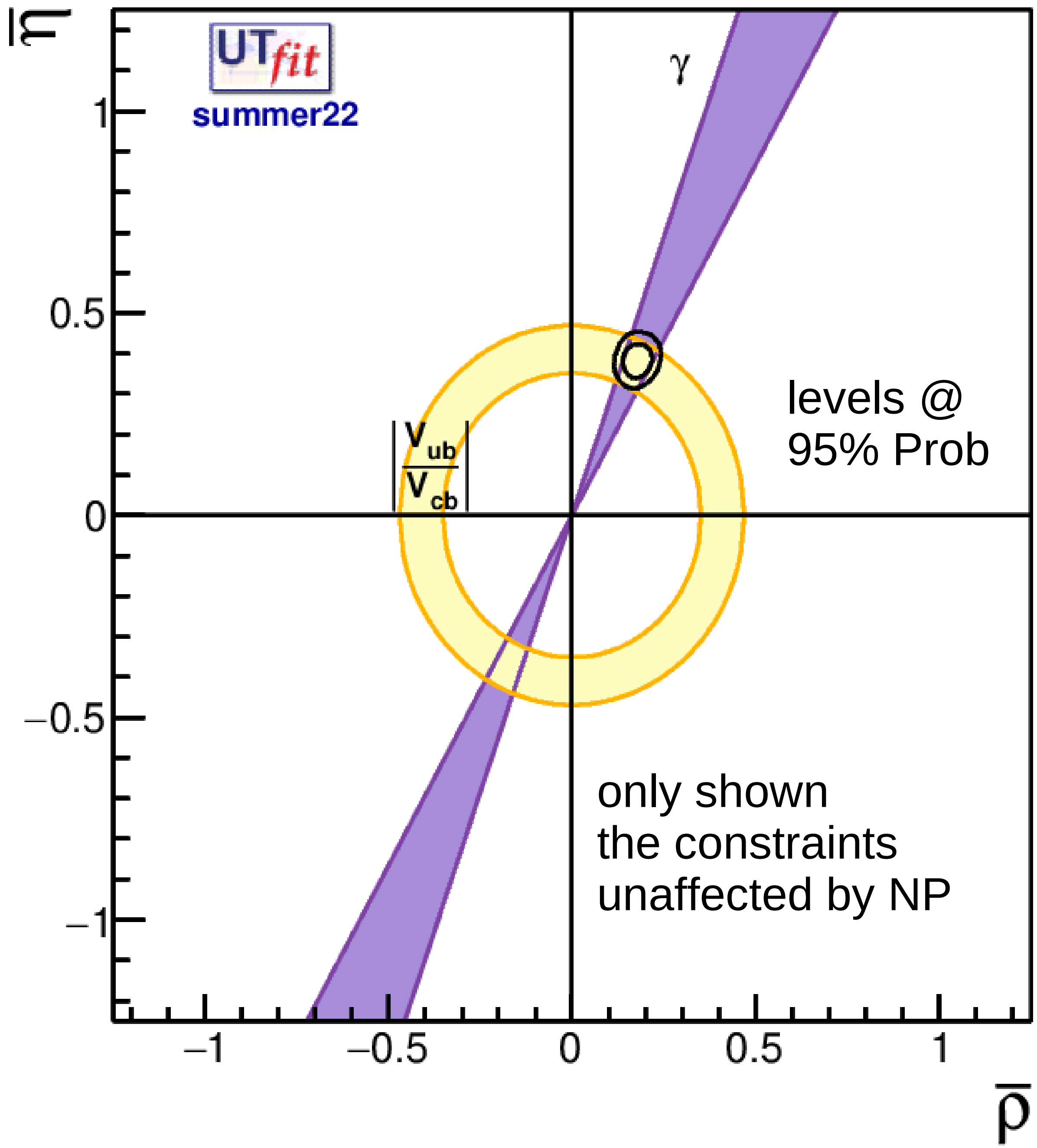
$\phi_s = 2\beta_s$ vs $\Delta\Gamma_s$ from $B_s \to J/\psi\phi$

