Flavour physics as a test of the standard model and a probe of new physics

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Future flavours: Prospects for beauty, charm and tau physics, ICTS, Bangalore, India and Online

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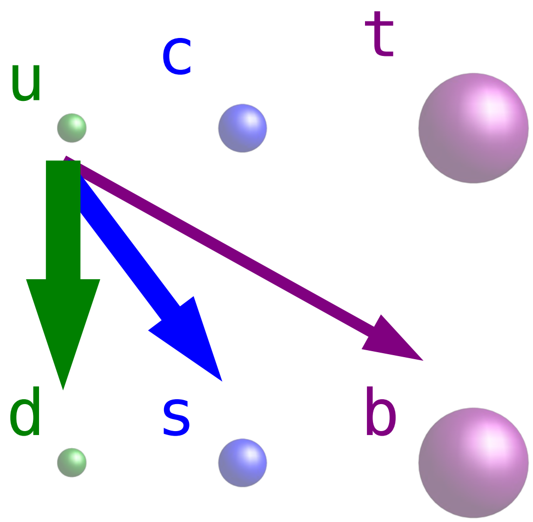
Outline

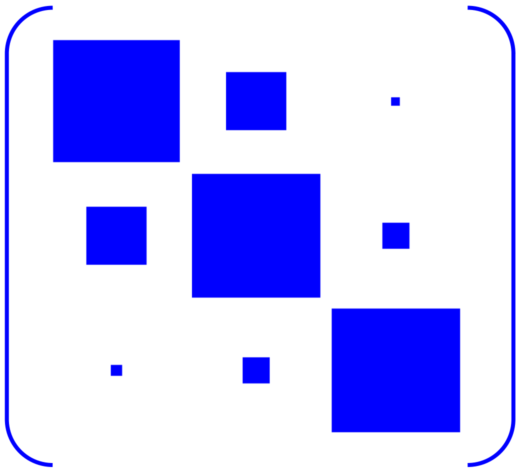
- General Introduction:
  - motivations
  - the tool: the Unitarity Triangle fit
- Standard Model fit
  - SM constraints
  - checking for tensions
  - SM predictions
- Beyond the Standard Model:
  - model-independent analysis
  - NP-specific constraints
  - New-physics scale analysis

Flavour mixing and CP violation in the Standard Model

- The CP symmetry is violated in any field theory having in the Lagrangian at least one phase that cannot be re-absorbed
- The **mass eigenstates** are not eigenstates of the weak interaction. This feature of the Standard Model Hamiltonian produces the (unitary) **mixing matrix** V_{CKM}.

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \approx \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\bar{\rho}-i\bar{\eta}) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\bar{\rho}-i\bar{\eta}) & -A\lambda^2 & 1 \end{pmatrix}$$





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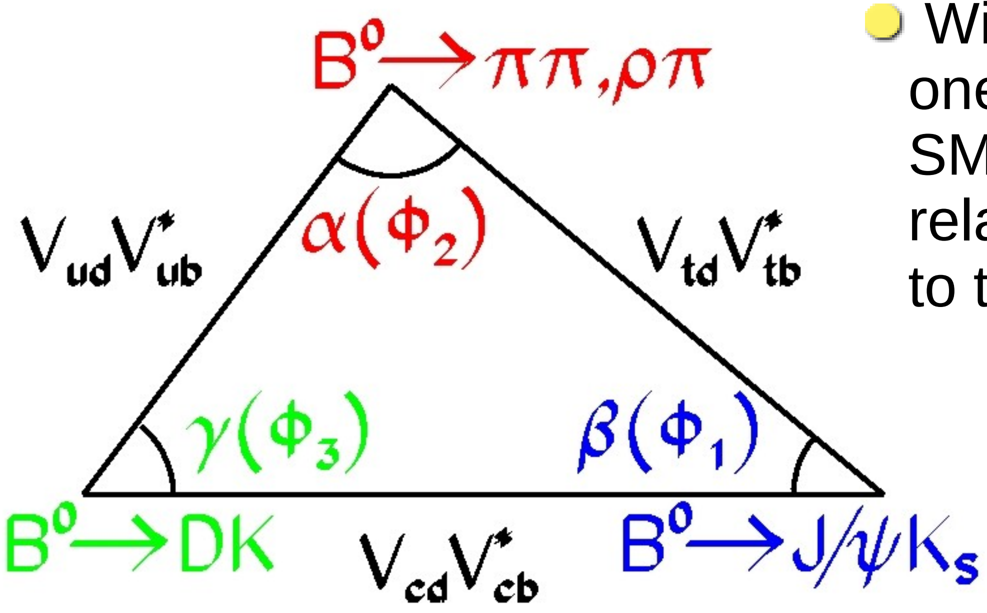


- With three families of quarks, there is one phase that allows CP violation in the SM. All the flavour mixing processes are related (through the unitarity of the V_{CKM}) to this phase.

Unitarity Triangle

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

All the angles are related to the CP asymmetries of specific B decays

CKM matrix and Unitarity Triangle

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

many observables
functions of $\bar{\rho}$ and $\bar{\eta}$:
overconstraining

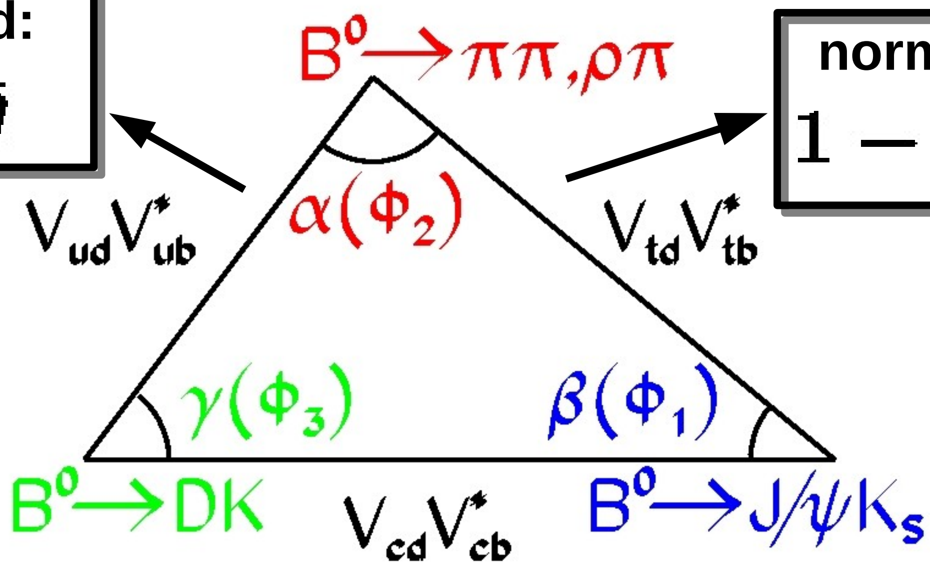
$$\alpha = \pi - \beta - \gamma$$

normalized:

$$\bar{\rho} + i\bar{\eta}$$

normalized:

$$1 - \bar{\rho} - i\bar{\eta}$$



$$\gamma = atan\left(\frac{\bar{\eta}}{\bar{\rho}}\right)$$

$$\beta = atan\left(\frac{\bar{\eta}}{(1-\bar{\rho})}\right)$$

UTfit

RELOADED

www.utfit.org

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

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

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

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

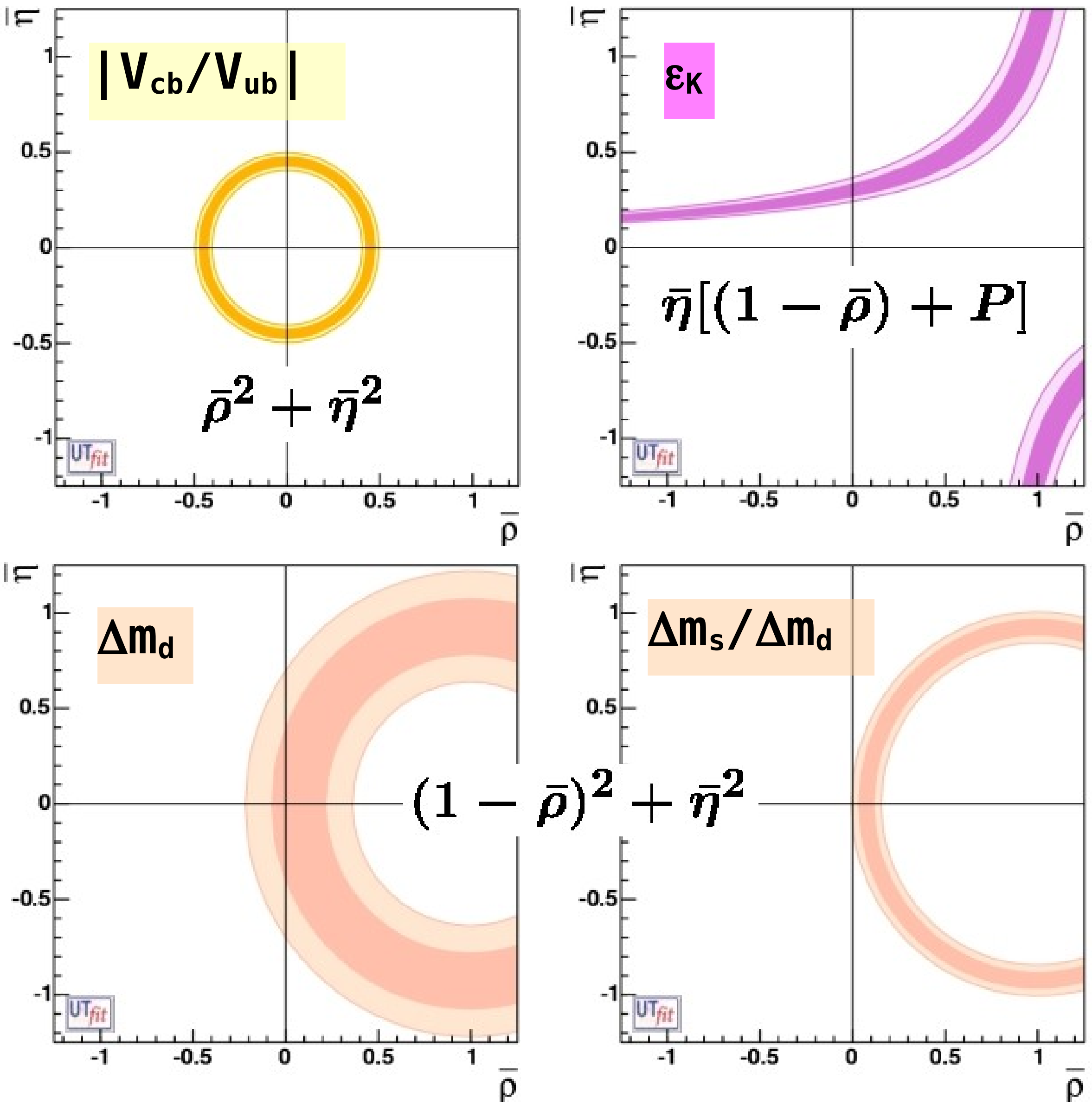
$(b\to u)/(b\to c)$	$\bar{\rho}^2+\bar{\eta}^2$	$\bar{\Lambda},\lambda_1,F(1),\ ...$
ϵ_K	$\bar{\eta}[(1-\bar{\rho})+P]$	B_K }
Δm_d	$(1-\bar{\rho})^2+\bar{\eta}^2$	$f_B^2 B_B$
$\Delta m_d/\Delta m_s$	$(1-\bar{\rho})^2+\bar{\eta}^2$	ξ
$A_{CP}(J/\psi K_S)$	$\sin 2\beta$	

, **mt**

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

The LEP-style analysis in the $\bar{\rho}$-$\bar{\eta}$ plane:



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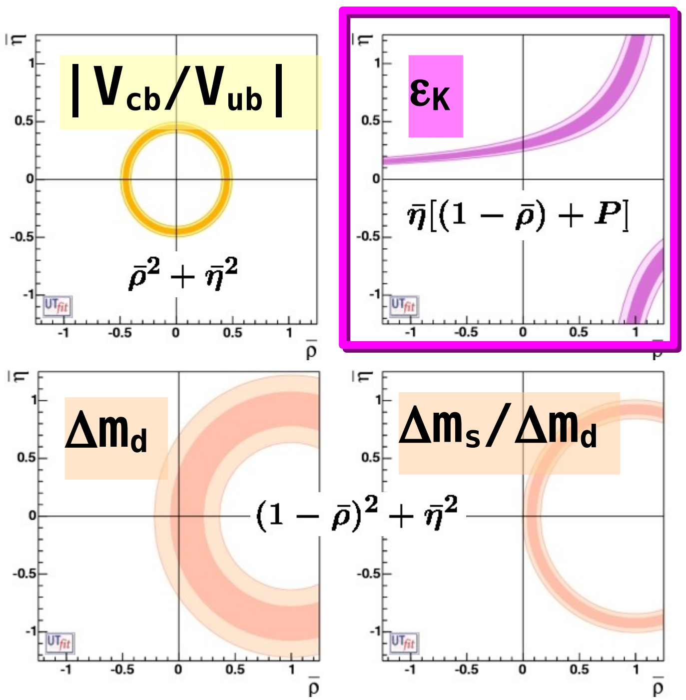
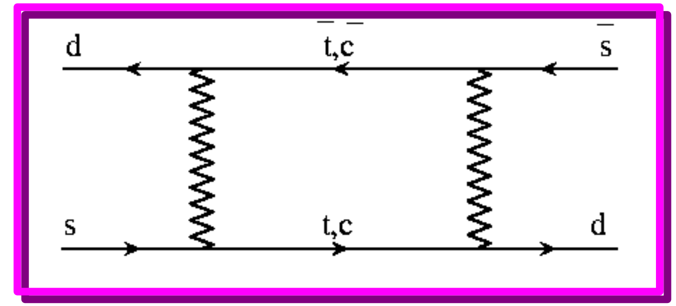


ε_K from $\bar{K}$-K mixing



$\varepsilon_K = (2.228 \pm 0.011) \cdot 10^{-3}$

PDG

$$B_K = \frac{<K|J_\mu J^\mu|\bar{K}>}{<K|J_\mu|0><0|J^\mu|\bar{K}>}$$

$B_K = 0.756 \pm 0.016$

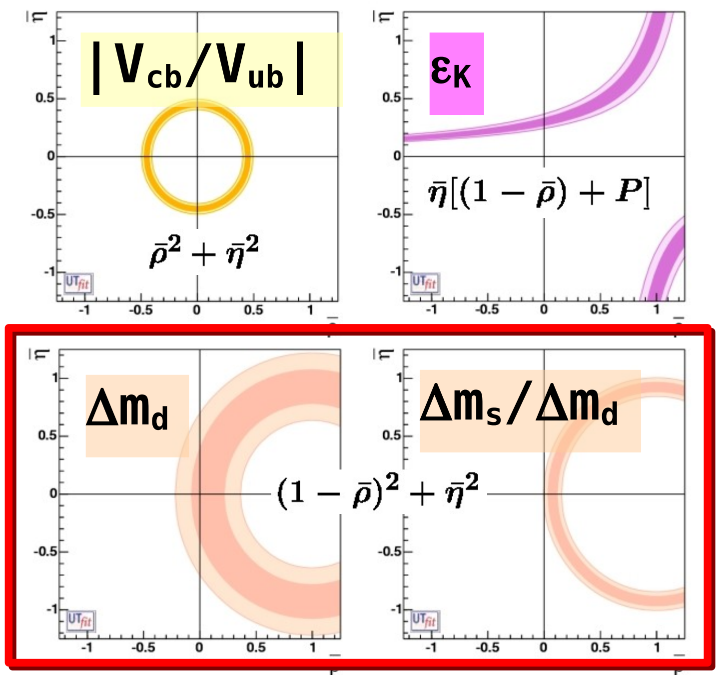
FLAG 2019

from lattice QCD

$$|\varepsilon_K| = C_\varepsilon B_K A^2 \lambda^6 \bar{\eta}\{-\eta_1 S_0(x_c)(1-\lambda^2/2) + \eta_3 S_0(x_c, x_t) + \eta_2 S_0(x_t) A^2 \lambda^4 (1-\bar{\rho})\}$$

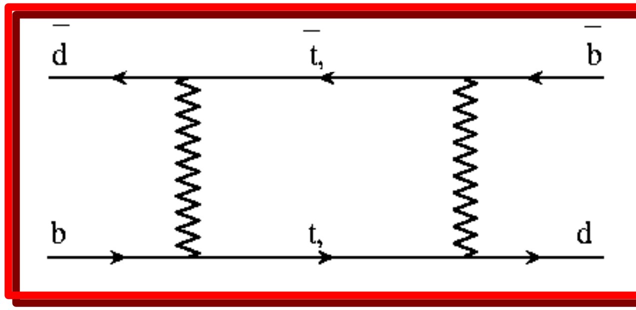
S_0 = Inami-Lim functions for c-c, c-t, e t-t contributions
(from perturbative calculations)

The LEP-style analysis in the $\bar{\rho}$-$\bar{\eta}$ plane:



Δm_q from $\bar{B}_q$-B_q mixing

q=d.s



$\Delta m_d = 0.5065 \pm 0.0019\ ps^{-1}$ HFLAV

$\Delta m_S = 17.765 \pm 0.006\ ps^{-1}$ HFLAV

$$\Delta m_d = \frac{G_F^2}{6\pi^2} m_W^2 \eta_b S(x_t) m_{B_d} f_{B_d}^2 \hat{B}_{B_d} |V_{tb}|^2 |V_{td}|^2 = $$

$$= \frac{G_F^2}{6\pi^2} m_W^2 \eta_b S(x_t) m_{B_d} f_{B_d}^2 \hat{B}_{B_d} |V_{cb}|^2 \lambda^2 ((1-\bar{\rho})^2 + \bar{\eta}^2)$$

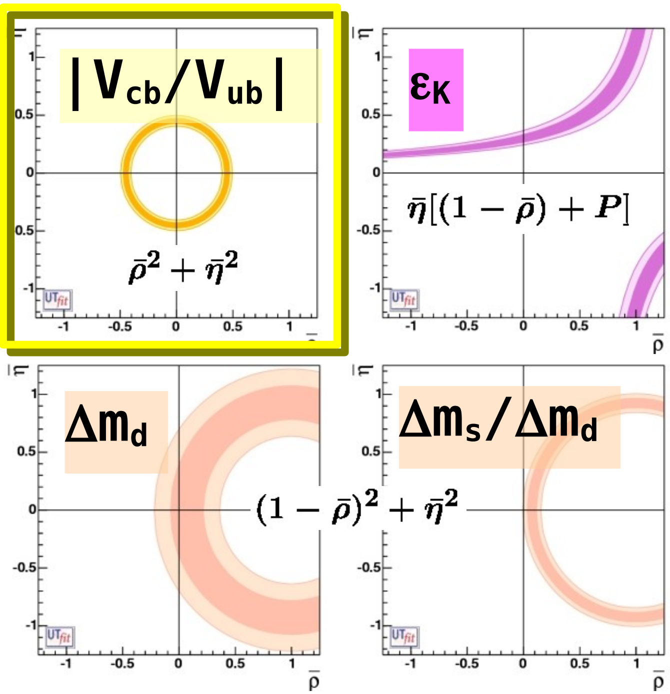
$$\Delta m_d \approx [(1-\rho)^2 + \eta^2] \frac{f_{B_s}^2 B_{B_s}}{\xi^2}$$

$$\Delta m_s \approx f_{B_s}^2 B_{B_s}$$

S = Inami-Lim function
for the t-t contribution
(from perturbative calculations)

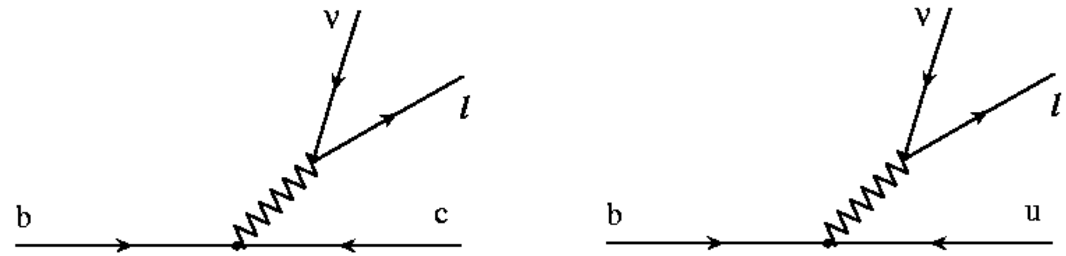
B_{B_q} and f_{B_q} from lattice QCD

The LEP-style analysis in the $\bar{\rho}$-$\bar{\eta}$ plane:



$$\left|\frac{V_{ub}}{V_{cb}}\right| = \frac{\lambda}{1 - \frac{\lambda^2}{2}} \sqrt{\bar{\rho}^2 + \bar{\eta}^2}$$

