

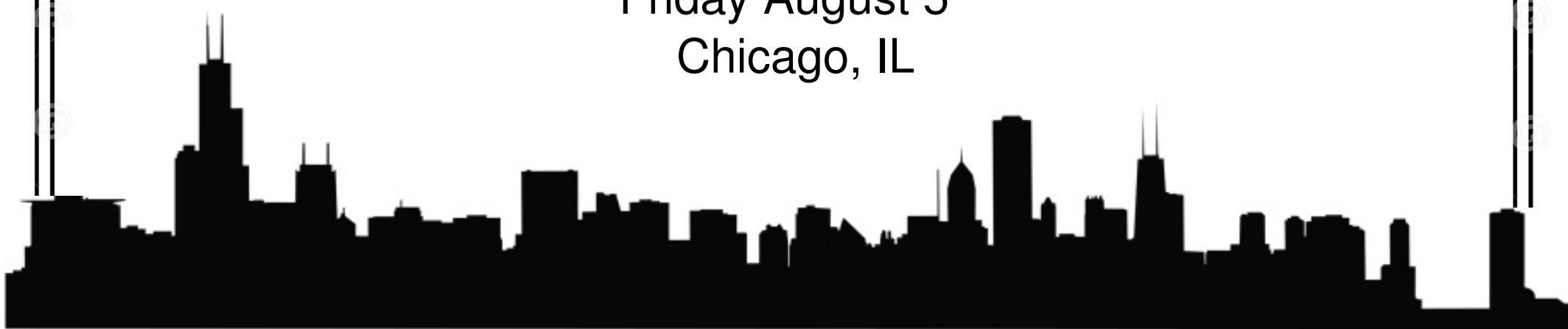
Unitarity Triangle analysis beyond the Standard Model

from UTfit 

Marcella Bona

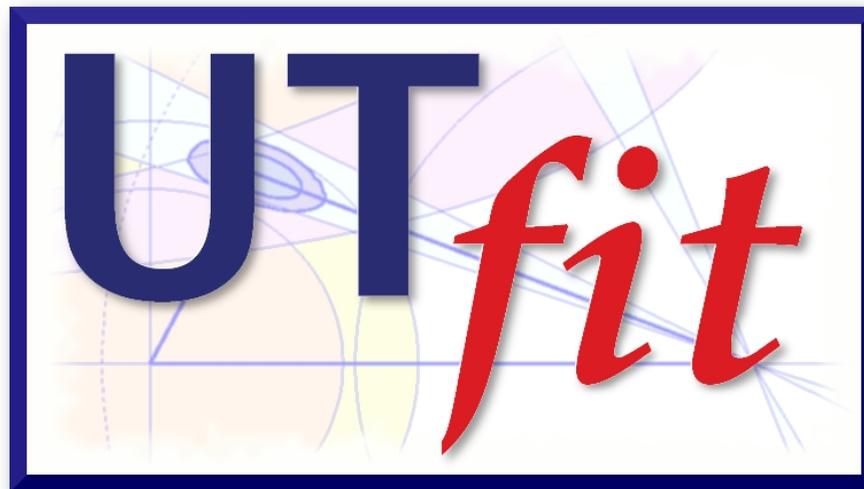
QMUL 

ICHEP 2016
Friday August 5th
Chicago, IL



Unitarity Triangle analysis beyond 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
- New Physics UT analysis:
 - model-independent analysis
 - provides limits on the allowed deviation from the SM
 - translate into a NP scale in the different sectors



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:

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

Bayes Theorem

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

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

$(b \rightarrow u)/(b \rightarrow c)$	$\bar{\rho}^2 + \bar{\eta}^2$	$\bar{\Lambda}, \lambda_1, F(1), \dots$
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
$A_{CP}(J/\psi K_S)$	$\sin 2\beta$	

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}

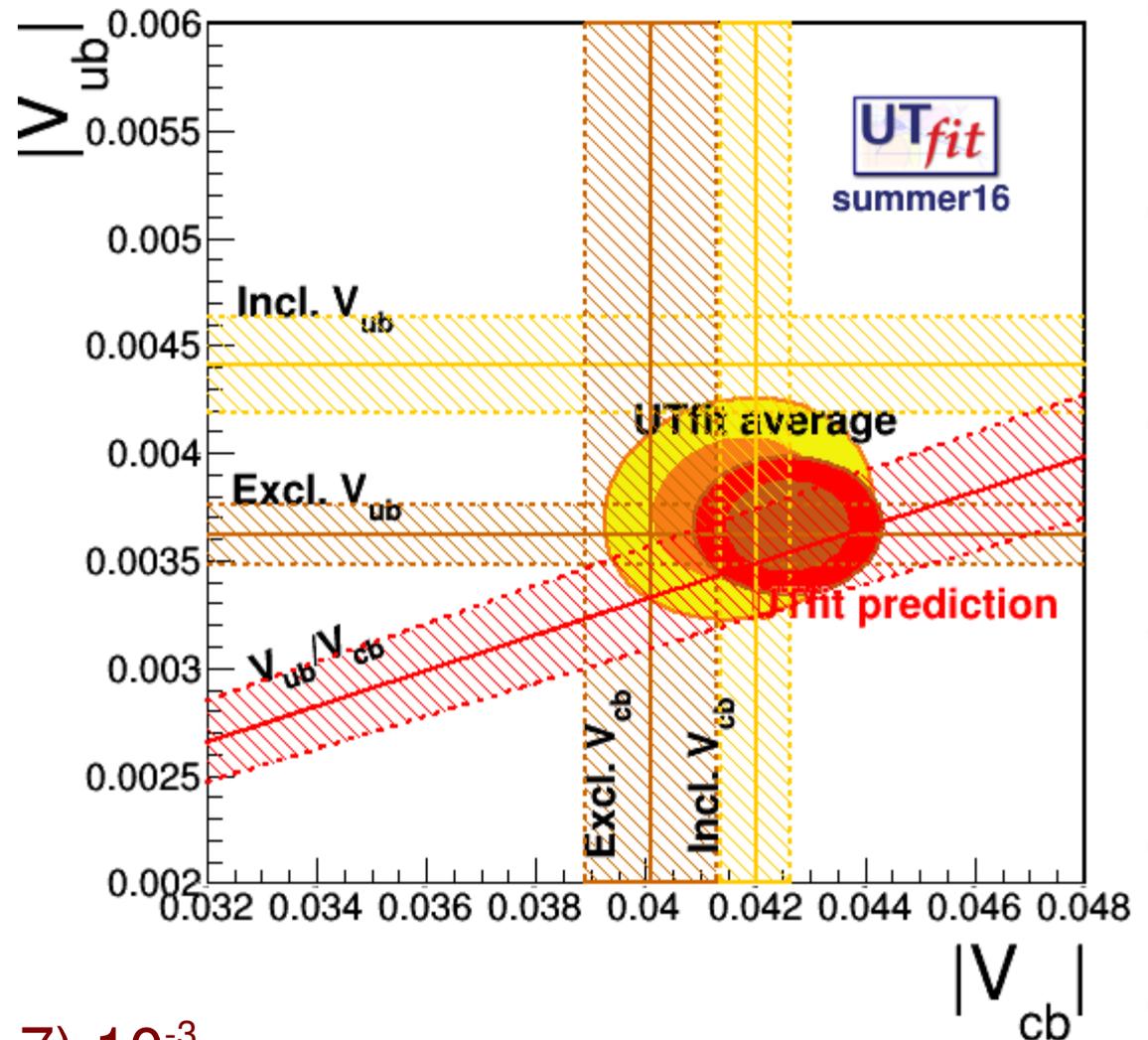
2D average inspired by D'Agostini skeptical procedure (hep-ex/9910036) with $\sigma=1$. Very similar results obtained from a 2D a la PDG procedure.

