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

UTfit

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}

updated for ICHEP16

Average of the two FLAG Nf=2+1 averages

$|V_{cb}|$ *(excl)* = (40.1 ± 1.2) 10^{-3}

$|V_{cb}|$ *(incl)* = (42.00 ± 0.64) 10^{-}

Gambino 1606.06174

~1.3σ discrepancy

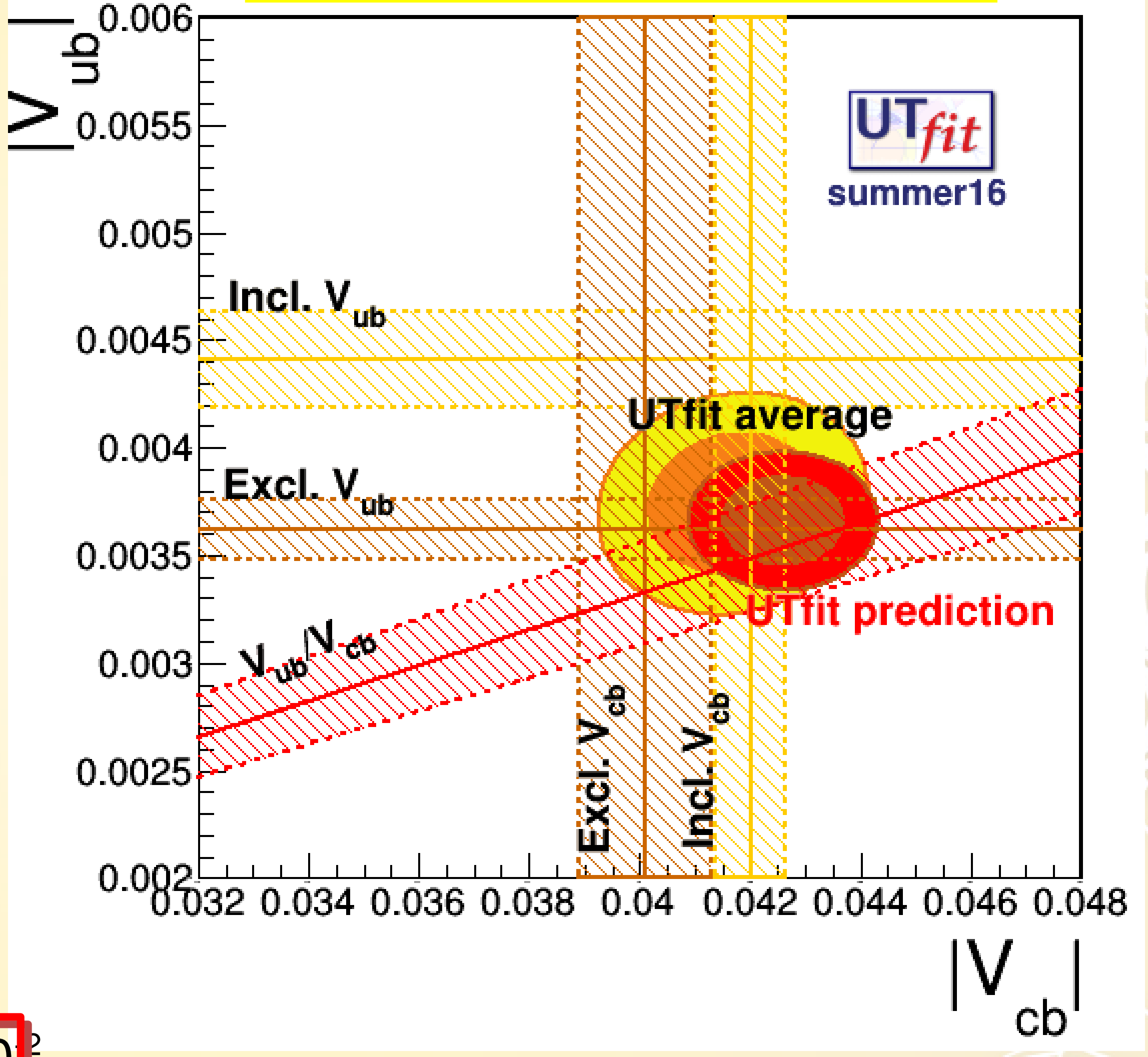
Nf=2+1 FLAG average

$|V_{ub}|$ *(excl)* = (3.62 ± 0.14) 10^{-3}

$|V_{ub}|$ *(incl)* = (4.41 ± 0.22) 10^{-3}

~3σ discrepancy

$|V_{ub} / V_{cb}|$ *(LHCb)* = (8.3 ± 0.6) 10^{-2}



V_{cb} and V_{ub}

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.