$|V_{ub}/V_{cb}|$



tree diagrams
b → c and b → u transition

- negligible new physics contributions
- inclusive and exclusive semileptonic B decay branching ratios

QCD corrections to be included

- inclusive measurements: OPE
- exclusive measurements: form factors from lattice QCD

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

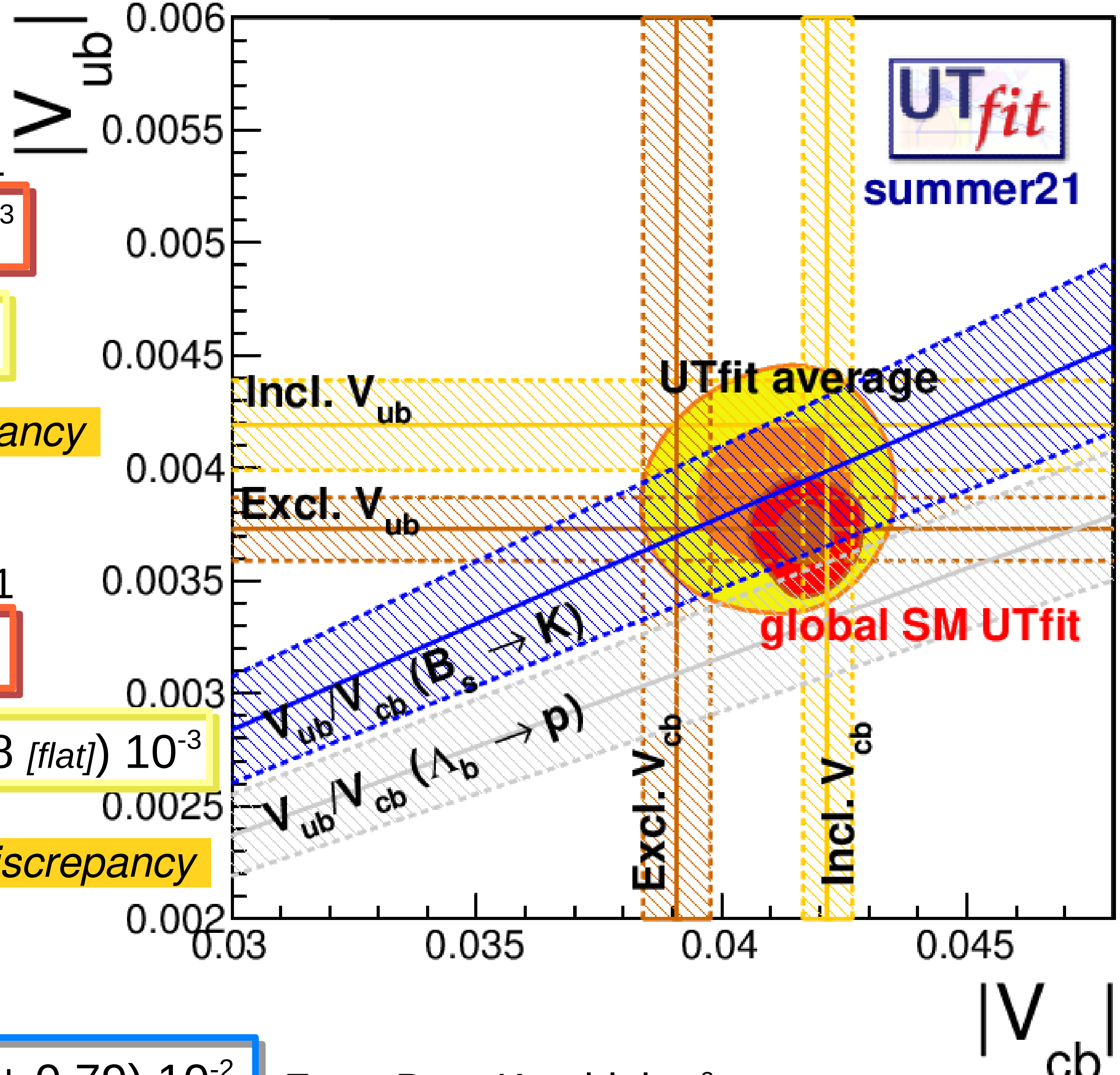
from FLAG 2019 arXiv:1902.08191

$|V_{ub}|$ *(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%

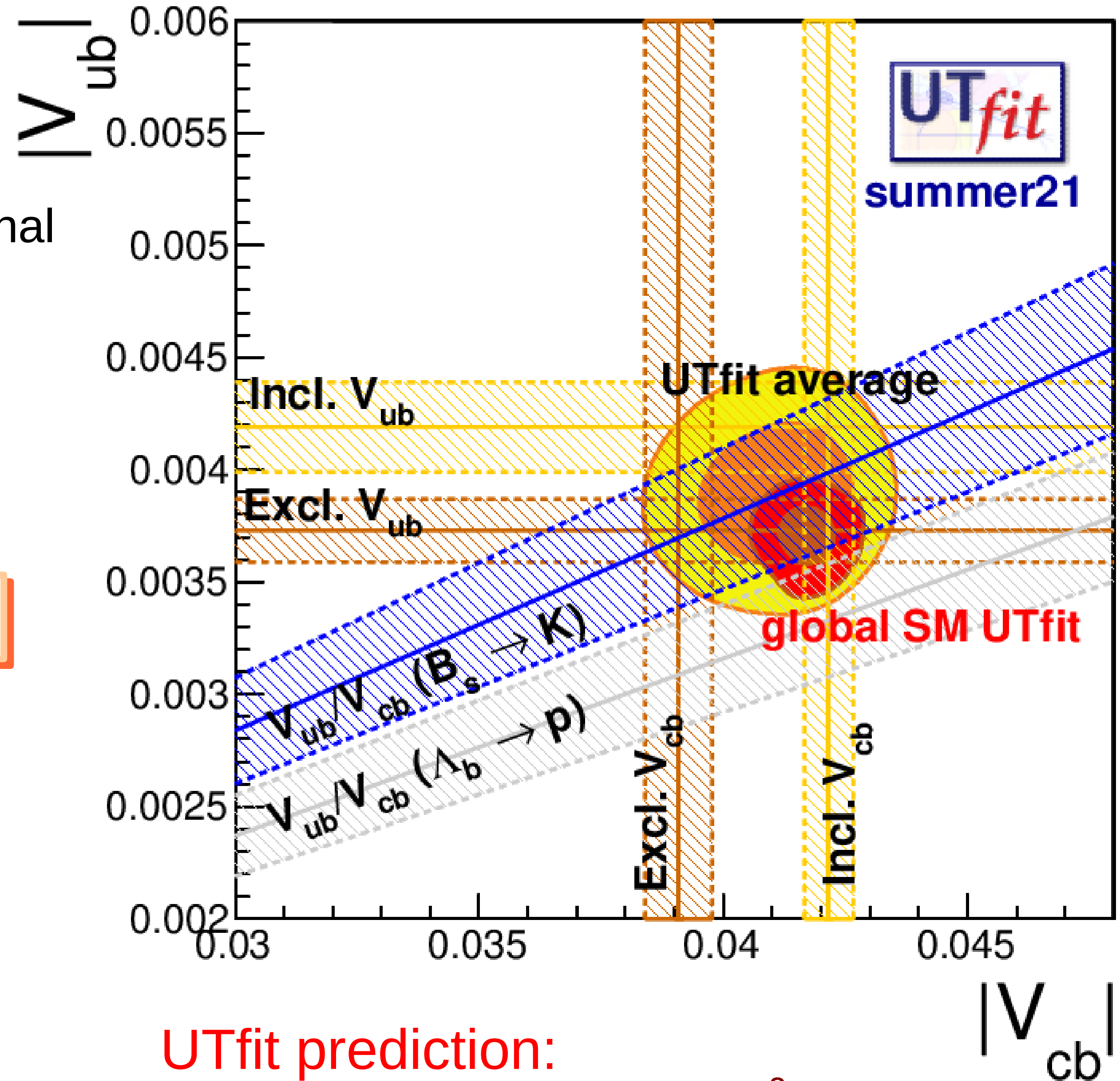
$|V_{ub}| = (3.89 \pm 0.21)\ 10^{-3}$

uncertainty ~ 5.4%

From global SM fit

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

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

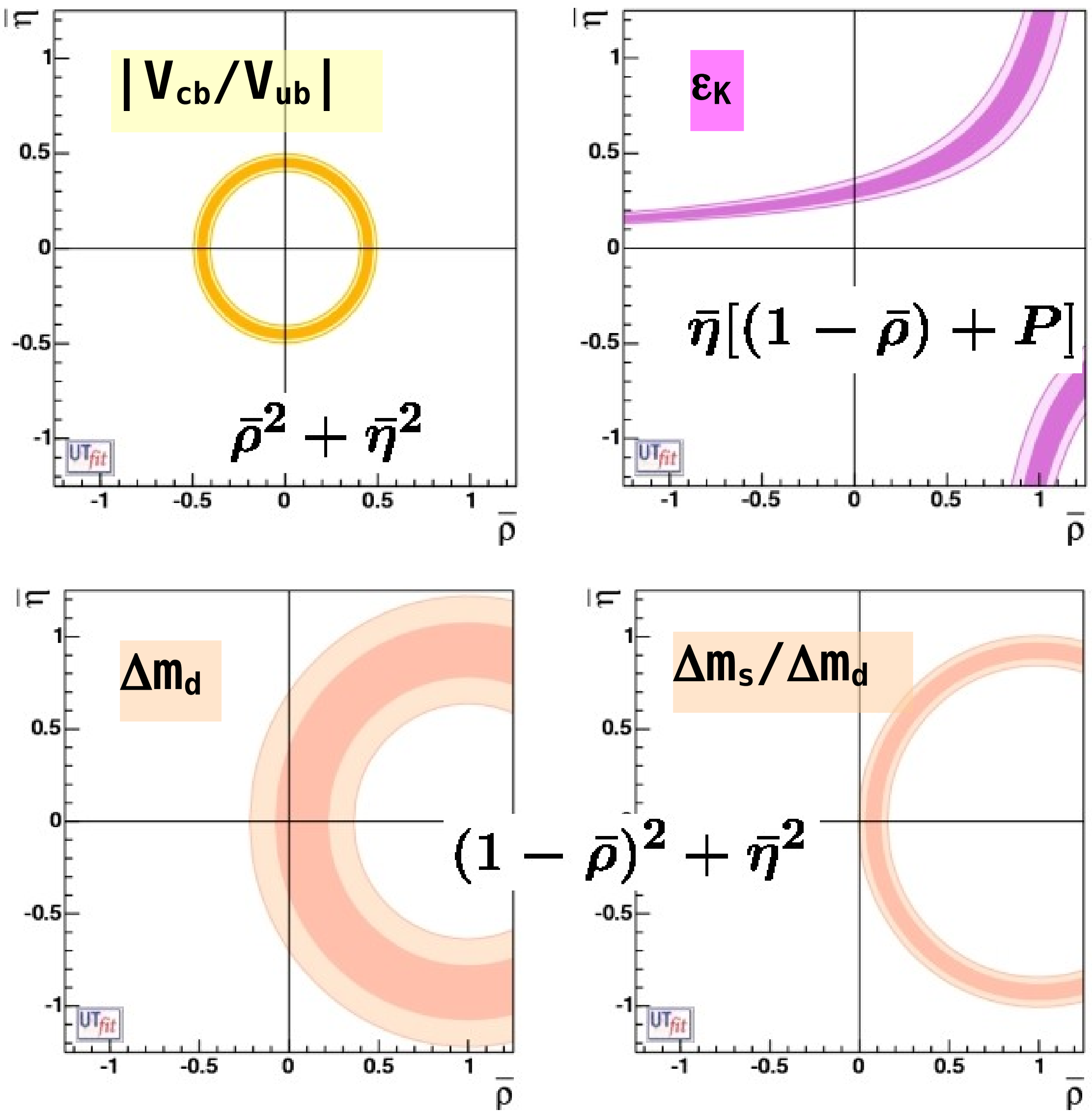


UTfit prediction:

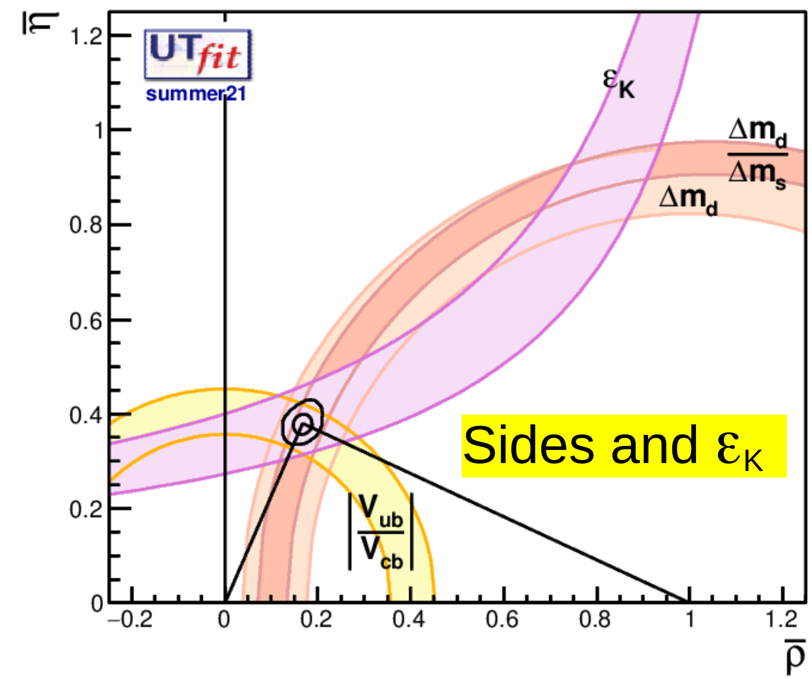
$|V_{cb}| = (41.9 \pm 0.5)\ 10^{-3}$

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

The LEP-style analysis in the $\bar{\rho}$-$\bar{\eta}$ plane:



levels @
95% Prob

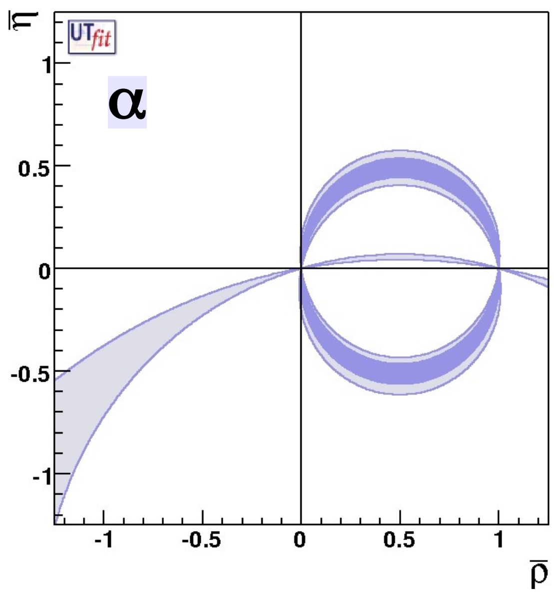


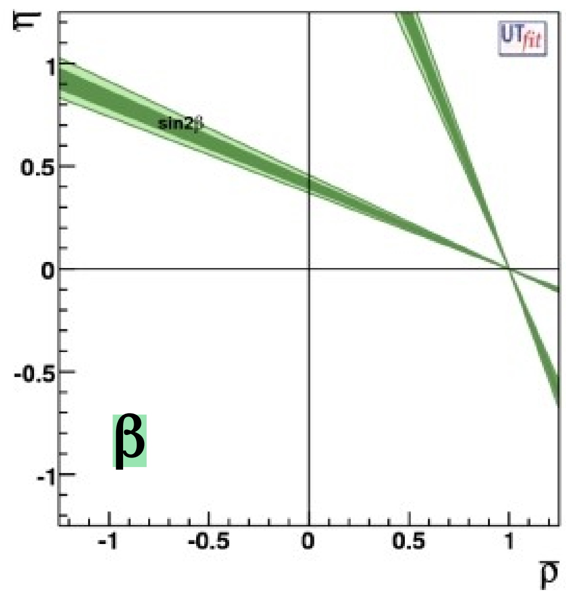
~10%

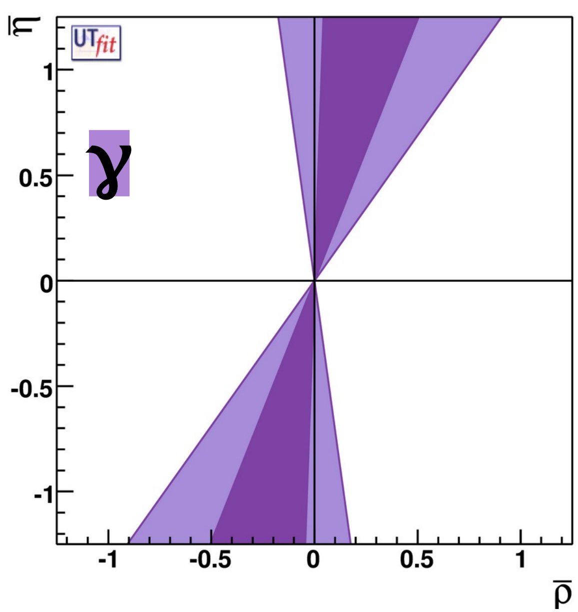
$\bar{\rho} = 0.169 \pm 0.017$
$\bar{\eta} = 0.383 \pm 0.025$

~7%

Angle constraints in the $\bar{\rho}$-$\bar{\eta}$ plane:

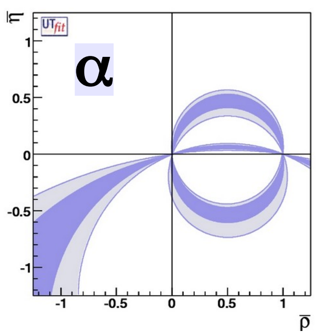


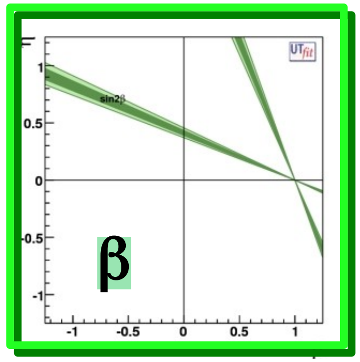


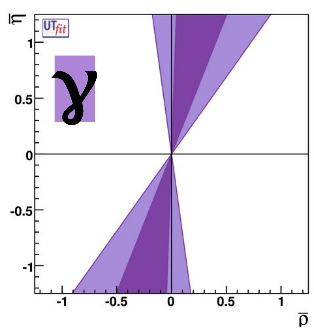


B factories
+LHCb

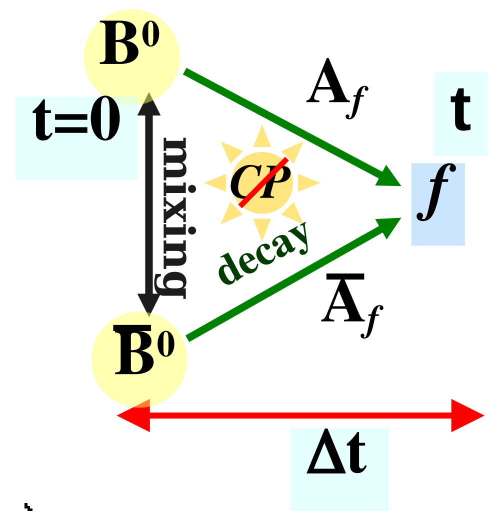
Angle constraints in the $\bar{\rho}$-$\bar{\eta}$ plane:







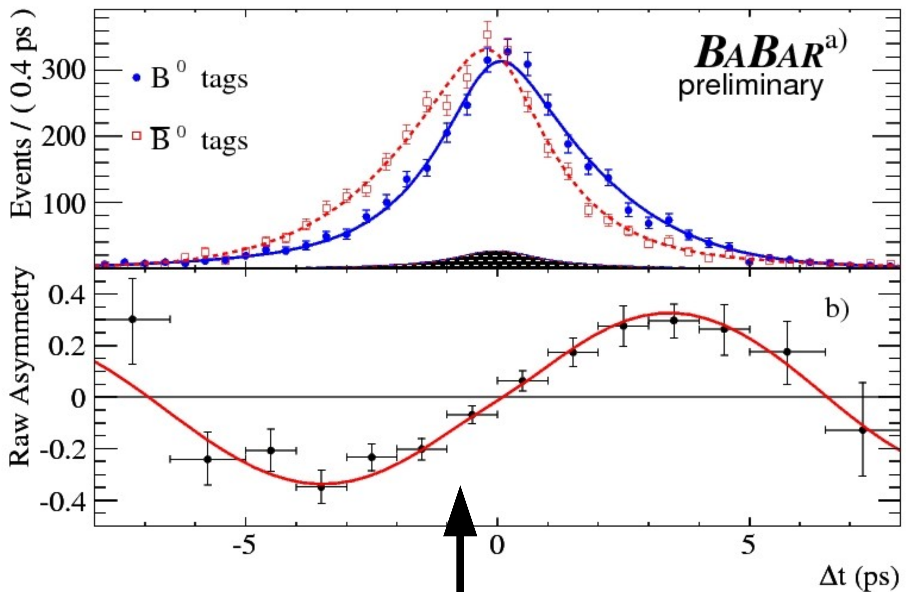
sin2β from time-dependent A_{CP} in $B \to J/\psi K$



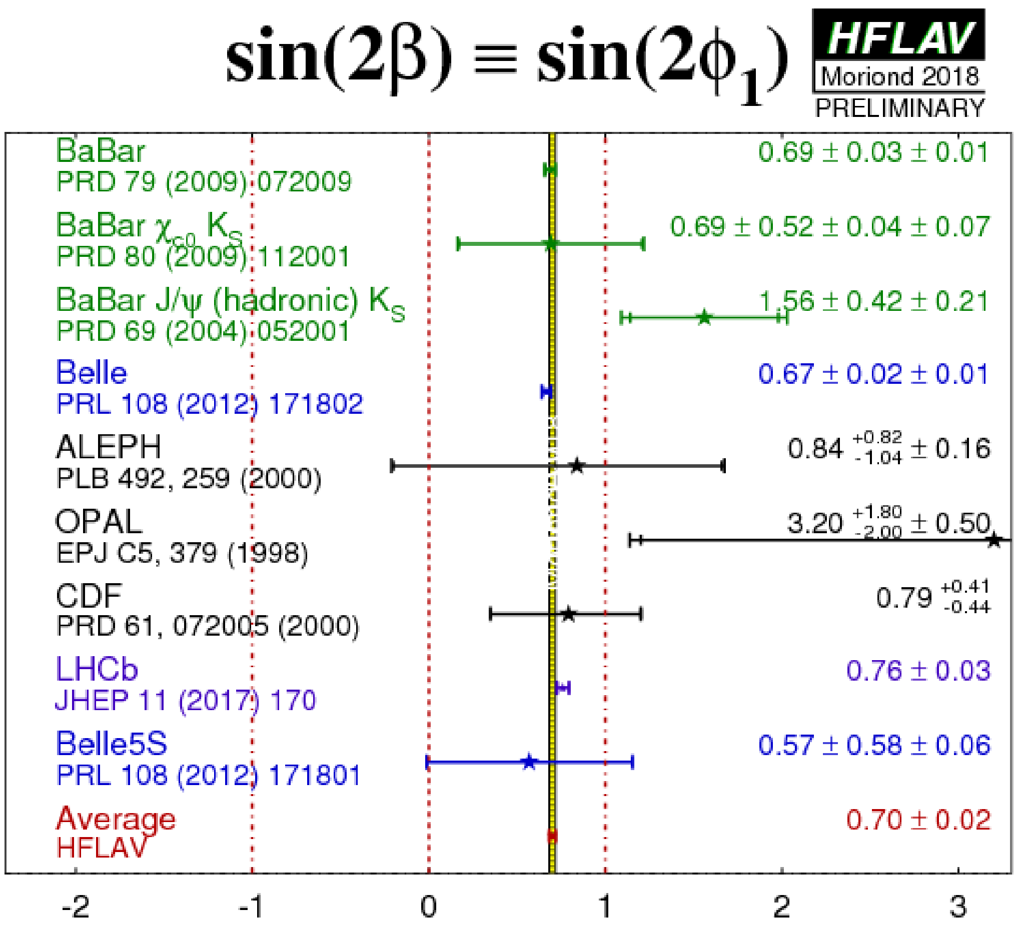
$$a_{f_{CP}}(t) = \frac{\mathrm{Prob}(B^0(t) \to f_{CP}) - \mathrm{Prob}(\overline{B^0}(t) \to f_{CP})}{\mathrm{Prob}(\overline{B^0}(t) \to f_{CP}) + \mathrm{Prob}(B^0(t) \to f_{CP})} = C_f \cos \Delta m_d t \ + \ S_f \sin \Delta m_d t$$

$$a_{f_{CP}}(t) = -\eta_{CP} \sin \Delta m_d \Delta t \sin 2\beta$$

Latest $\sin 2\beta$ results:



raw asymmetry
as function of Δt



$\sin 2\beta(J/\psi K^0) = 0.698 \pm 0.017$

HFLAV

data-driven theoretical uncertainty

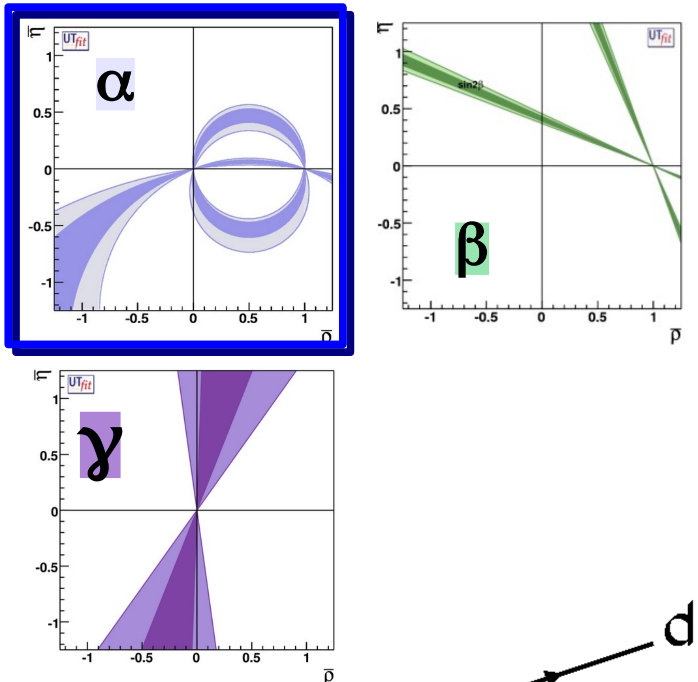
$\Delta S = -0.01 \pm 0.01$

$\sin 2\beta(J/\psi K^0) = 0.688 \pm 0.020$

UTfit Input

M.Ciuchini, M.Pierini, L.Silvestrini
Phys. Rev. Lett. 95, 221804 (2005)

Angle constraints in the $\bar{\rho}$-$\bar{\eta}$ plane:



α: CP violation in $B^0 \rightarrow \pi^+\pi^-$

- considering the tree (T) only:

  $\lambda_{\pi\pi} = e^{2ia}$

  $C_{\pi\pi} = 0$

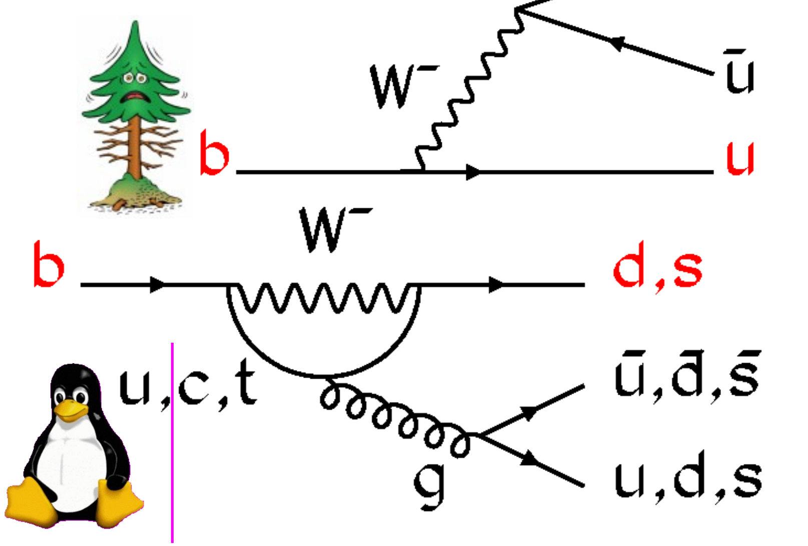
  $S_{\pi\pi} = \sin(2\alpha)$

- adding the penguins (P):

$$\lambda_{\pi\pi} = e^{2i\alpha}\frac{1+|P/T|e^{i\delta}e^{i\gamma}}{1+|P/T|e^{i\delta}e^{-i\gamma}}$$

$$C_{\pi\pi} \propto \sin(\delta)$$

$$S_{\pi\pi} = \sqrt{1-C^2_{\pi\pi}}\,\sin(2\alpha_{eff})$$



Angle constraints in the $\bar{\rho}$-$\bar{\eta}$ plane:

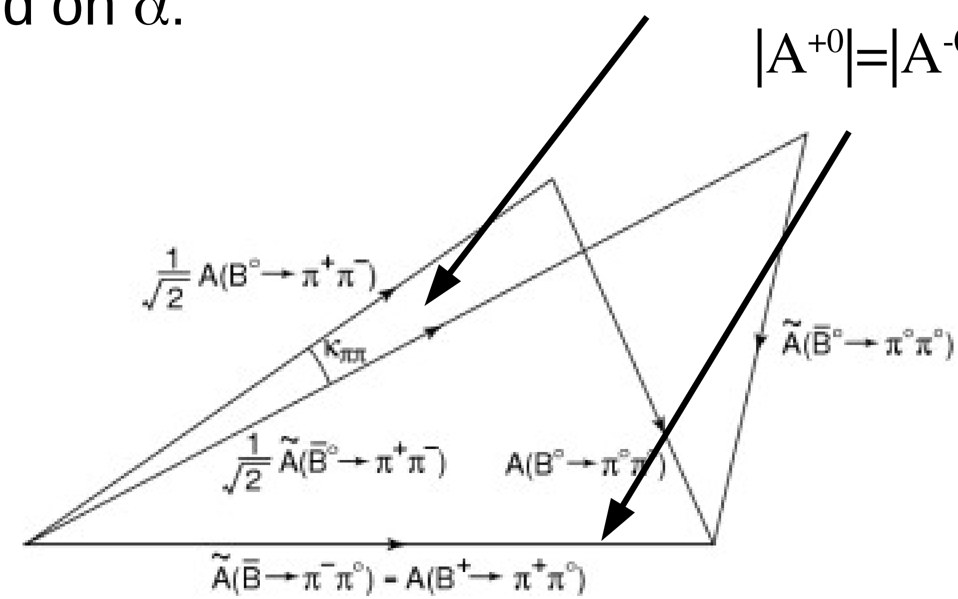
from $\alpha_{eff} \rightarrow$ to α: isospin analysis

- $B \rightarrow \pi^+\pi^-$, $\pi^+\pi^0$, $\pi^0\pi^0$ decays are connected from isospin relations
- $\pi\ \pi$ states can have I = 2 or I = 0
  - the gluonic penguins contribute only to the I = 0 state (ΔI=1/2)
  - $\pi^+\pi^0$ is a pure I = 2 state (ΔI = 3/2) and it gets contribution only from the tree diagram
  - triangular relations allow for the determination of the phase difference induced on α:

$$2\alpha_{eff} = 2\alpha + \kappa_{\pi\pi}$$

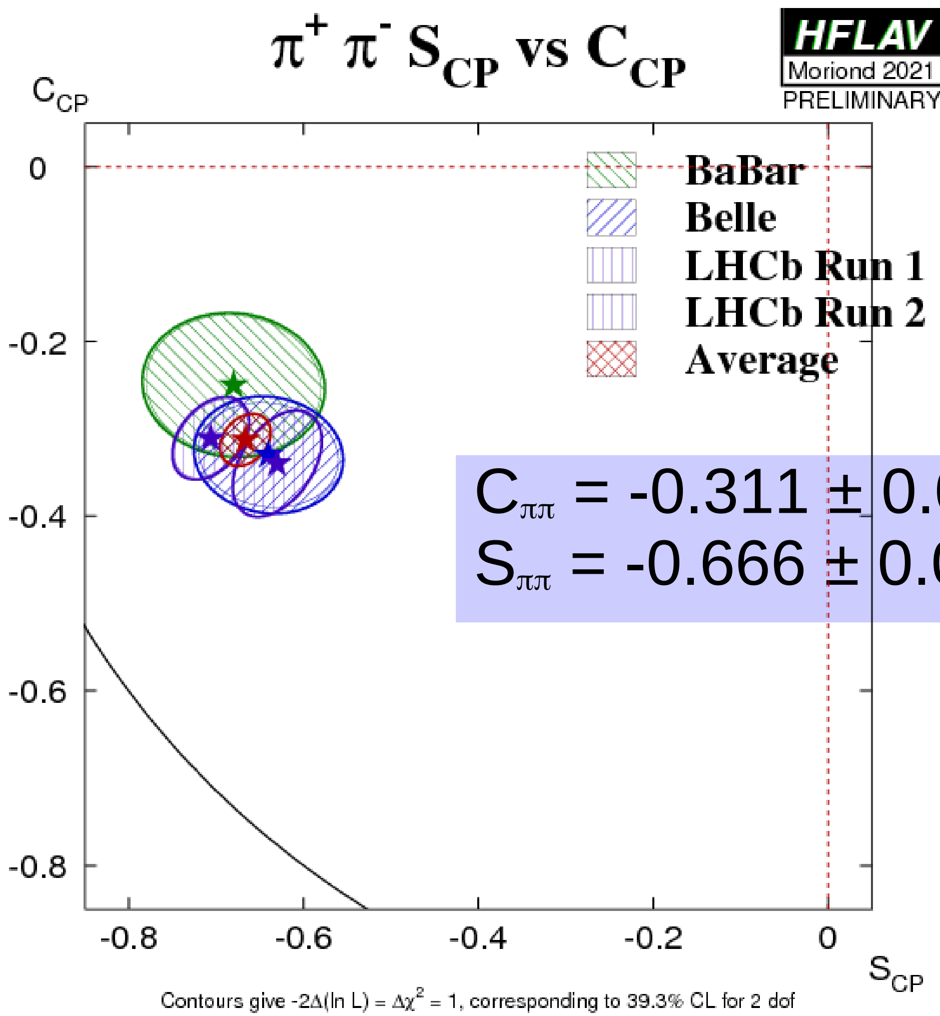
$$|A^{+0}| = |A^{-0}|$$

Both BR(B^0) and BR(B^0) have to be measured in all the $\pi\pi$ channels

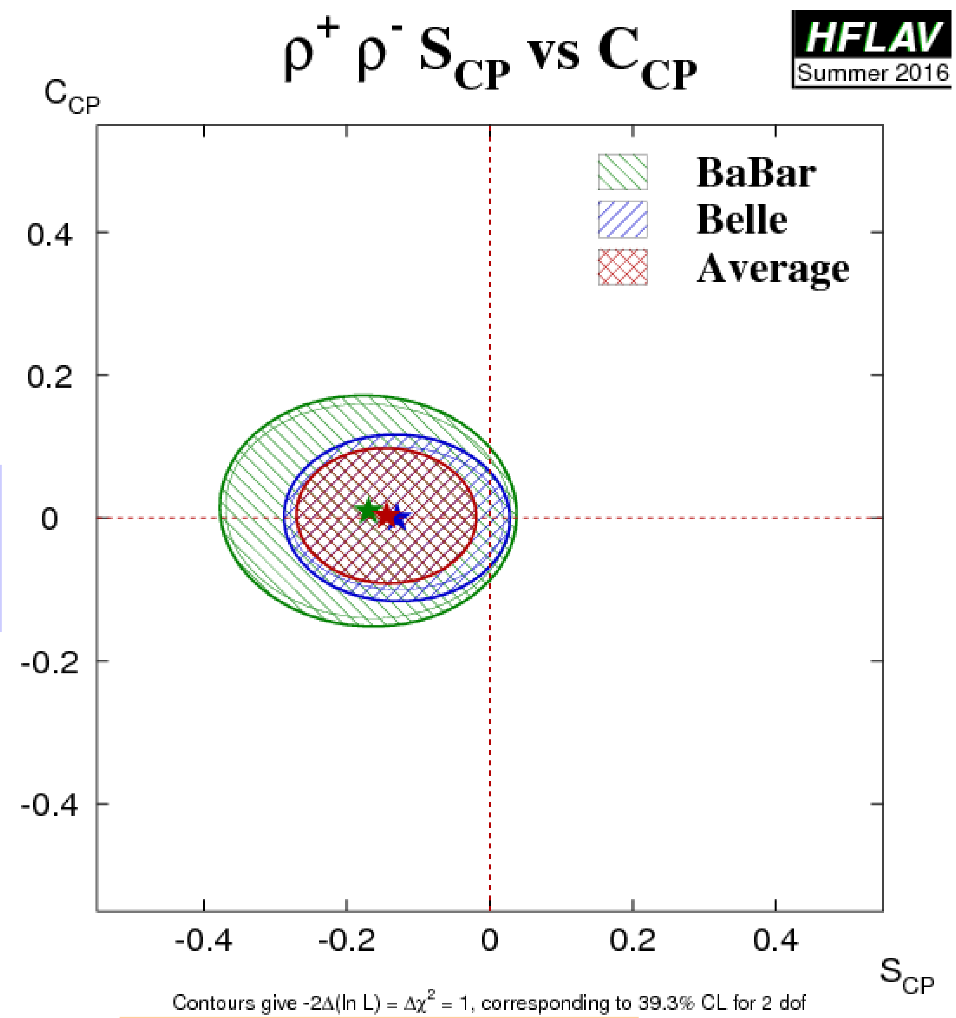


Angle constraints in the $\bar{\rho}$-$\bar{\eta}$ plane:

α result for $\pi^+\pi^-$ and $\rho^+\rho^-$

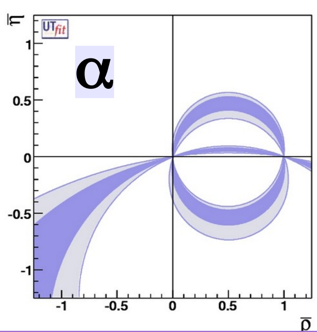


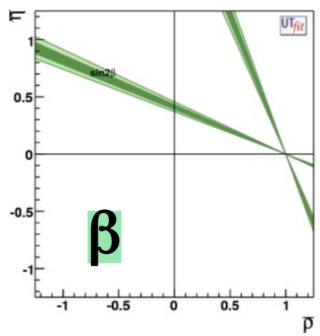
$C_{\pi\pi}$ = -0.311 ± 0.030
$S_{\pi\pi}$ = -0.666 ± 0.029

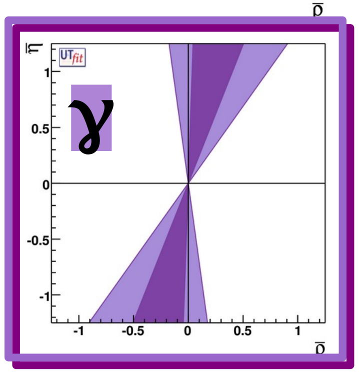


$C_{\rho\rho}$ = 0.00 ± 0.09
$S_{\rho\rho}$ = -0.14 ± 0.13

Angle constraints in the $\bar{\rho}$-$\bar{\eta}$ plane:

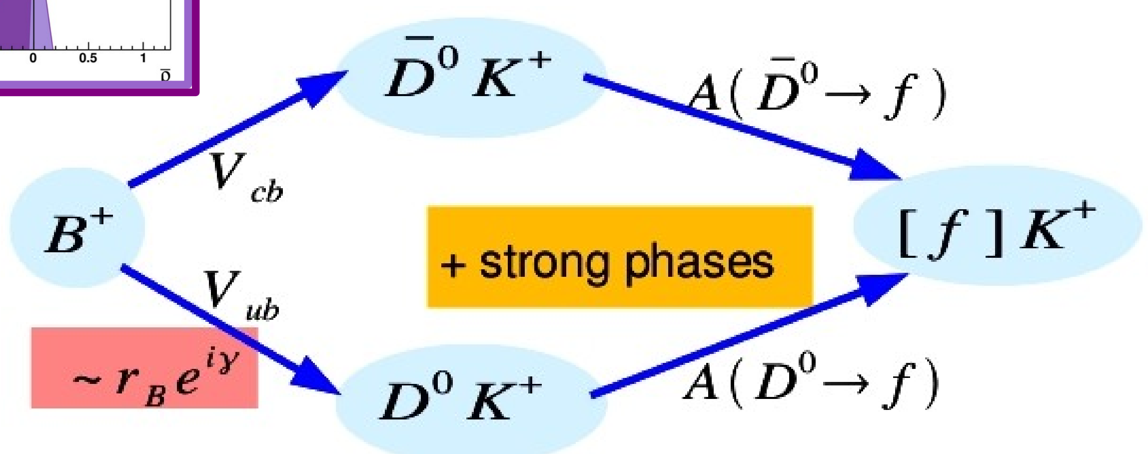




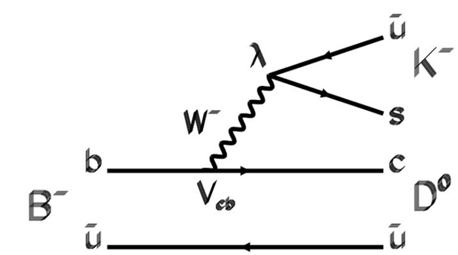


γ and DK trees

- $D^{(*)}K^{(*)}$ decays: from BRs and BR ratios, no time-dependent analysis, just rates
- the phase γ is measured exploiting interferences: two amplitudes leading to the same final states
- some rates can be really small: ~ 10^{-7}