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

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



NP analysis results



$\bar{\rho} = 0.169 \pm 0.025$
$\bar{\eta} = 0.365 \pm 0.026$

SM is

$\bar{\rho} = 0.160 \pm 0.009$
$\bar{\eta} = 0.345 \pm 0.009$

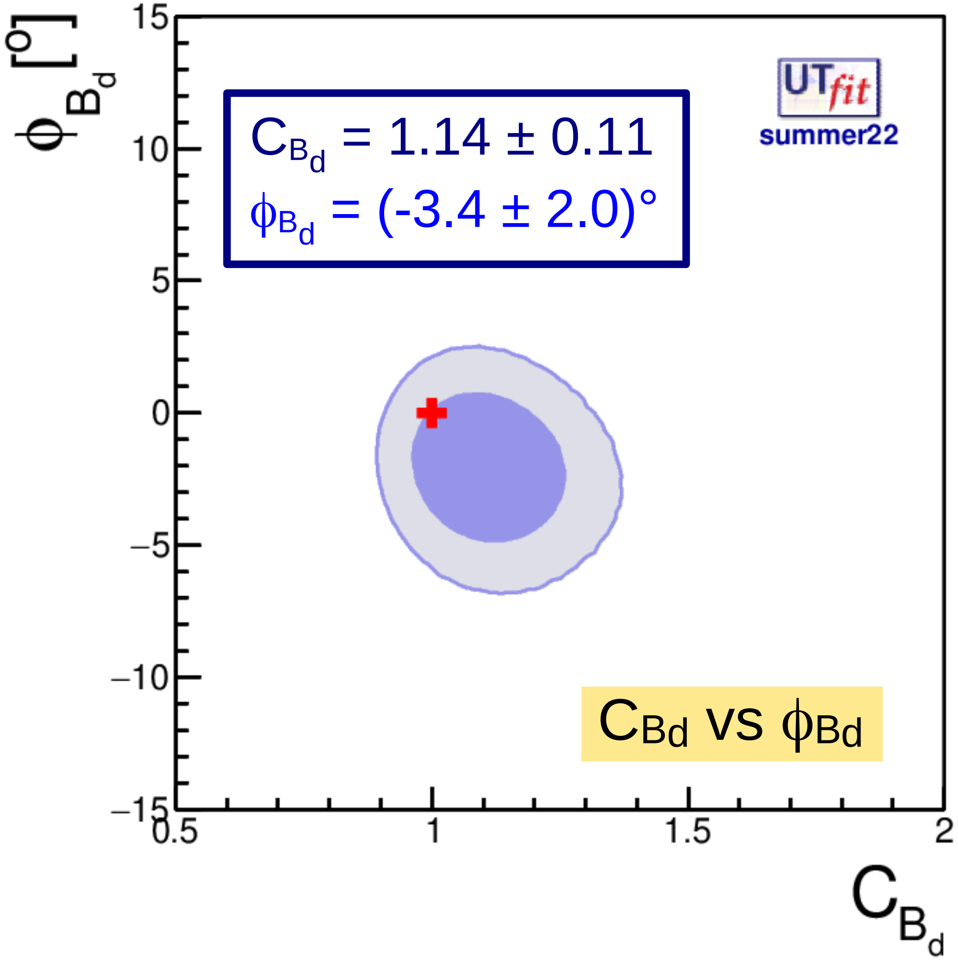
NP parameter results

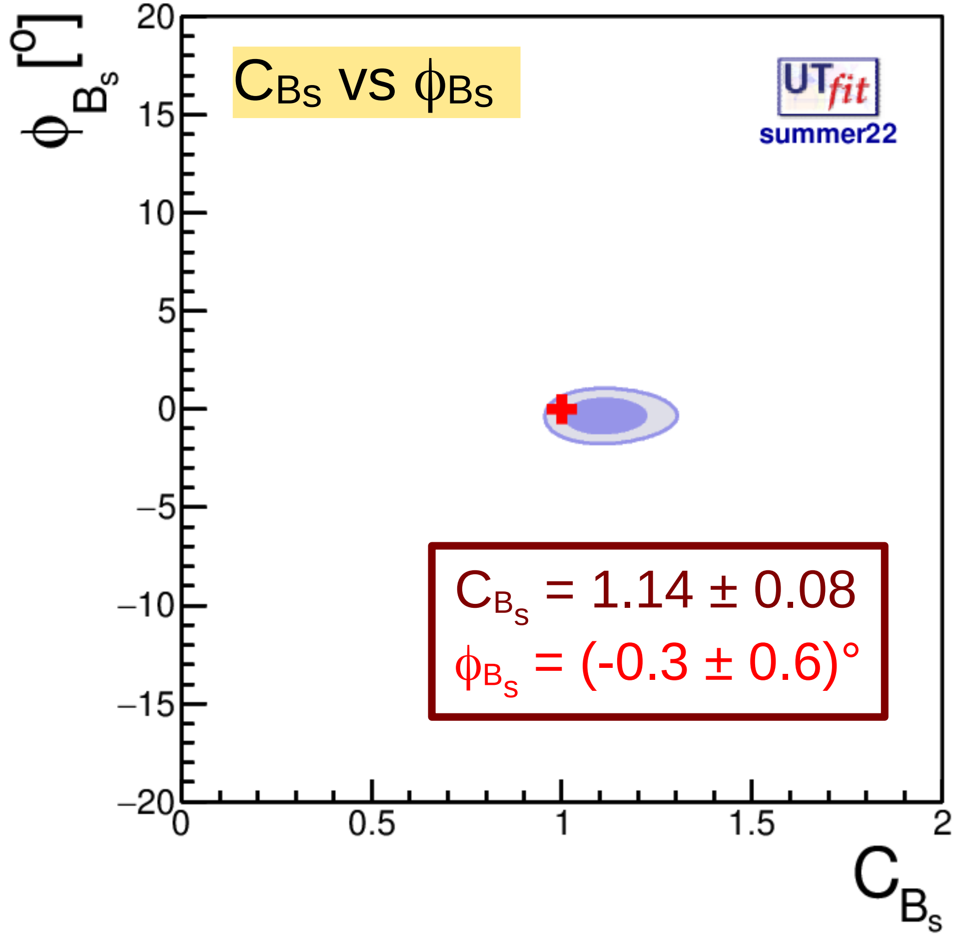
$$A_q = C_{B_q} e^{2i\phi_{B_q}} A_q^{SM} e^{2i\phi_q^{SM}}$$