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

uncertainty $\sim 2.4\%$

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

uncertainty $\sim 5.6\%$

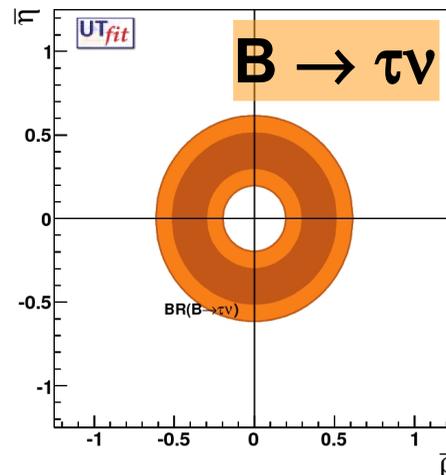
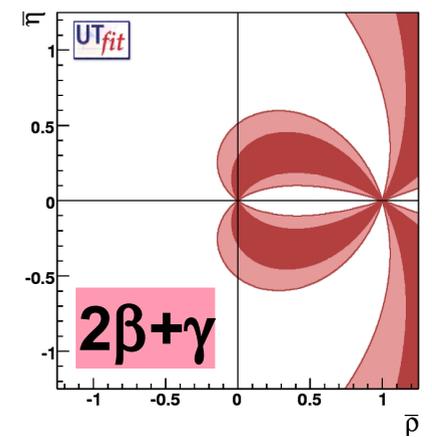
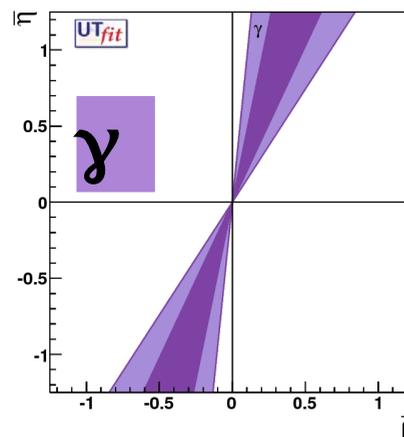
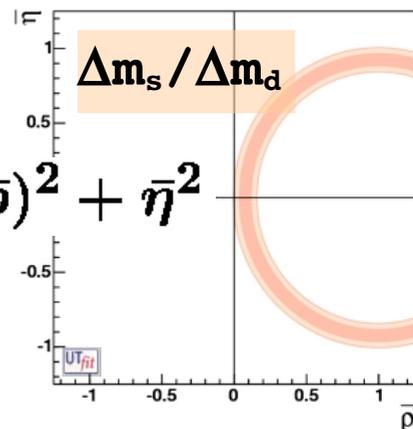
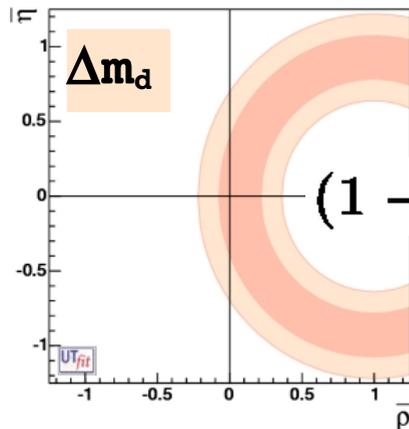
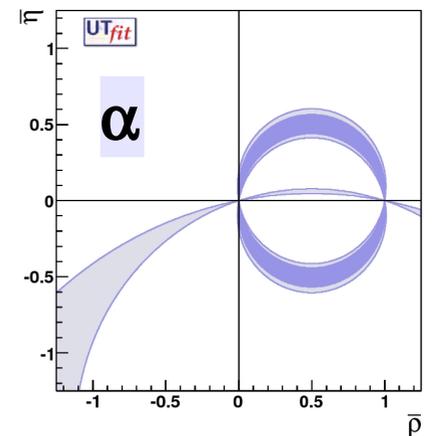
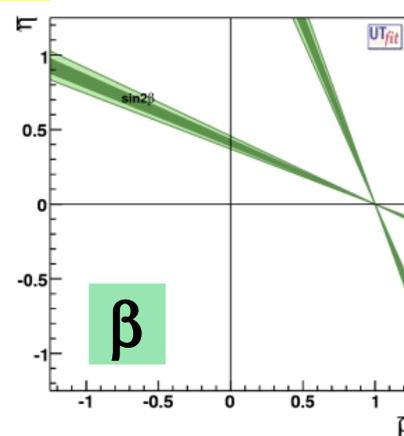
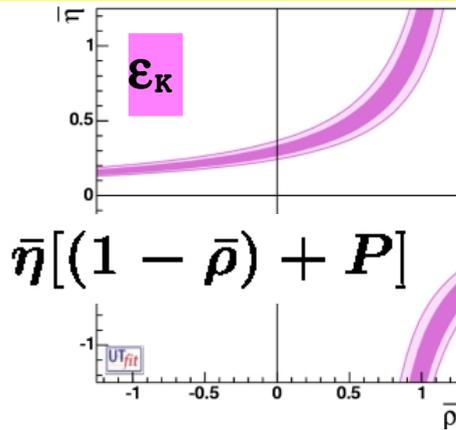
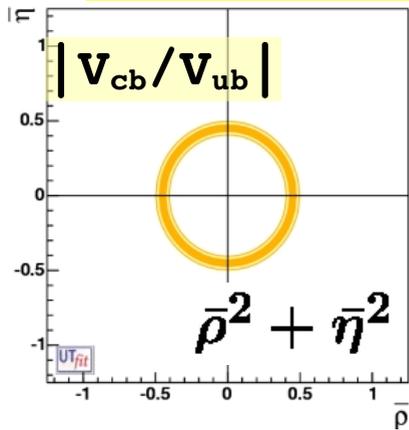


$$V_{cb} = (42.6 \pm 0.7) 10^{-3}$$

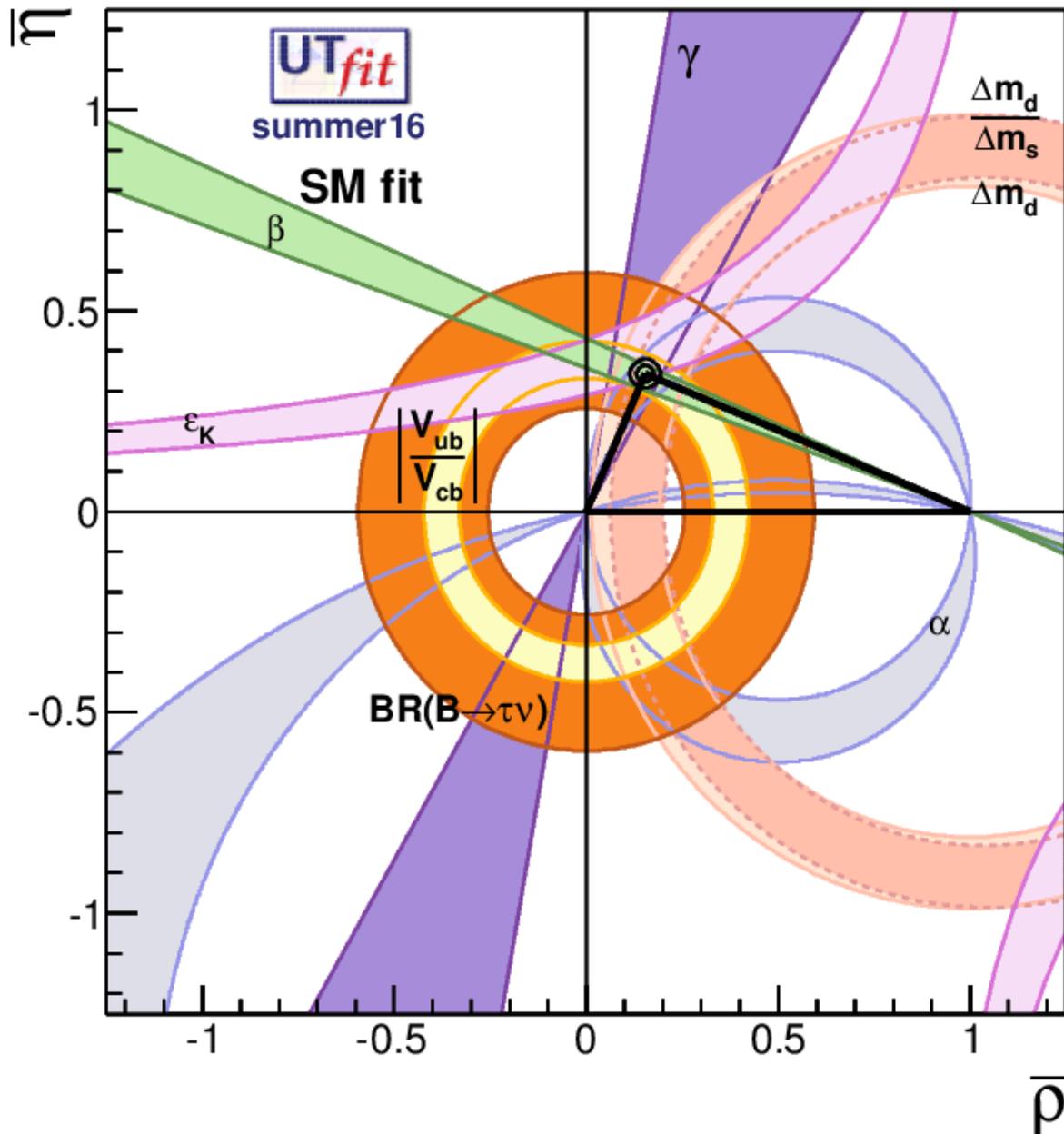
$$V_{ub} = (3.66 \pm 0.13) 10^{-3}$$

UTfit predictions

Unitarity Triangle analysis:



Unitarity Triangle analysis in the SM:



evels @
95% Prob

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

Unitarity Triangle analysis in the SM:

obtained excluding
the given constraint
from the fit

Observables	Measurement	Prediction	Pull ($\# \sigma$)
$\sin 2\beta$	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
$ V_{ub} \cdot 10^3$	3.74 ± 0.21	3.66 ± 0.11	< 1
$ V_{ub} \cdot 10^3$ (incl)	4.41 ± 0.22	–	~ 2.9
$ V_{ub} \cdot 10^3$ (excl)	3.62 ± 0.14	–	< 1
$ V_{cb} \cdot 10^3$	41.7 ± 1.0	42.6 ± 0.7	< 1
β_s	0.97 ± 0.94	1.05 ± 0.04	< 1
$\text{BR}(B \rightarrow \tau \nu)[10^{-4}]$	1.06 ± 0.20	0.81 ± 0.06	~ 1.2
$A_{\text{SL}}^d \cdot 10^3$	0.2 ± 2.0	-0.283 ± 0.024	< 1
$A_{\text{SL}}^s \cdot 10^3$	1.7 ± 3.0	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 $\Delta F=2$ transitions

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

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

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

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

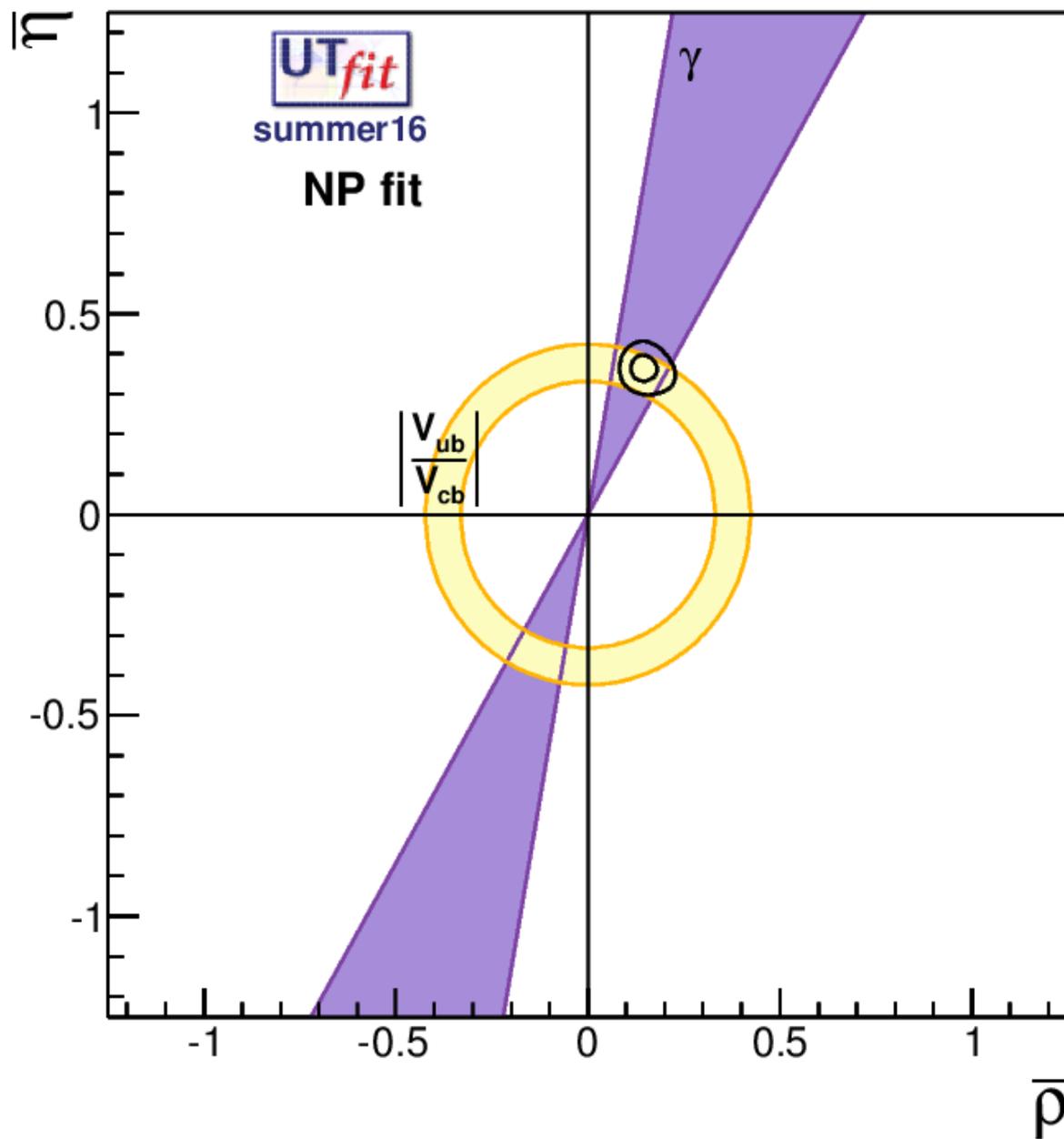
$$A_{SL}^q = \text{Im}(\Gamma_{12}^q / A_q)$$

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

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

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

NP analysis results



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

SM is

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

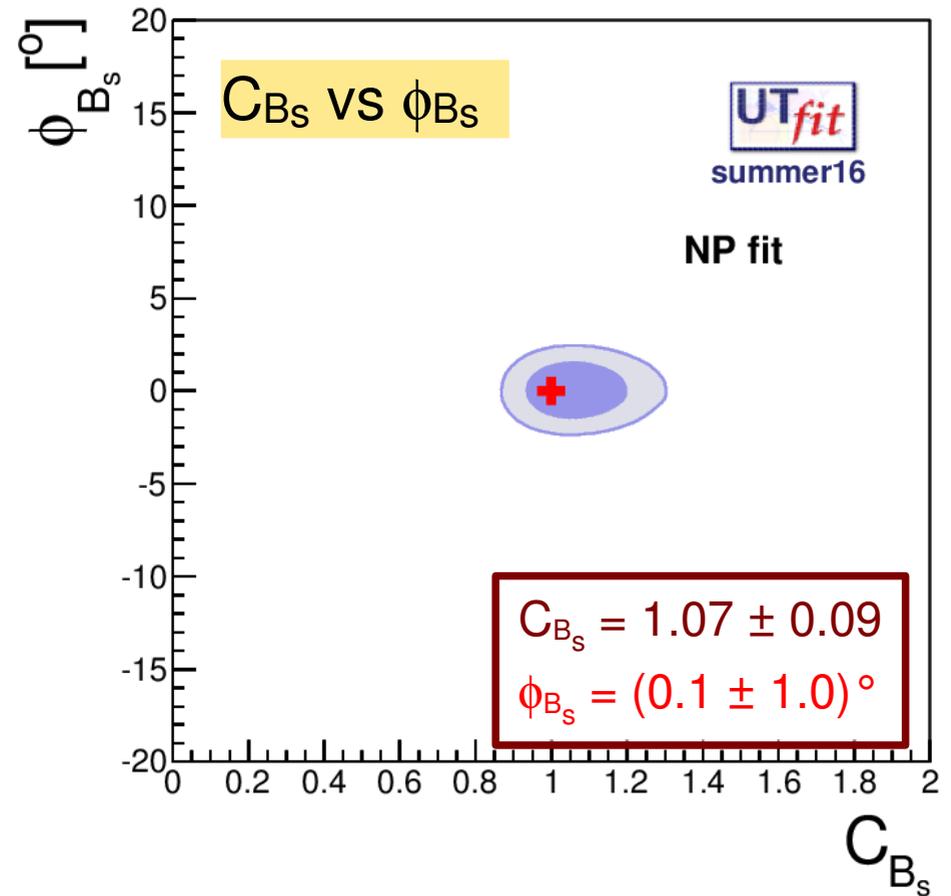
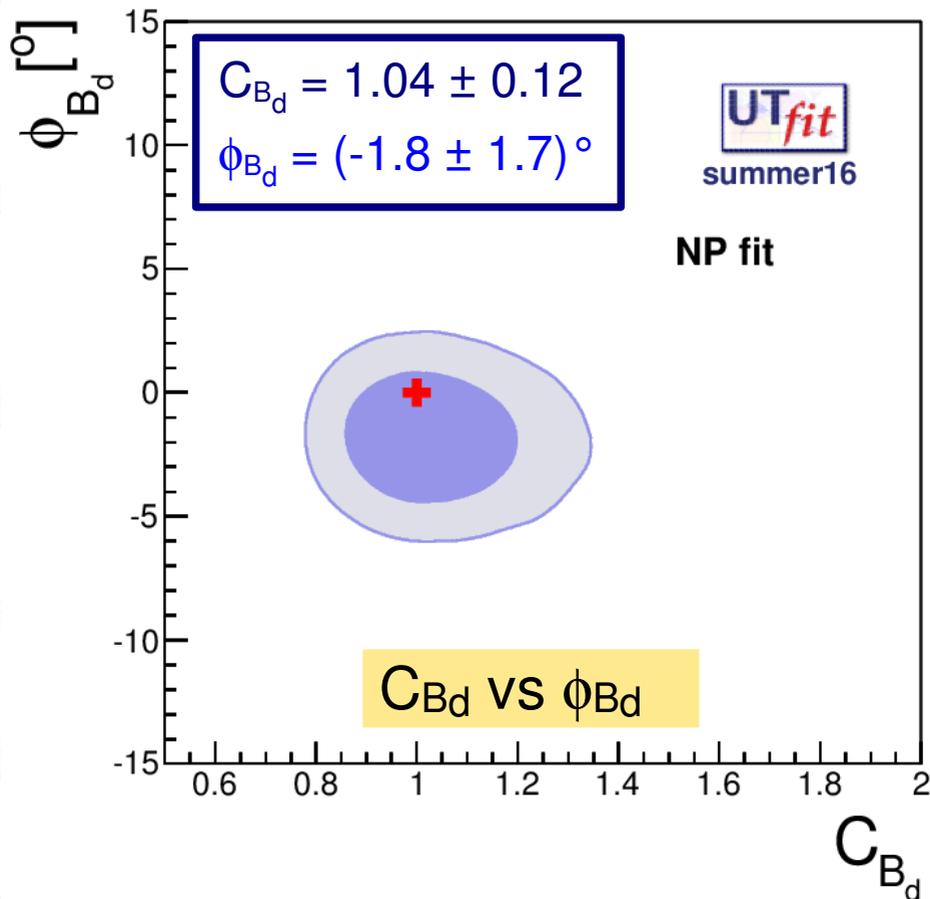
NP parameter results