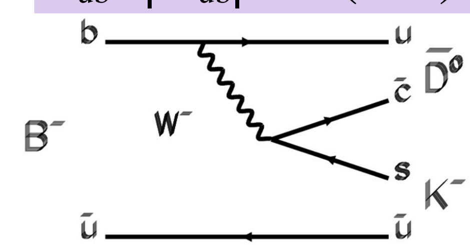


$B \to D^{(*)0}(\bar{D}^{(*)0}) K^{(*)}$ decays can proceed both through V_{cb} and V_{ub} amplitudes

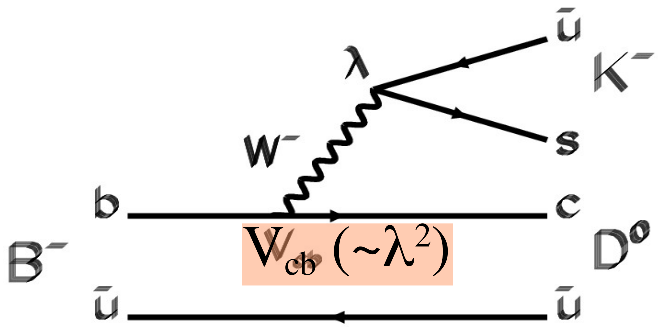


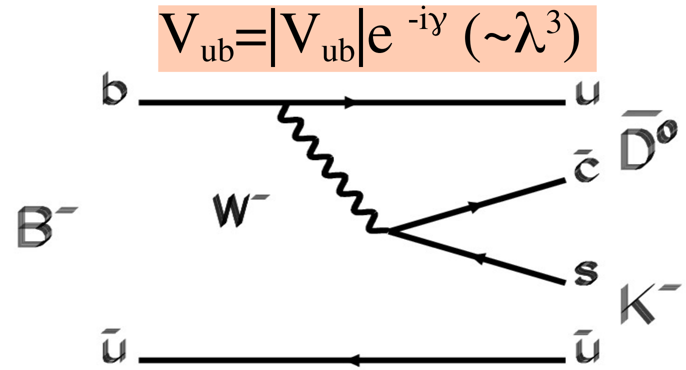
V_{cb} $(\sim\lambda^2)$

$V_{ub}=|V_{ub}|e^{-i\gamma}$ $(\sim\lambda^3)$



Sensitivity to γ: the ratio r_B





δ_B = strong phase diff.

$$A(B^- \to D^0 K^-) = A_B \qquad A(B^- \to \bar{D}^0 K^-) = A_B r_B e^{i(\delta_B - \gamma)}$$

$$A(B^+ \to \bar{D}^0 K^+) = A_B \qquad A(B^+ \to D^0 K^+) = A_B r_B e^{i(\delta_B + \gamma)}$$

r_B = amplitude ratio

$$r_B = \left| \frac{B^- \to \bar{D}^0 K^-}{B^- \to D^0 K^-} \right| = \sqrt{\bar{\eta}^2 + \bar{\rho}^2} \times F_{CS}$$

$\sqrt{\bar{\eta}^2 + \bar{\rho}^2}$ → **~0.36**

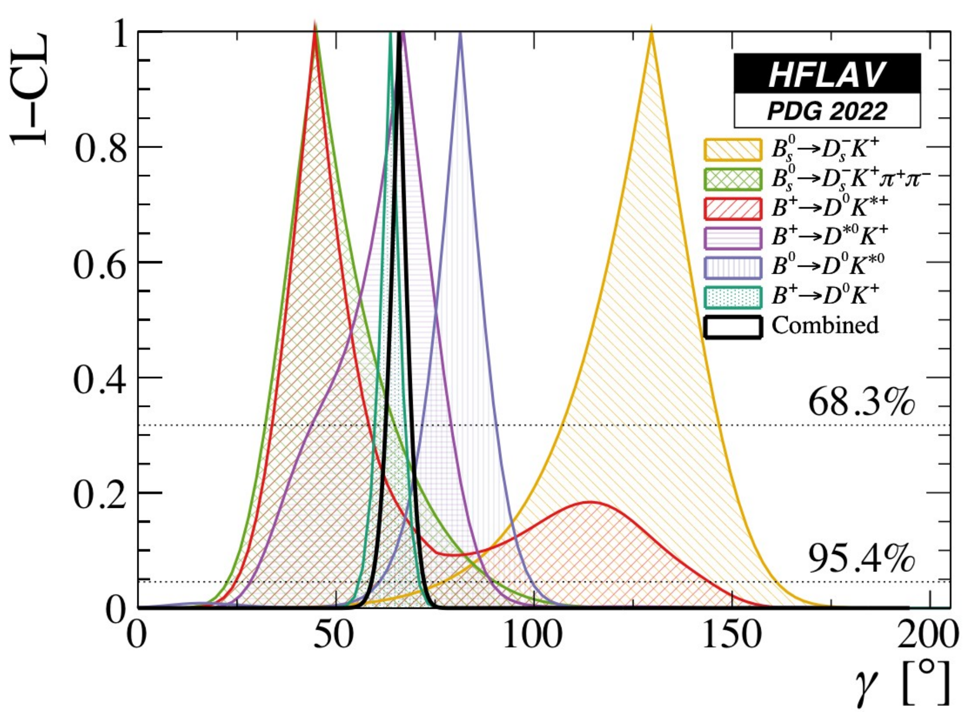
F_{CS} → hadronic contribution channel-dependent

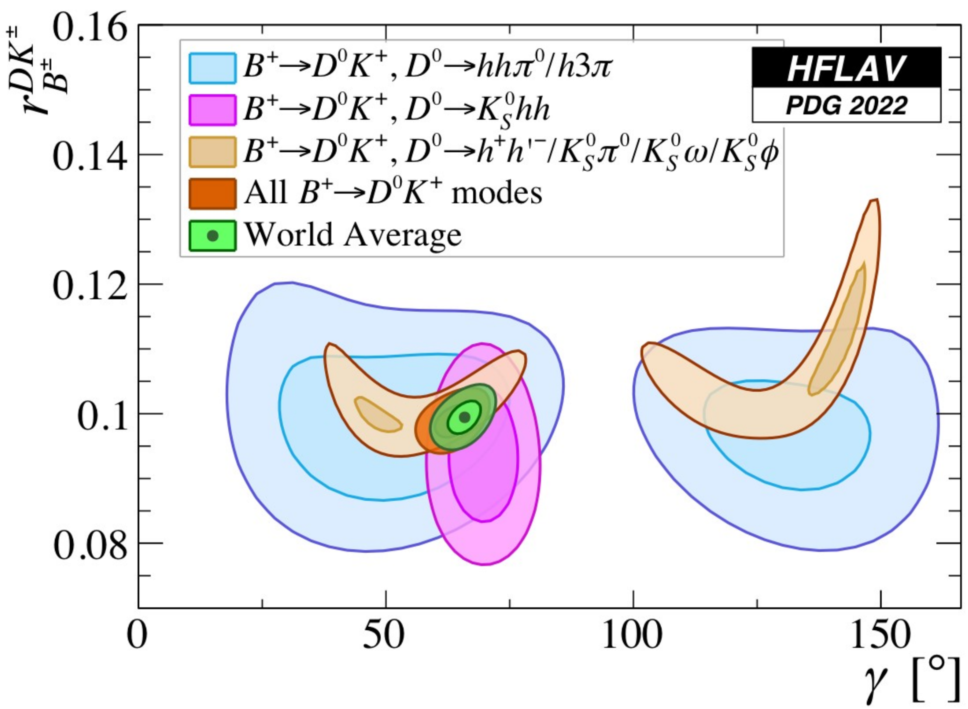
- in $B^+ \to D^{(*)0} K^+$: r_B is ~0.1
- while in $B^0 \to D^{(*)0} K^0$ r_B could be ~0.2-0.4
- to be measured: $r_B(DK)$, $r^*_B(D^*K)$ and $r^S_B(DK^*)$

Angle constraints in the $\bar{\rho}$-$\bar{\eta}$ plane:

γ and DK trees

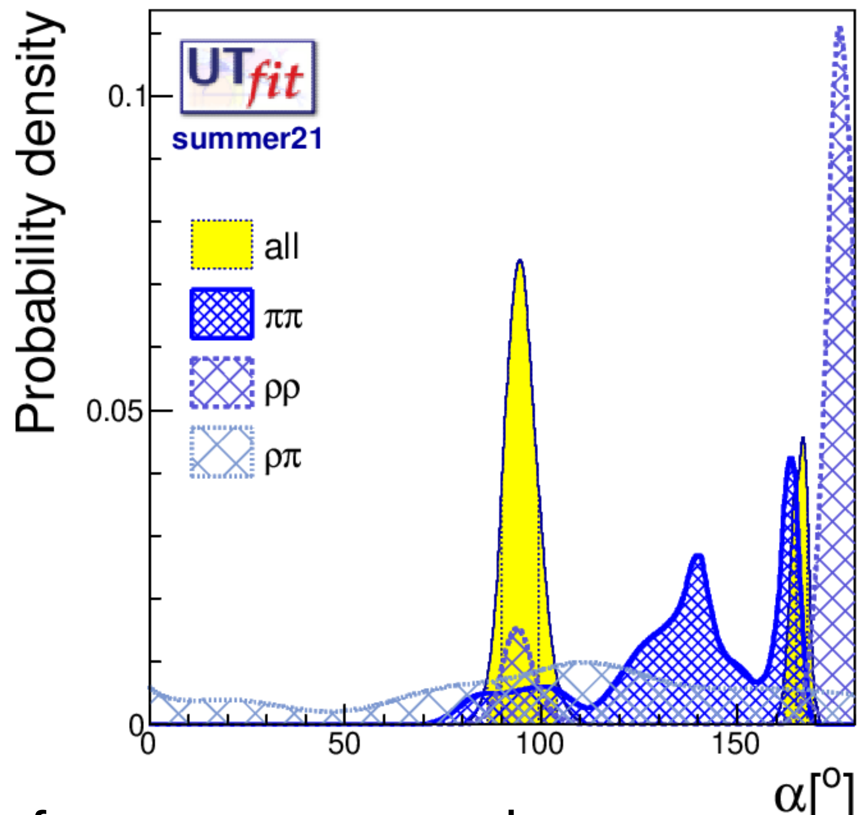
Parameter: γ ≡ φ₃ from all B → DK and similar b → cu-bar s & b → uc-bar s modes	
$\gamma \equiv \varphi_3$	$(65.9\ ^{+3.3}_{-3.5})^\circ$
$r_B(DK^+) = 0.0994 \pm 0.0026$	$\delta_B(DK^+) = (127.7\ ^{+3.6}_{-3.9})^\circ$
$r_B(D^*K^+) = 0.104\ ^{+0.013}_{-0.014}$	$\delta_B(D^*K^+) = (314.8\ ^{+7.9}_{-9.9})^\circ$
$r_B(DK^{*+}) = 0.101\ ^{+0.016}_{-0.034}$	$\delta_B(DK^{*+}) = (48\ ^{+59}_{-16})^\circ$
$r_B(DK^{*0}) = 0.257\ ^{+0.021}_{-0.023}$	$\delta_B(DK^{*0}) = (194.1\ ^{+9.6}_{--8.8})^\circ$



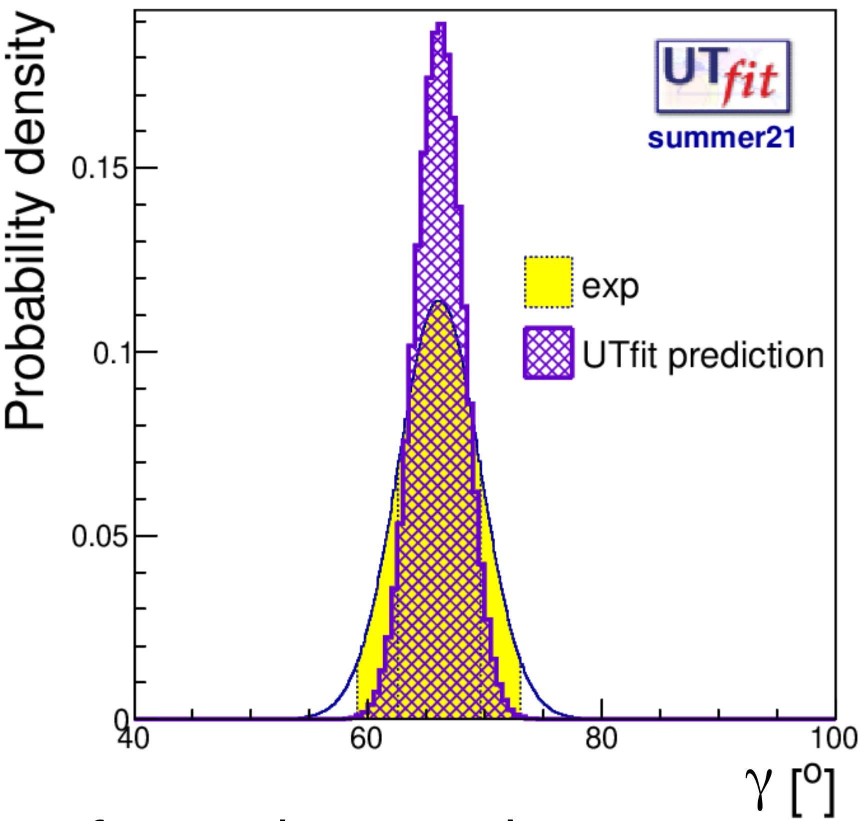


sin2α (ϕ_2) and γ (ϕ_3)

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



γ updated with all the latest results (LHCb)

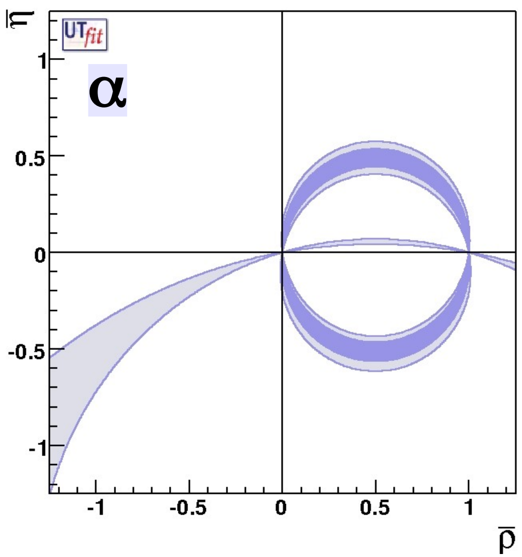


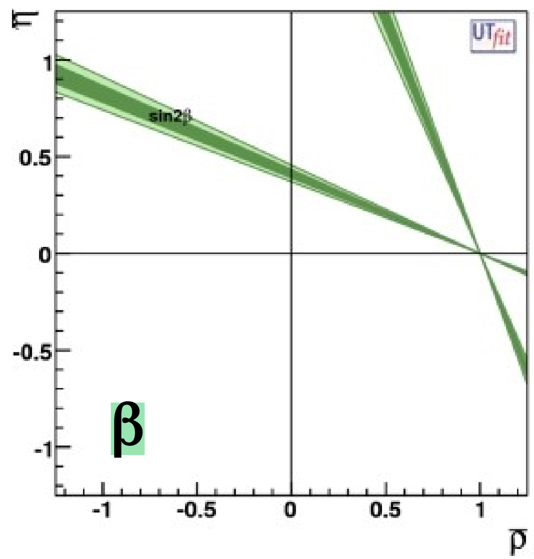
α from ππ, ρρ, πρ decays:
combined SM: (93.6 ± 4.2)°
UTfit prediction: (90.5 ± 2.1)°

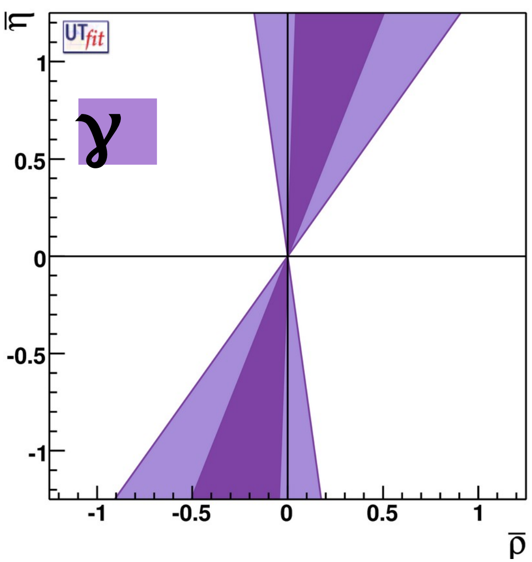
α from HFLAV: 85.5 ± 4.6

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

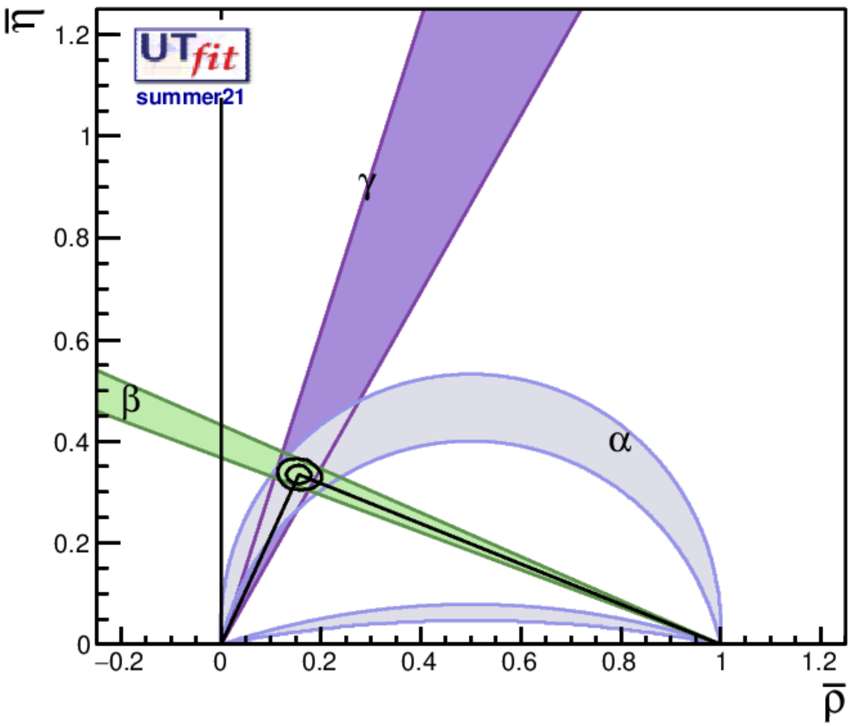
Angle constraints in the $\bar{\rho}$-$\bar{\eta}$ plane:







levels @
95% Prob

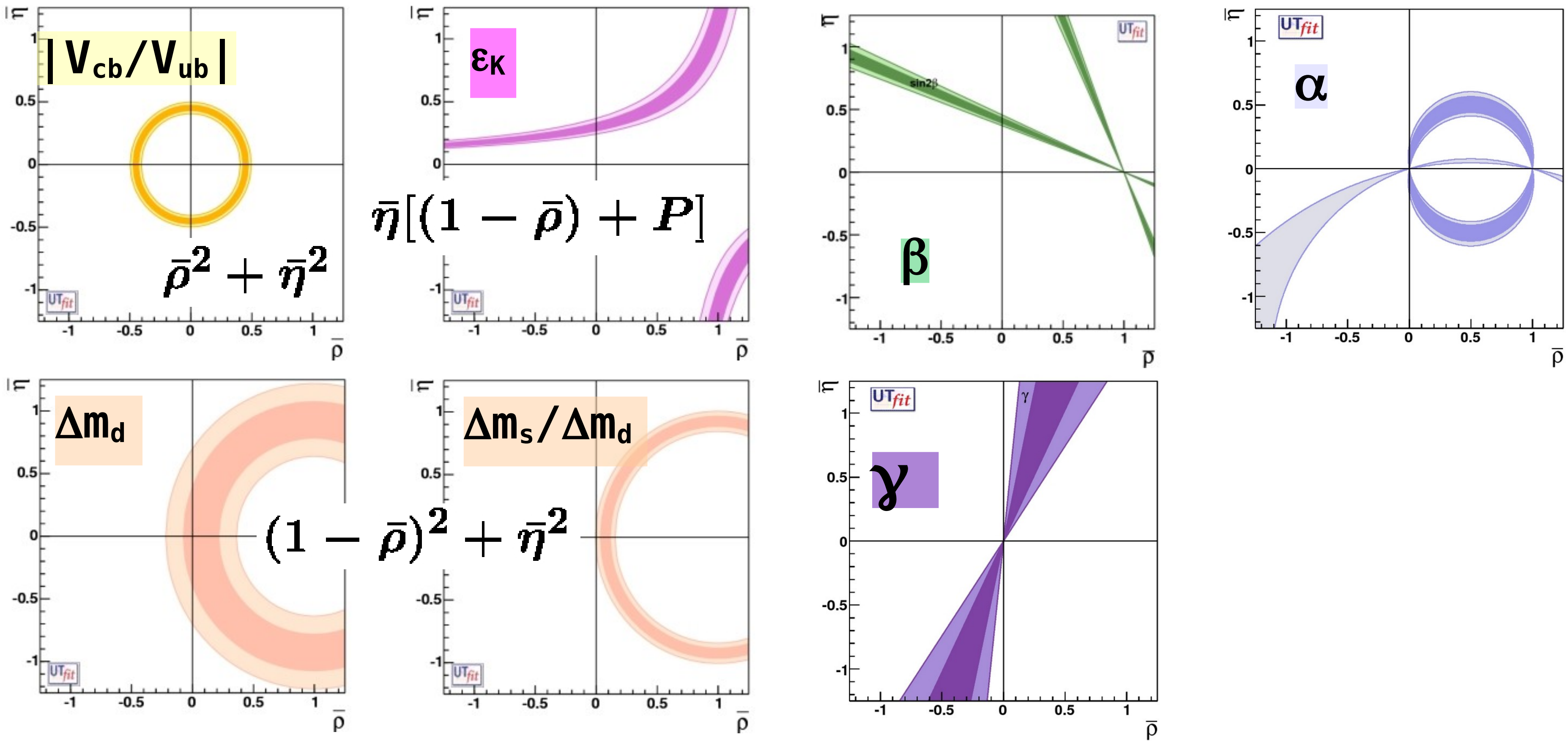


~12%

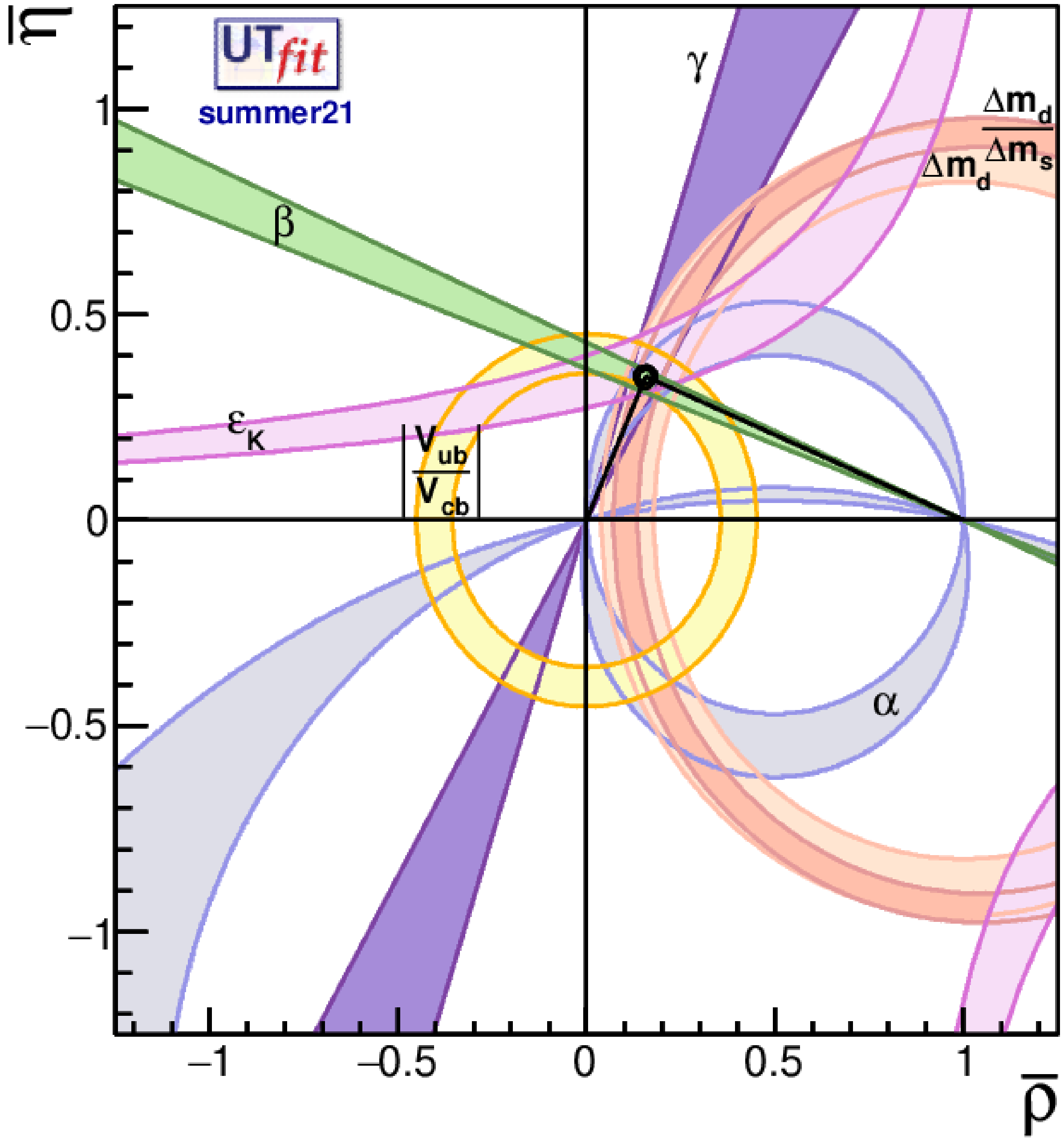
$\bar{\rho}$ = 0.156 ± 0.018
$\bar{\eta}$ = 0.335 ± 0.018

~5%

Unitarity Triangle analysis in the SM:



Unitarity Triangle analysis in the SM:



levels @
95% Prob

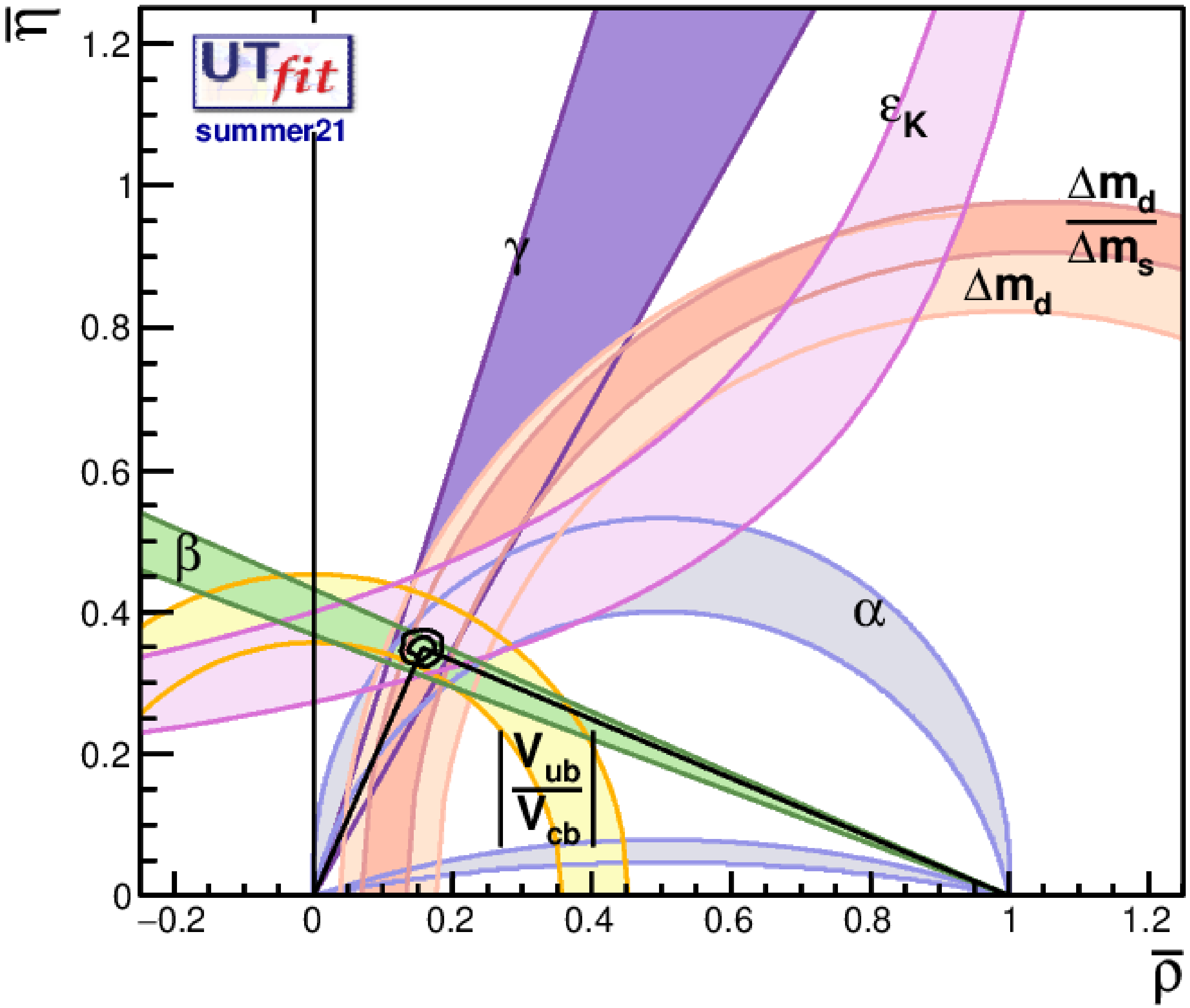
~8%

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

~3%

Unitarity Triangle analysis in the SM:

zoomed in..



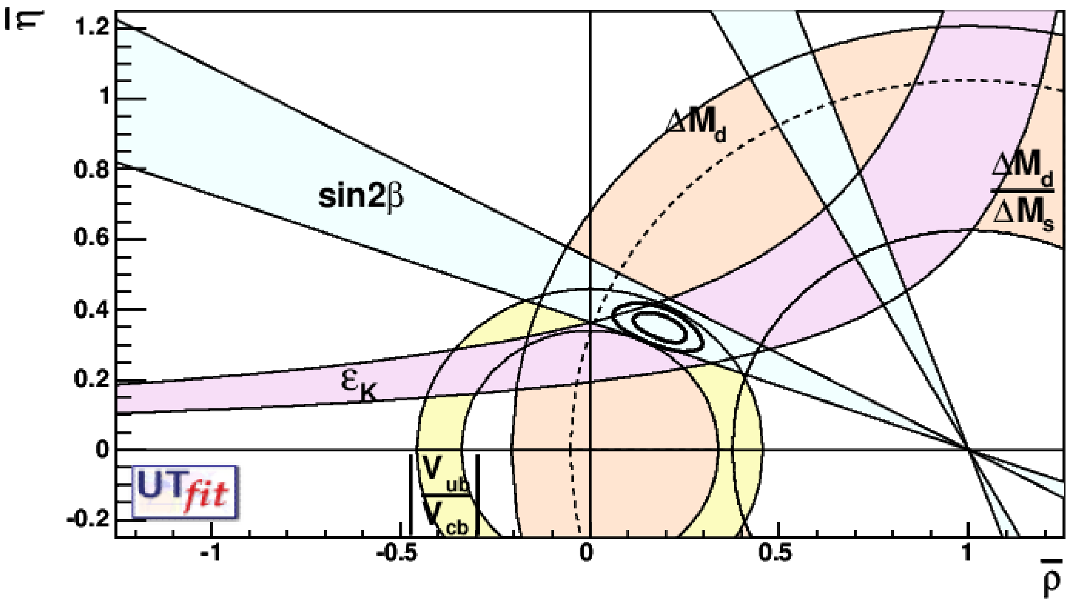
levels @ 95% Prob

~8%

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

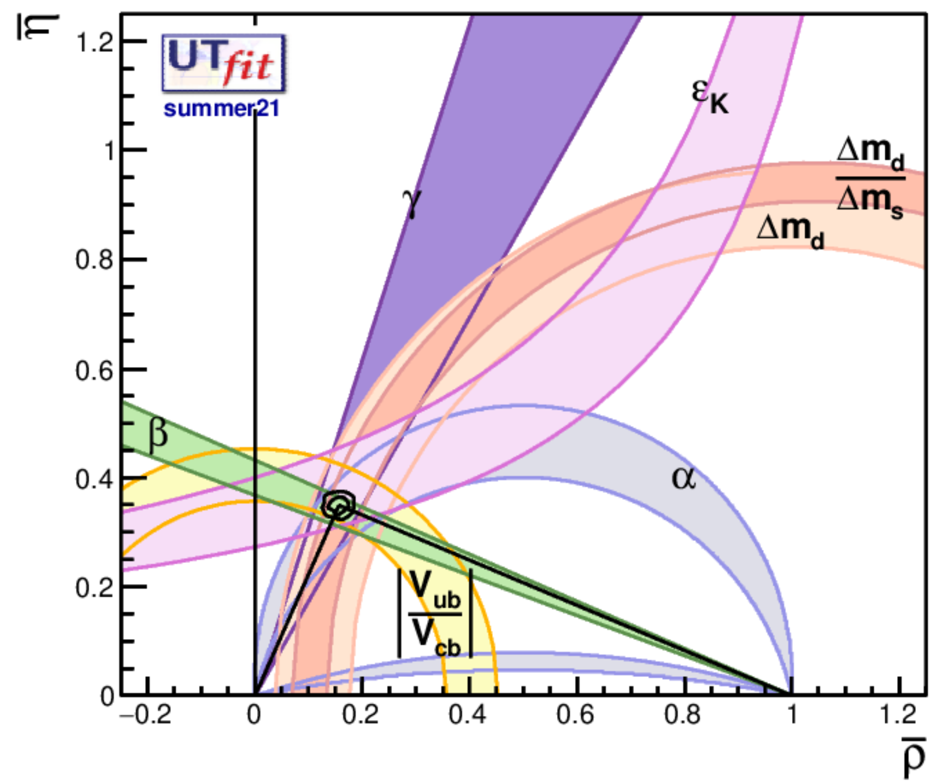
~3%

Unitarity Triangle analysis in the SM:

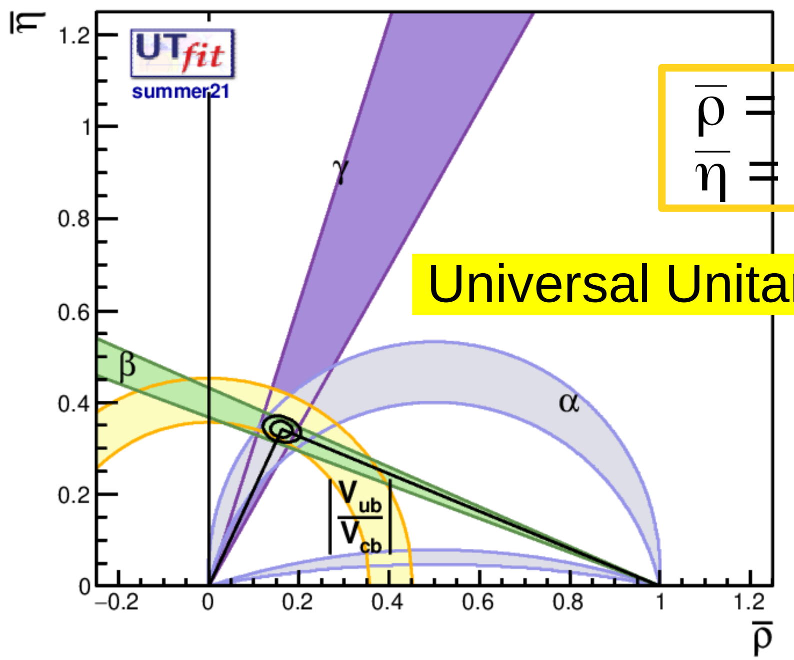


2004

2021



Some interesting configurations

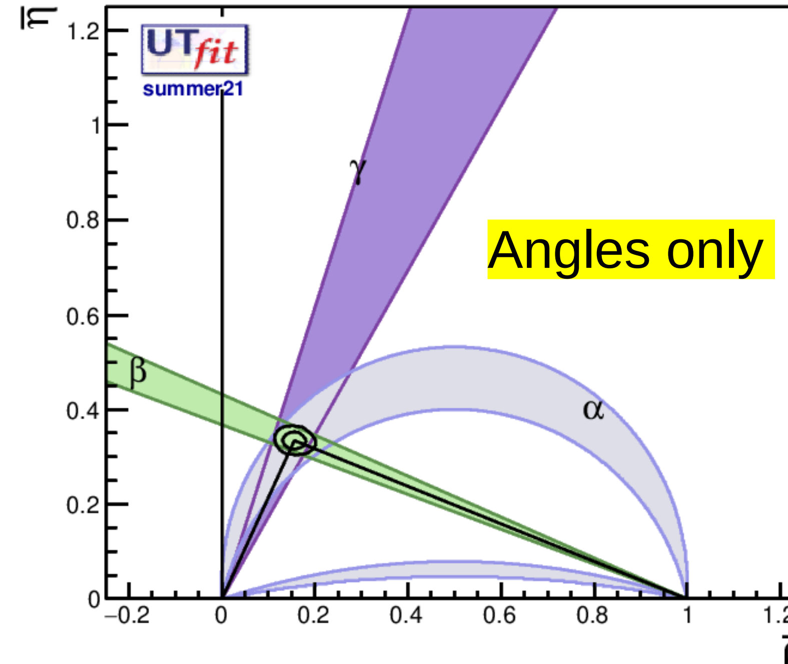


~10%

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

~3%

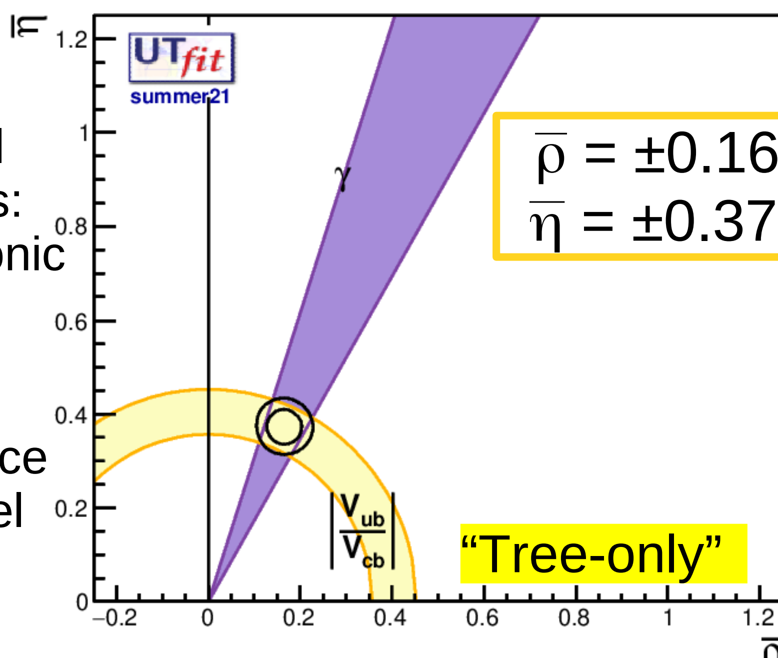
Universal Unitary Triangle



Angles only

Tree-level processes: Semileptonic and DK B decays

→ reference for model building

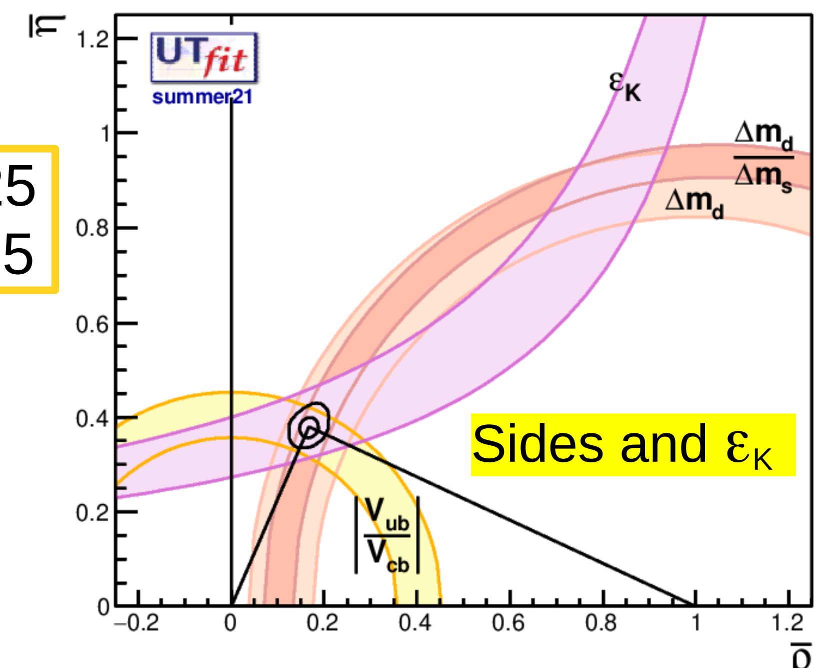


~15%

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

~7%

"Tree-only"