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

K system

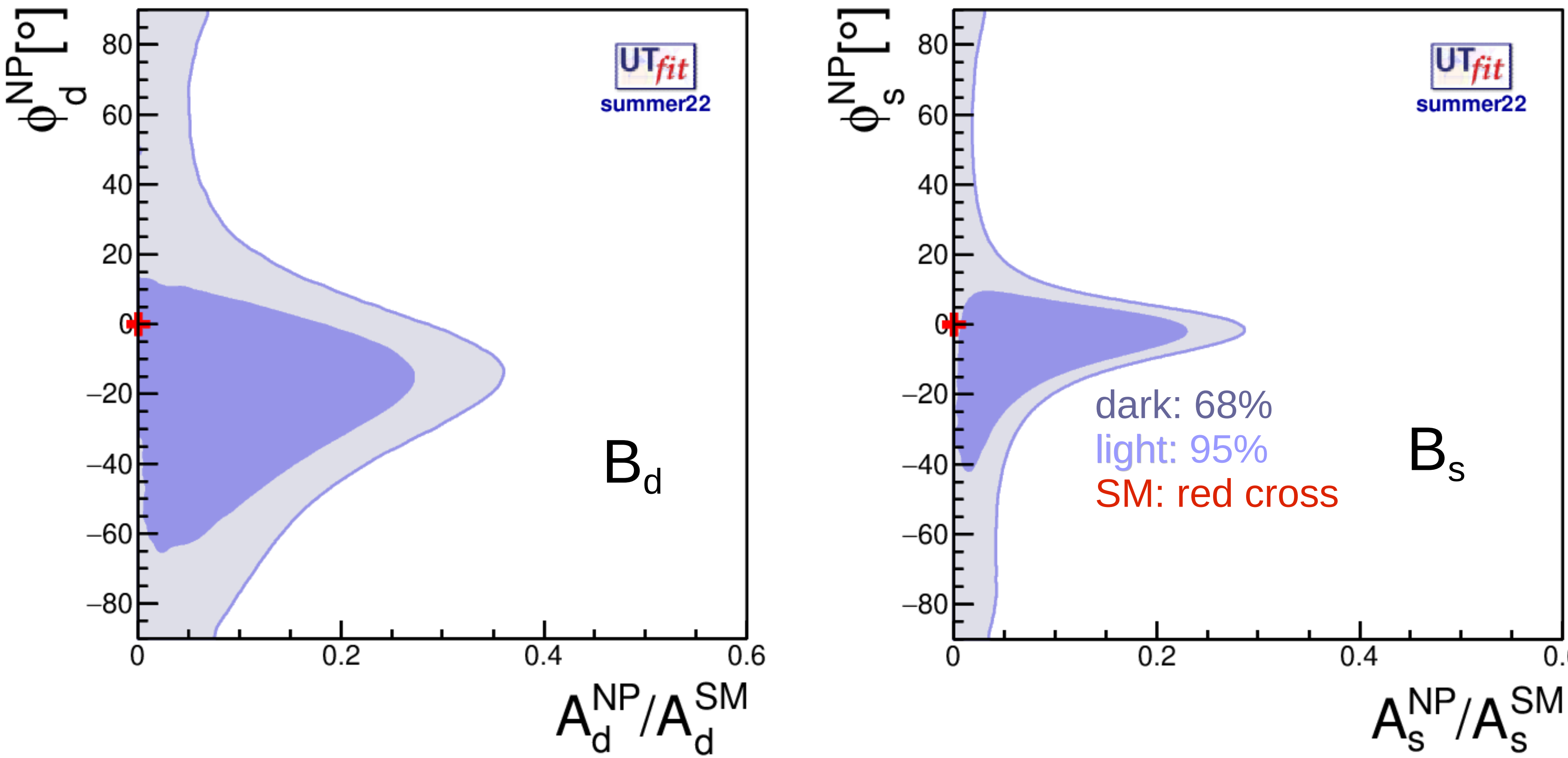
$C_{\epsilon_K} = 1.12 \pm 0.12$





NP parameter results

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



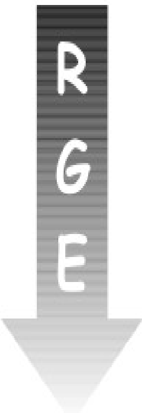
The ratio of NP/SM amplitudes is:

< 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



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

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

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~1, arbitrary phase
- NMFV: $C(\Lambda) = \alpha \times |F_{SM}|/\Lambda^2$ — $F_i \sim |F_{SM}|$, arbitrary phase
- MFV: $C(\Lambda) = \alpha \times |F_{SM}|/\Lambda^2$ — $F_1 \sim |F_{SM}|$, $F_{i\neq1} \sim 0$, 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

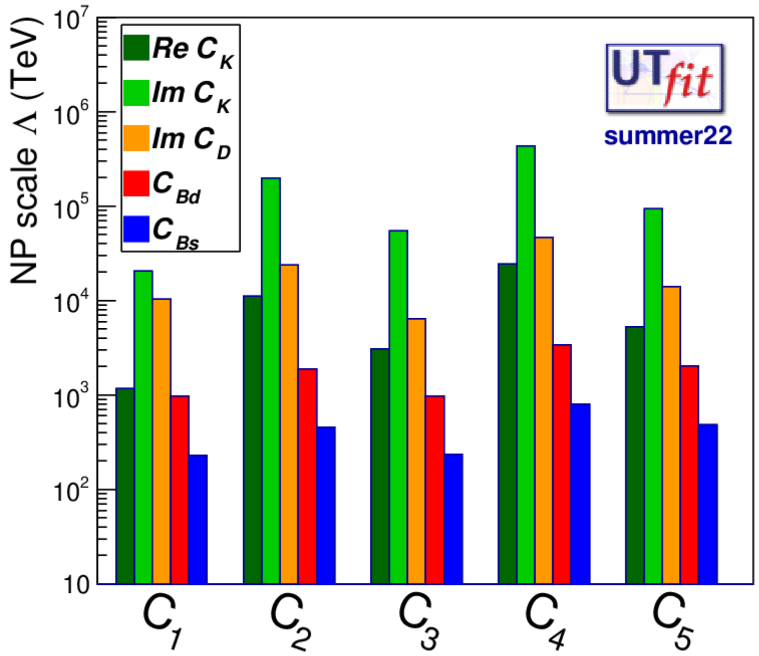
If no NP effect is seen lower bound on NP scale Λ

