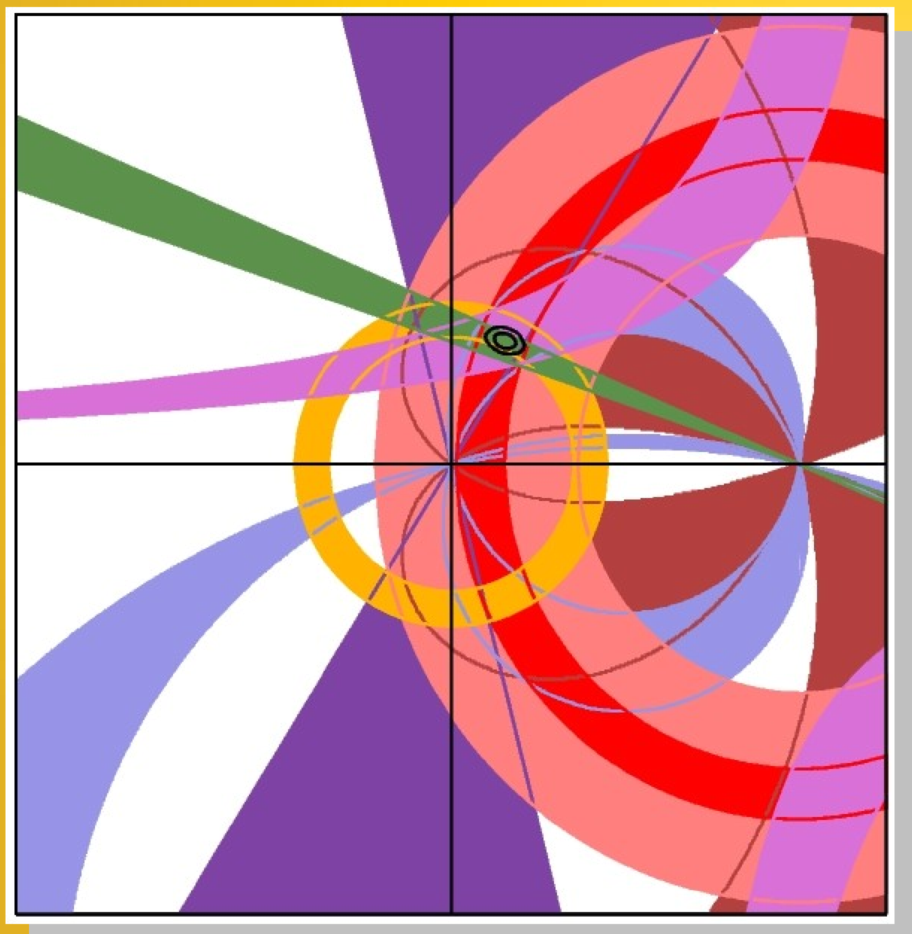
Status of the CKM picture in the light of recent results



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February 19th, 2013

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 for SM observables (ex. $\sin 2\beta$, Δm_s, ...)

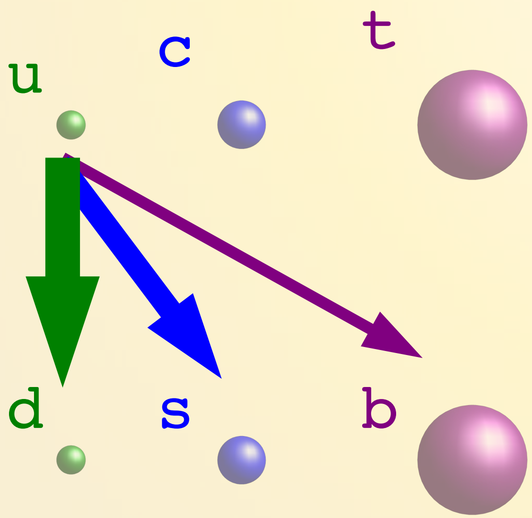
.. and beyond

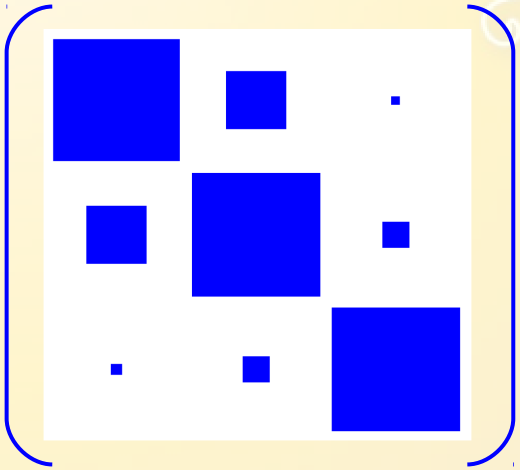
- NP UT analysis:
  - model-indipendent analysis
  - provides limit on the allowed deviations from the SM
  - NP scale analysis update

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}.