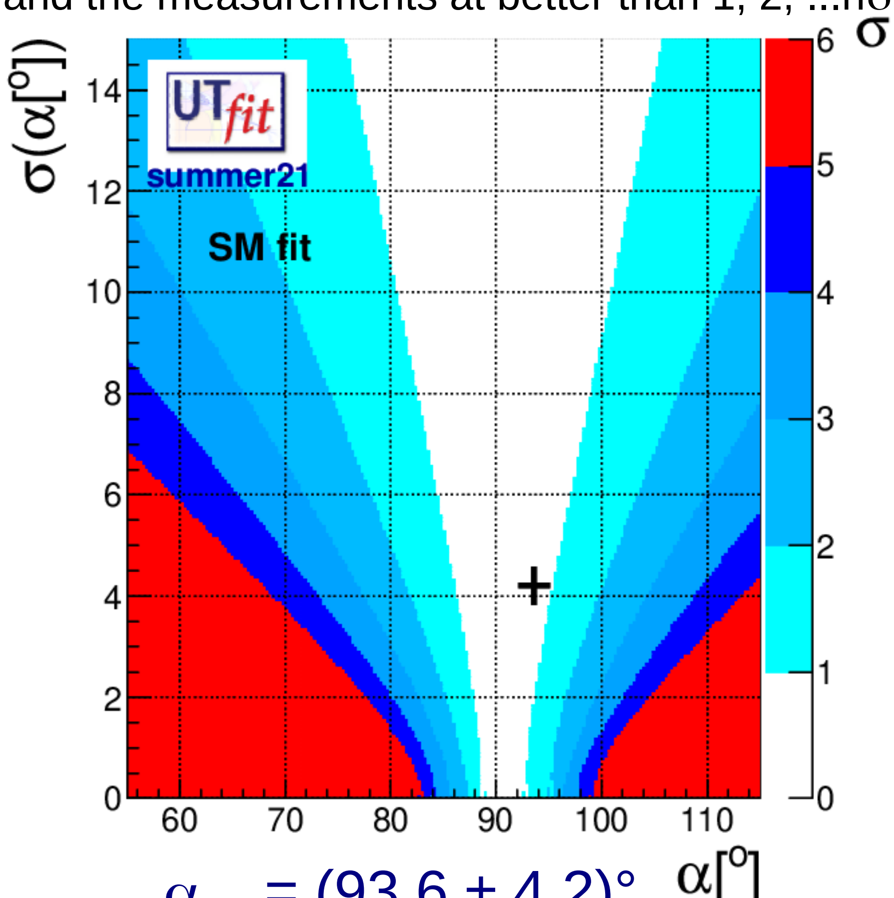
Sides and ε_K

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

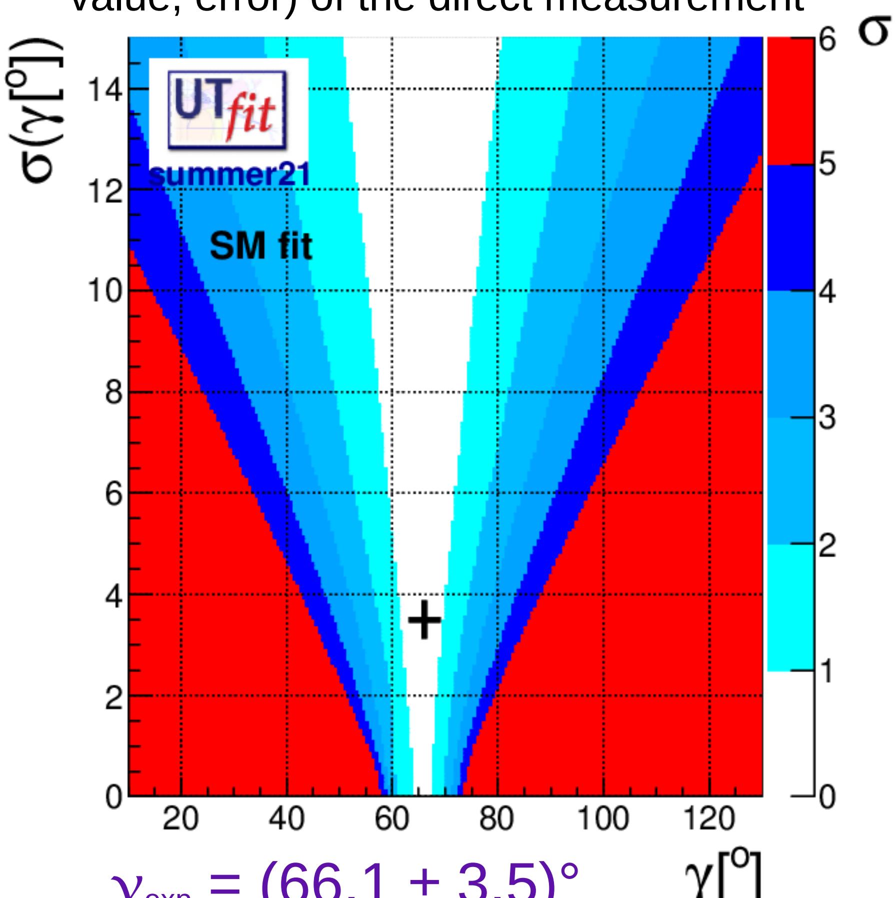
Color code: agreement between the predicted values and the measurements at better than 1, 2, ...nσ

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



$\alpha_{exp} = (93.6 \pm 4.2)°$

$\alpha_{UTfit} = (90.5 \pm 2.1)°$



$\gamma_{exp} = (66.1 \pm 3.5)°$

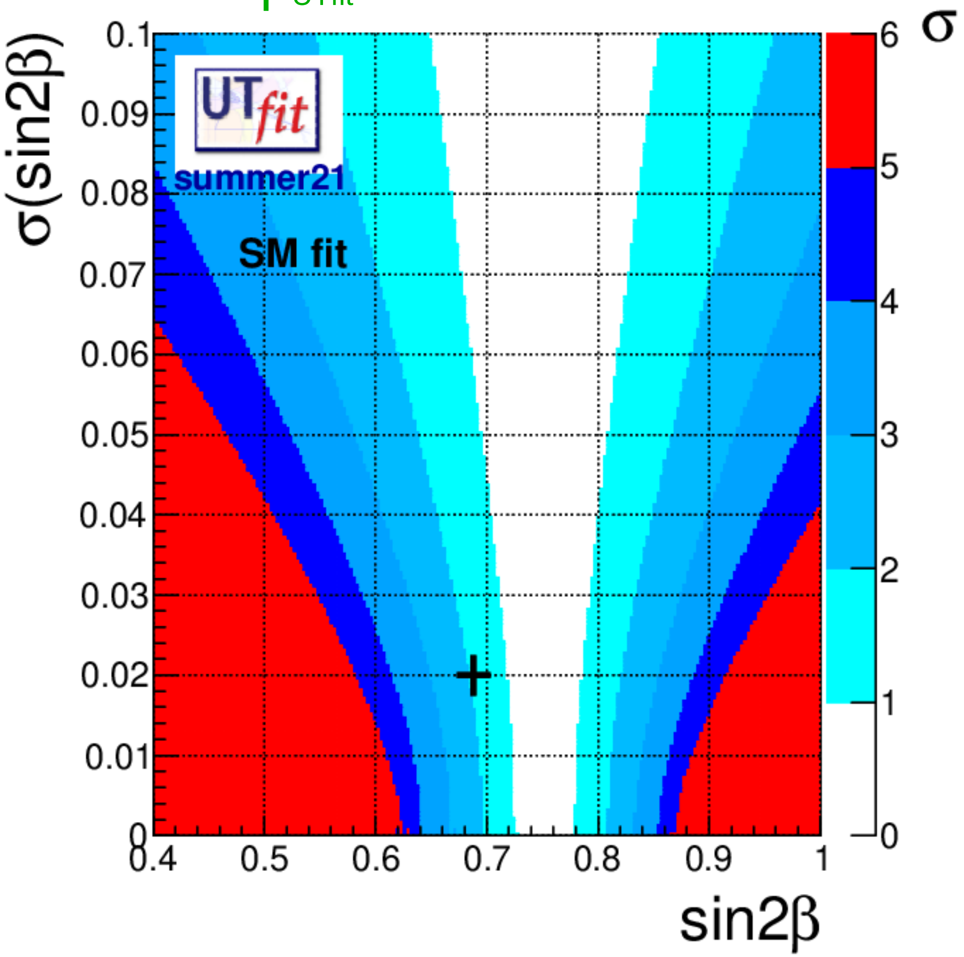
$\gamma_{UTfit} = (66.1 \pm 2.1)°$

Checking the usual *tensions*..

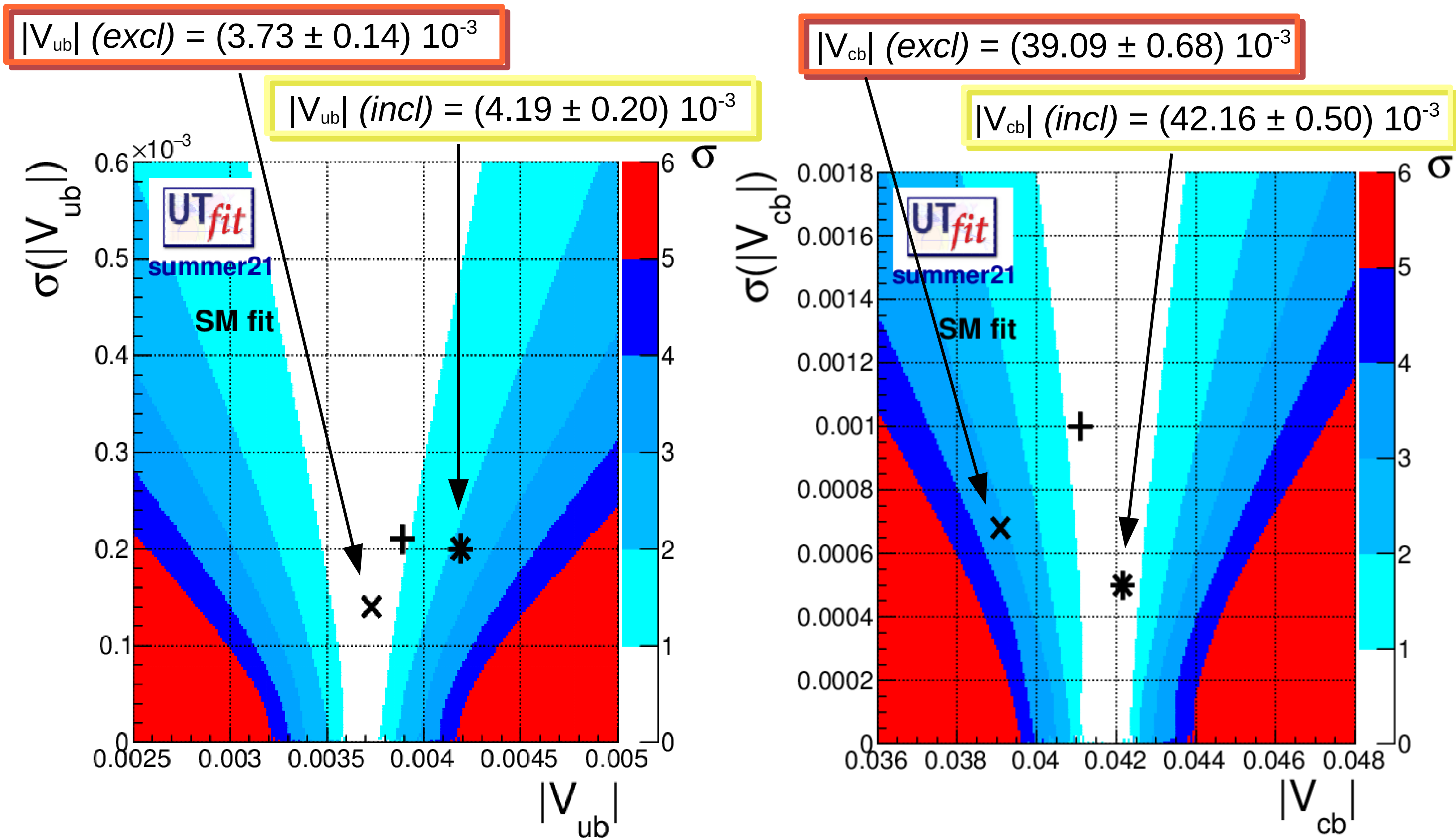
~1.4σ

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

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



Checking the usual *tensions*..



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

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

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

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

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
$\lvert V_{cb}\rvert \cdot 10^3$	40.4 ± 1.3	41.9 ± 0.5	< 1
$\lvert V_{cb}\rvert \cdot 10^3$ (incl)	42.16 0.50		< 1
$\lvert V_{cb}\rvert \cdot 10^3$ (excl)	39.09 0.68		~ 2.4
$\lvert V_{ub}\rvert \cdot 10^3$	3.89 ± 0.21	3.68 ± 0.10	< 1
$\lvert V_{ub}\rvert \cdot 10^3$ (incl)	4.19 ± 0.20	-	~ 1.7
$\lvert V_{ub}\rvert \cdot 10^3$ (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 (NP)

Consider for example B_s mixing process.
Given the SM amplitude, we can define

$$C_{B_s} e^{-2i\phi_{B_s}} = \frac{\langle \overline{B}_s | H_{eff}^{SM} + H_{eff}^{NP} | B_s \rangle}{\langle \overline{B}_s | H_{eff}^{SM} | B_s \rangle} = 1 + \frac{A_{NP}\, e^{-2i\phi_{NP}}}{A_{SM}\, e^{-2i\beta_s}}$$

All NP effects can be parameterized in terms of one complex parameter for each meson mixing, to be determined in a simultaneous fit with the CKM parameters (now there are enough experimental constraints to do so).

For kaons we use *Re* and *Im*, since the two exp. constraints ε_K and Δm_K are directly related to them (with distinct theoretical issues)

$$C_{\varepsilon_K} = \frac{\mathrm{Im}\langle K^0 | H_{eff}^{full} | \overline{K}^0 \rangle}{\mathrm{Im}\langle K^0 | H_{eff}^{SM} | \overline{K}^0 \rangle}$$

$$C_{\Delta m_K} = \frac{\mathrm{Re}\langle K^0 | H_{eff}^{full} | \overline{K}^0 \rangle}{\mathrm{Re}\langle K^0 | H_{eff}^{SM} | \overline{K}^0 \rangle}$$

UT analysis including new physics (NP)

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):

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

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

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

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

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

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

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

UT analysis including new physics (NP)

M.Bona *et al* (UTfit)
Phys.Rev.Lett. 97:151803,2006

	ρ, η	C_{Bd}, ϕ_{Bd}	$C_{\varepsilon K}$	C_{Bs}, Bs
V_{ub}/V_{cb}	X			
γ (DK)	X			
ε_K	X		X	
$\sin 2\beta$	X	X		
Δm_d	X	X		
α	X	X		
A_{SL} B_d	X	X X		
$\Delta\Gamma_d/\Gamma_d$	X	X X		
$\Delta\Gamma_s/\Gamma_s$	X			X X
Δm_s				X
A_{CH}	X	X X		X X

model independent assumptions

SM → SM+NP

tree level

SM	SM+NP
$(V_{ub}/V_{cb})^{SM}$	$(V_{ub}/V_{cb})^{SM}$
γ^{SM}	γ^{SM}

Bd Mixing

SM	SM+NP
β^{SM}	$\beta^{SM}+\phi_{Bd}$
α^{SM}	$\alpha^{SM}-\phi_{Bd}$
Δm_d	$C_{Bd}\Delta m_d$

Bs Mixing

SM	SM+NP
Δm_s^{SM}	$C_{Bs}\Delta m_s^{SM}$
β_s^{SM}	$\beta_s^{SM}+\phi_{Bs}$

K Mixing

SM	SM+NP
ε_K^{SM}	$C\varepsilon_K$ ε_K^{SM}

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

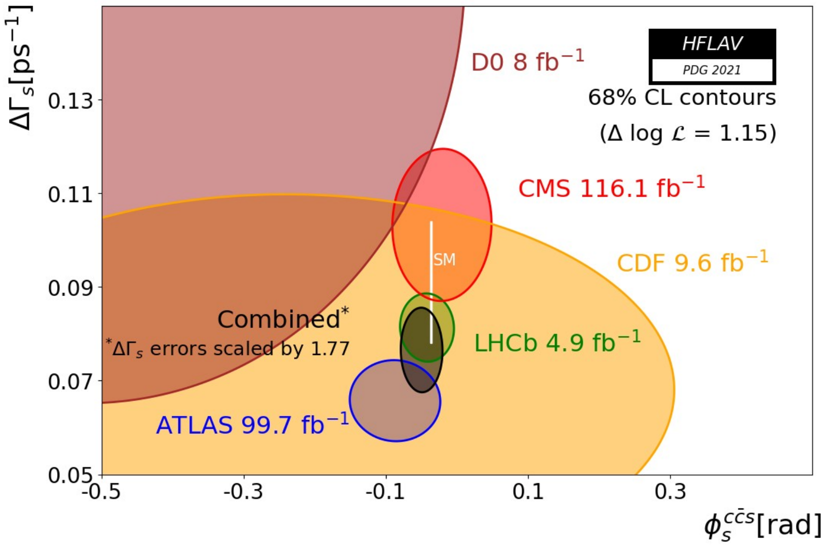
$$\tau^{FS}(B_s) = 1.527 \pm 0.011 \text{ ps}$$