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

K system

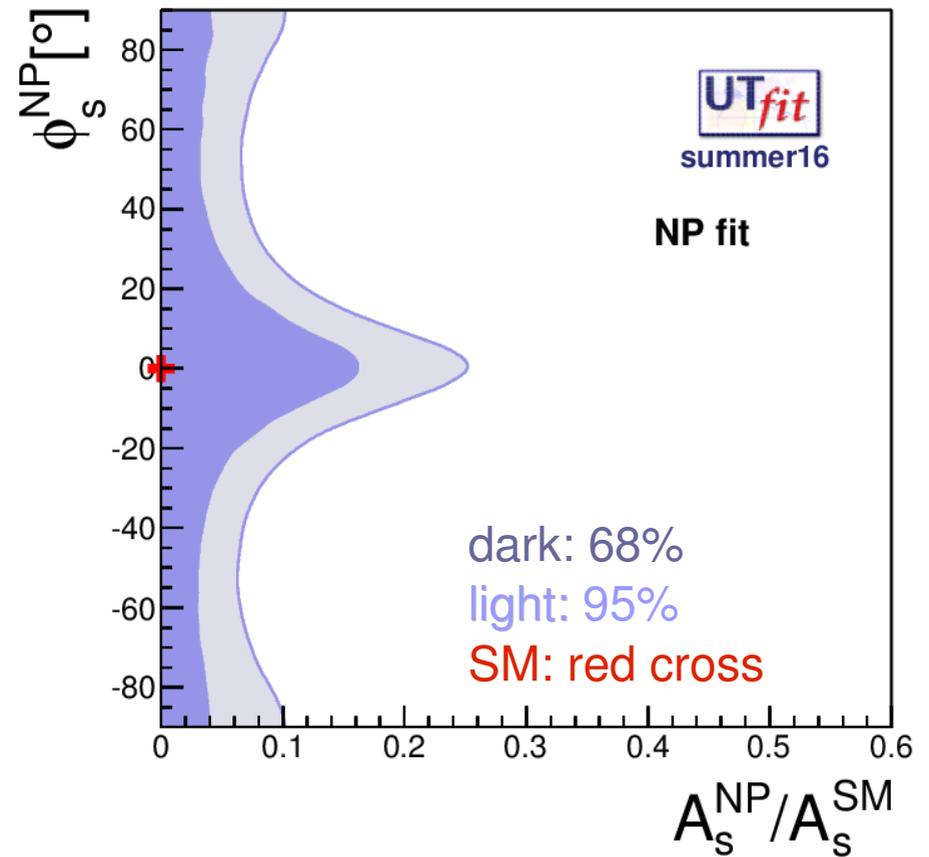
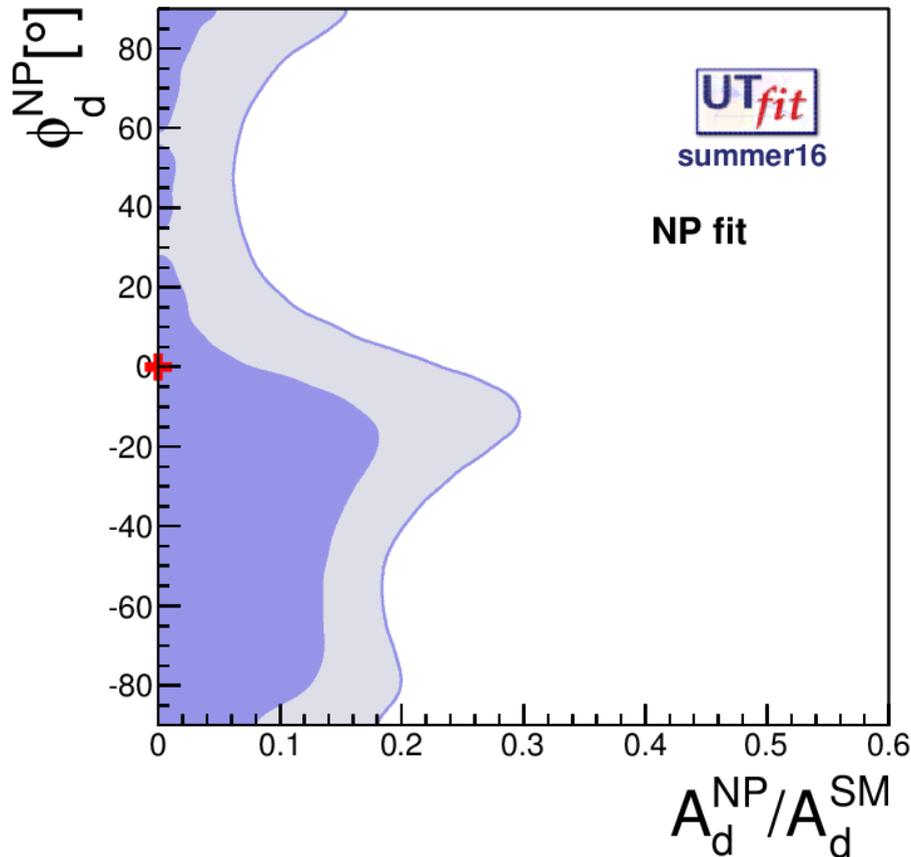
$$C_{\varepsilon_K} = 1.05 \pm 0.11$$

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



NP parameter results

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



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

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

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

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

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

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

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

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

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

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

effective BSM Hamiltonian for $\Delta F=2$ transitions

The Wilson coefficients C_i have in general the form

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

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 $\Delta F=2$ transitions)

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

$\alpha (L_i)$ is the coupling among NP and SM

- ⊙ $\alpha \sim 1$ for strongly coupled NP
- ⊙ $\alpha \sim \alpha_w (\alpha_s)$ 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