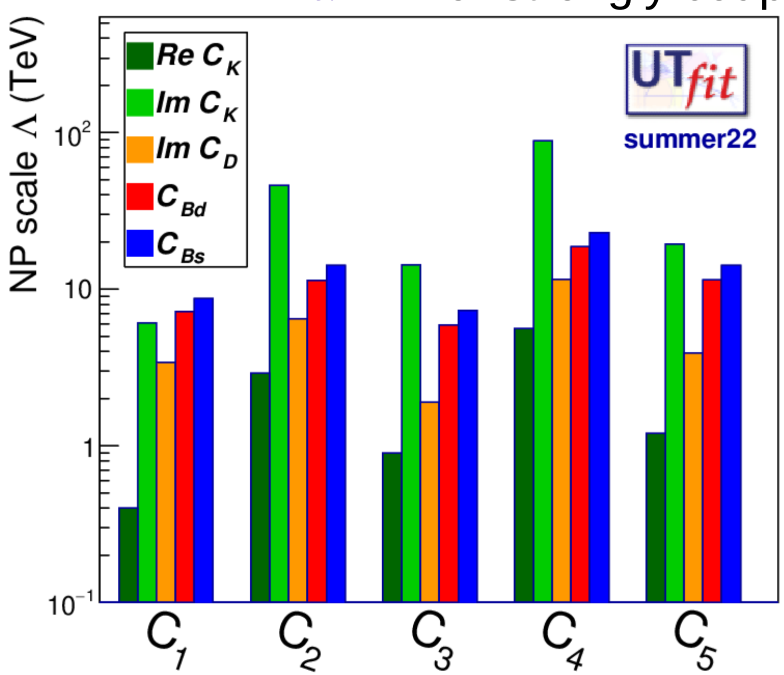
F is the flavour coupling and so
F_{SM} is the combination of CKM factors for the considered process

results from the Wilson coefficients

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

NMFV: $C(\Lambda) = \alpha \times |F_{SM}|/\Lambda^2$,
$F_i \sim |F_{SM}|$, arbitrary phase
$\alpha \sim 1$ for strongly coupled NP





$\Lambda > 4.4\ 10^5$ TeV

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

$\Lambda > 95$ TeV

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

$\Lambda > 1.3\ 10^4$ TeV

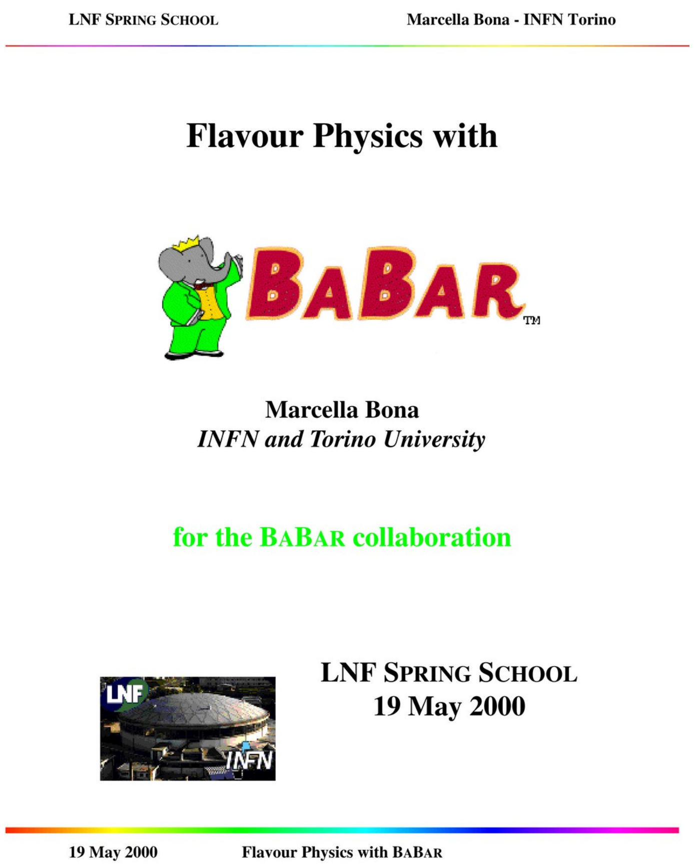
$\alpha \sim \alpha_W$ in case of loop coupling through weak interactions

$\Lambda > 2.9$ TeV

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

conclusions

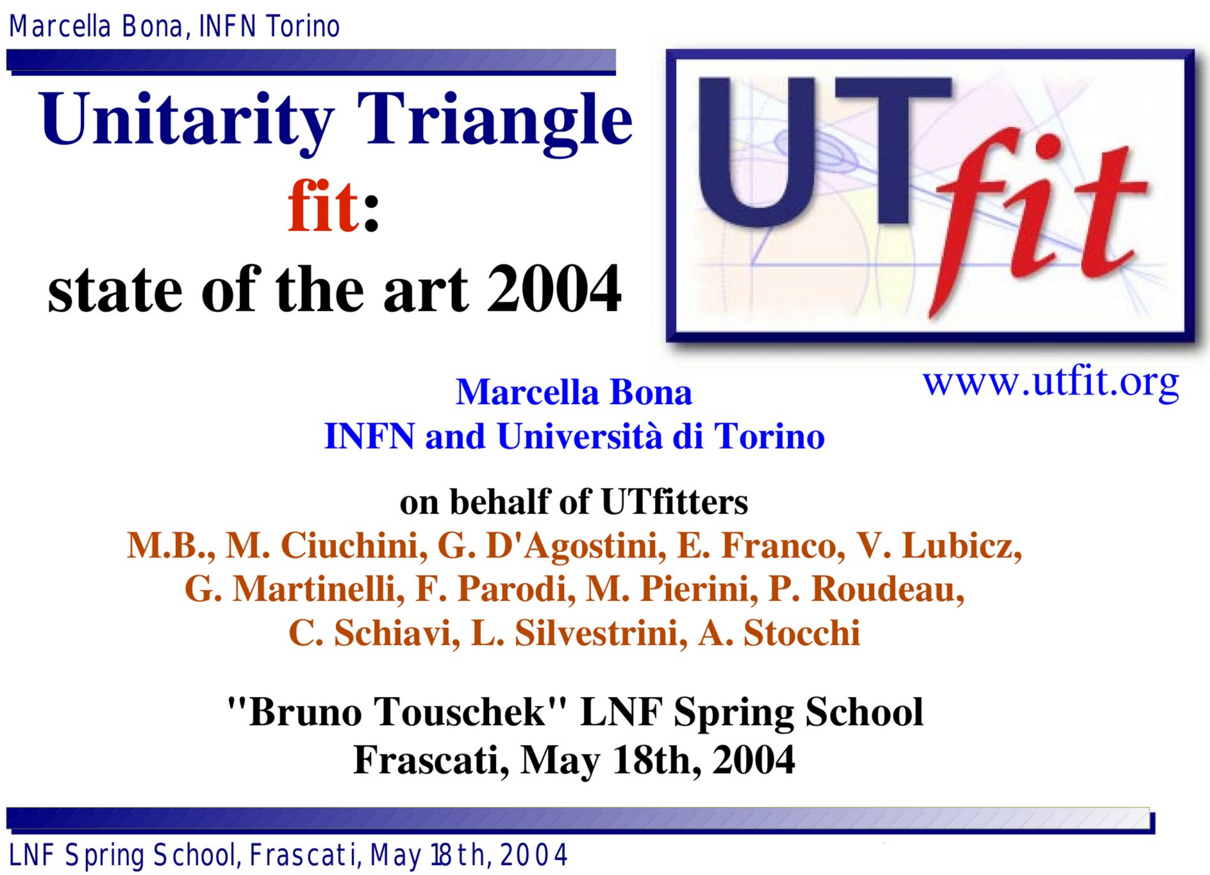
- SM analysis displays very good (improved) overall consistency
- Still open discussion on semileptonic inclusive vs exclusive: exclusive fit shows tension, V_{cb} now showing the biggest discrepancy..
- UTA provides determination of NP contributions to $\Delta F=2$ amplitudes. It currently leaves space for NP at the level of ~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.