HFLAV

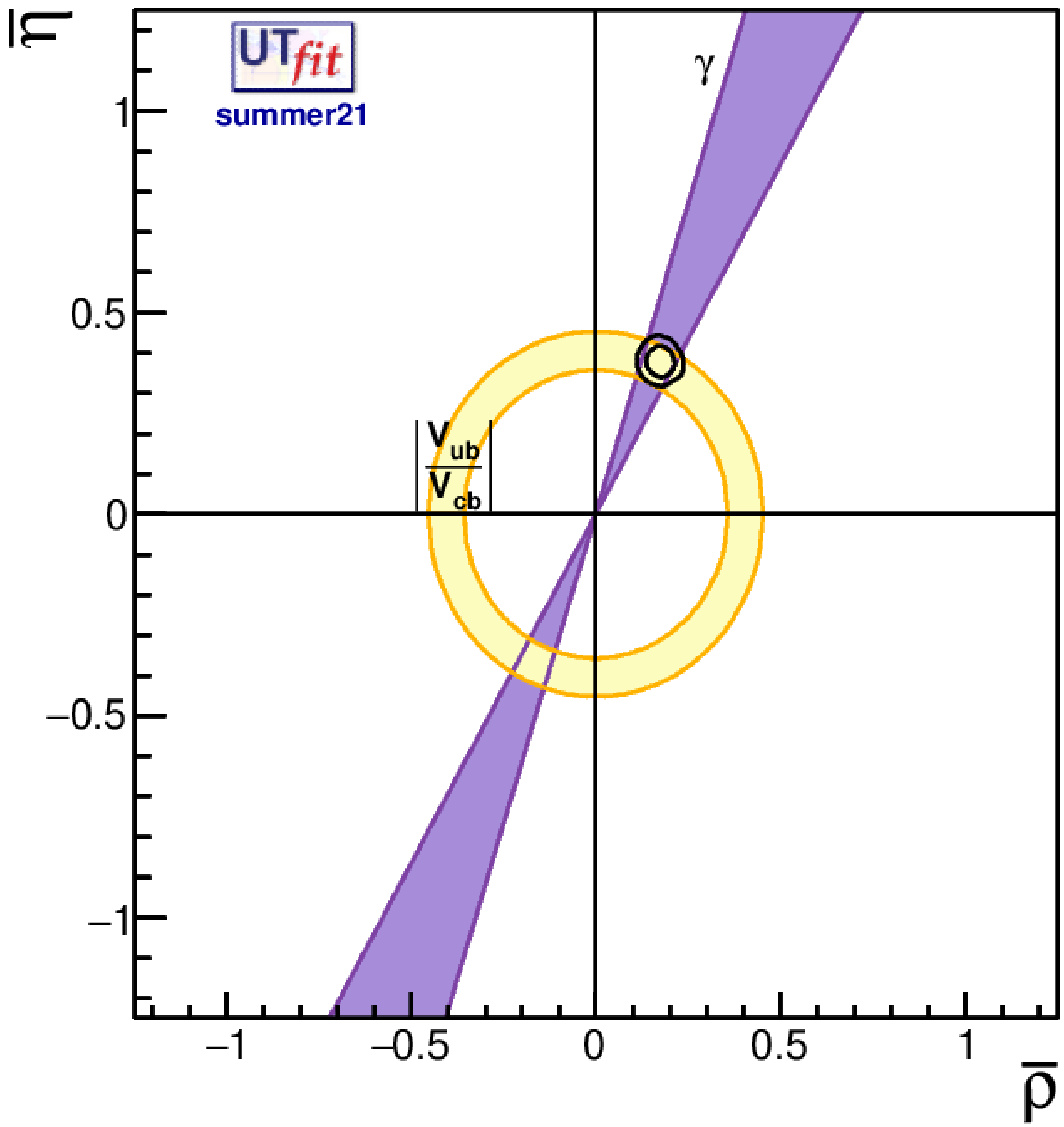
$\phi_s = 2\beta_s$ vs $\Delta\Gamma_s$ from $B_s \to J/\psi\phi$

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

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

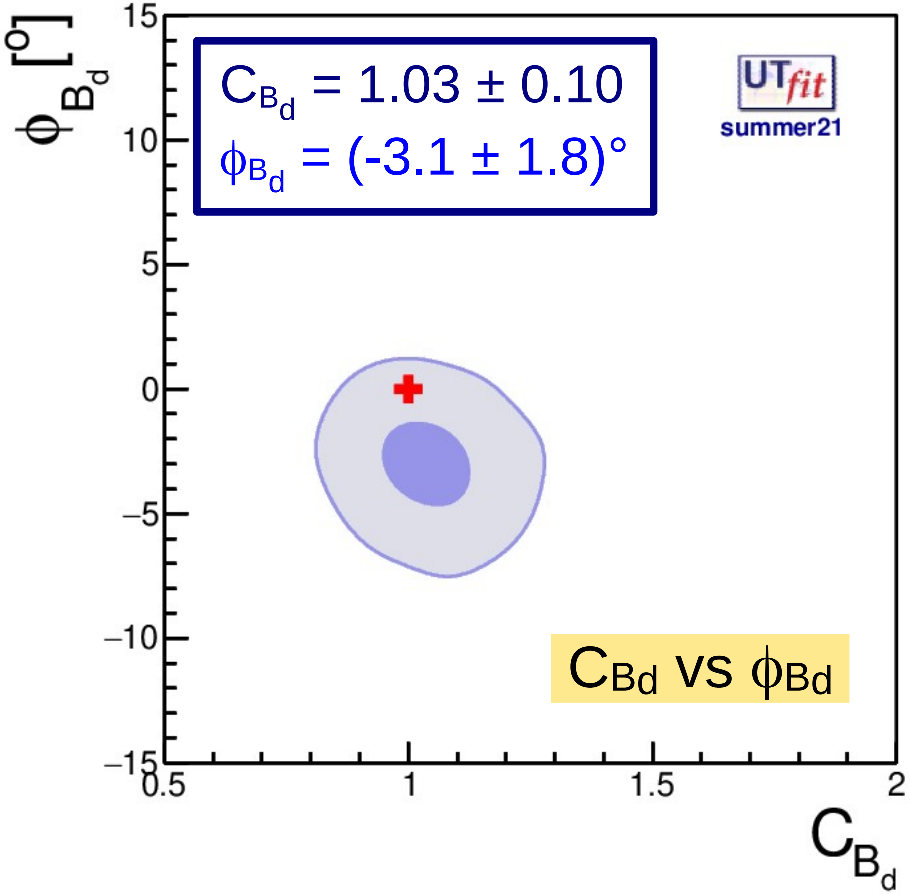
NP parameter results

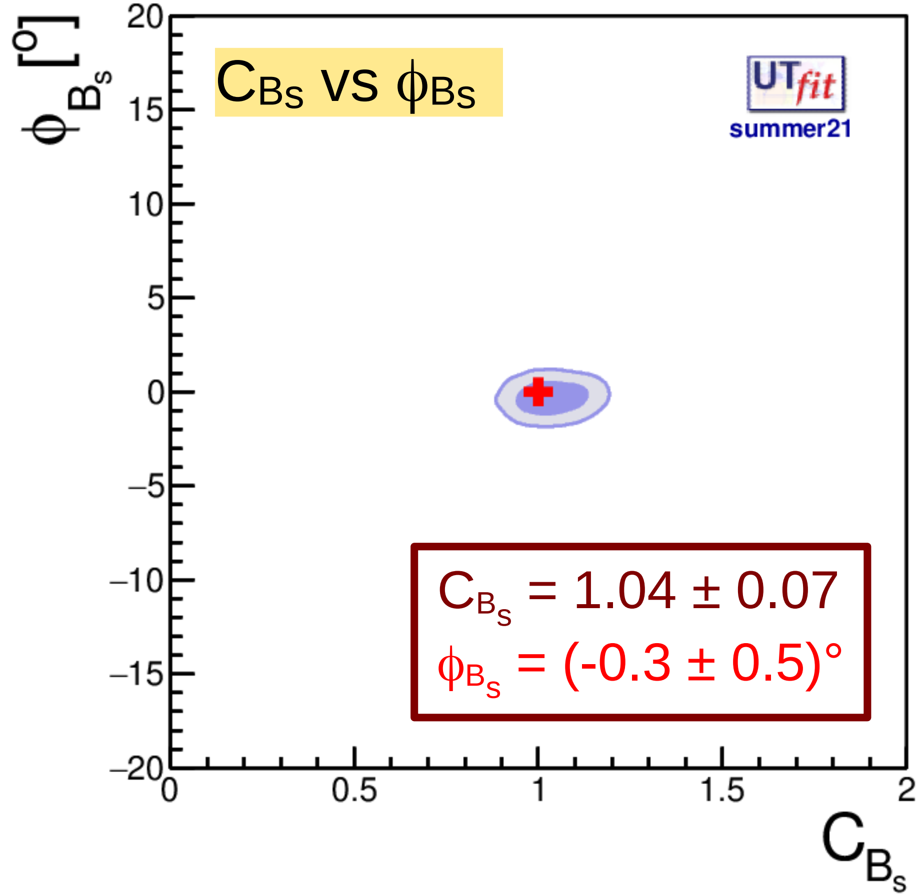
$$A_q = C_{B_q} e^{2i\phi_{B_q}} A_q^{SM} e^{2i\phi_q^{SM}}$$

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

K system

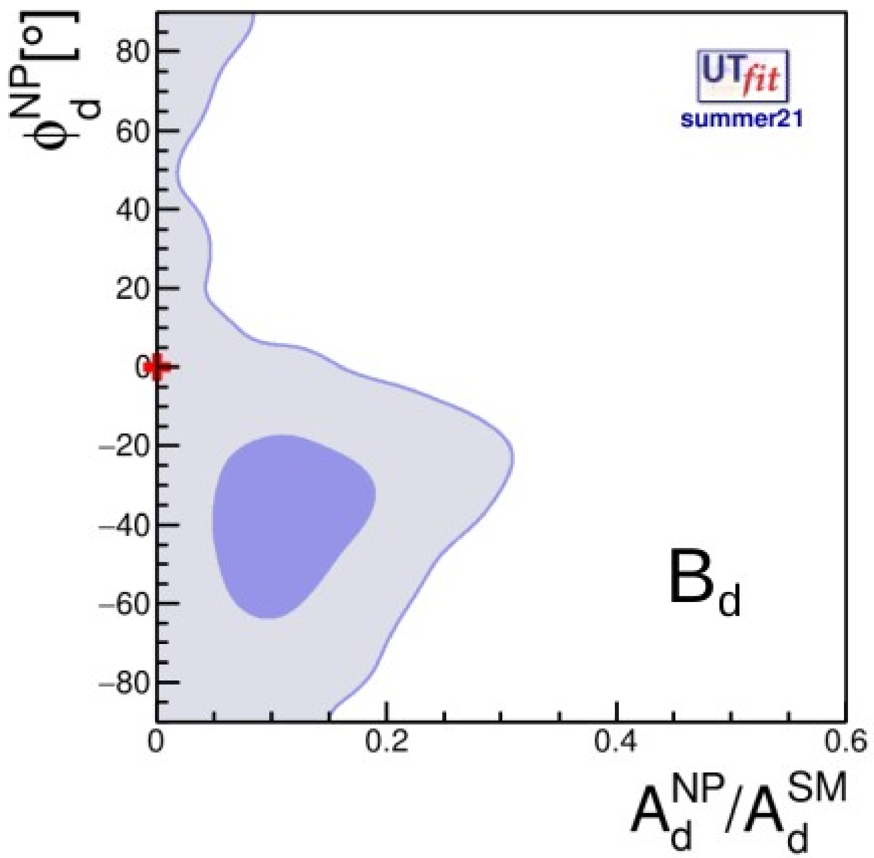
$C_{\epsilon_K} = 1.05 \pm 0.10$

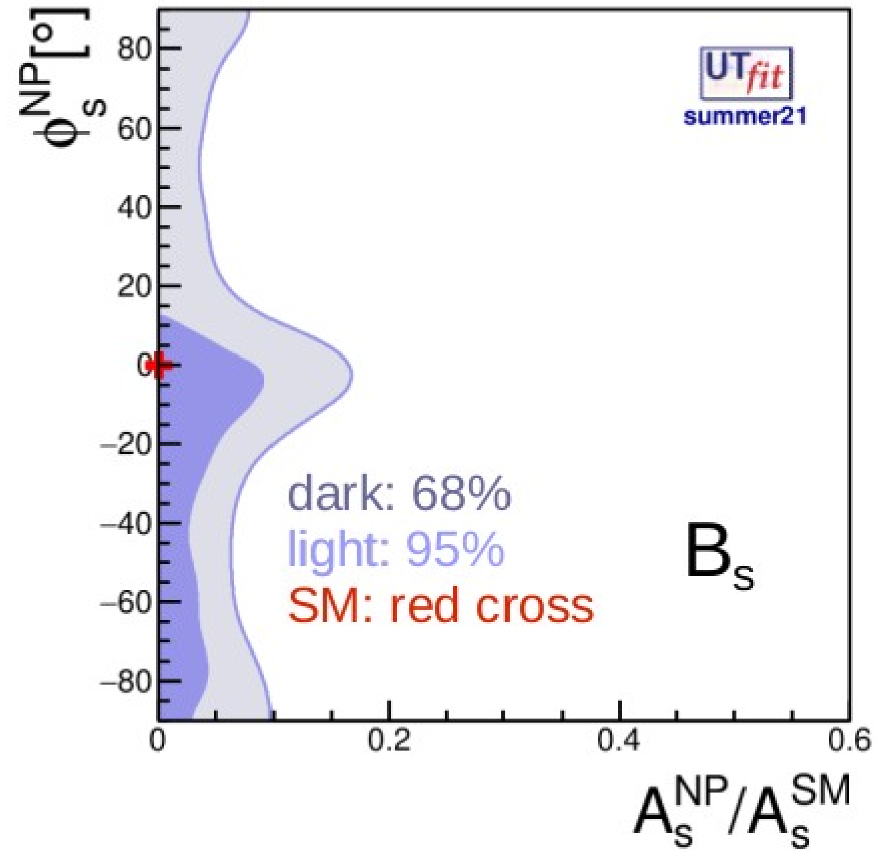




NP parameter results

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





The ratio of NP/SM amplitudes is:

< 18% @68% prob. (30% @95%) in B_d mixing

< 10% @68% prob. (18% @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 ΔF=2 processes)

Testing the new-physics 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: $C(\Lambda) = \alpha \times |F_{SM}|/\Lambda^2$ — $F_1 \sim |F_{SM}|$, $F_{i\neq1} \sim 0$, 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

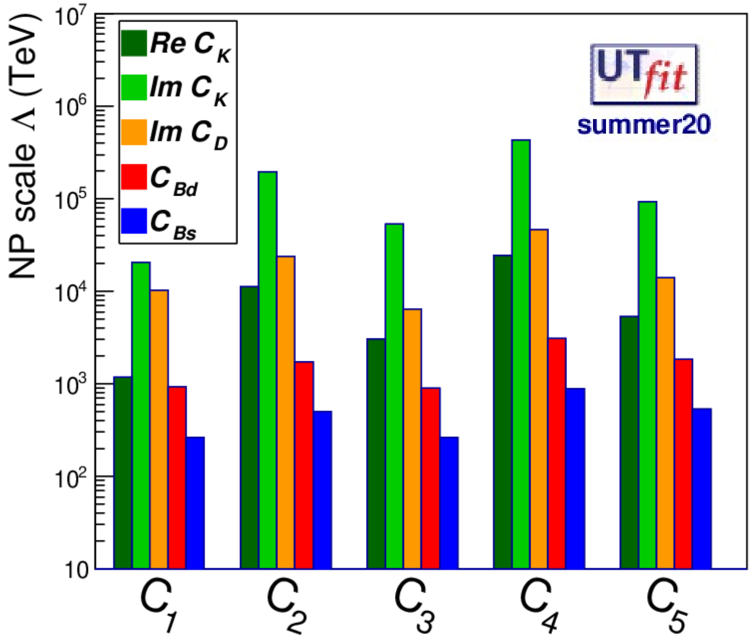
If no NP effect is seen lower bound on NP scale Λ

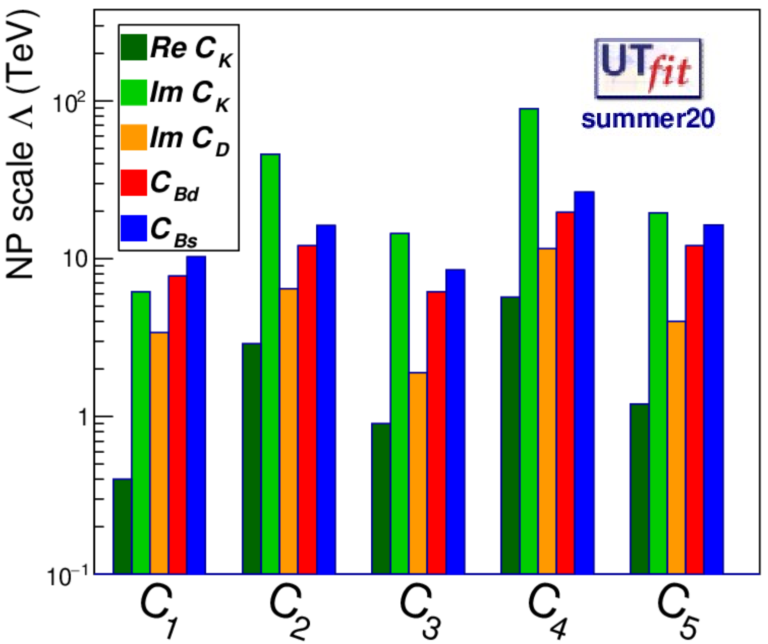
F is the flavour coupling and so
F_{SM} is the combination of CKM factors for the considered process

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





$\Lambda > 4.3\ 10^5$ 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

- ◉ test of the SM consistency and the CKM mechanism: comparison between inputs and indirect determinations
  - ◎ using all the available inputs from experiments and theoretical and lattice QCD calculation
  - ◎ extraction of the most accurate SM predictions

- ◉ model-independent new physics:
  - ◎ overconstraining of the SM fit allows for extraction of generic amplited and phase for all the systems (K, B_d, B_s)
  - ◎ scale analysis: putting bounds on the Wilson coefficients give insights into the NP scale in different NP scenarios

- ◉ LHC(b) and Belle II will reach better precision and provide new measurements

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

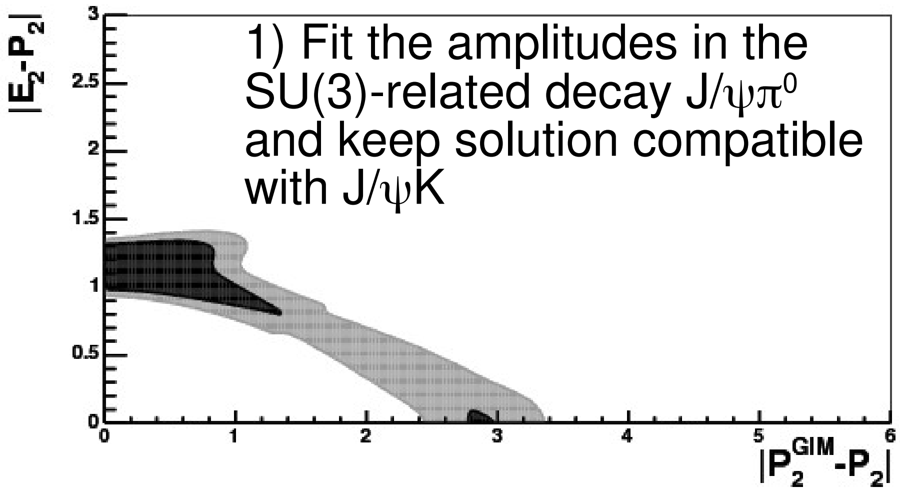
theory error on sin2β:

A.Buras, L.Silvestrini
Nucl.Phys.B569:3-52(2000)

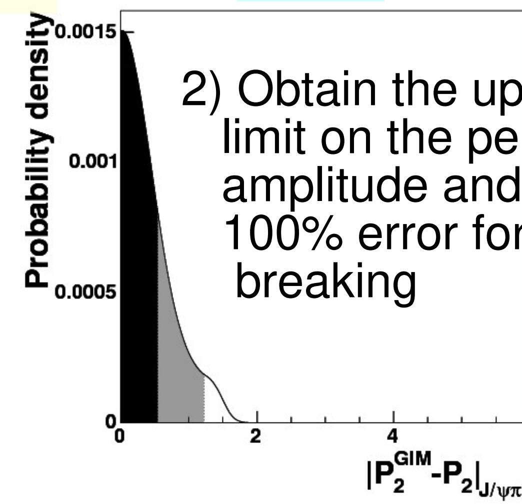
Channel	Cl.	E_1	E_2	EA_2	A_2	P_1	P_2	P_3	P_1^{GIM}	P_2^{GIM}	P_3^{GIM}	P_4	P_4^{GIM}
			$\frac{1}{N}$	$\frac{1}{N^2}$	$\frac{1}{N}$	$\frac{1}{N}$	$\frac{1}{N^2}$		$\frac{1}{N}$	$\frac{1}{N^2}$		$\frac{1}{N^3}$	$\frac{1}{N^3}$
$B_d \to J/\psi K^0$	C	–	λ^2	–	–	–	λ^2	–	–	λ^4	–	–	–
$B_d \to \pi^0 J/\psi$	D	–	λ^3	λ^3	–	–	λ^3	–	–	λ^3	–	$[\lambda^3]$	$[\lambda^3]$