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





CKM matrix and Unitarity Triangle

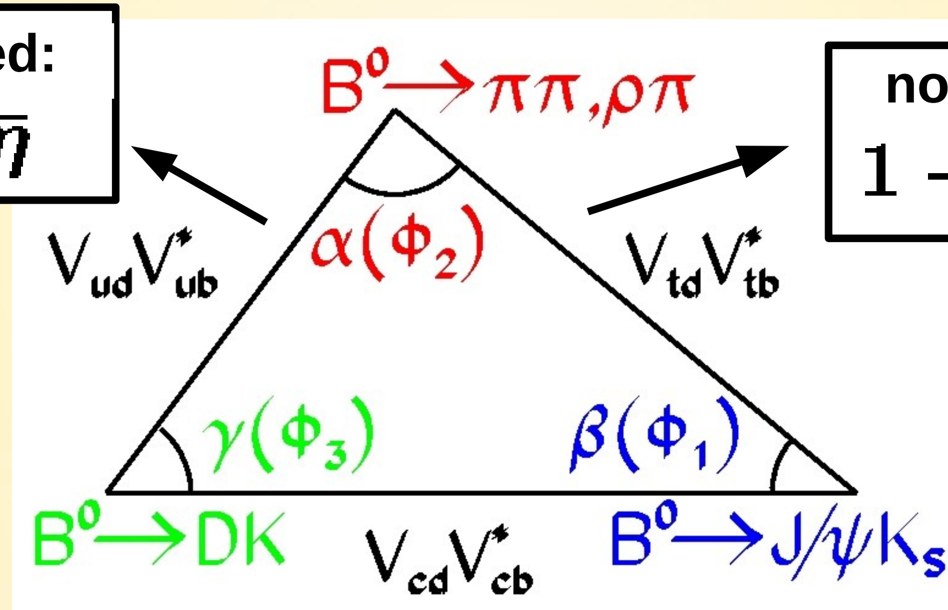
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

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

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

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

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



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

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

www.utfit.org

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://krone.physik.unizh.ch/~lunghi/webpage/LatAves/page3/page3.htm),
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
$A_{CP}(J/\psi K_S)$	$\sin 2\beta$	

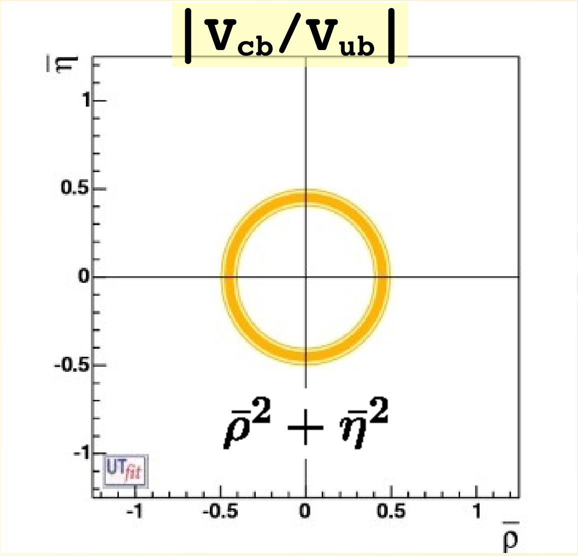
, mt

Standard Model + OPE/HQET/ Lattice QCD to go from quarks to hadrons

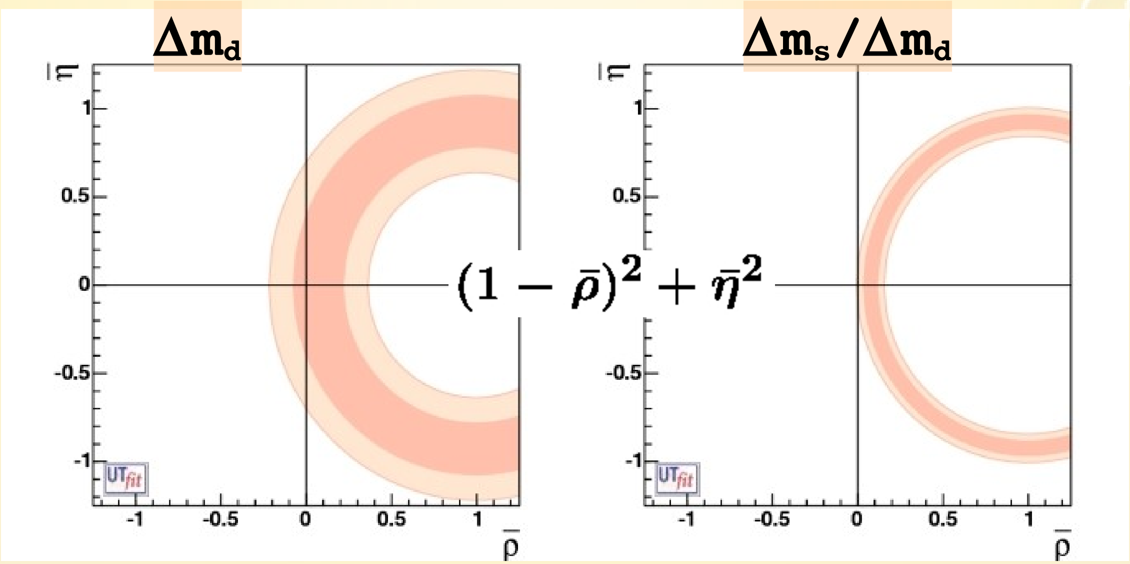
M. Bona *et al*. (UTfit Collaboration) JHEP 0507:028,2005 hep-ph/0501199
M. Bona *et al*. (UTfit Collaboration) JHEP 0603:080,2006 hep-ph/0509219

CP-conserving inputs

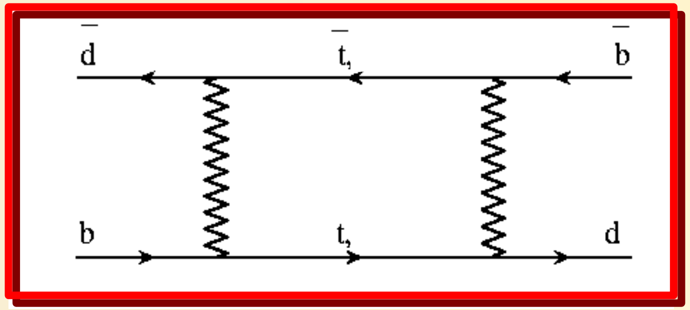
$|V_{ub}|/|V_{cb}| \sim R_b$ (tree-level)