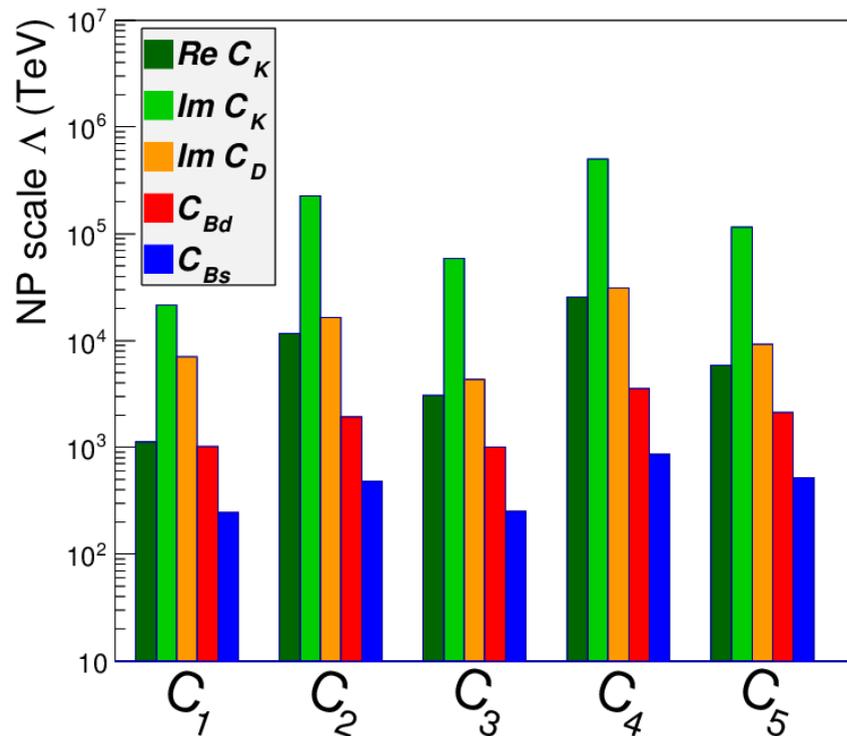
F_{SM} is the combination of CKM factors for the considered process

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

results from the Wilson coefficients

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

$\alpha \sim 1$ for strongly coupled NP



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

Non-perturbative NP

$$\Lambda > 5.0 \cdot 10^5 \text{ TeV}$$

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

$$\Lambda > 1.5 \cdot 10^4 \text{ TeV}$$

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,

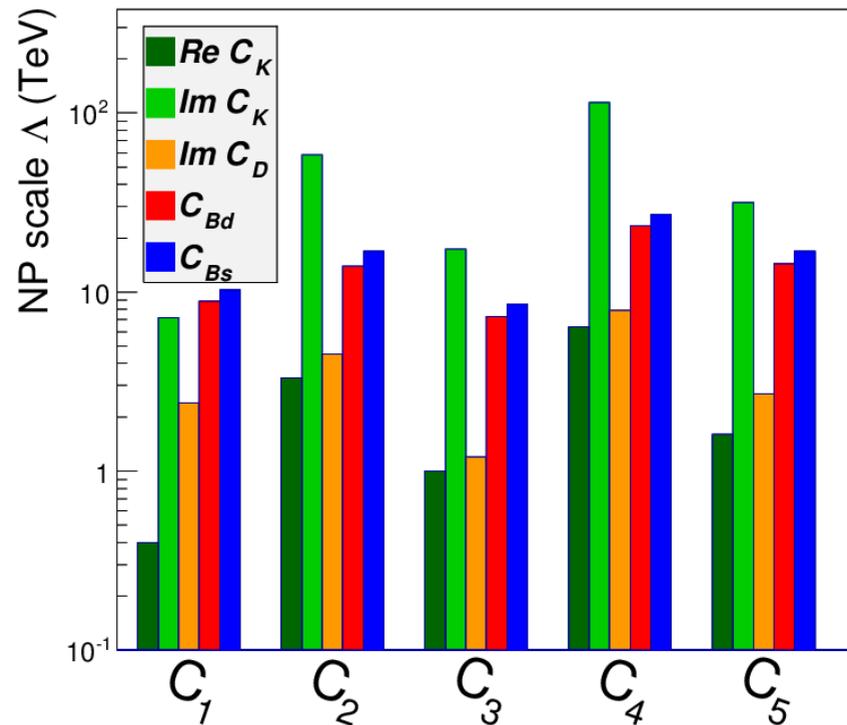
errors from both CKM

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 future

In the next decade, Belle-II and LHCb upgrade will push down the exp. error on $\sin 2\beta(s)$ to less than 0.01

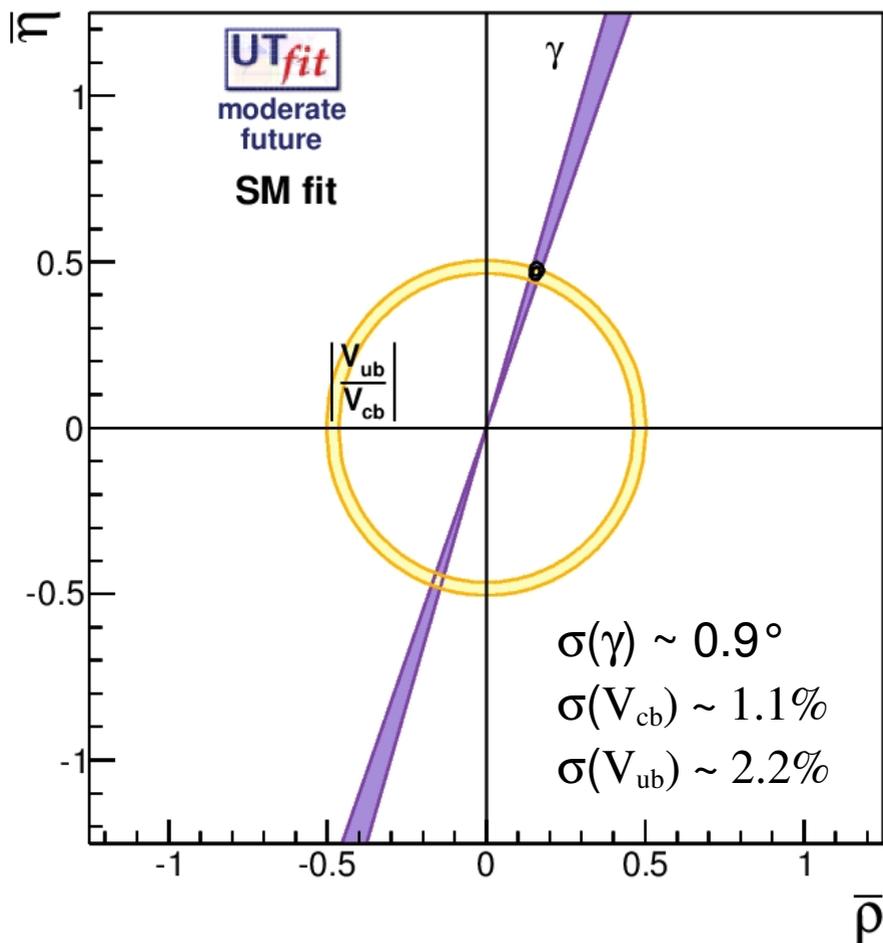
Theory error can be kept below 0.01 using control channels as $S(B \rightarrow J/\psi\pi)$

B-parameters will go below the % level, new ideas to attack long-distance in K and D

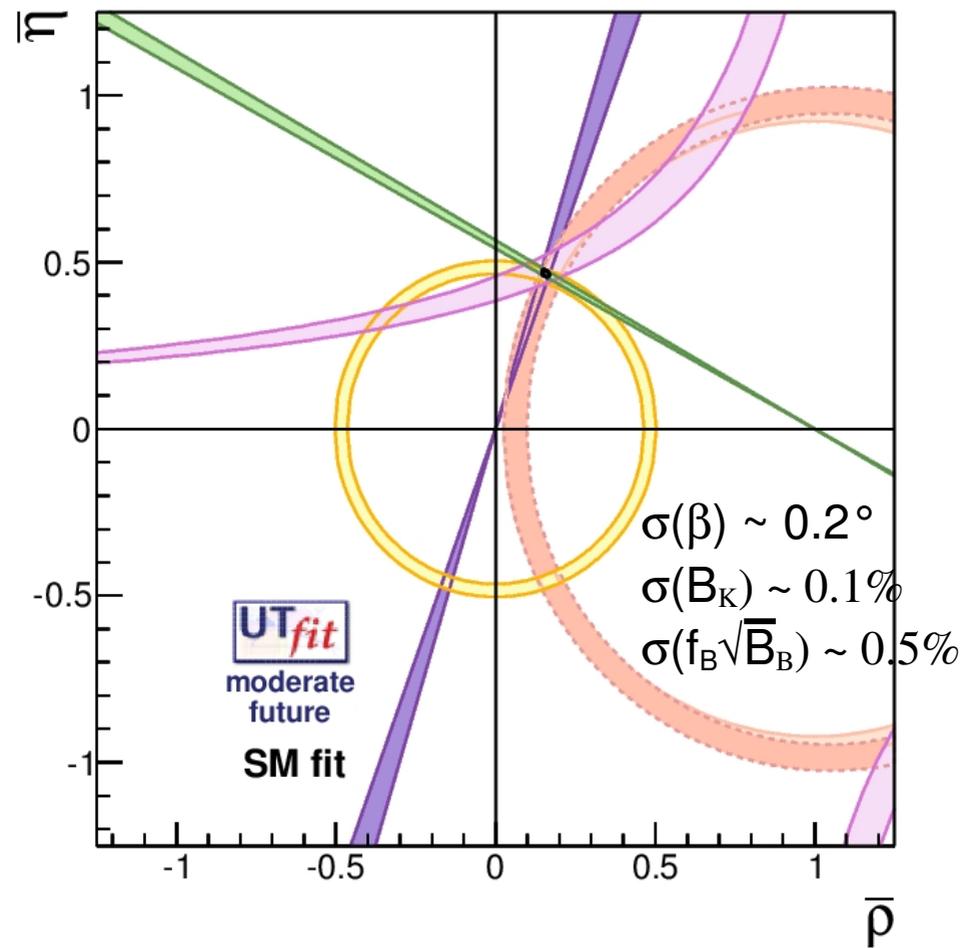
Improving γ , α and $|V_{cb}|$ & $|V_{ub}|$ crucial!