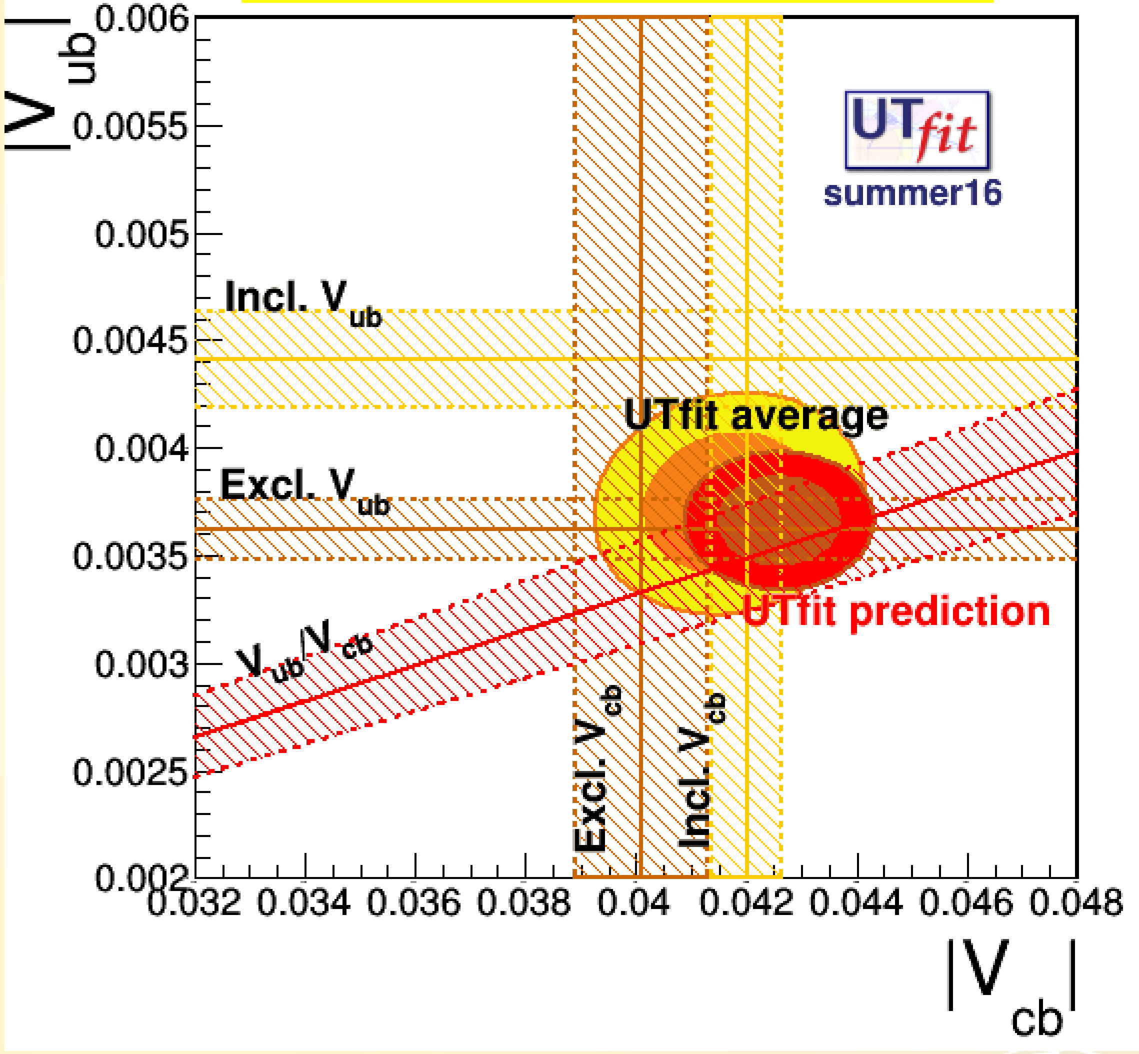
$|V_{cb}| = (41.7 \pm 1.0)\ 10^{-3}$

uncertainty ~ 2.4%

$|V_{ub}| = (3.74 \pm 0.21)\ 10^{-3}$

uncertainty ~ 5.6%

updated for ICHEP16



$|V_{cb}| = (42.6 \pm 0.7)\ 10^{-3}$

$|V_{ub}| = (3.66 \pm 0.13)\ 10^{-3}$

UTfit predictions

V_{cb} and V_{ub}

New HFAG

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

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

New HFAG

~3.3σ discrepancy

New HFAG

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

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

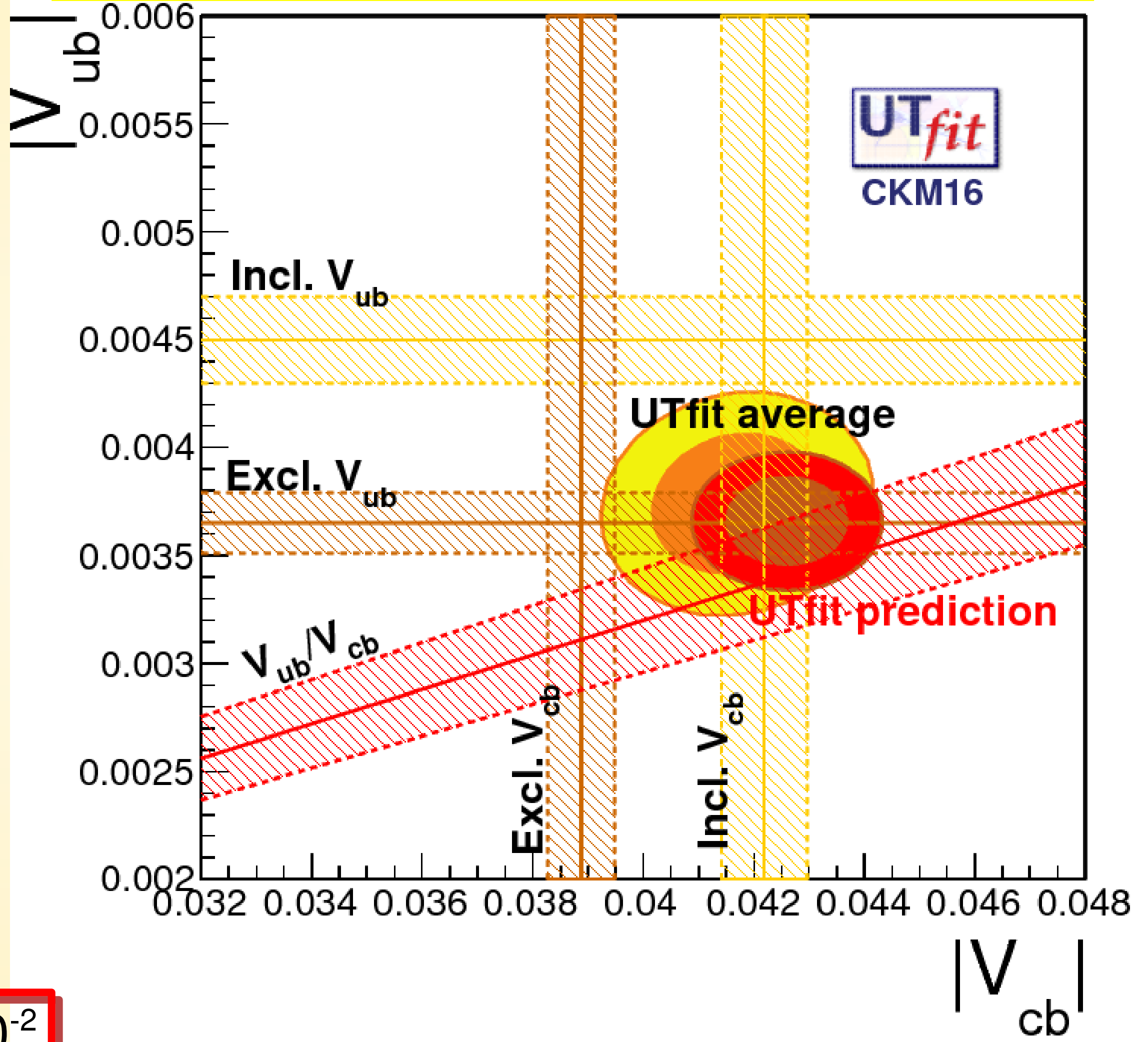
New HFAG

~3.4σ discrepancy

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

Updated value

new HFAG numbers @CKM16

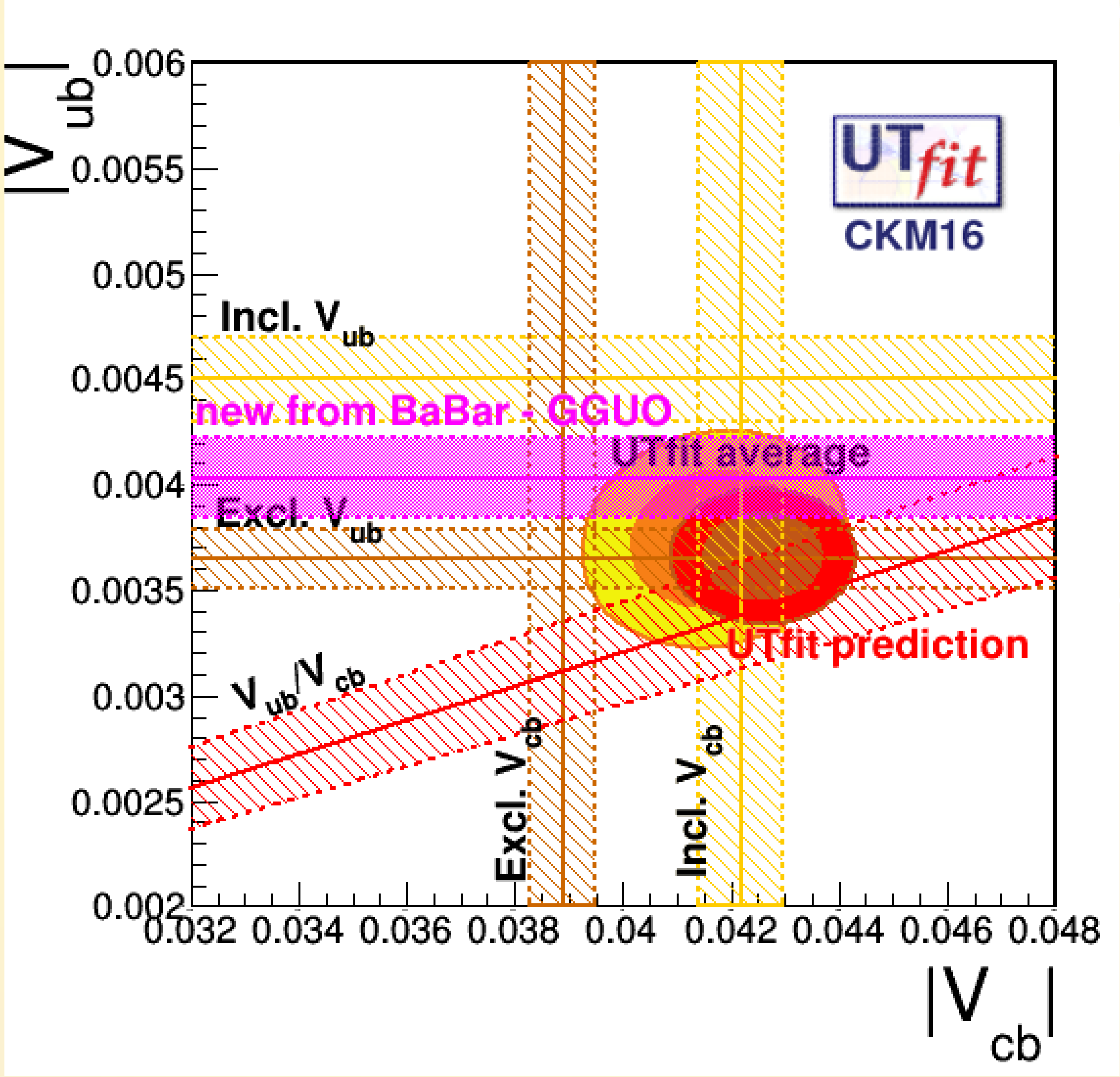


UTfit average not updated!

V_{cb} and V_{ub}

some new extra results @CKM16:
a lay(wo)man's visualisation..

new BaBar result for inclusive V_{ub} @Kowalewski on Tue in WG2

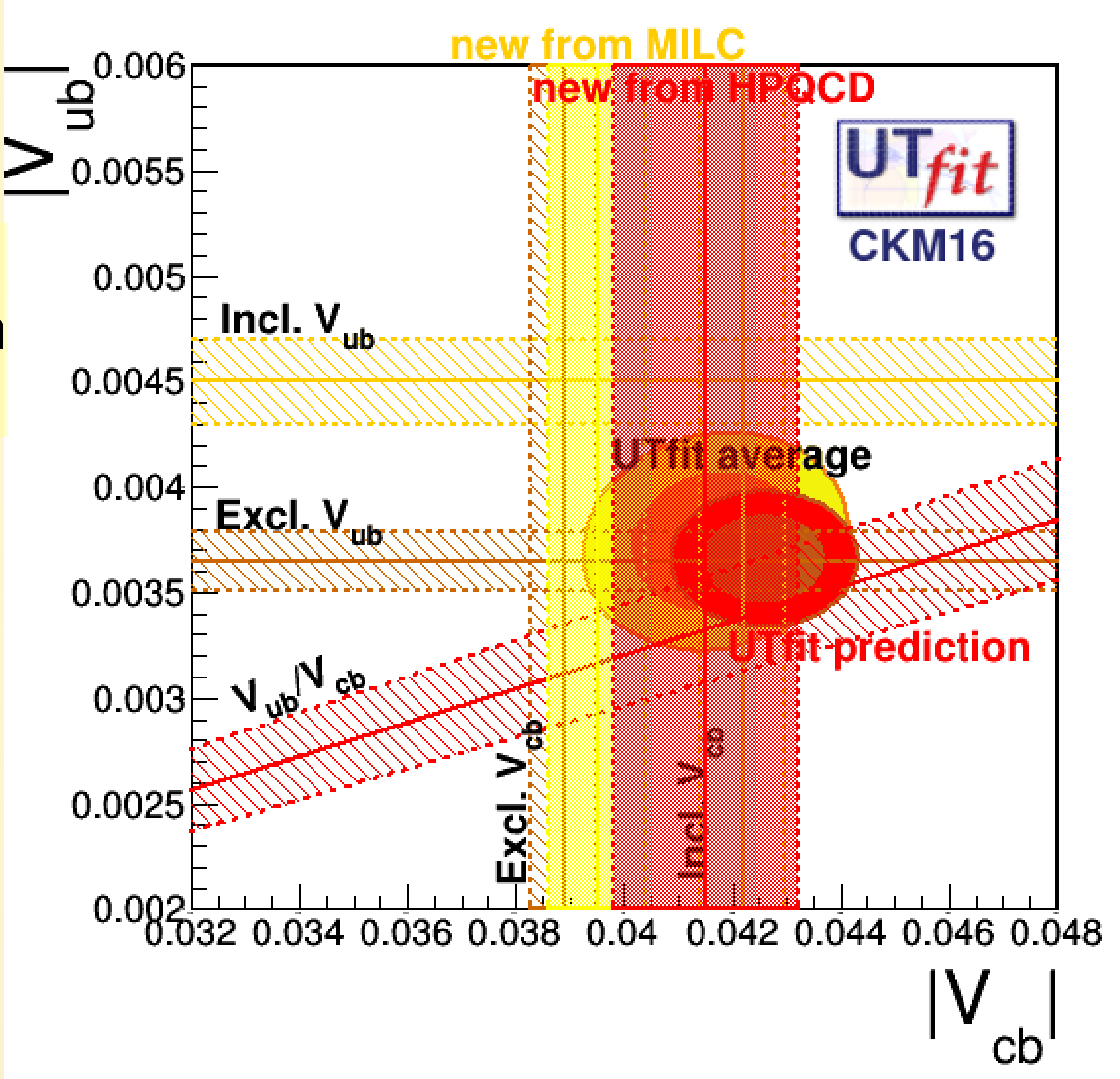


V_{cb} and V_{ub}

some new extra results @CKM16:
a lay(wo)man's visualisation..

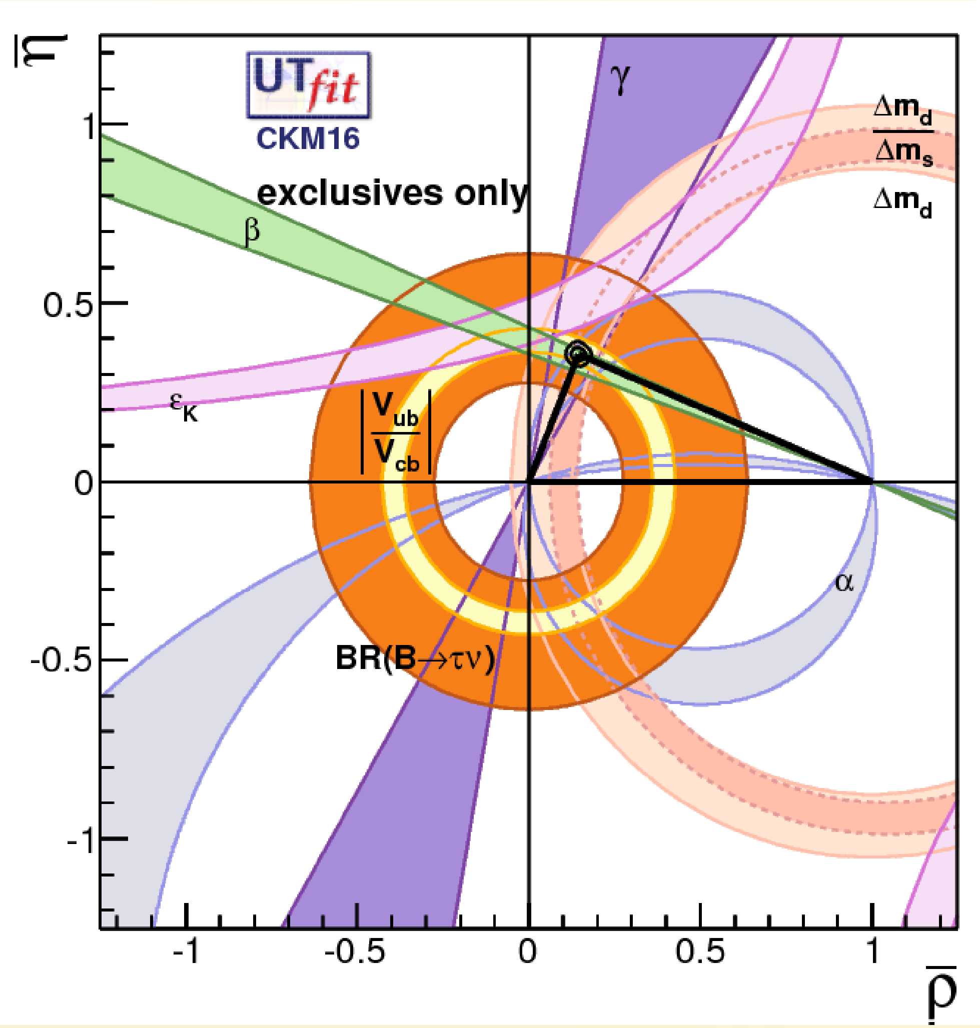
new from Fermilab Lattice collaboration MILC