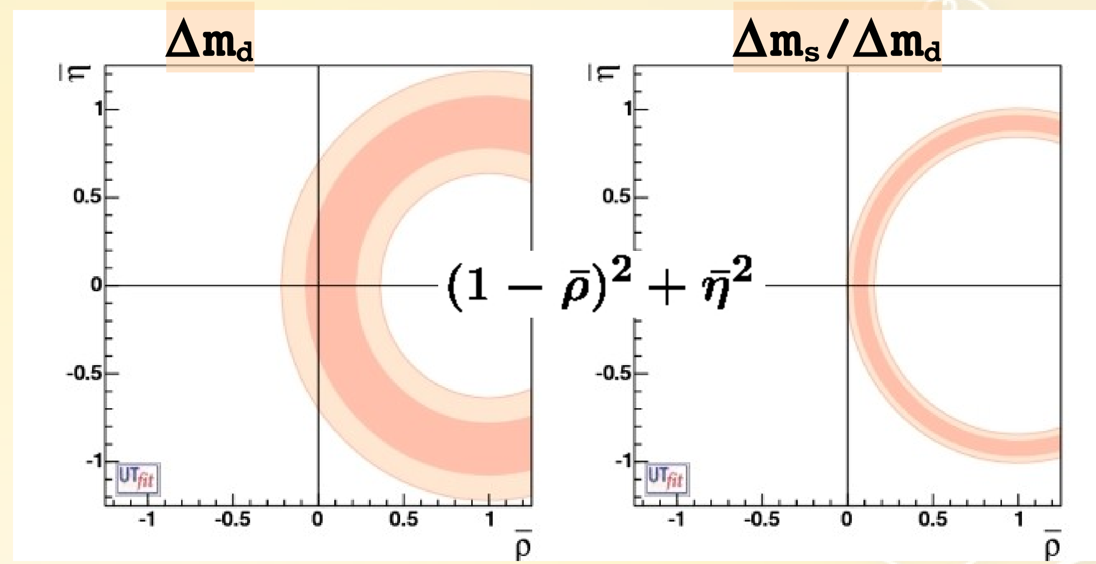


B_d-B_d and B_s-B_s mixing



B_d and B_s mixing





$\Delta m_d = (0.507 \pm 0.004)\ \mathrm{ps}^{-1}$

$\Delta m_s = (17.72 \pm 0.04)\ \mathrm{ps}^{-1}$

New world average from CDF and LHCb

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

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

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

B_K	0.73 ± 0.03	flag10 $N_f = 2$
f_{B_s}	$233 \pm 10\ MeV$	UTfit $N_f = 2$ & 2+1
f_{B_s}/f_{B_d}	1.200 ± 0.02	
$\hat{B}_{B_s}$	1.33 ± 0.06	HPQCD09 $N_f = 2+1$
$\hat{B}_{B_s}/\hat{B}_{B_d}$	1.05 ± 0.07	