Look at the future

errors predicted from Belle II + LHCb upgrade



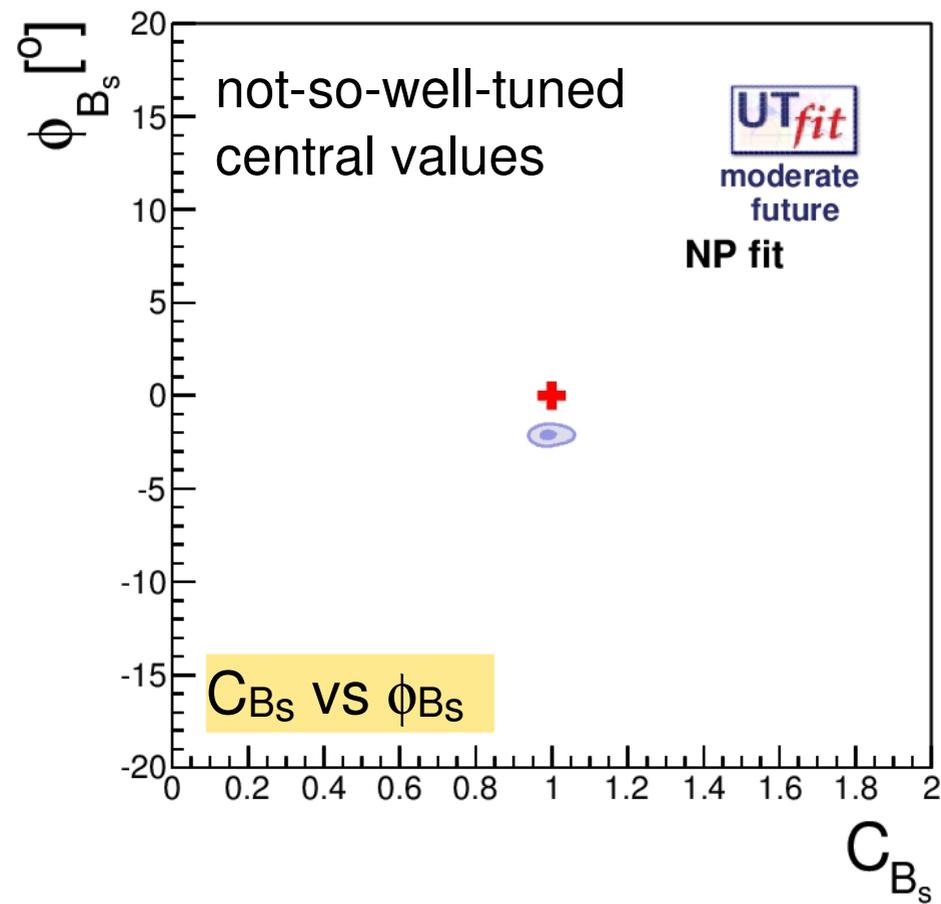
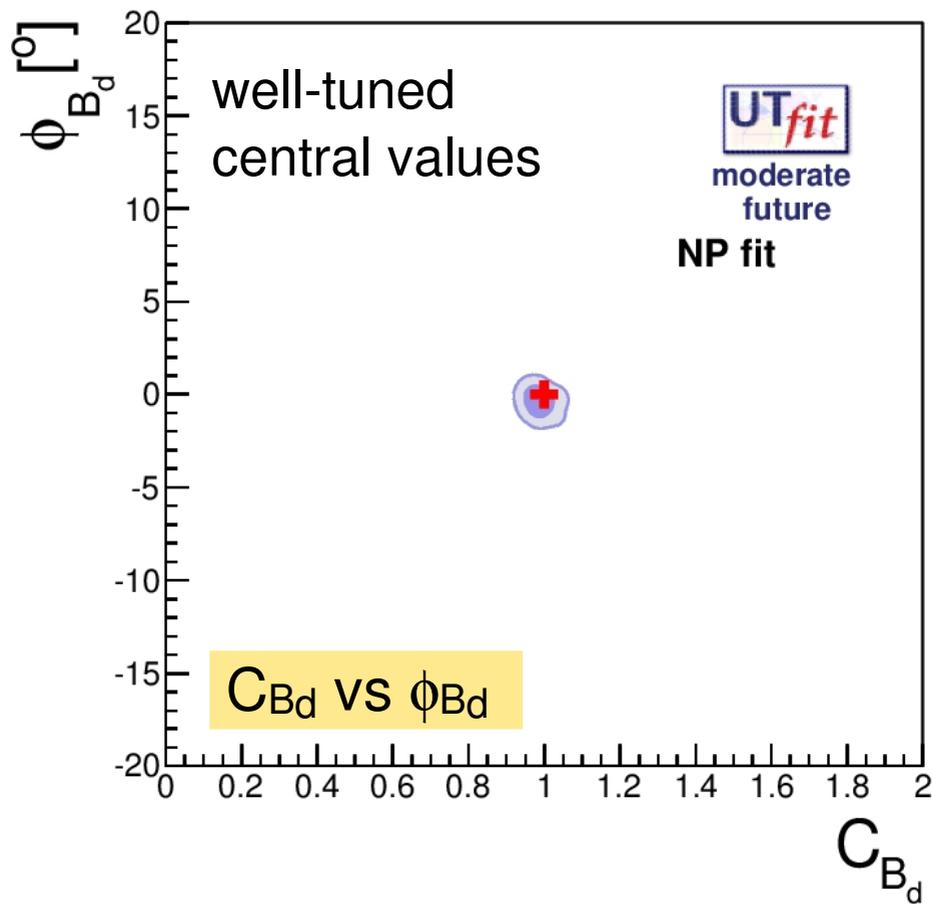
errors from tree-only fit on ρ and η :
 $\sigma(\rho) = 0.008$ [currently 0.050]
 $\sigma(\eta) = 0.010$ [currently 0.035]



errors from 5-constraint fit on ρ and η :
 $\sigma(\rho) = 0.005$ [currently 0.015]
 $\sigma(\eta) = 0.004$ [currently 0.013]

Look at the future

errors predicted from
Belle II + LHCb upgrade



errors on general NP parameters:

$$\sigma(C_{B_d}) = 0.03 \text{ [currently } 0.12\text{]}$$

$$\sigma(\phi_{B_d}) = 0.7 \text{ [currently } 1.7\text{]}$$

$$\sigma(C_{B_s}) = 0.03 \text{ [currently } 0.09\text{]}$$

$$\sigma(\phi_{B_s}) = 0.3 \text{ [currently } 1.0\text{]}$$

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

new-physics-specific constraints

B meson mixing matrix element NLO calculation
 Ciuchini et al. JHEP 0308:031,2003.