On a personal note

I gave my first official BaBar talk in this very room

Note: portrait slides, possibly to be printed ?!?



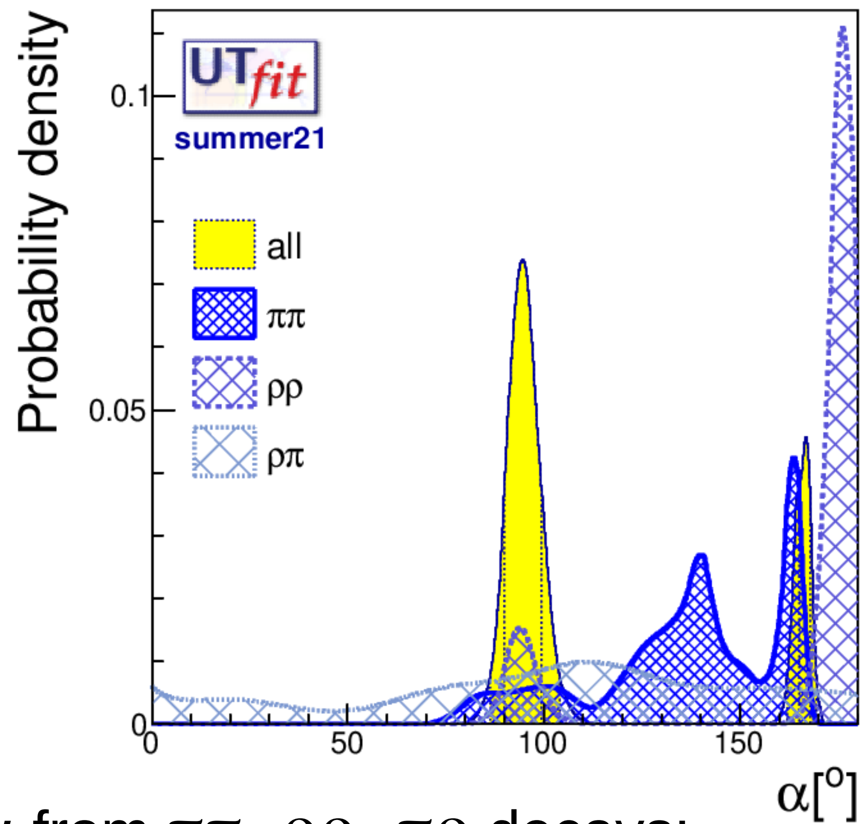
And also one of the very first UTfit talk:

UTfit is turning 20 next year..

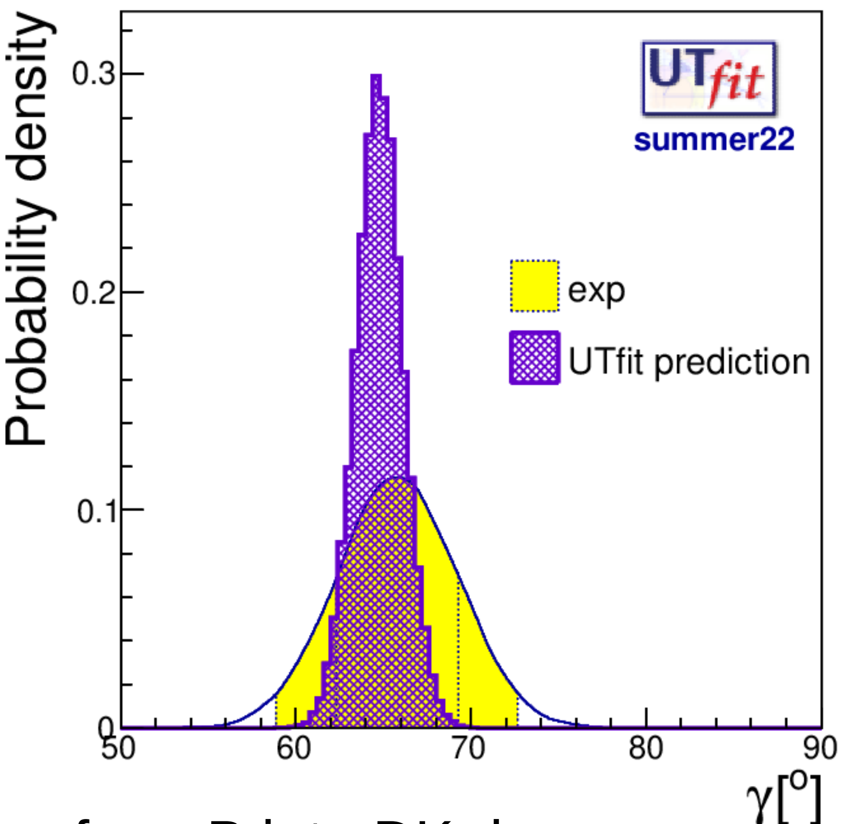
Back up slides

sin2α (ϕ_2) and γ (ϕ_3)