V_{cb} and V_{ub}

Laiho *et al*

V_{cb} *(excl)* = (39.5 ± 1.0) 10^{-3}

HFAG

V_{cb} *(incl)* = (41.7 ± 0.7) 10^{-3}

~1.8σ discrepancy

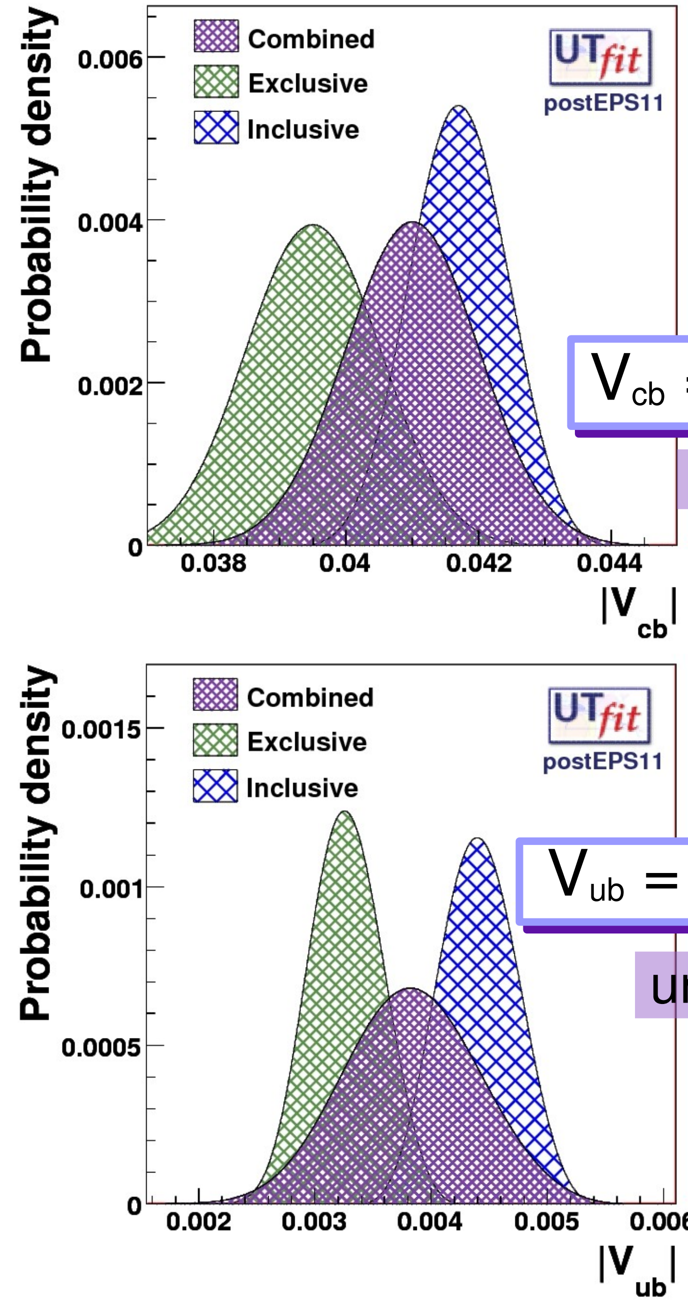
Laiho *et al*

V_{ub} *(excl)* = (3.28 ± 0.30) 10^{-3}

UTfit from HFAG

V_{ub} *(incl)* = (4.40 ± 0.31) 10^{-3}

~2.6σ discrepancy



UTfit input value: average à la PDG

V_{cb} = (41.0 ± 1.0) 10^{-3}

uncertainty ~ 2.4%

UTfit input value: average à la PDG

V_{ub} = (3.82 ± 0.56) 10^{-3}

uncertainty ~ 15%

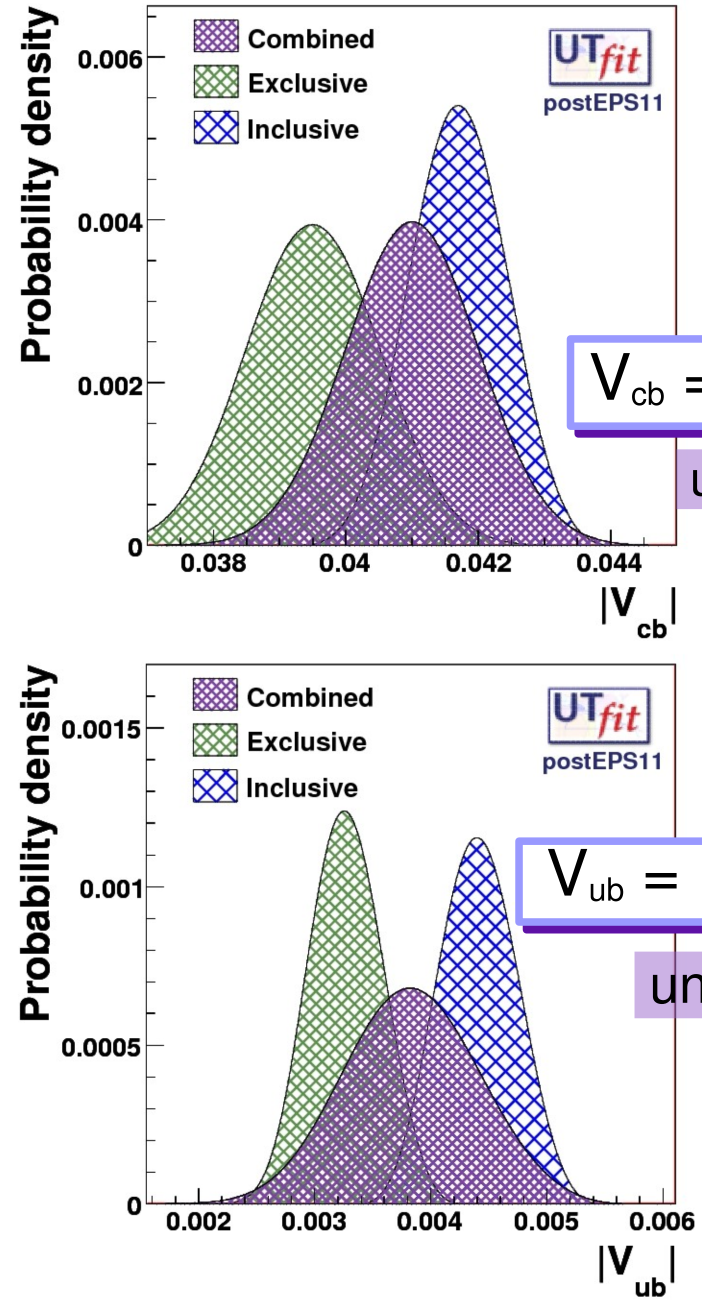
V_{cb} and V_{ub}

B-factory legacy book:
V_{cb} = 41.67 ± 0.63

CKMfitter
41.15 ± 0.33 ± 0.59

B-factory legacy book:
V_{ub} = 3.95 ± 0.54

CKMfitter
3.75 ± 0.14 ± 0.25



UTfit input value: average à la PDG

V_{cb} = (41.0 ± 1.0) 10^{-3}

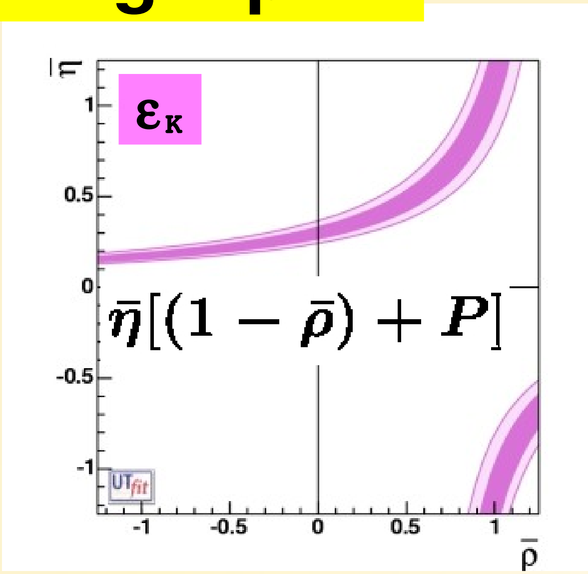
uncertainty ~ 2.4%

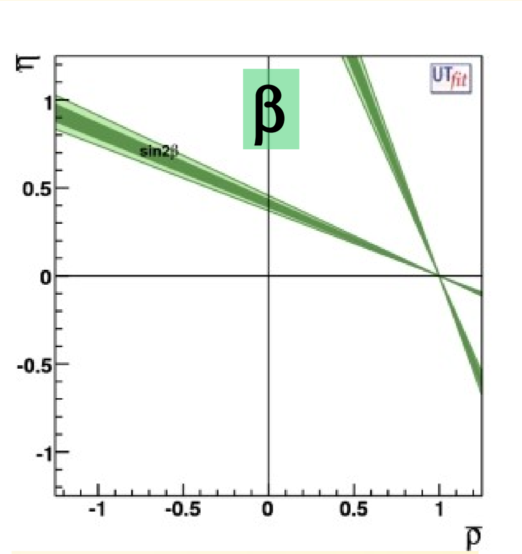
UTfit input value: average à la PDG

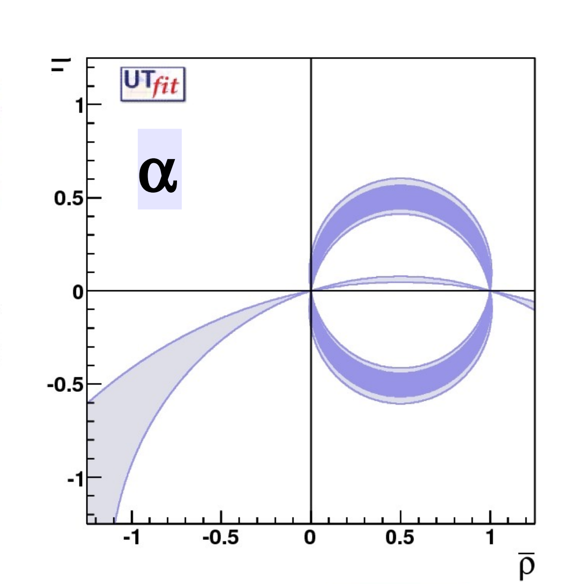
V_{ub} = (3.82 ± 0.56) 10^{-3}

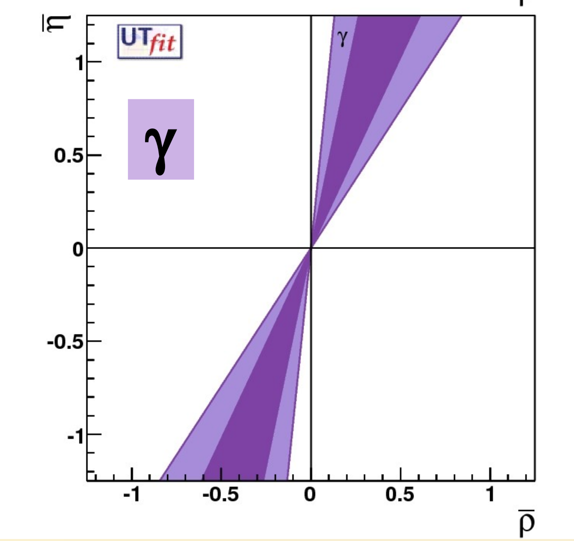
uncertainty ~ 15%

CP-violating inputs









ε_K from K-K mixing

$\rightarrow B_K = 0.730 \pm 0.030$ flag10 $N_f = 2$

sin2β from $B \rightarrow J/\psi K^0$ + theory

$\sin 2\beta(J/\psi K^0) = 0.665 \pm 0.024$ HFAG

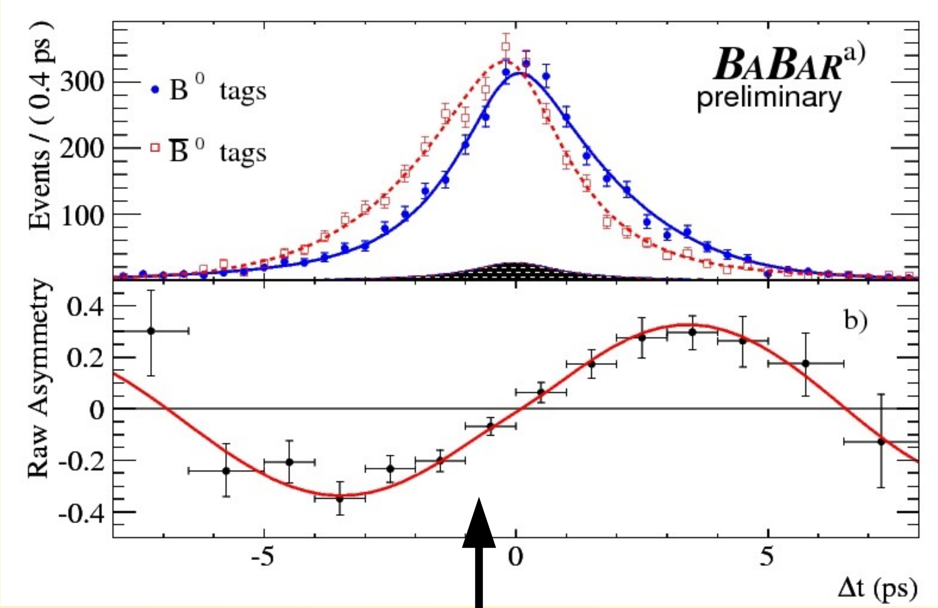
α from ππ, ρρ, πρ decays:

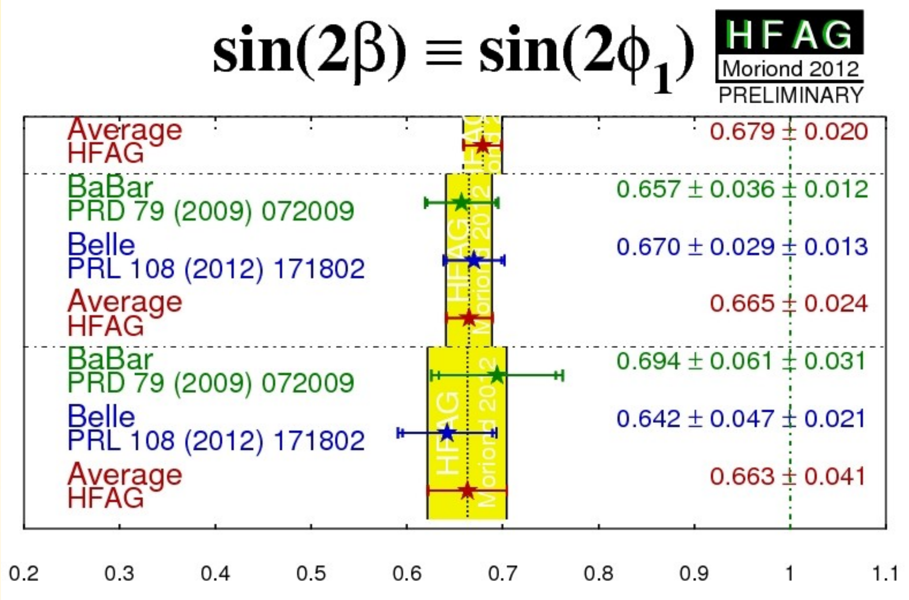
combined: $(91.1 \pm 6.7)°$

γ from $B \rightarrow DK$ decays (tree level)

Latest sin2β results:

LHCb not competitive yet with a 0.07 error





raw asymmetry as function of Δt

BABAR Collaboration PRD 79:072009, 2009

Belle Collaboration PRL 108:171802, 2012

UTfit values

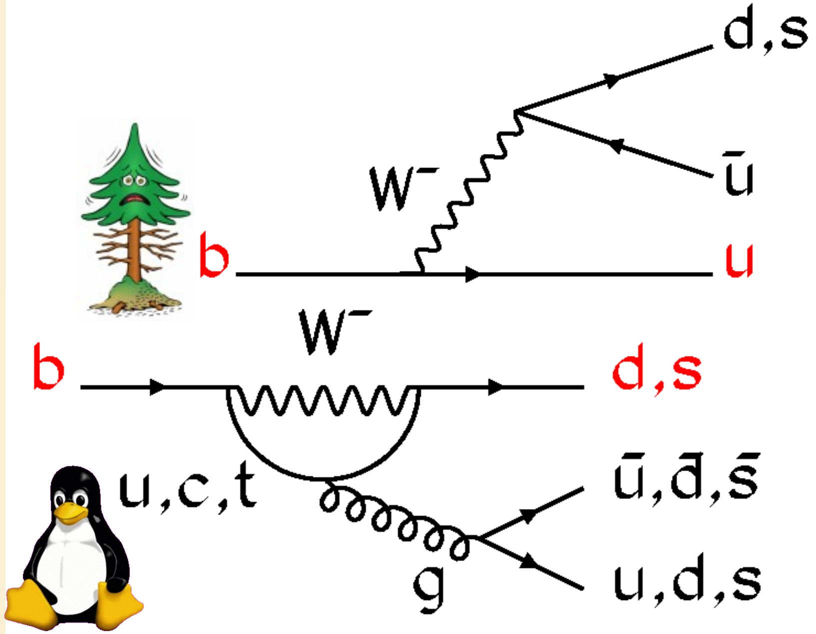
$\sin 2\beta(J/\psi K^0) = 0.665 \pm 0.024$