new from HPQCD collaboration @Davis on Mon in Plenary

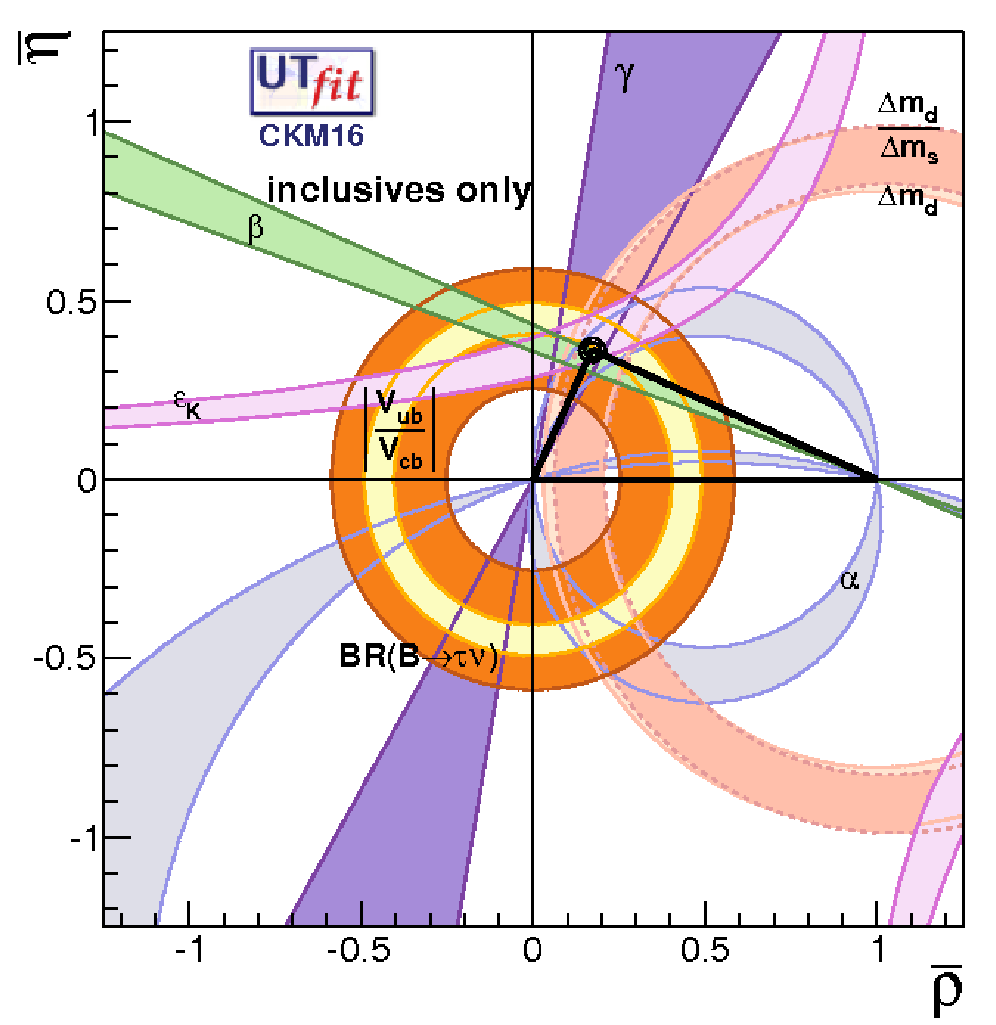


exclusives vs inclusives

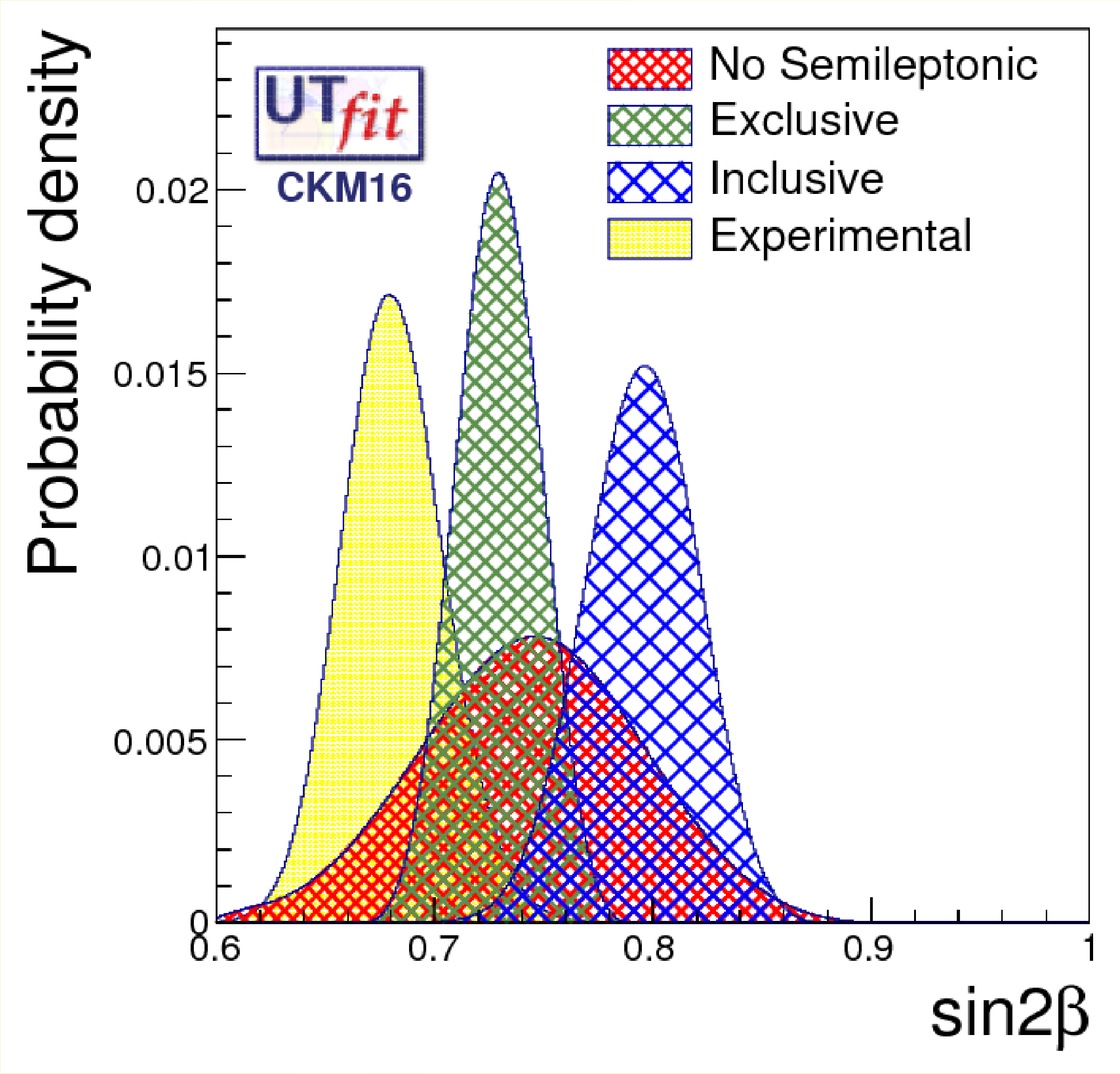
only exclusive values



only inclusive values



exclusives vs inclusives



$\sin 2\beta_{exp} = 0.745 \pm 0.050$

$\sin 2\beta_{exp} = 0.729 \pm 0.019$

$\sin 2\beta_{exp} = 0.796 \pm 0.026$

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

$\sin 2\beta_{UTfit} = 0.725 \pm 0.030$

$\sin 2\alpha$ (ϕ_2) from charmless B decays: $\pi\pi$, $\rho\rho$, $\pi\rho$

$\pi^0\pi^0$ from Belle at CKM14

to be updated soon (?)

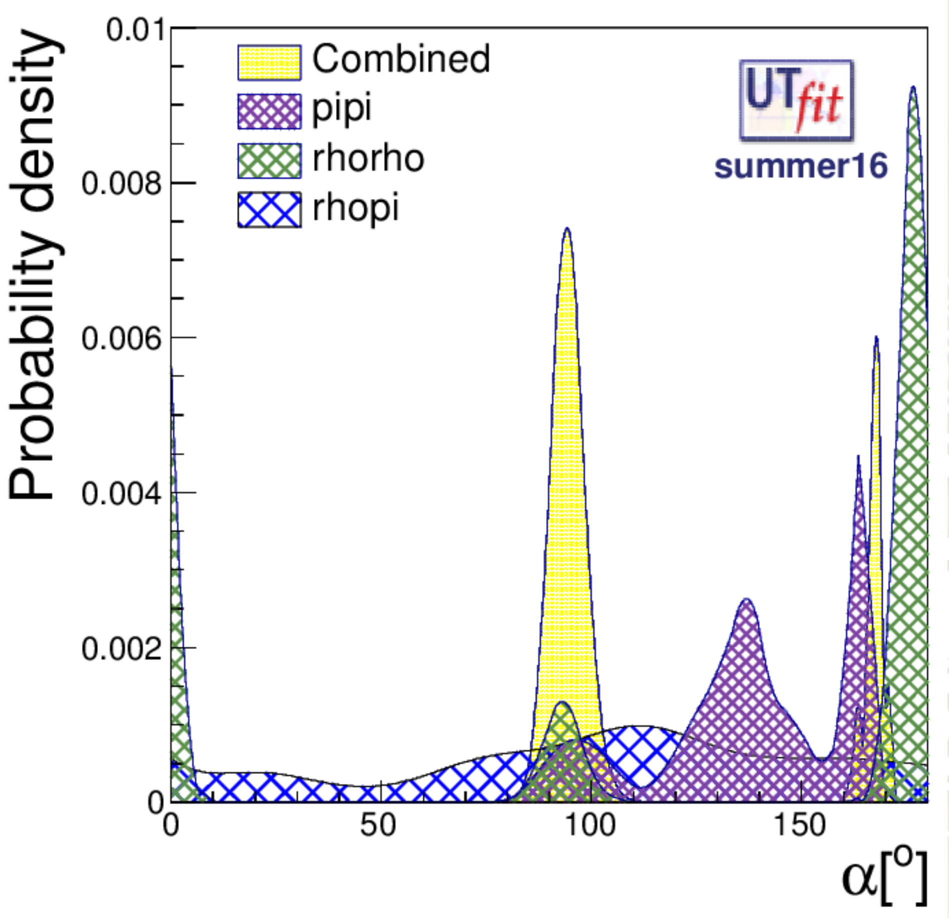
BR($\pi^0\pi^0$) = $(1.17 \pm 0.13)\ 10^{-6}$

HFAG 2014

a *à la PDG* average would give an inflated uncertainty of 0.41

$\rho^+\rho^-$ average updated including Belle arXiv:1510.01245

$\rho^0\rho^0$ average updated including LHCb arXiv:1503.07770

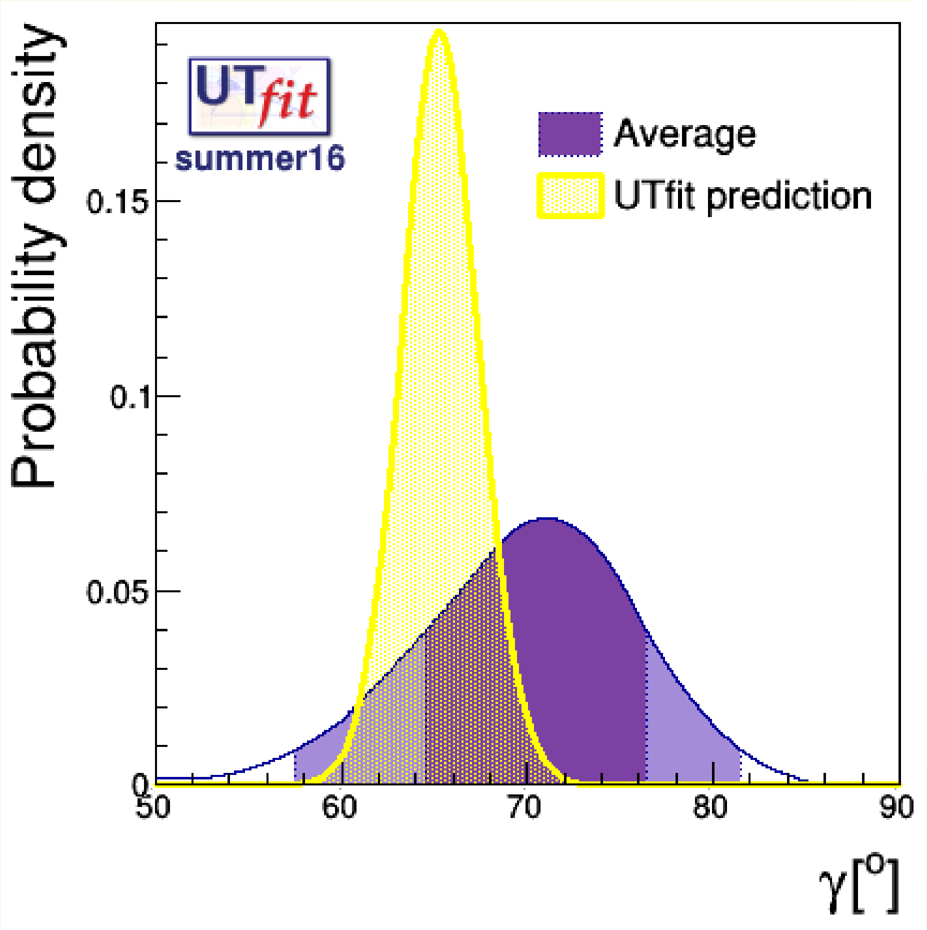


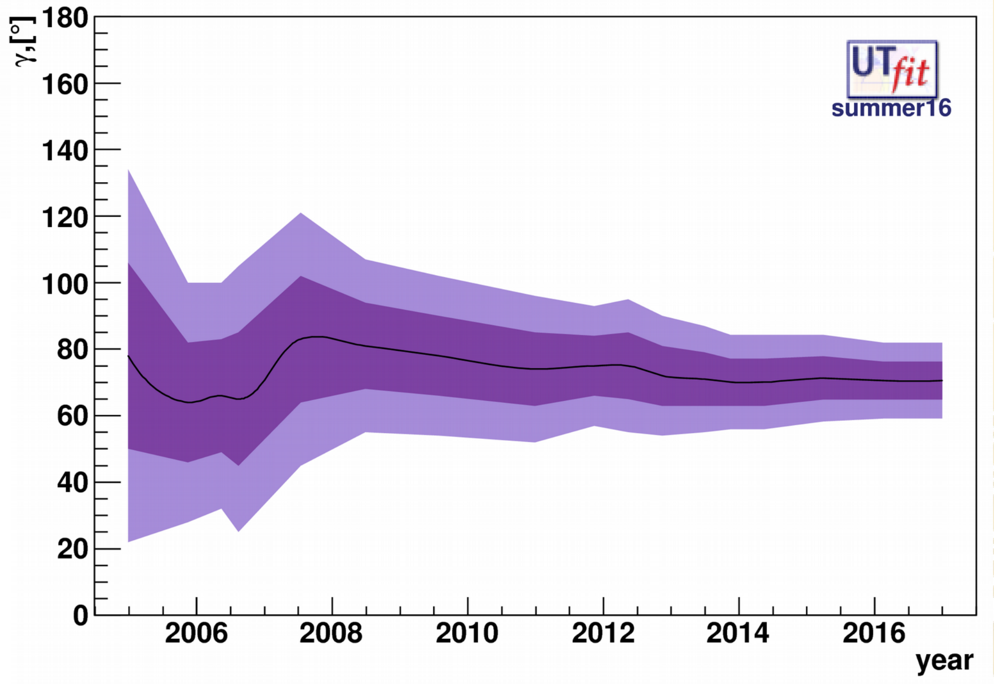
α from $\pi\pi$, $\rho\rho$, $\pi\rho$ decays:

combined: $(94.2 \pm 4.5)°$

UTfit prediction: $(90.9 \pm 2.5)°$

γ and DK trees



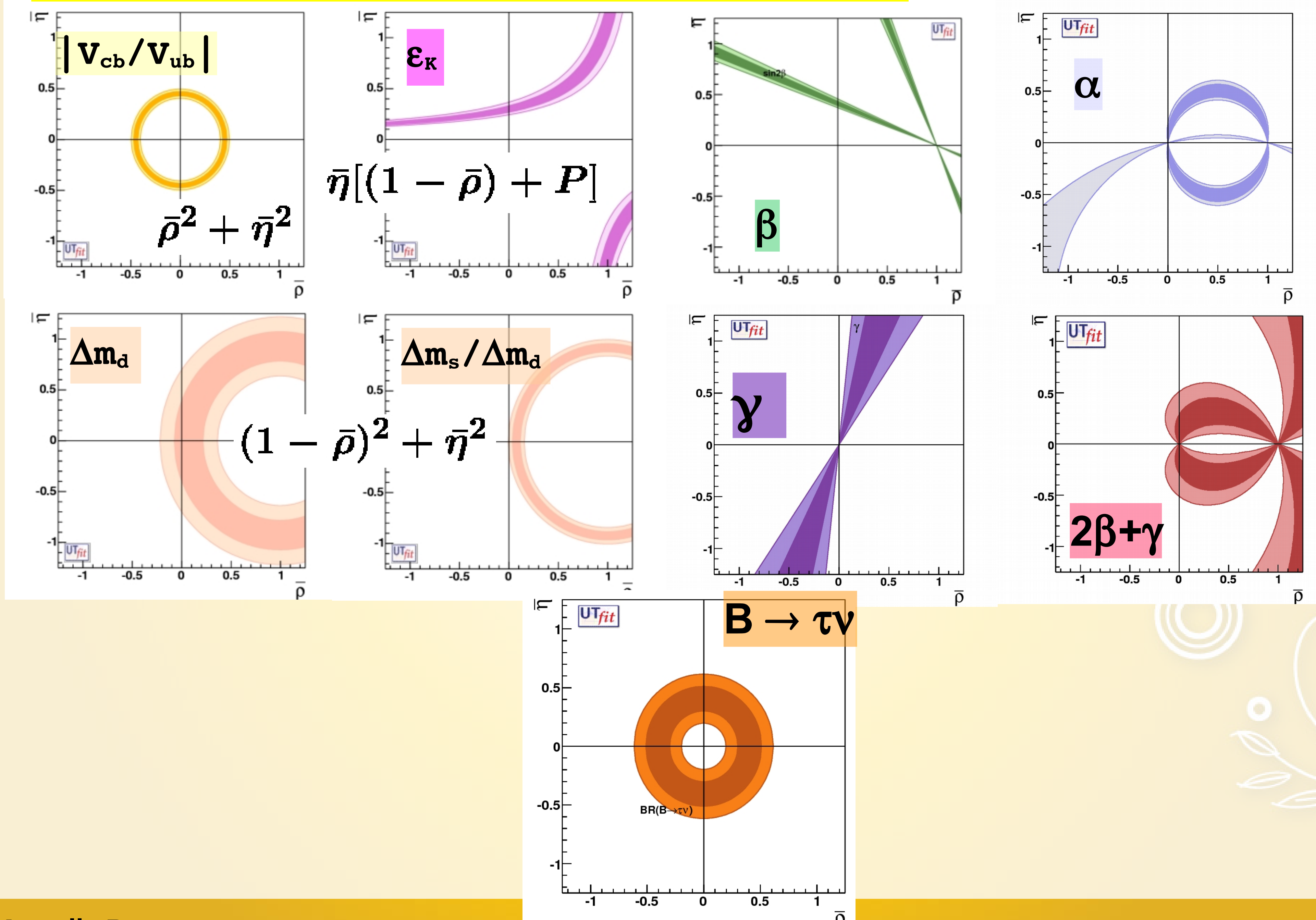


After a decade of analyses and almost 50 papers published, the world average uncertainty has decreased by a factor 3

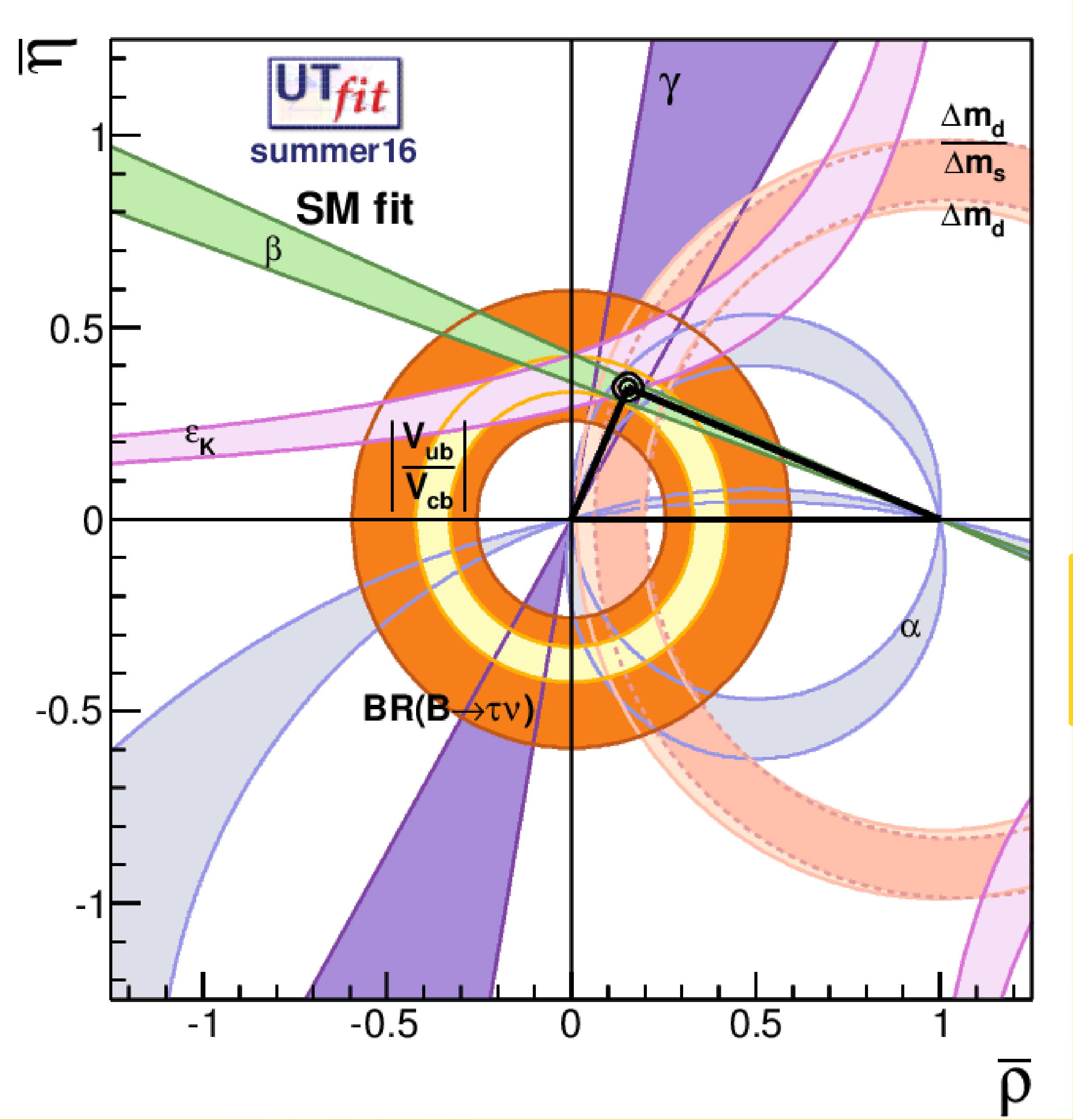
combined: (70.5 ± 5.7)°

UTfit prediction: (65.4 ± 2.1)°

Unitarity Triangle analysis in the SM:



Unitarity Triangle analysis in the SM:



levels @
95% Prob

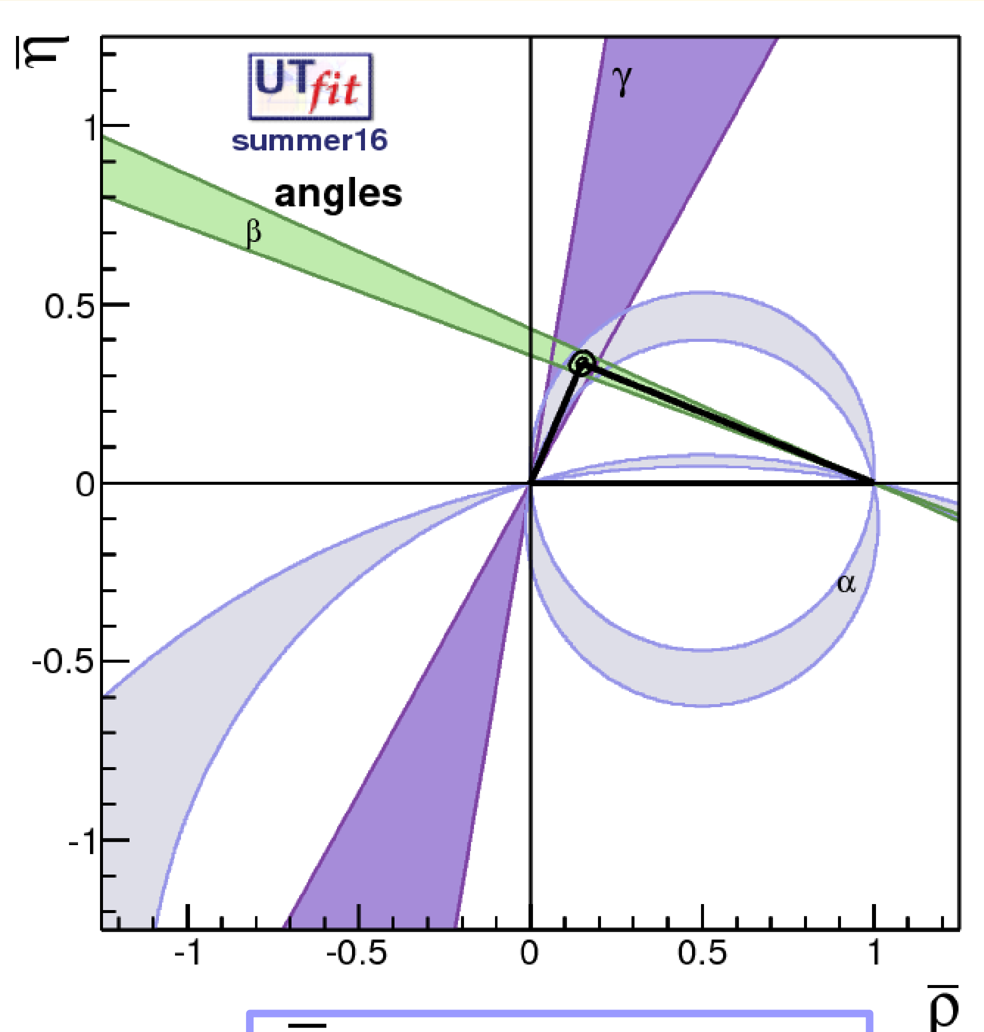
~10 %

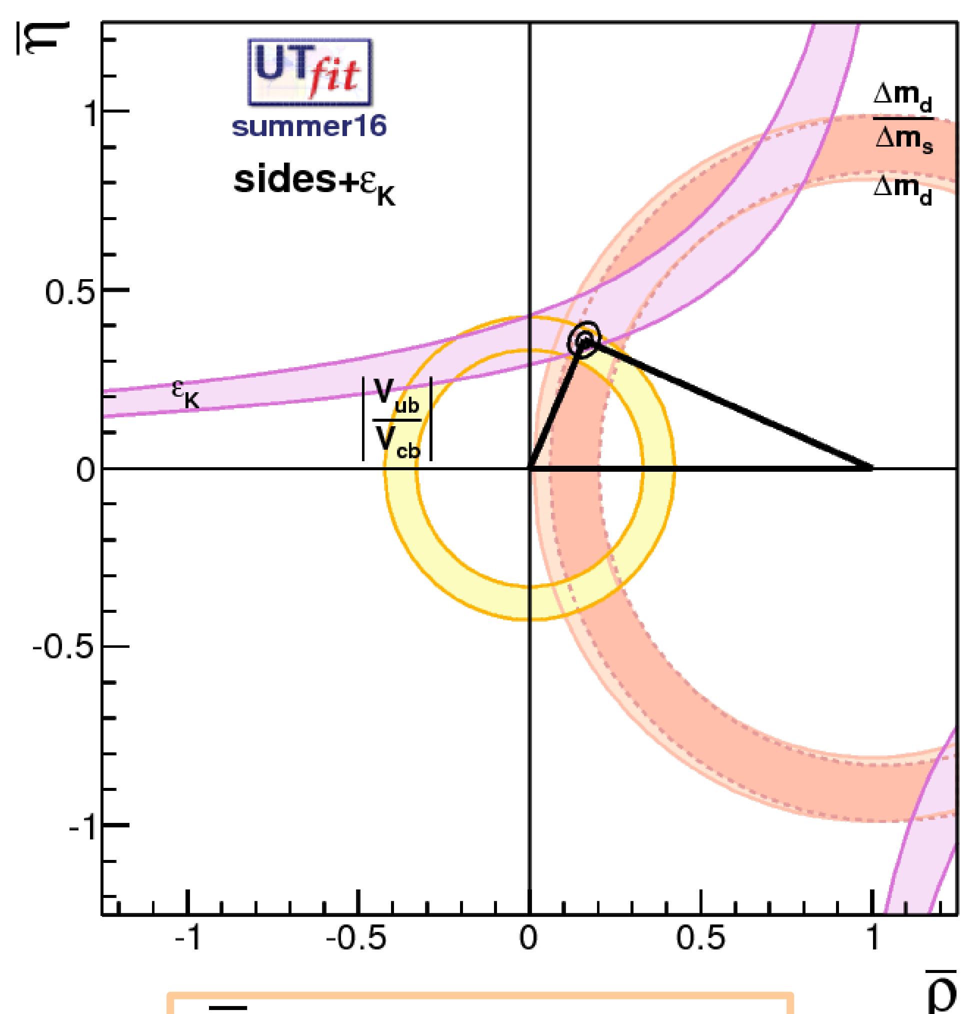
$\bar{\rho} = 0.154 \pm 0.015$
$\bar{\eta} = 0.344 \pm 0.013$

~4%

angles vs sides (and ε_K)

levels @
95% Prob





$\bar{\rho} = 0.147 \pm 0.022$
$\bar{\eta} = 0.333 \pm 0.016$

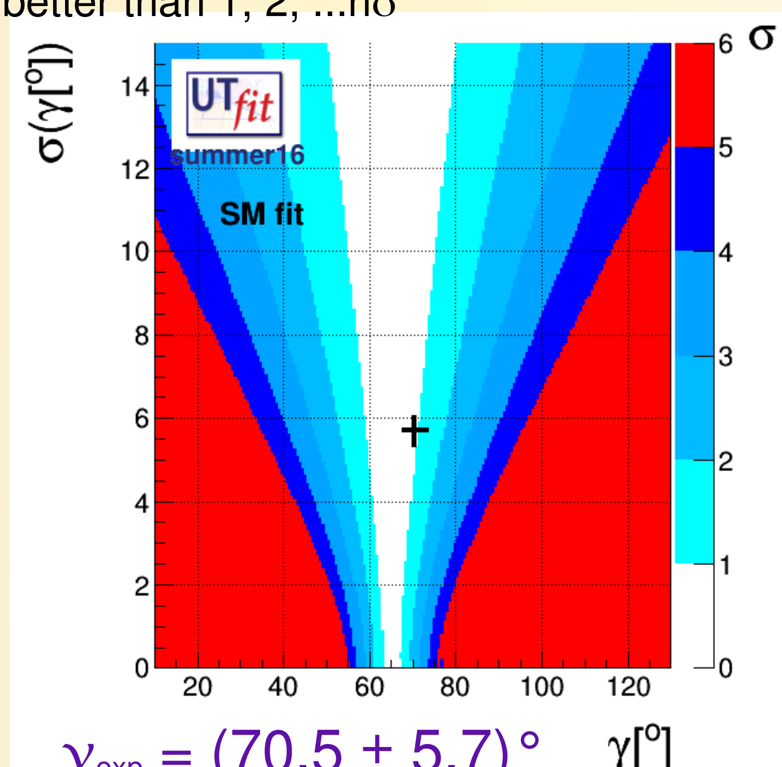
$\bar{\rho} = 0.160 \pm 0.018$
$\bar{\eta} = 0.359 \pm 0.021$

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

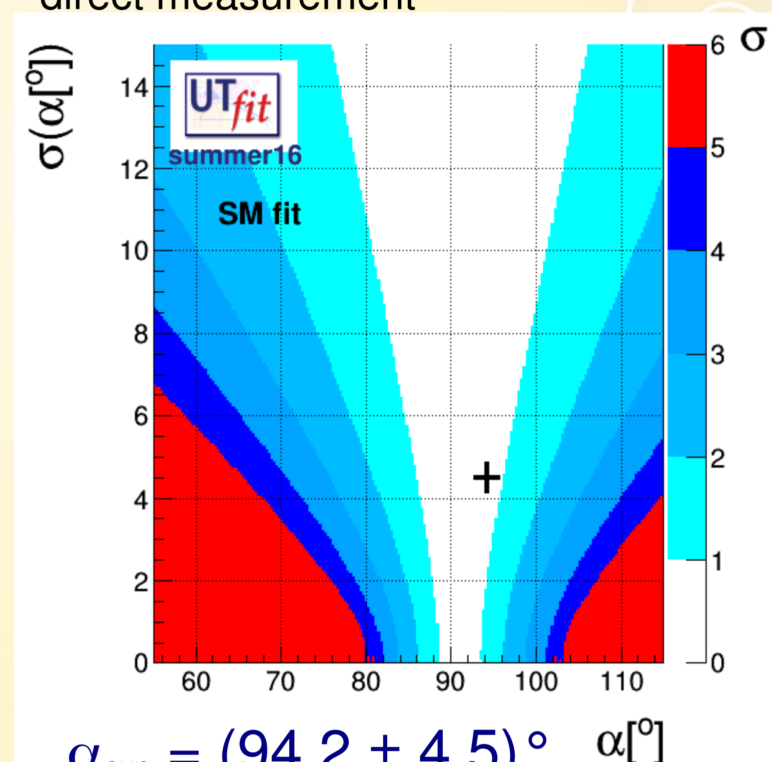
Color code: agreement between the predicted values and the measurements at better than 1, 2, ...nσ

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



$\gamma_{exp} = (70.5 \pm 5.7)°$

$\gamma_{UTfit} = (65.4 \pm 2.1)°$



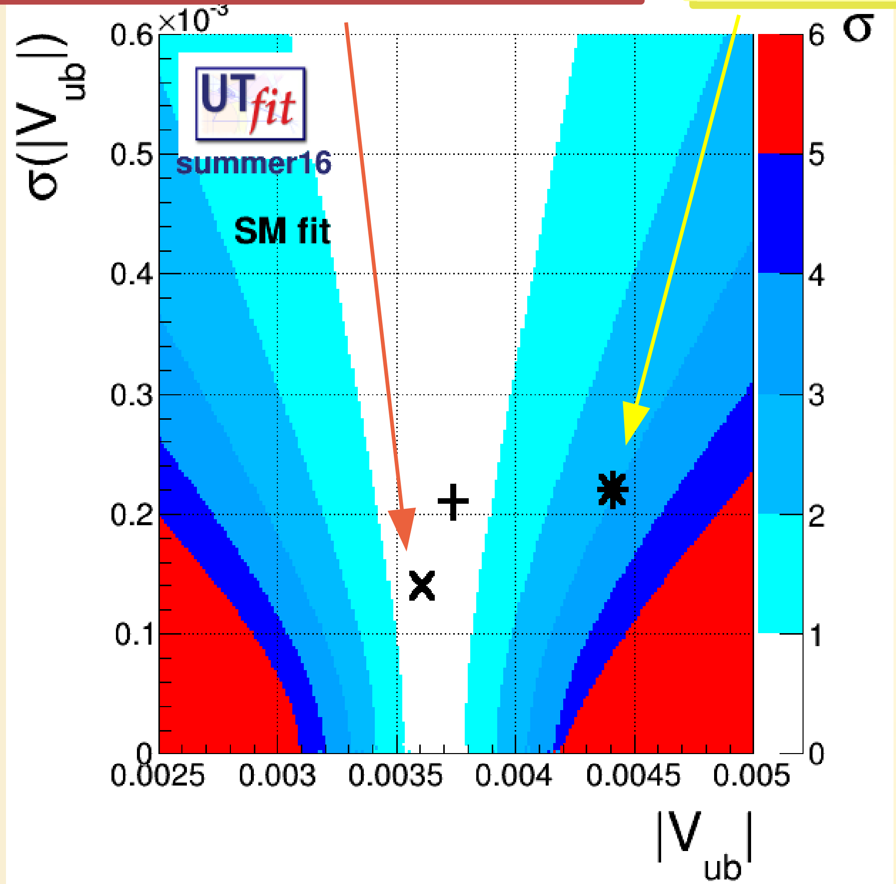
$\alpha_{exp} = (94.2 \pm 4.5)°$

$\alpha_{UTfit} = (90.9 \pm 2.5)°$

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

V_{ub} *(excl)* = (3.62 ± 0.14) 10^{-3}

V_{ub} *(incl)* = (4.41 ± 0.22) 10^{-3}



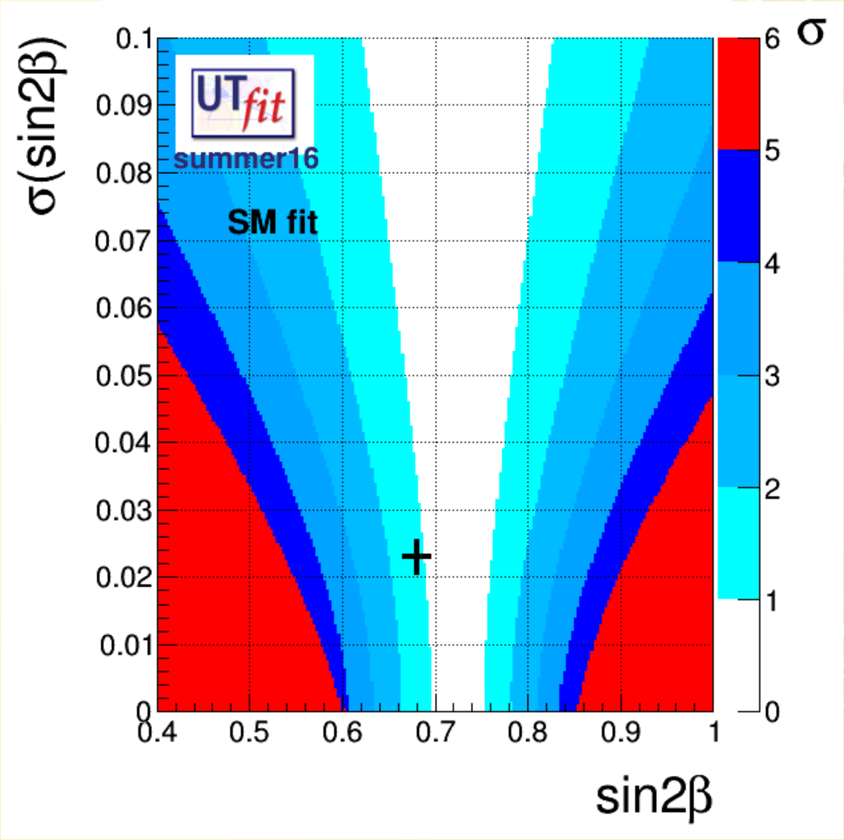
Vub_{exp} = (3.74 ± 0.21) · 10^{-3}

Vub_{UTfit} = (3.66 ± 0.11) · 10^{-3}

~1.2σ

$\sin 2\beta_{exp}$ = 0.680 ± 0.023

$\sin 2\beta_{UTfit}$ = 0.725 ± 0.030



Unitarity Triangle analysis in the SM:

obtained excluding the given constraint from the fit

Observables	Measurement	Prediction	Pull (#σ)
$\sin 2\beta$	0.680 ± 0.023	0.725 ± 0.030	~ 1.2
γ	70.5 ± 5.7	65.4 ± 2.1	< 1
α	94.2 ± 4.5	90.9 ± 2.5	< 1
$\lvert V_{ub}\rvert \cdot 10^3$	3.74 ± 0.21	3.66 ± 0.11	< 1
$\lvert V_{ub}\rvert \cdot 10^3$ (incl)	4.41 ± 0.22	-	~ 2.9
$\lvert V_{ub}\rvert \cdot 10^3$ (excl)	3.62 ± 0.14	-	< 1
$\lvert V_{cb}\rvert \cdot 10^3$	41.7 ± 1.0	42.6 ± 0.7	< 1
β_s	0.97 ± 0.94	1.05 ± 0.04	< 1
$BR(B \to \tau\nu)[10^{-4}]$	1.06 ± 0.20	0.81 ± 0.06	~ 1.2
$A_{SL}^{d} \cdot 10^3$	0.2 ± 2.0	-0.283 ± 0.024	< 1
$A_{SL}^{s} \cdot 10^3$	1.7 ± 3.0	0.013 ± 0.001	< 1