$V^*_{cb}V_{cs}$ $V^*_{tb}V_{ts}$ $V^*_{ub}V_{us}$

$V^*_{cb}V_{cd}$ $V^*_{tb}V_{td}$ $V^*_{ub}V_{ud}$

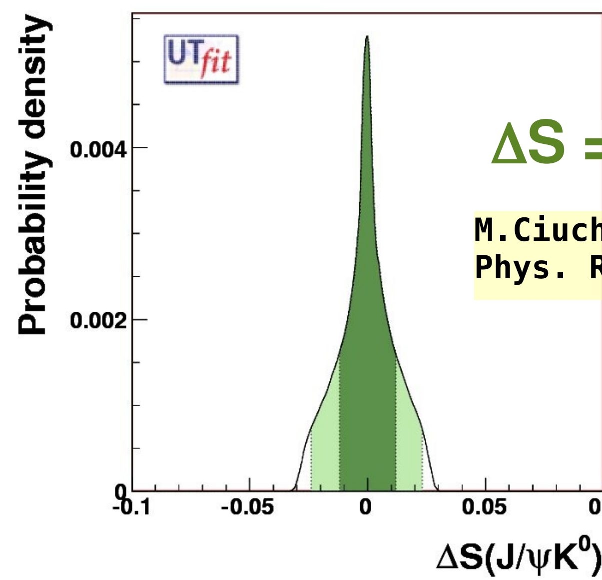


1) Fit the amplitudes in the SU(3)-related decay $J/\psi\pi^0$ and keep solution compatible with $J/\psi K$



2) Obtain the upper limit on the penguin amplitude and add 100% error for SU(3) breaking

3) Fit the amplitudes in $J/\psi K^0$ imposing the upper bound on the CKM suppressed amplitude and extract the error on sin2β



ΔS = 0.000 ± 0.012

M.Ciuchini, M.Pierini, L.Silvestrini
Phys. Rev. Lett. 95, 221804 (2005)

lattice QCD inputs

updated in early 2020

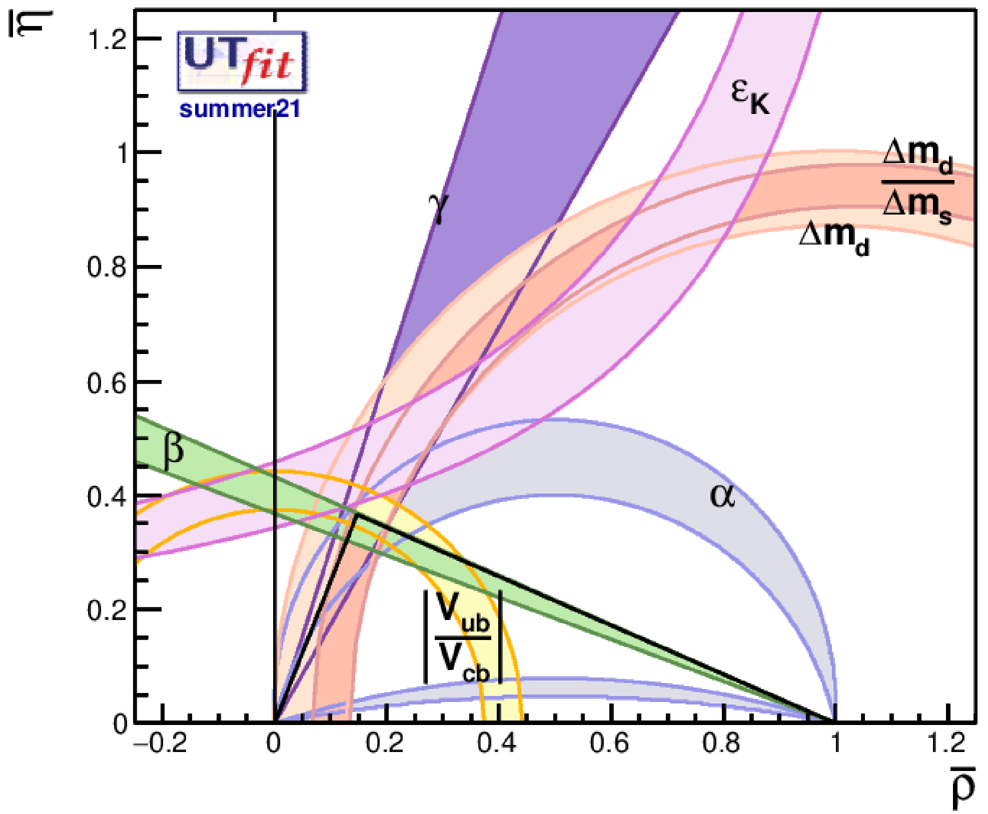
Observables	Measurement
B_K	0.756 ± 0.016
f_{Bs}	0.2301 ± 0.0012
f_{Bs}/f_{Bd}	1.208 ± 0.005
B_{Bs}/B_{Bd}	1.032 ± 0.038
B_{Bs}	1.35 ± 0.06

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

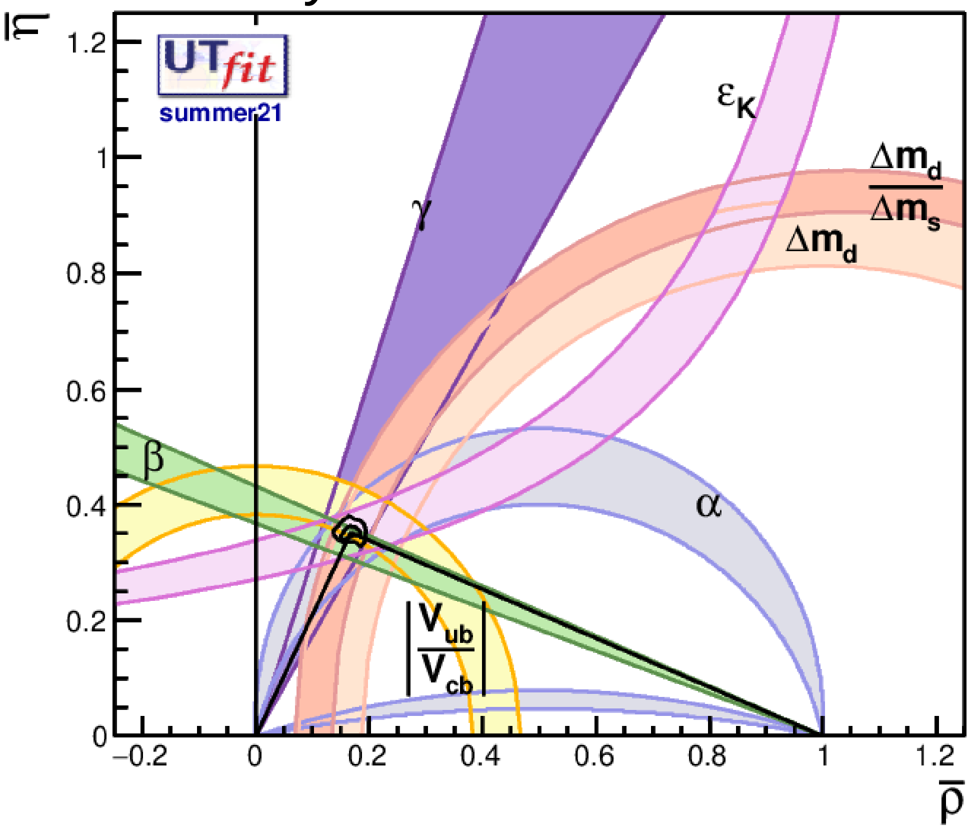
We quote, instead, the weighted average of the N_f=2+1+1 and N_f=2+1 results with the error rescaled when chi2/dof > 1, as done by FLAG for the N_f=2+1+1 and N_f=2+1 averages separately

exclusives vs inclusives

only exclusive values



only inclusive values



effective BSM Hamiltonian for ΔF=2 transitions

Most general form of the effective Hamiltonian for ΔF=2 processes

$$\mathcal{H}_{\text{eff}}^{K-\bar{K}} = \sum_{i=1}^{5} C_i\, Q_i^{sd} + \sum_{i=1}^{3} \tilde{C}_i\, \tilde{Q}_i^{sd}$$

$$\mathcal{H}_{\text{eff}}^{B_q-\bar{B}_q} = \sum_{i=1}^{5} C_i\, Q_i^{bq} + \sum_{i=1}^{3} \tilde{C}_i\, \tilde{Q}_i^{bq}$$

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)

contribution to the mixing amplitutes

analytic expression for the contribution to the mixing amplitudes

Lattice QCD

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

arXiv:0707.0636: for "magic numbers" a,b and c, $\eta = \alpha_s(\Lambda)/\alpha_s(m_t)$

analogously for the K system

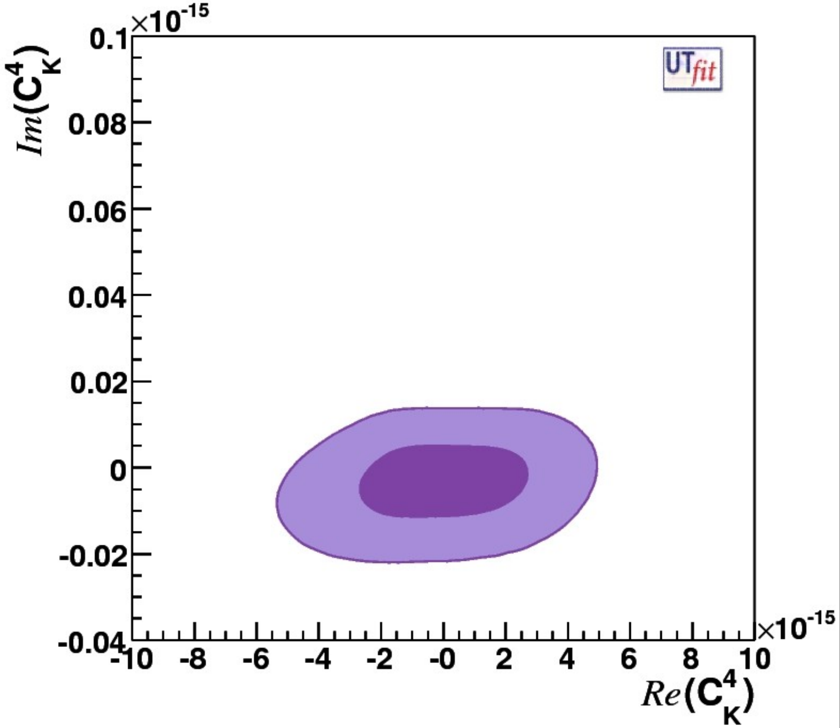
$$\langle \bar{K}^0 | \mathcal{H}_{\rm eff}^{\Delta S=2} | K^0 \rangle_i = \sum_{j=1}^{5} \sum_{r=1}^{5} \left(b_j^{(r,i)} + \eta\, c_j^{(r,i)} \right) \eta^{a_j}\, C_i(\Lambda)\, R_r\, \langle \bar{K}^0 | Q_1^{sd} | K^0 \rangle$$

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



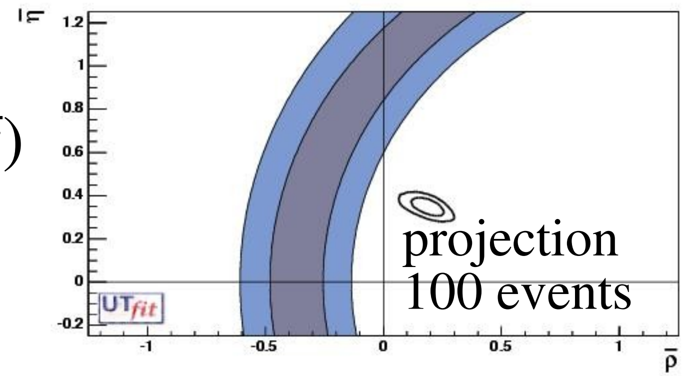
To obtain the lower bound for loop-mediated contributions, one simply multiplies the bounds by $\alpha_s \sim 0.1$ or by $\alpha_W \sim 0.03$.

some old plots coming back to fashion:

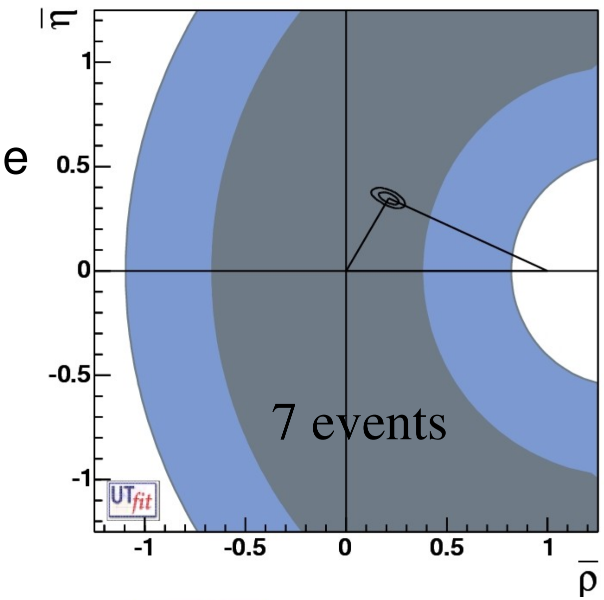
As NA62 and KOTO are analysing data:

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

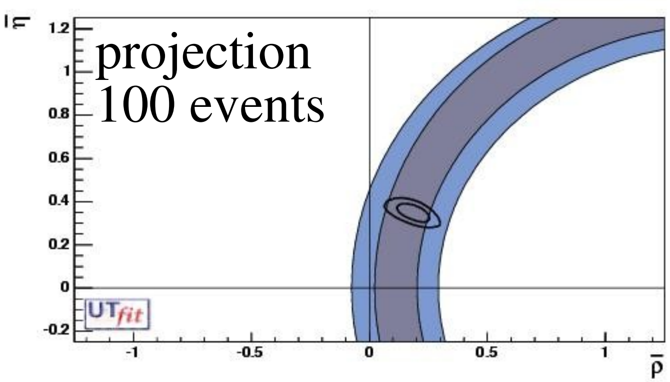
E949 central value

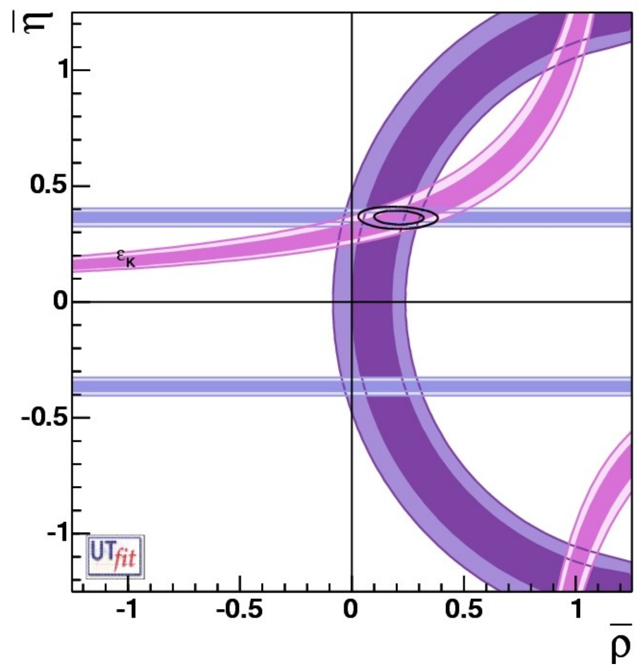


2007 global fit area



SM central value

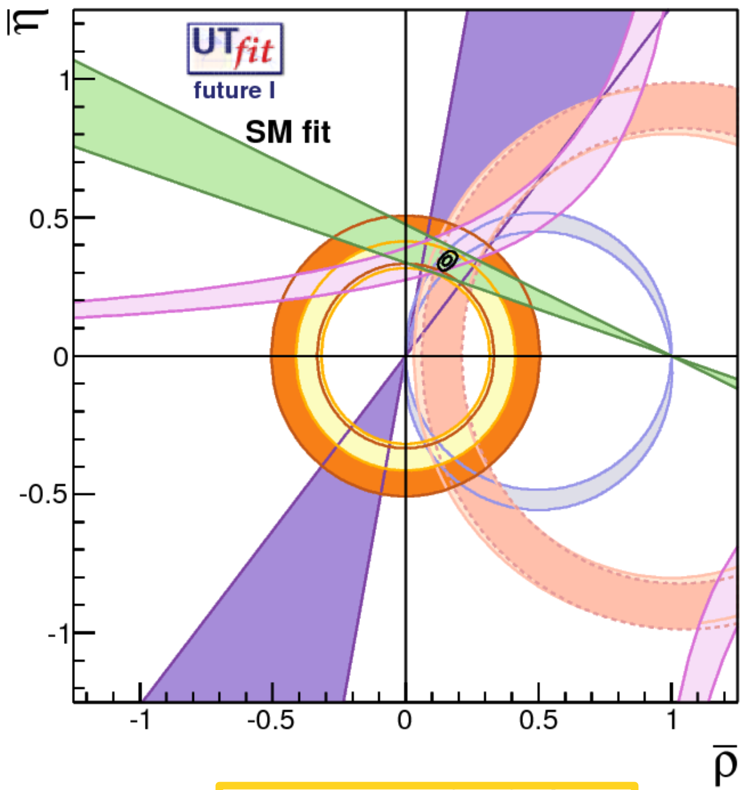


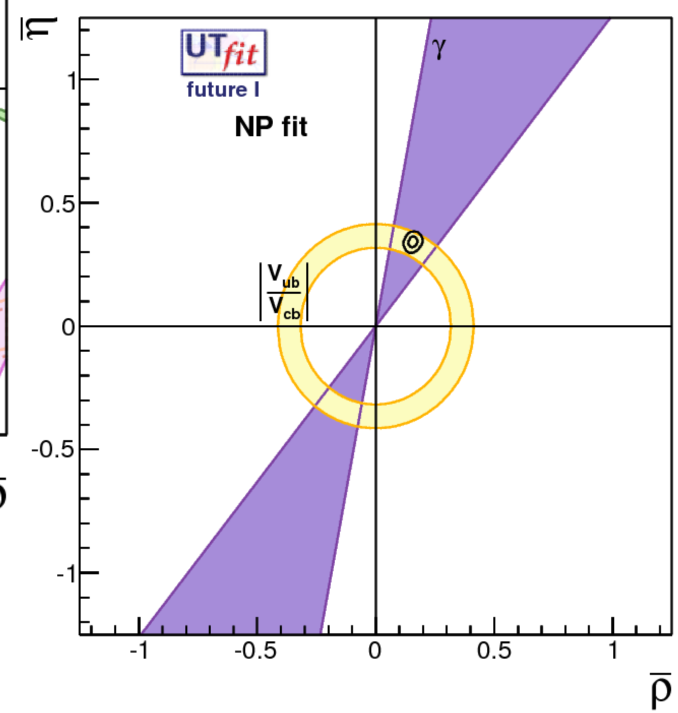


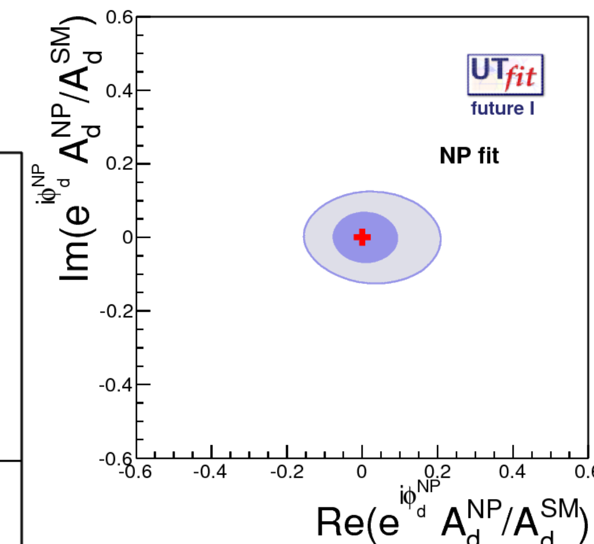
including
$BR(K^0 \to \pi^0\nu\bar{\nu})$
SM central value

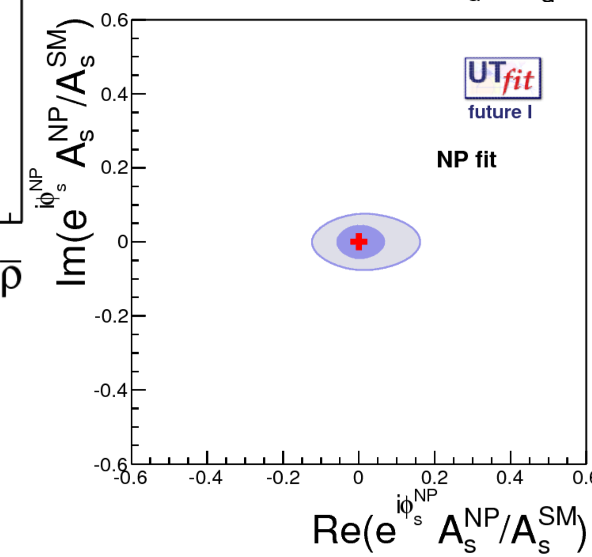
look at the near future

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









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

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

current sensitivity

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

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