data-driven theoretical uncertainty

$\Delta S = 0.000 \pm 0.012$

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

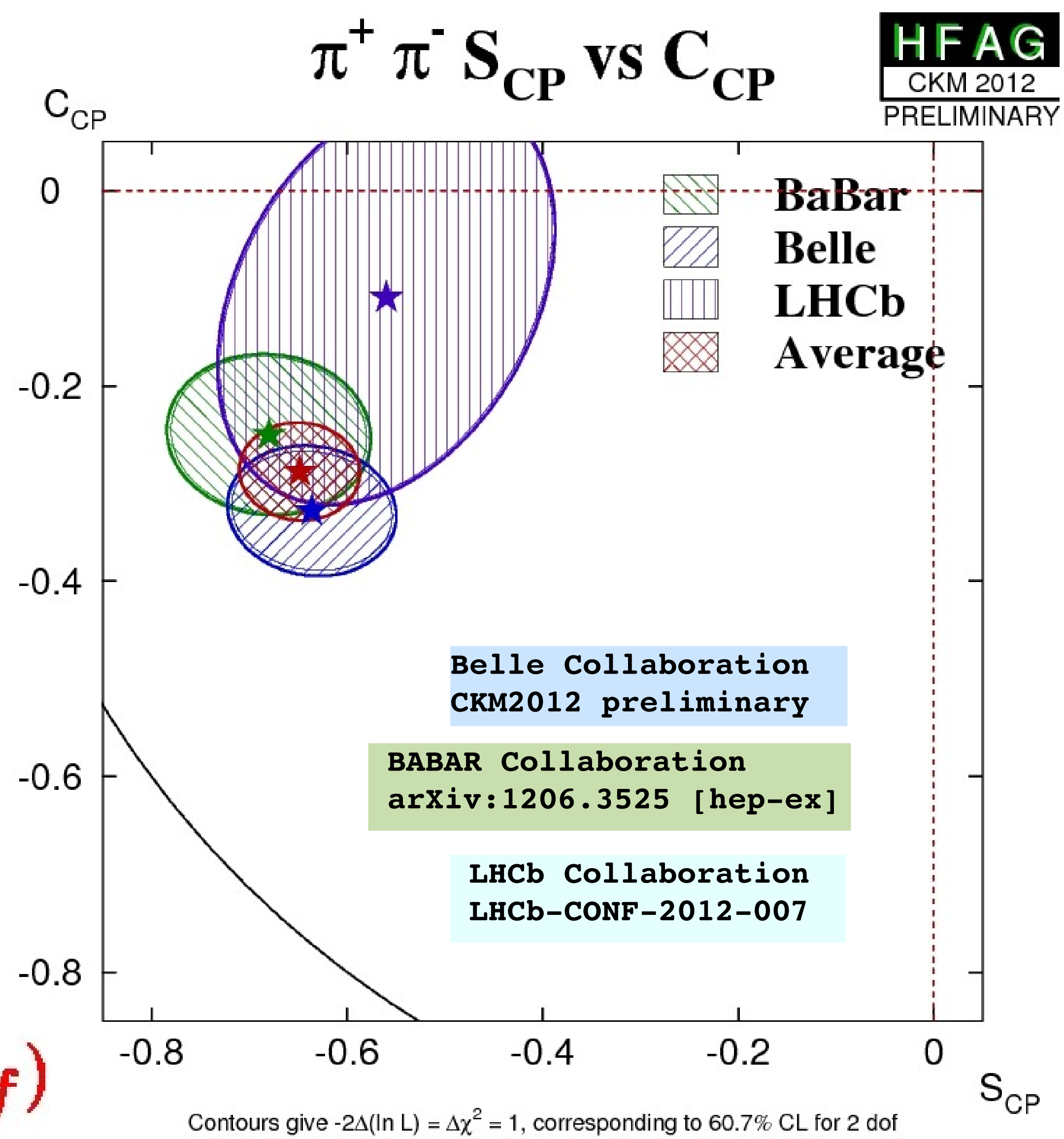
α: CP violation in $B^0 \to \pi\pi/\rho\rho$



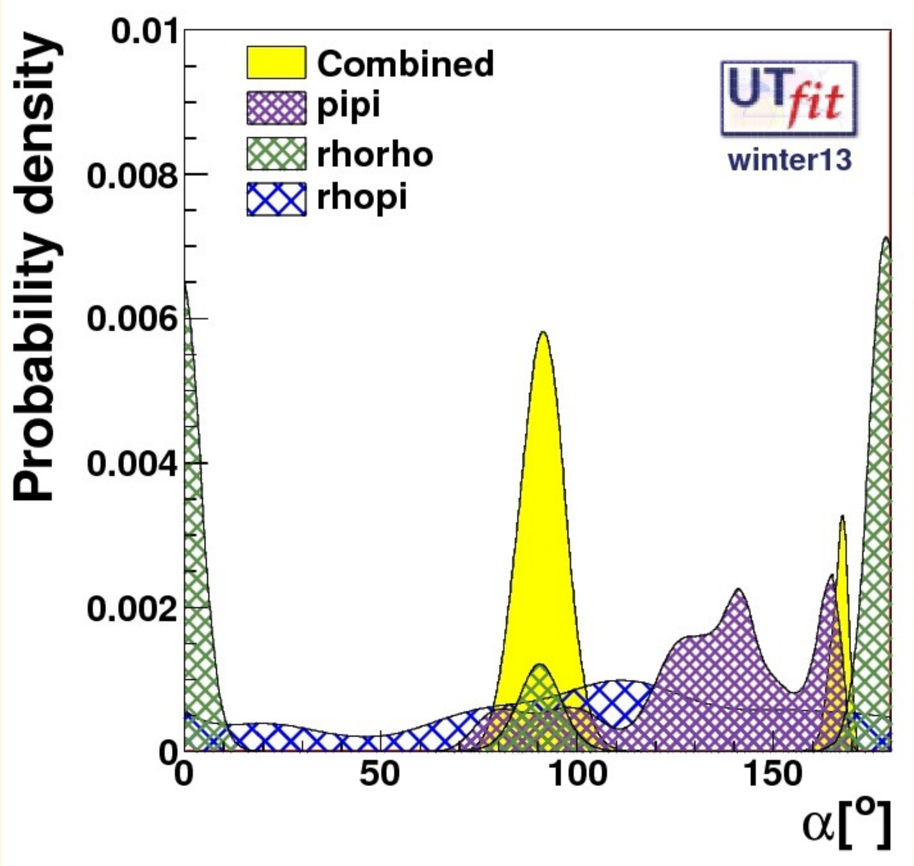
$$\lambda_{\pi\pi} = e^{2i\alpha}\frac{1+|P/T|e^{i\delta}e^{i\gamma}}{1+|P/T|e^{i\delta}e^{-i\gamma}}$$