LHCb arXiv:1605.09768

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

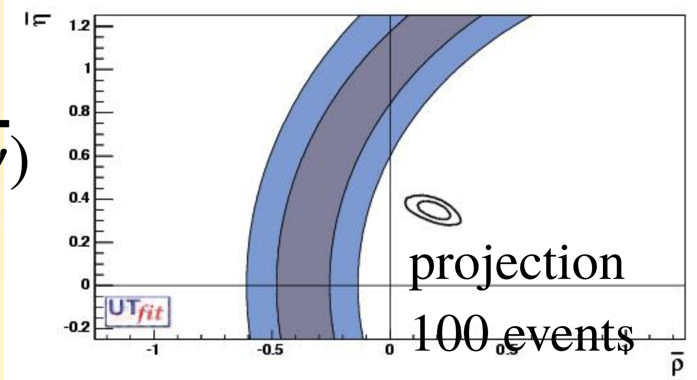
for B_{Bs}, B_{bs}/B_{bd}:
update w.r.t. the Nf=2+1 FLAG average (no Nf=2+1+1 results yet)
updating the FNAL/MILC result to FNAL/MILC 2016 (1602.03560)

some old plots coming back to fashion:

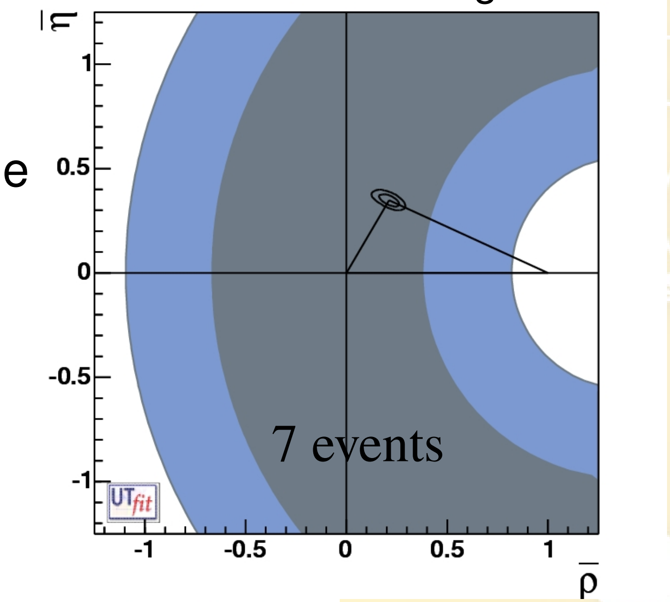
As NA62 and KOTO are approaching data taking:

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

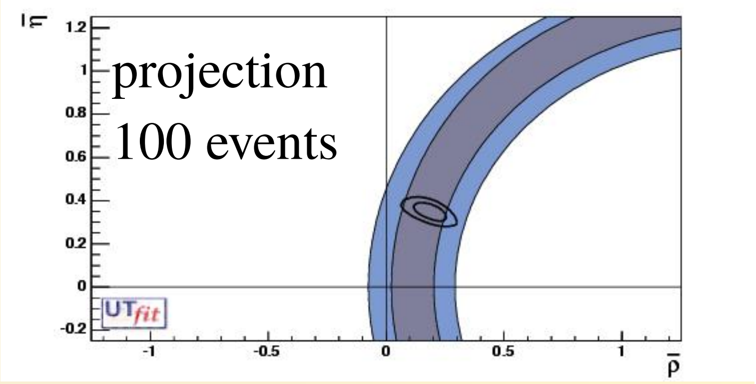
E949 central value

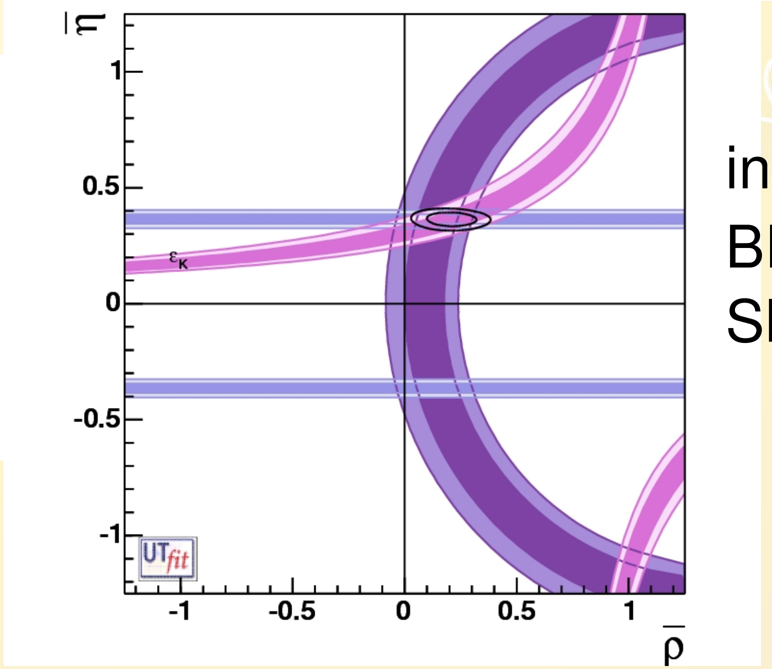


2007 global fit area



SM central value





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

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

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

semileptonic asymmetries in B^0 and B_s: sensitive to NP effects in both size and phase. Currently using a 2D average done by LHCb in 1605.09768 (pre-ICHEP16 value).

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

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

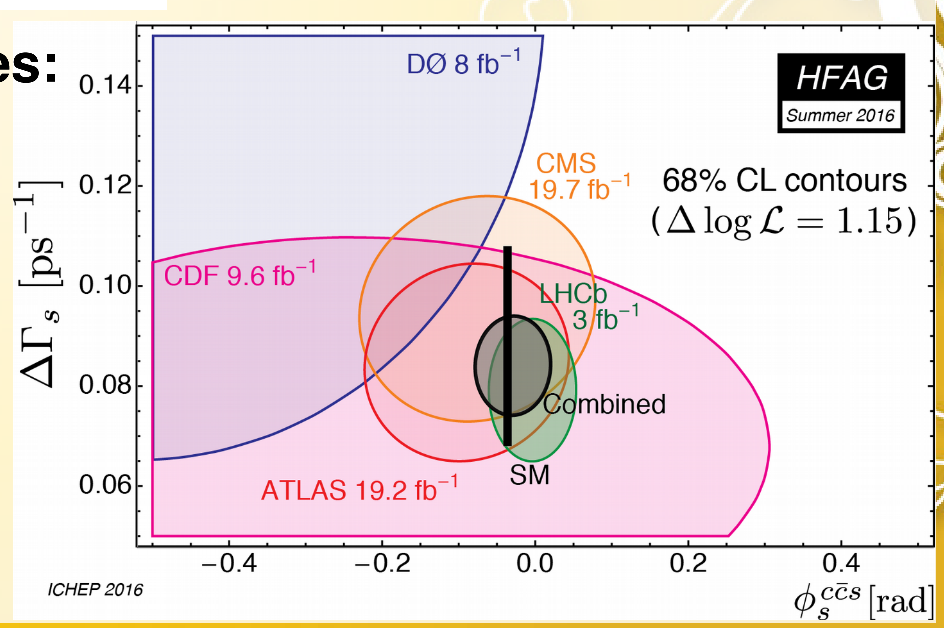
$$A^{\mu\mu}_{SL} \times 10^3 = -7.9 \pm 2.0$$

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

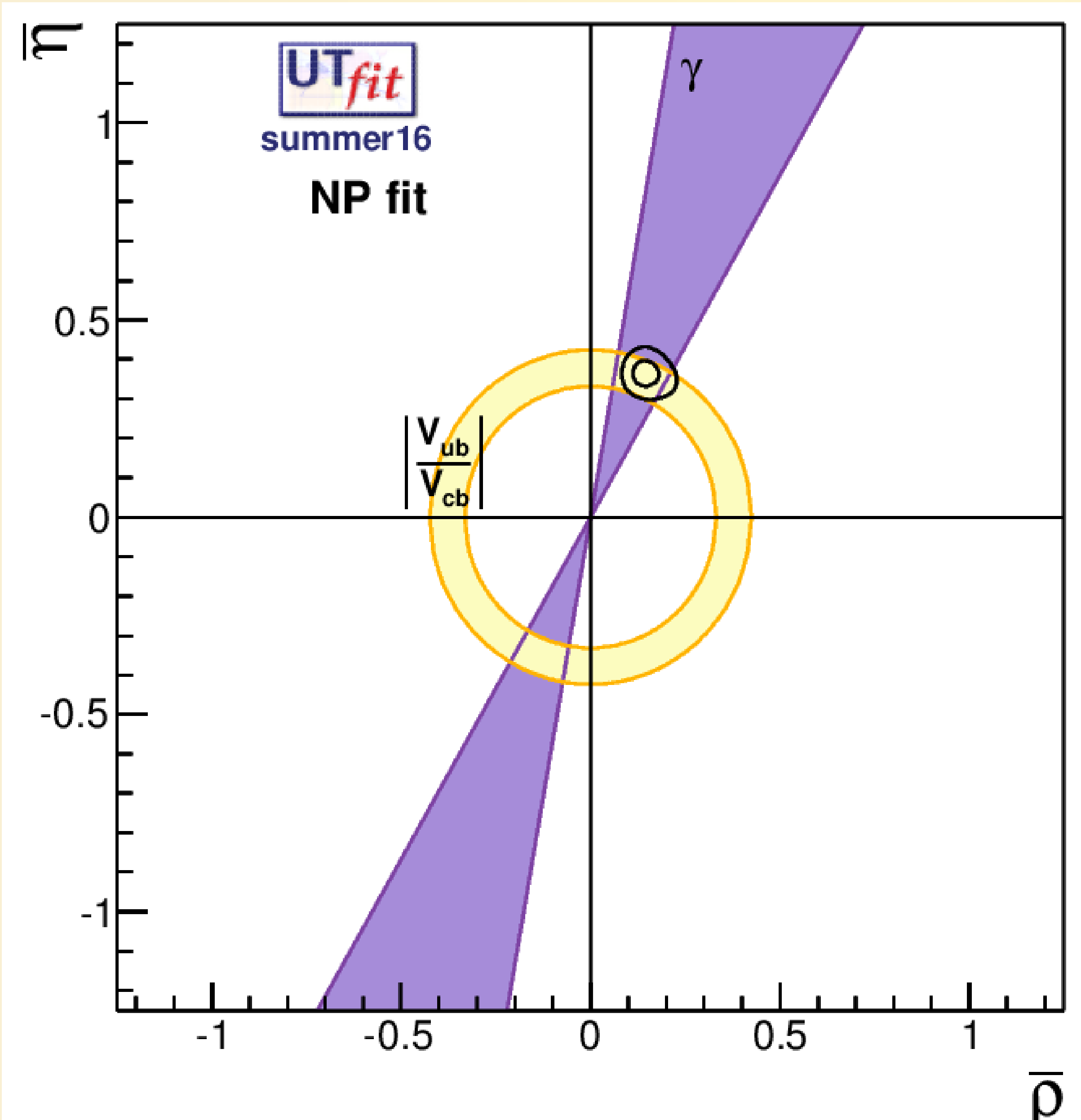
$\tau^{FS}(B_s) = 1.511 \pm 0.014$ ps **HFAG**