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



γ updated with all the latest results (LHCb)



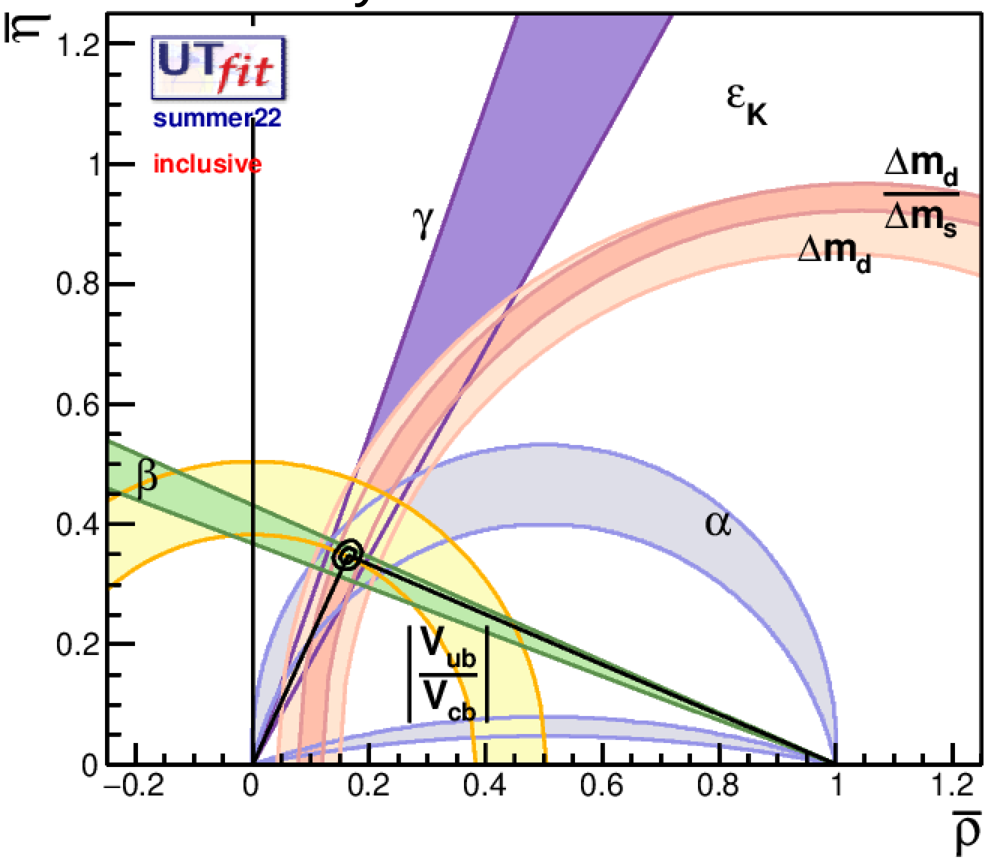
α from $\pi\pi$, $\rho\rho$, $\pi\rho$ decays:
combined SM: $(95.0 \pm 4.7)°$
UTfit prediction: $(92.3 \pm 1.5)°$

α from HFLAV: 85.5 ± 4.6

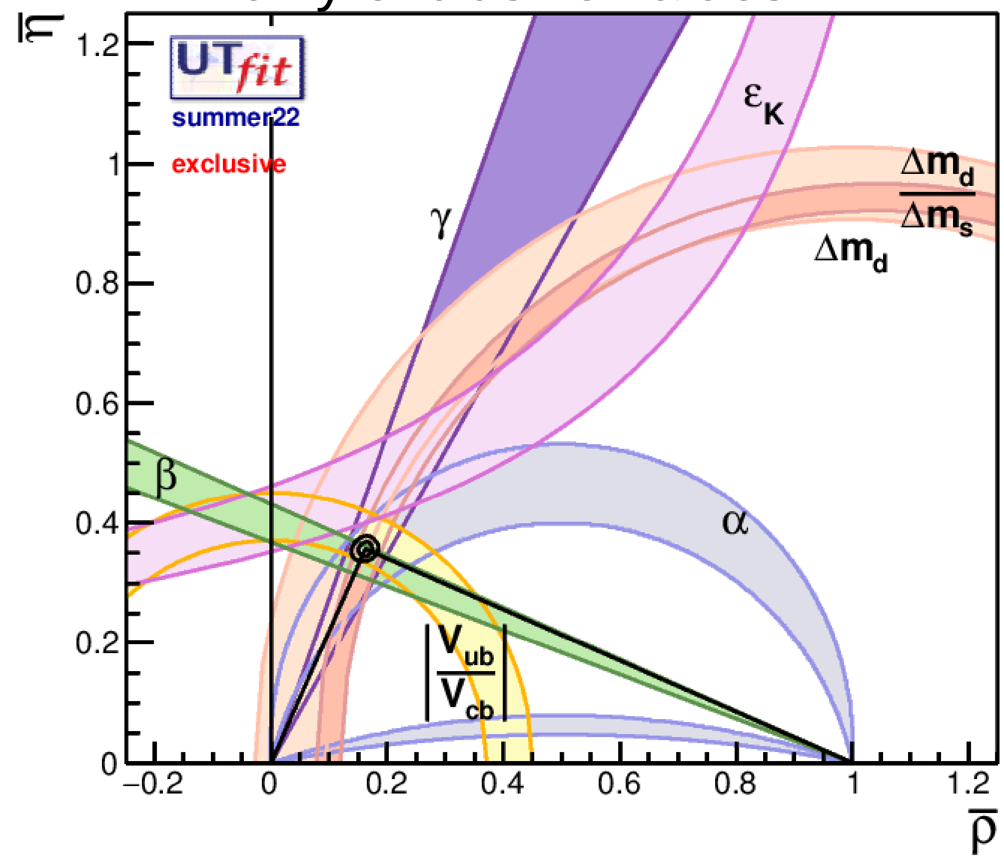
γ from B into DK decays:
HFLAV: $(65.8 \pm 3.4)°$
UTfit prediction: $(64.9 \pm 1.3)°$