C_{pen} and ϕ_{pen} are
 parameterize possible
 NP contributions from
b \rightarrow s penguins

$$\frac{\Gamma_{12}^q}{A_q^{\text{full}}} = -2 \kappa C_{B_q} \left\{ e^{2\phi_{B_q}} \left(n_1 + \frac{n_6 B_2 + n_{11}}{B_1} \right) - \frac{e^{(\phi_q^{\text{SM}} + 2\phi_{B_q})}}{R_t^q} \left(n_2 + \frac{n_7 B_2 + n_{12}}{B_1} \right) + \frac{e^{2(\phi_q^{\text{SM}} + \phi_{B_q})}}{R_t^{q^2}} \left(n_3 + \frac{n_8 B_2 + n_{13}}{B_1} \right) + e^{(\phi_q^{\text{Pen}} + 2\phi_{B_q})} C_q^{\text{Pen}} \left(n_4 + n_9 \frac{B_2}{B_1} \right) - e^{(\phi_q^{\text{SM}} + \phi_q^{\text{Pen}} + 2\phi_{B_q})} \frac{C_q^{\text{Pen}}}{R_t^q} \left(n_5 + n_{10} \frac{B_2}{B_1} \right) \right\}$$

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

angular analysis as a function of proper time

and b-tagging

additional sensitivity from the $\Delta\Gamma_s$ terms

ϕ_s and $\Delta\Gamma_s$:
 from HFAG

contribution to the mixing amplitudes

analytic expression for the contribution to the mixing amplitudes

$$\langle \bar{B}_q | \mathcal{H}_{\text{eff}}^{\Delta B=2} | B_q \rangle_i = \sum_{j=1}^5 \sum_{r=1}^5 \left(b_j^{(r,i)} + \eta c_j^{(r,i)} \right) \eta^{a_j} C_i(\Lambda) \langle \bar{B}_q | Q_r^{bq} | B_q \rangle$$

Lattice QCD

arXiv:0707.0636: for "magic numbers" a, b and c , $\eta = \alpha_s(\Lambda)/\alpha_s(m_t)$
(numerical values updated last in summer'12)

analogously for the K system

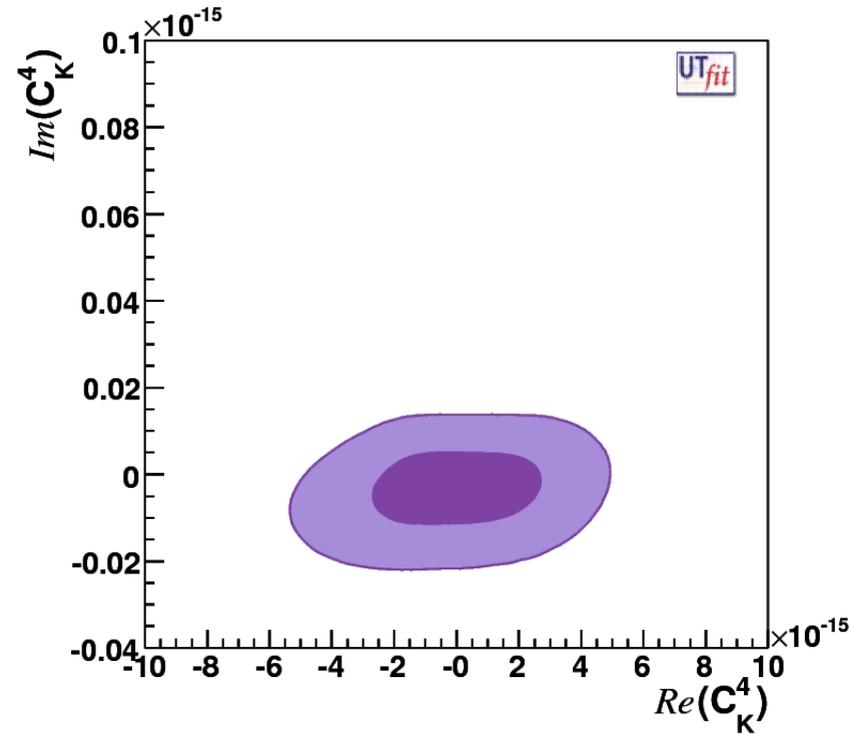
$$\langle \bar{K}^0 | \mathcal{H}_{\text{eff}}^{\Delta S=2} | K^0 \rangle_i = \sum_{j=1}^5 \sum_{r=1}^5 \left(b_j^{(r,i)} + \eta c_j^{(r,i)} \right) \eta^{a_j} C_i(\Lambda) R_r \langle \bar{K}^0 | Q_1^{sd} | K^0 \rangle$$

To obtain the p.d.f. for the Wilson coefficients $C_i(\Lambda)$ at the new-physics scale, we switch on **one coefficient at a time** in each sector and calculate its value from the result of the NP analysis.

Results from the Wilson coefficients

the results obtained for the flavour scenarios:
 In deriving the lower bounds on the NP scale, we assume $L_i = 1$,
 corresponding to strongly-interacting and/or tree-level NP.

Parameter	95% allowed range	Lower limit on Λ (TeV)	
	(GeV ⁻²)	for arbitrary NP	for NMFV
$\text{Re}C_K^1$	$[-9.6, 9.6] \cdot 10^{-13}$	$1.0 \cdot 10^3$	0.35
$\text{Re}C_K^2$	$[-1.8, 1.9] \cdot 10^{-14}$	$7.3 \cdot 10^3$	2.0
$\text{Re}C_K^3$	$[-6.0, 5.6] \cdot 10^{-14}$	$4.1 \cdot 10^3$	1.1
$\text{Re}C_K^4$	$[-3.6, 3.6] \cdot 10^{-15}$	$17 \cdot 10^3$	4.0
$\text{Re}C_K^5$	$[-1.0, 1.0] \cdot 10^{-14}$	$10 \cdot 10^3$	2.4
$\text{Im}C_K^1$	$[-4.4, 2.8] \cdot 10^{-15}$	$1.5 \cdot 10^4$	5.6
$\text{Im}C_K^2$	$[-5.1, 9.3] \cdot 10^{-17}$	$10 \cdot 10^4$	28
$\text{Im}C_K^3$	$[-3.1, 1.7] \cdot 10^{-16}$	$5.7 \cdot 10^4$	19
$\text{Im}C_K^4$	$[-1.8, 0.9] \cdot 10^{-17}$	$24 \cdot 10^4$	62
$\text{Im}C_K^5$	$[-5.2, 2.8] \cdot 10^{-17}$	$14 \cdot 10^4$	37



To obtain the lower bound for loop-mediated contributions,
 one simply multiplies the bounds by $\alpha_s \sim 0.1$ or by $\alpha_w \sim 0.03$.

$\sin 2\alpha(\phi_2)$ from charmless B decays: $\pi\pi$, $\rho\rho$, $\pi\rho$

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

to be updated soon (?)

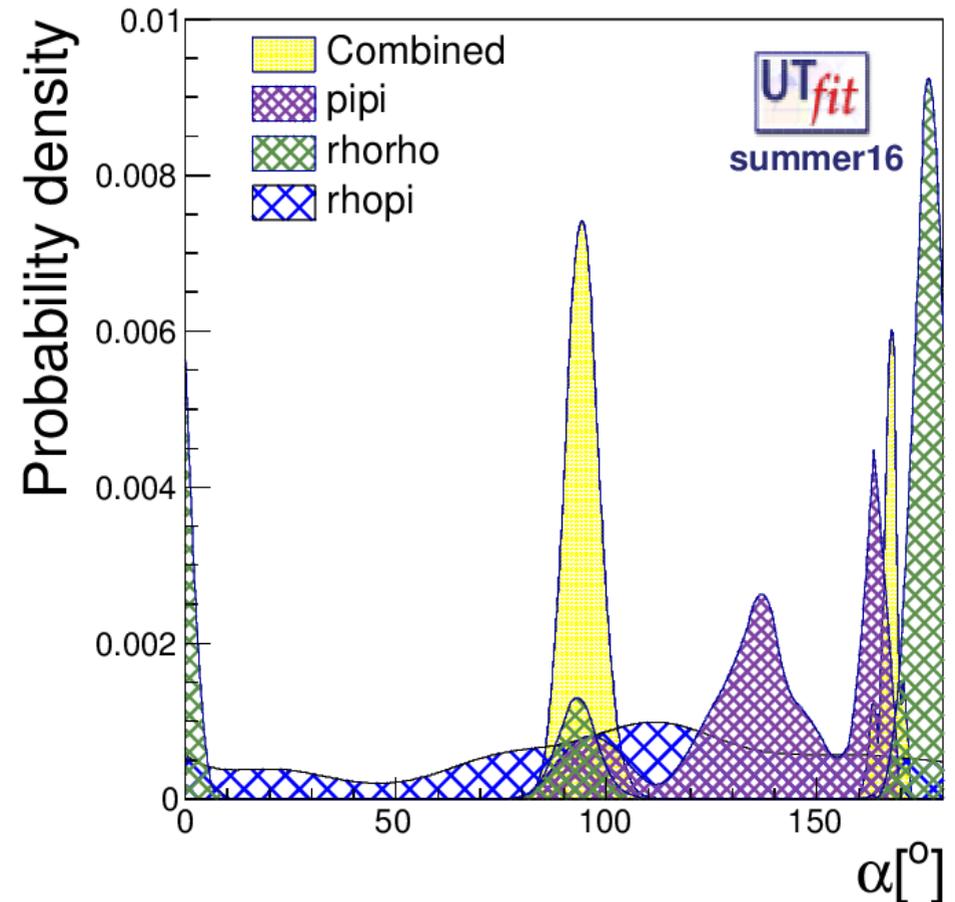
$$\text{BR}(\pi^0\pi^0) = (1.17 \pm 0.13) 10^{-6}$$