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

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



NP analysis results



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

SM is

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

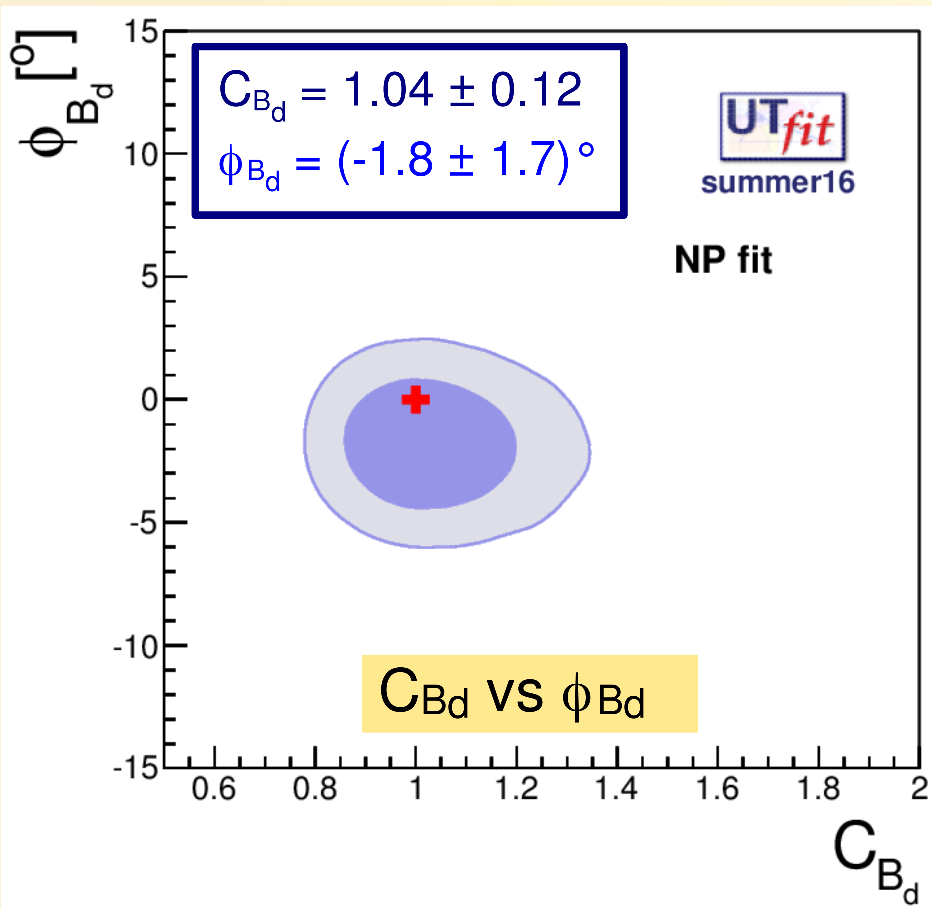
NP parameter results

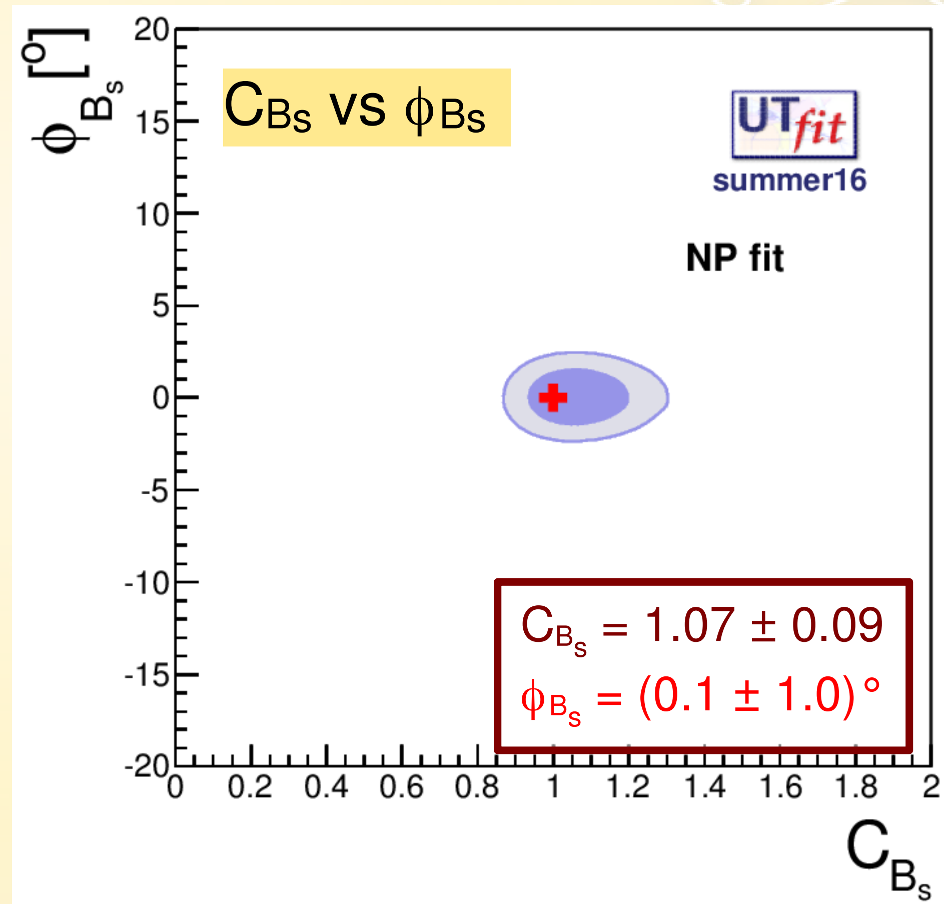
K system

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

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

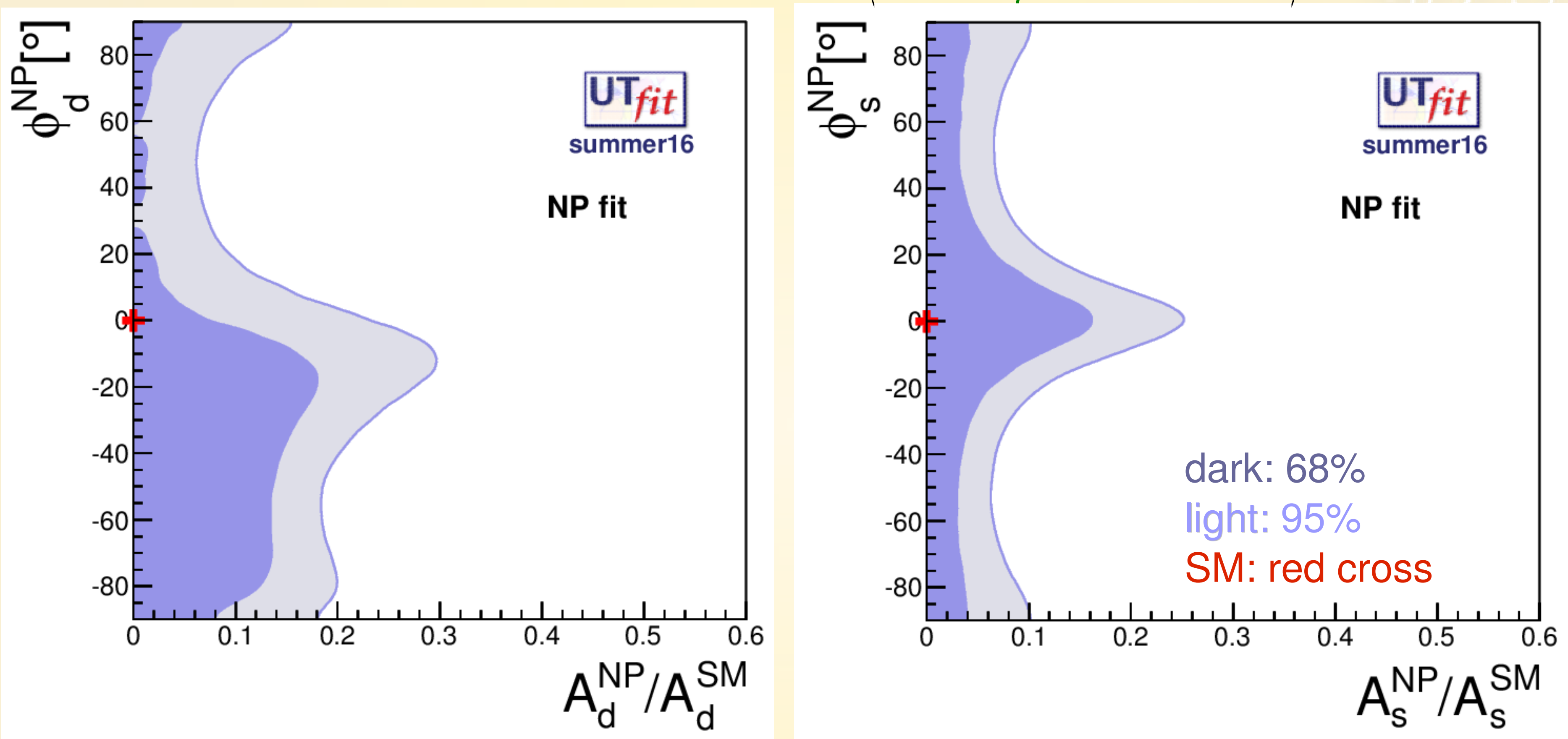
$$A_q = C_{B_q} e^{2i\phi_{B_q}} A_q^{SM} e^{2i\phi_q^{SM}}$$





NP parameter results

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



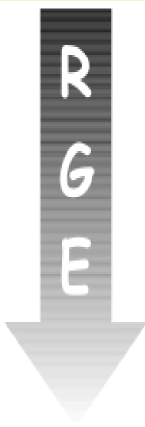
The ratio of NP/SM amplitudes is:

< 15% @68% prob. (30% @95%) in B_d mixing

< 15% @68% prob. (25% @95%) in B_s mixing

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

testing the new-physics scale



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

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

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

NP effects are enhanced

- up to a factor 10 by the values of the matrix elements especially for transitions among quarks of different chiralities
- up to a factor 8 by RGE

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

effective BSM Hamiltonian for ΔF=2 transitions

The Wilson coefficients C_i have in general the form

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

Putting bounds on the Wilson coefficients give insights into the NP scale in different NP scenarios that enter through F_i and 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 ΔF=2 transitions)

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

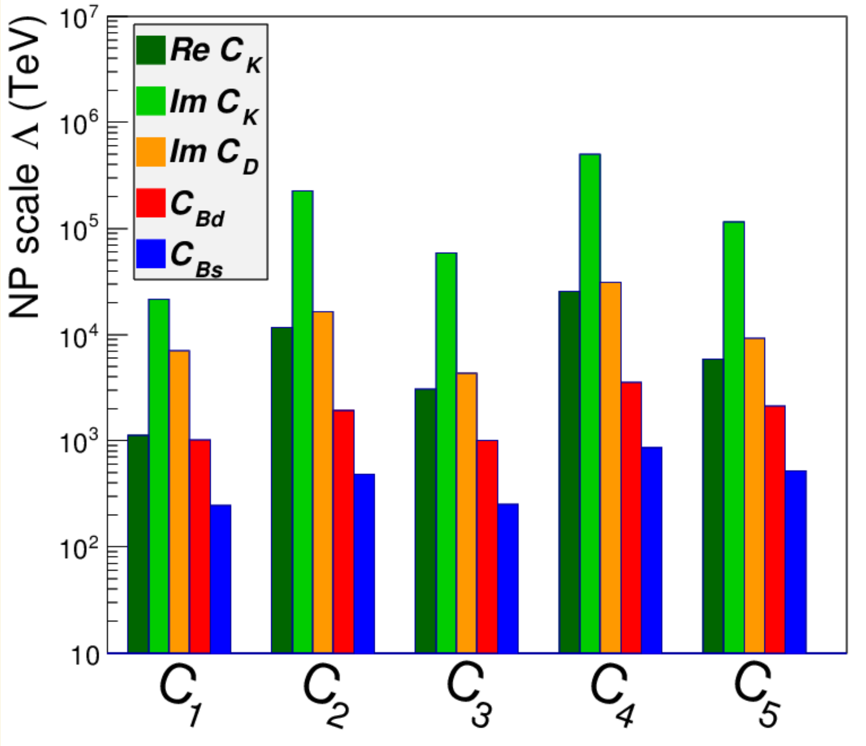
If no NP effect is seen
lower bound on NP scale Λ
if NP is seen
upper bound on NP scale Λ

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



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

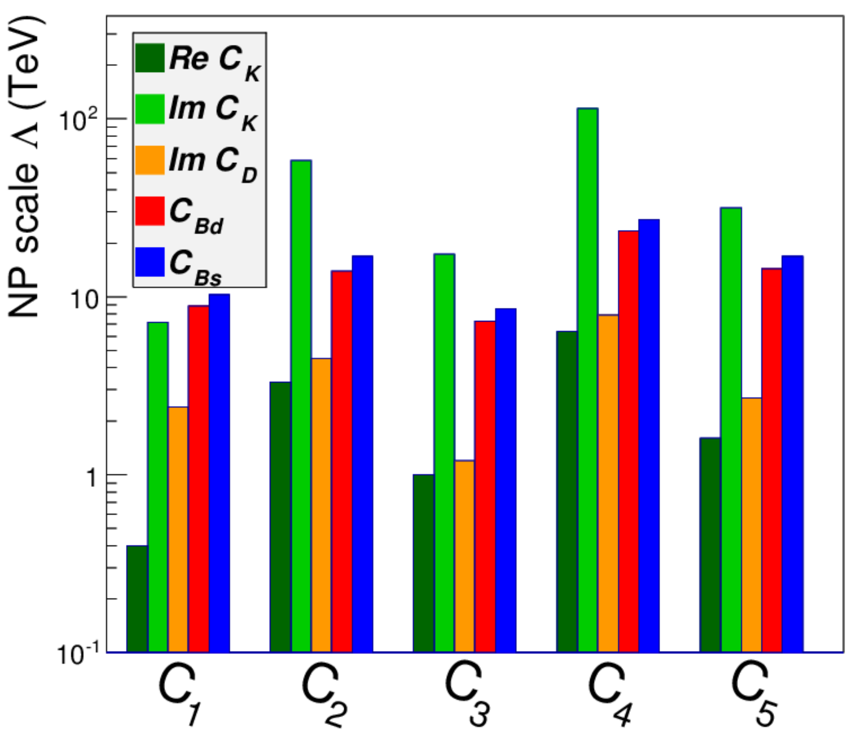
NP in α_W loops
$\Lambda > 1.5\ 10^4$ TeV