Inclusive vs Exclusive

only inclusive values



only exclusive values



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

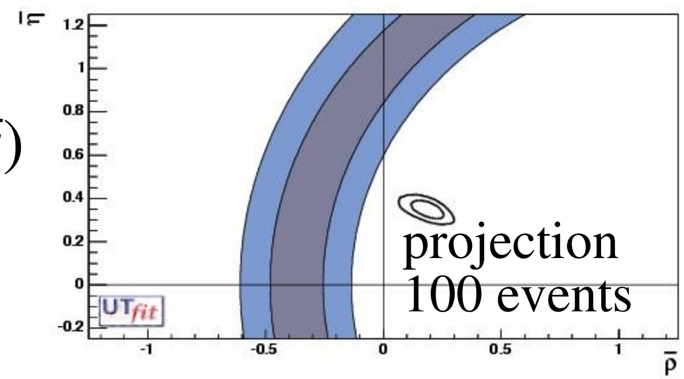
$\bar{\rho} = 0.162 \pm 0.009$
$\bar{\eta} = 0.356 \pm 0.009$
$\sin 2\beta = 0.755 \pm 0.020$

some old plots coming back to fashion:

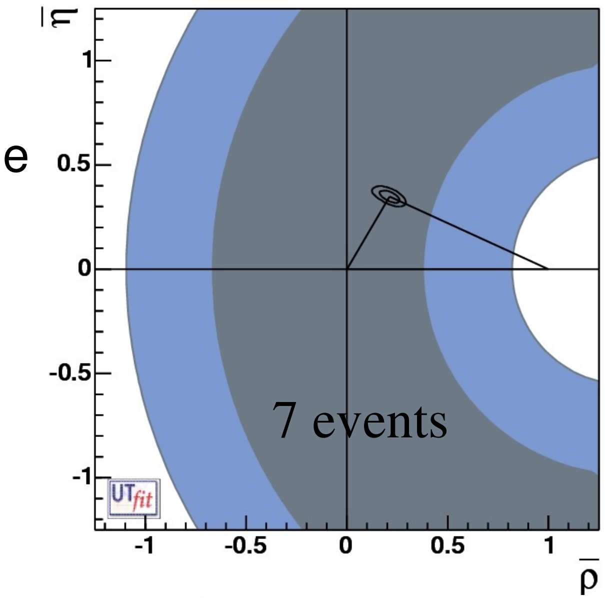
As NA62 and KOTO are analysing data:

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

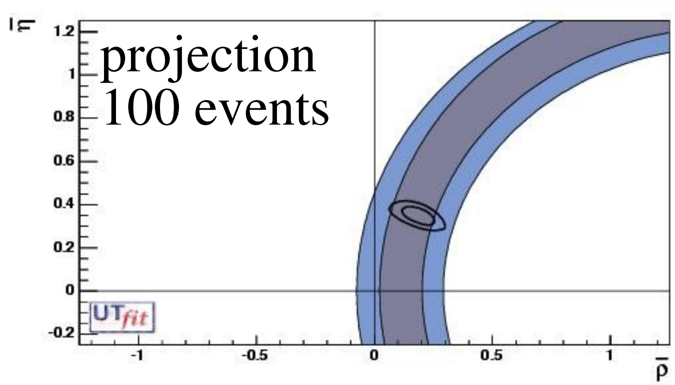
E949 central value

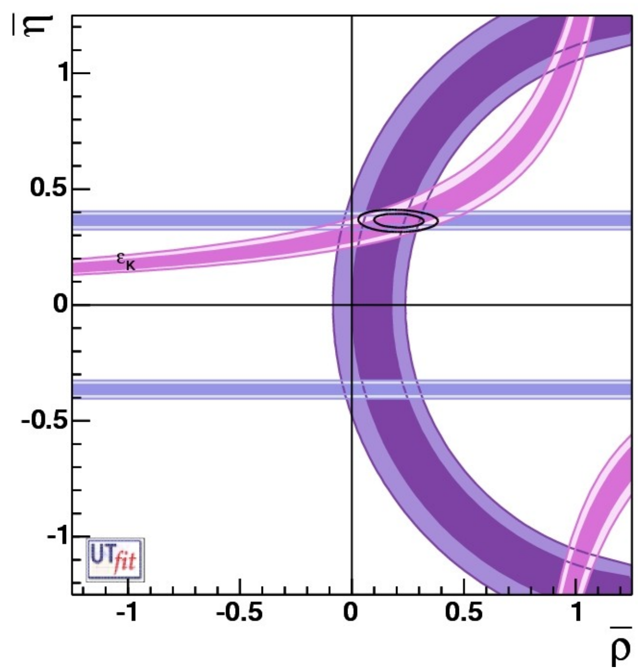


2007 global fit area



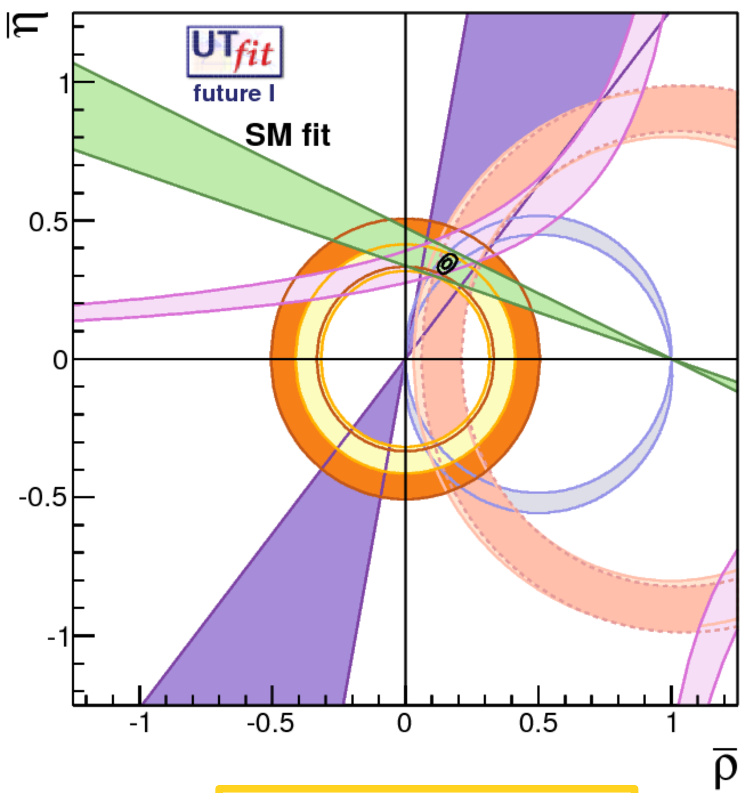
SM central value





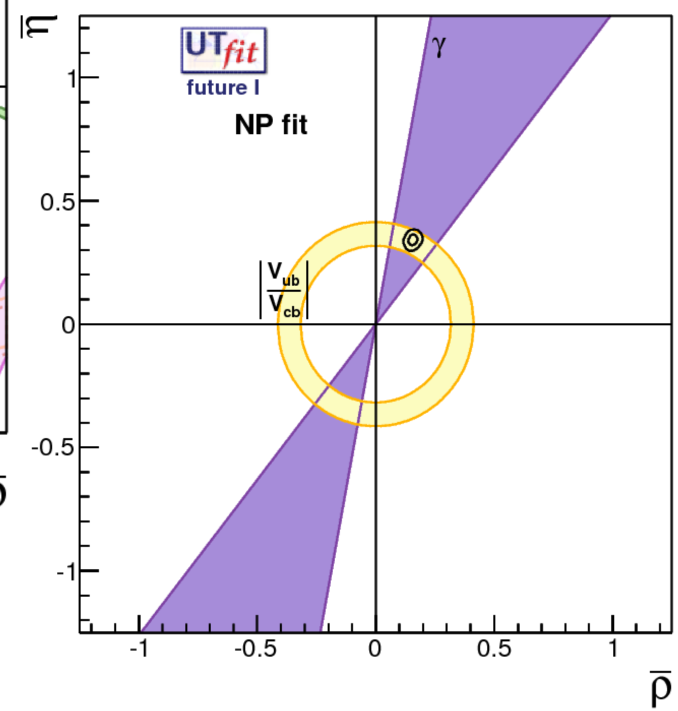
including BR($K^0 \to \pi^0 \nu\bar{\nu}$) SM central value

Old future predictions..

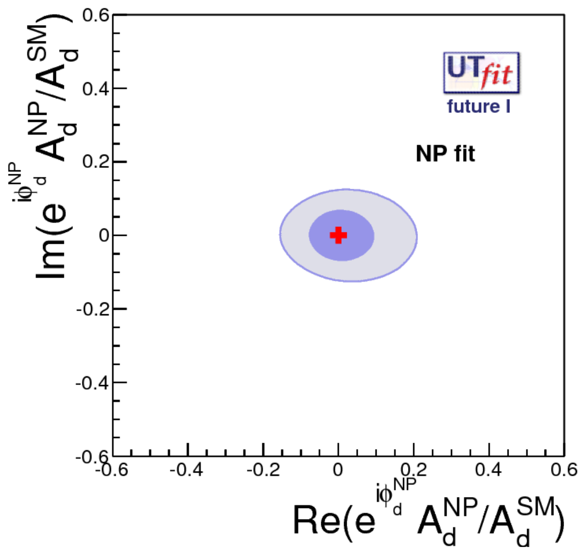


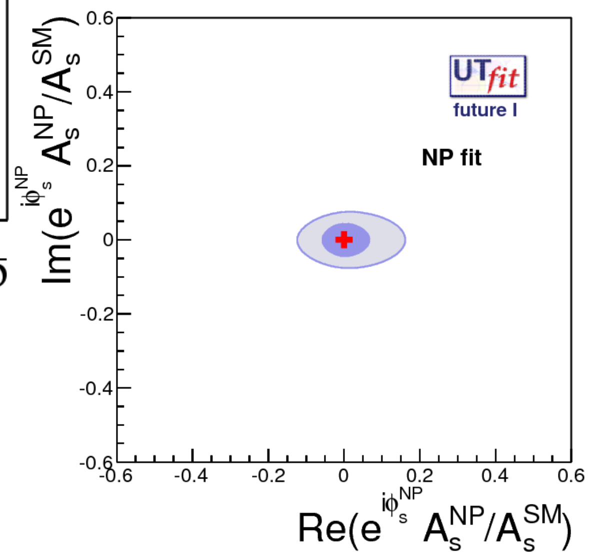
$\rho = \pm\ 0.015$
$\eta = \pm\ 0.015$

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



$\rho = \pm\ 0.016$
$\eta = \pm\ 0.019$





$\bar{\rho} = 0.154 \pm 0.015$
$\bar{\eta} = 0.344 \pm 0.013$

current sensitivity

$\bar{\rho} = 0.150 \pm 0.027$
$\bar{\eta} = 0.363 \pm 0.025$