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

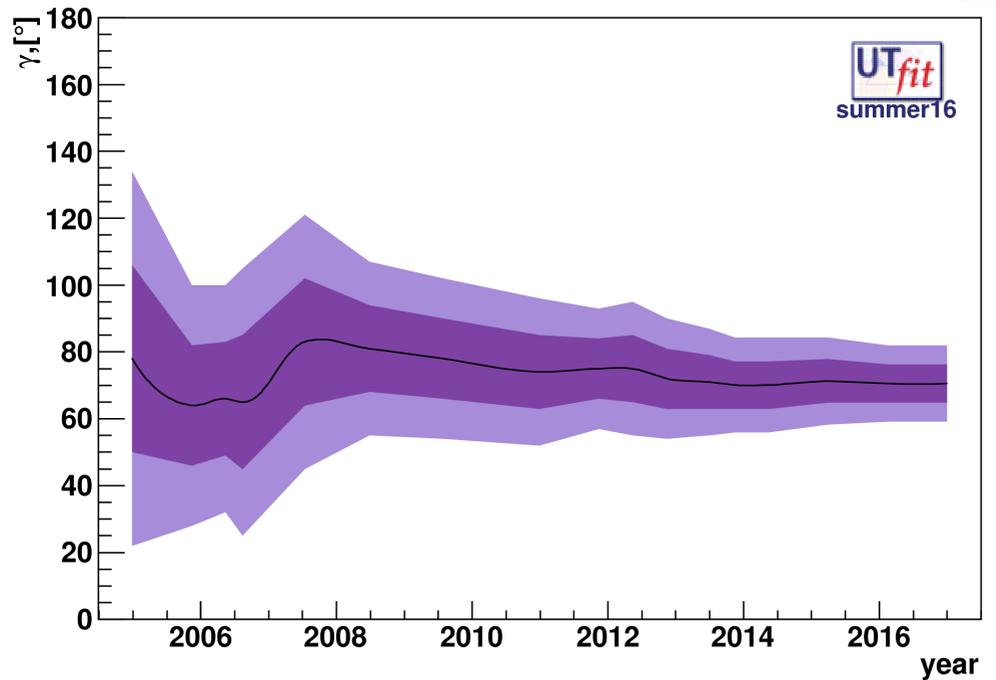
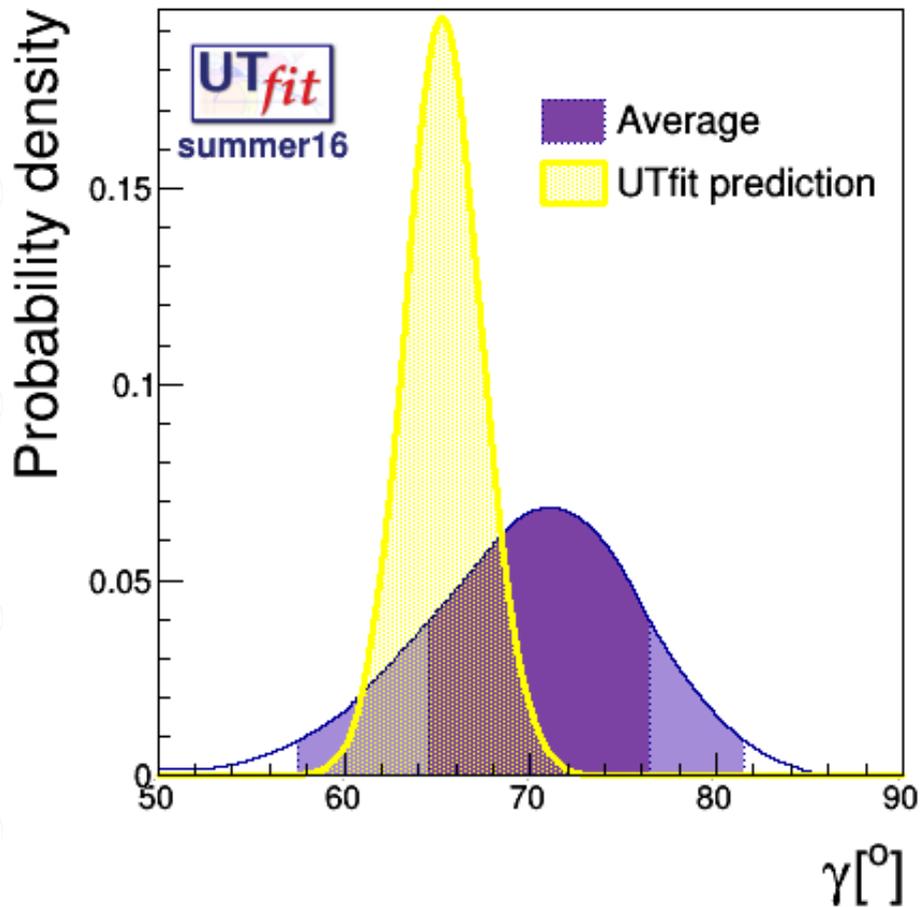


α from $\pi\pi$, $\rho\rho$, $\pi\rho$ decays:

combined: $(94.2 \pm 4.5)^\circ$

UTfit prediction: $(90.9 \pm 2.5)^\circ$

γ and DK trees



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

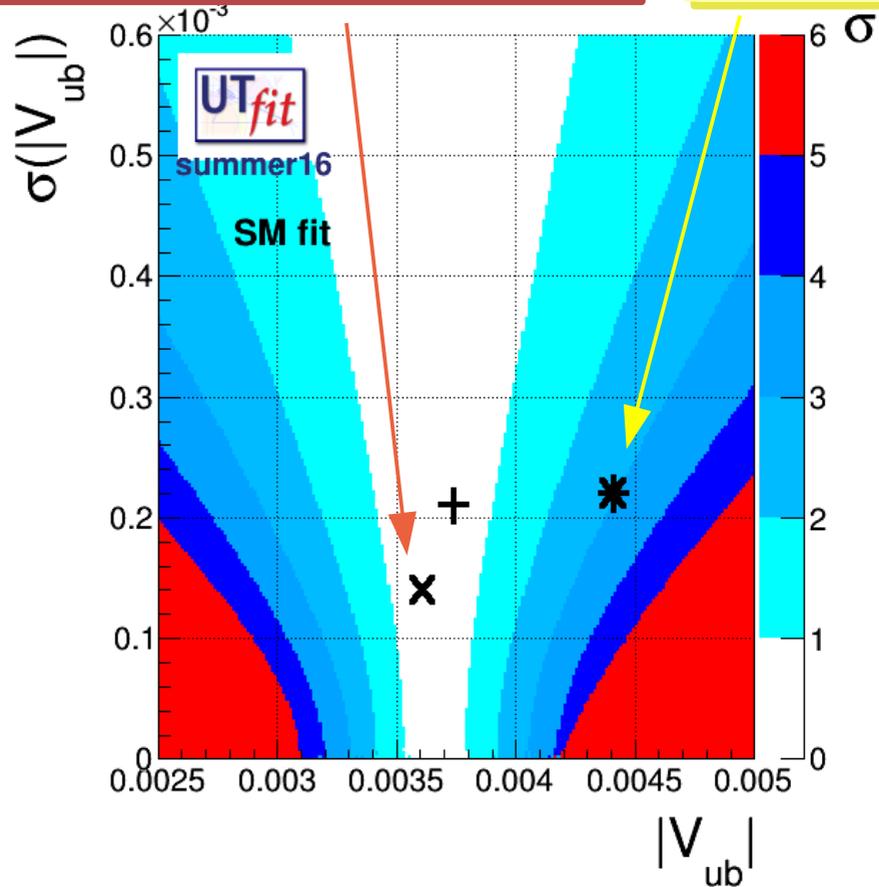
combined: $(70.5 \pm 5.7)^\circ$

UTfit prediction: $(65.4 \pm 2.1)^\circ$

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

$$V_{ub} (excl) = (3.62 \pm 0.14) 10^{-3}$$

$$V_{ub} (incl) = (4.41 \pm 0.22) 10^{-3}$$



$$V_{ub_{exp}} = (3.74 \pm 0.21) \cdot 10^{-3}$$

$$V_{ub_{UTfit}} = (3.66 \pm 0.11) \cdot 10^{-3}$$

$\sim 1.2\sigma$

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

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