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

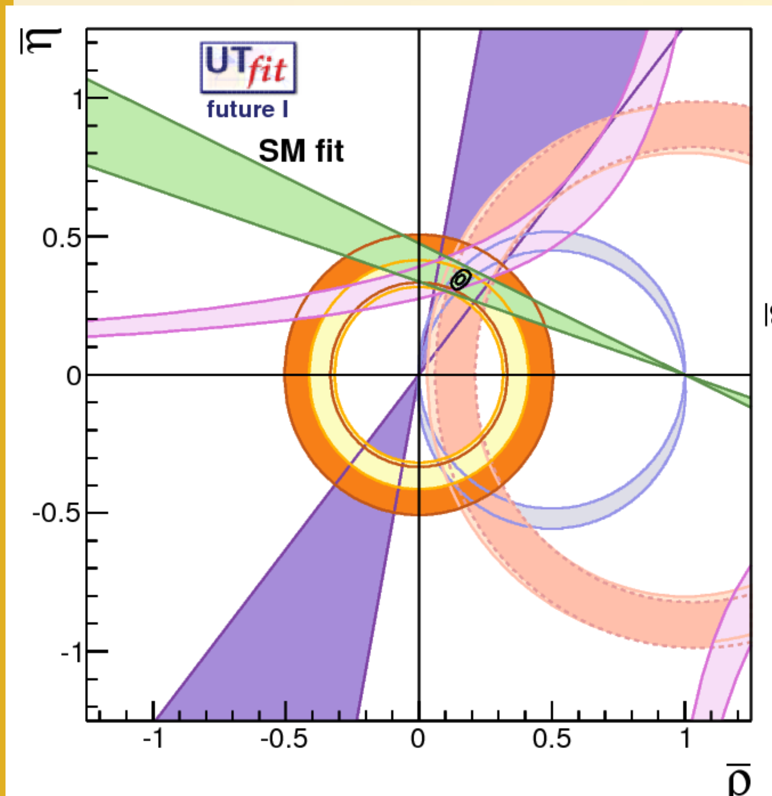
$B_{(s)}$ mixing provides very stringent constraints, especially if no new chiral structures are present

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

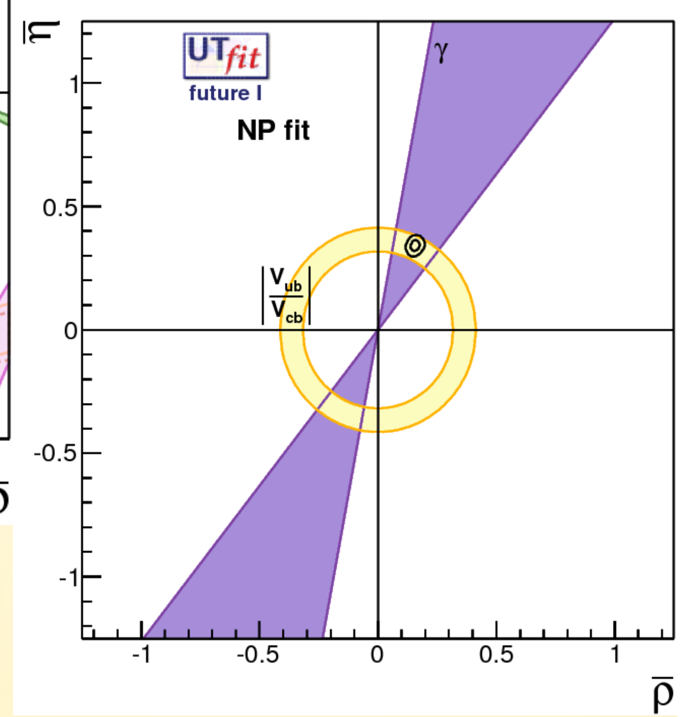
Look at the near future

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

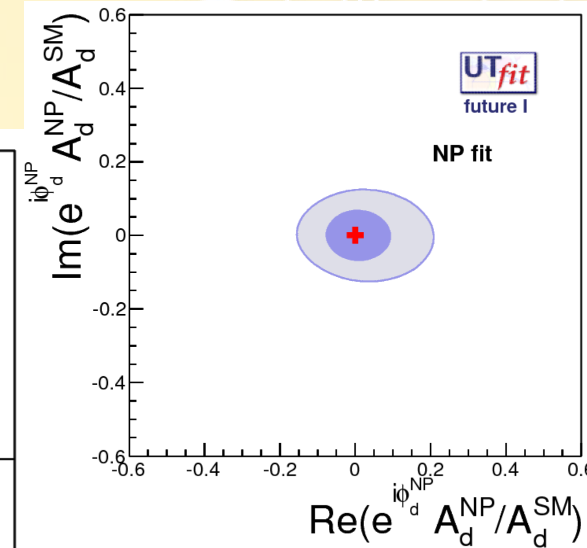
preliminary

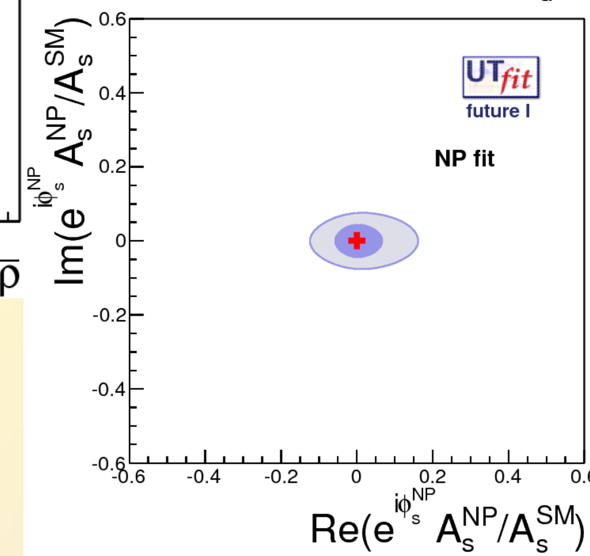


$\rho = \pm\, 0.015$
$\eta = \pm\, 0.015$



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





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

current sensitivity

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

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

V_{cb} and V_{ub}

Average of the two FLAG Nf=2+1 averages

V_{cb} *(excl)* = (40.1 ± 1.2) 10^{-3}

V_{cb} *(incl)* = (42.00 ± 0.64) 10^{-3}

Gambino 1606.06174

~3.0σ discrepancy

V_{ub} *(excl)* = (3.69 ± 0.14) 10^{-3}

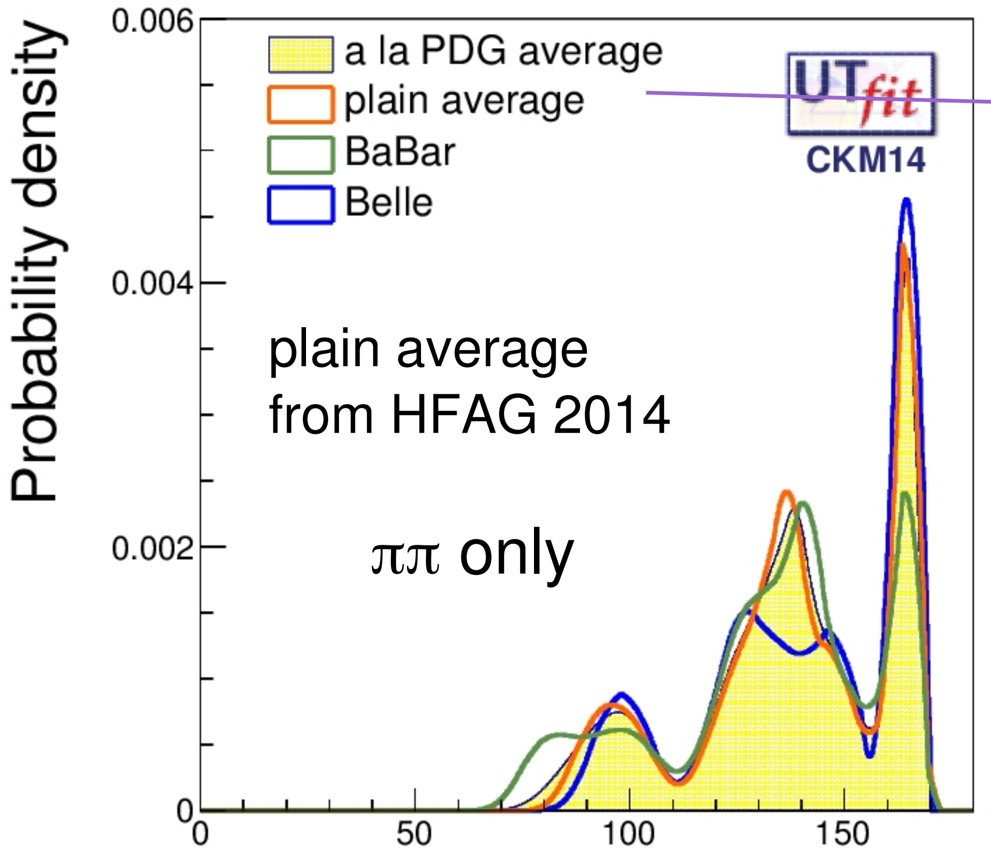
V_{ub} *(incl)* = (4.40 ± 0.22) 10^{-3}

~2.7σ discrepancy

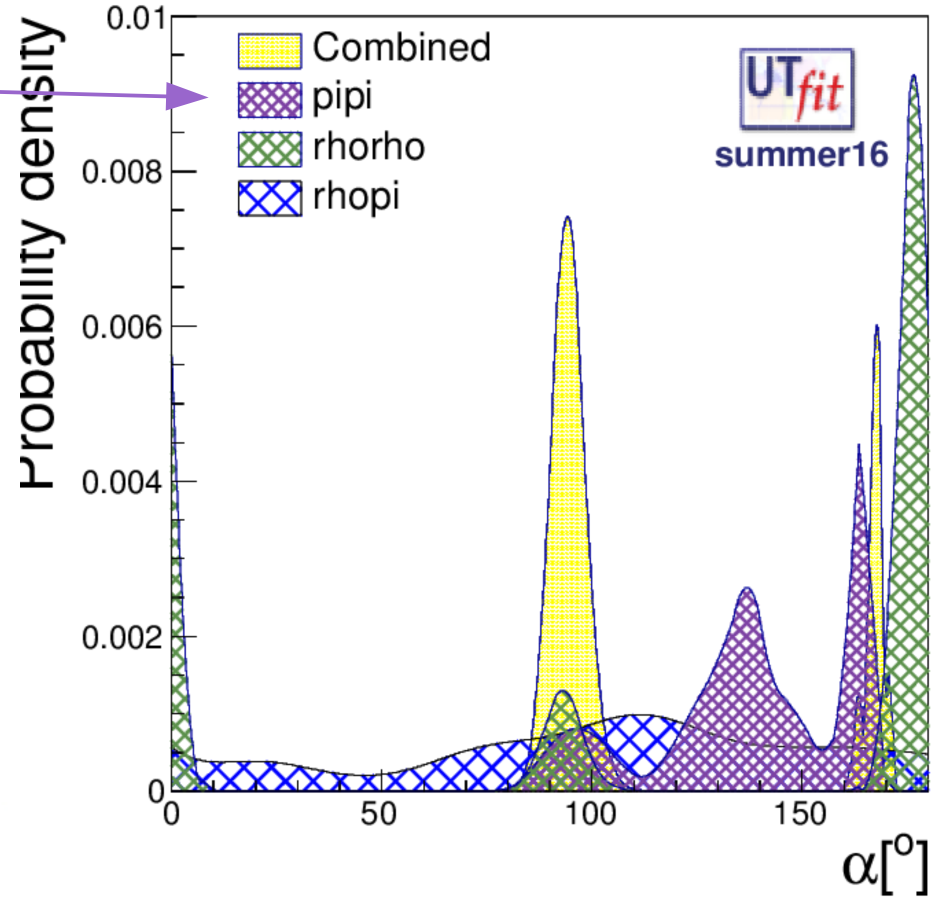
V_{ub} / V_{cb} *(LHCb)* = (8.3 ± 0.6) 10^{-2}

Average of the two FLAG Nf=2+1 averages:
- from B->D => 40.85(98) 10^{-3}
- from B->D* => 39.27(56)(49) 10^{-3}

sin2α (ϕ_2) from charmless B decays: pp, (ρρ, πρ)



$\pi^0\pi^0$ from Belle at CKM14



to be updated soon (?)

$BR(\pi^0\pi^0) = (1.17 \pm 0.13)\ 10^{-6}$

compared with a *à la PDG* average giving an inflated uncertainty of 0.41

α from ππ, ρρ, πρ decays:
combined: (94.2 ± 4.5) °