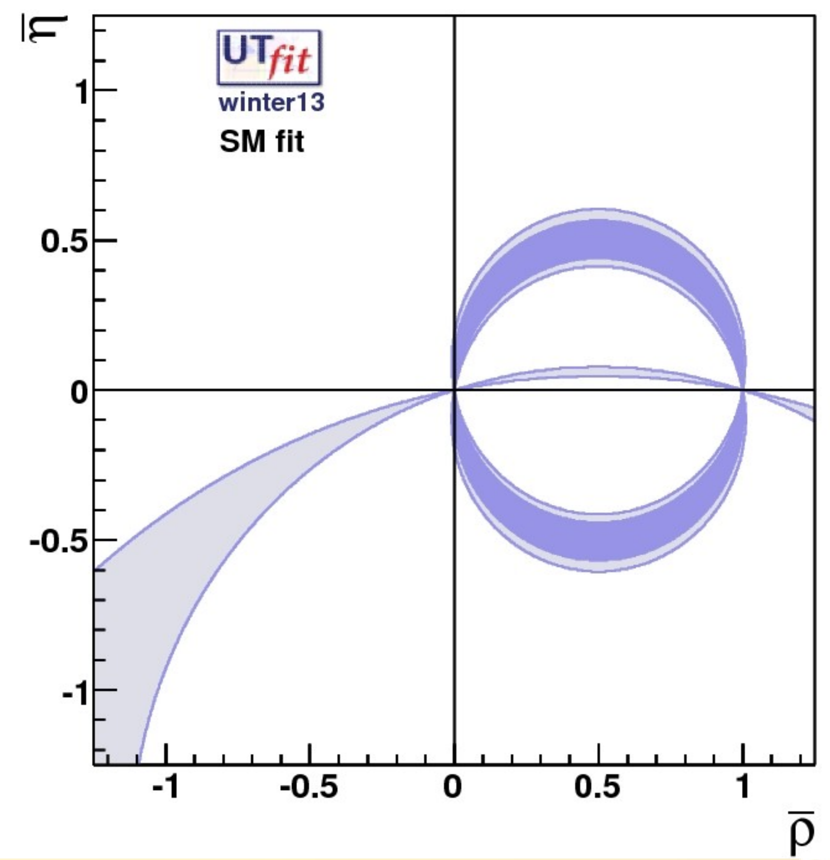
$$C_{\pi\pi} \propto \sin(\delta)$$

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



α: CP violation in $B^0 \to \pi\pi/\rho\rho$



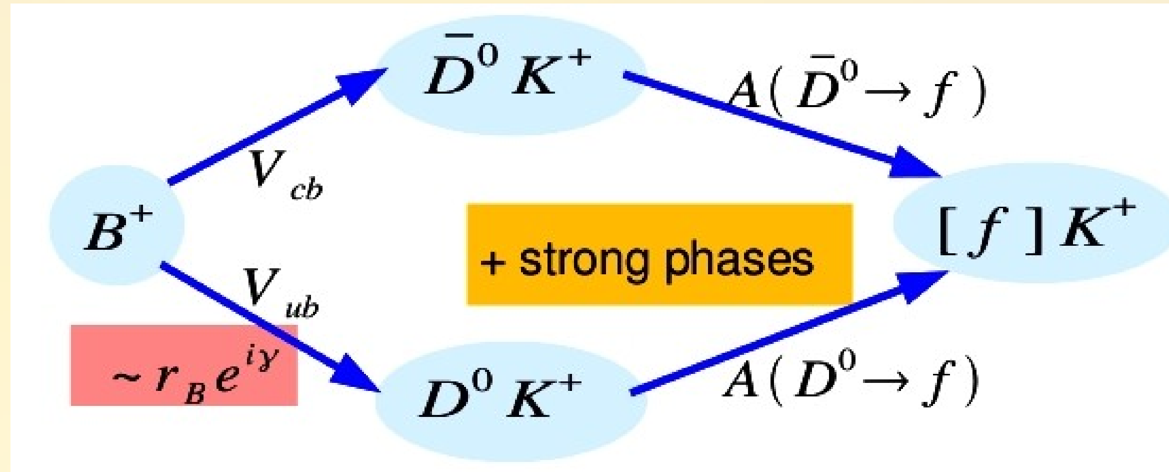


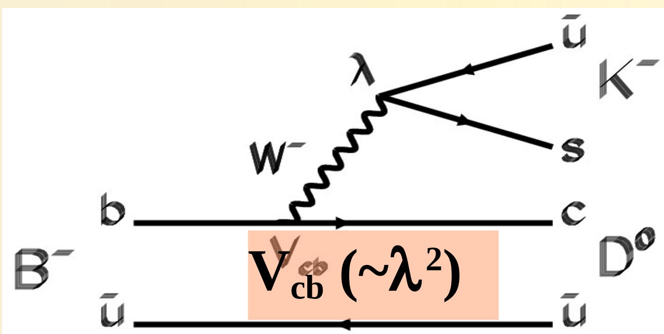
α from ππ, ρρ, πρ decays:

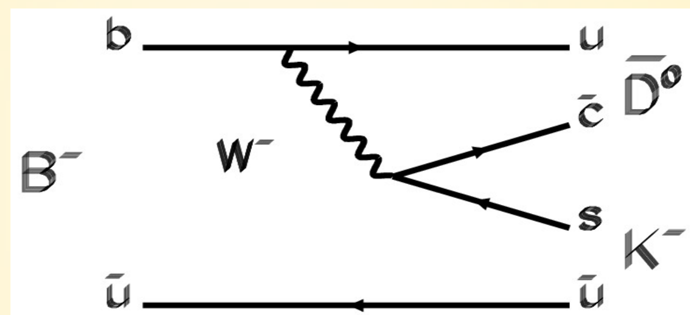
combined: (91.1 ± 6.7)°

γ and DK trees

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







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

δ_B = strong phase diff.

$$A(B^- \to D^0 K^-) = A_B$$
$$A(B^+ \to \bar{D}^0 K^+) = A_B$$

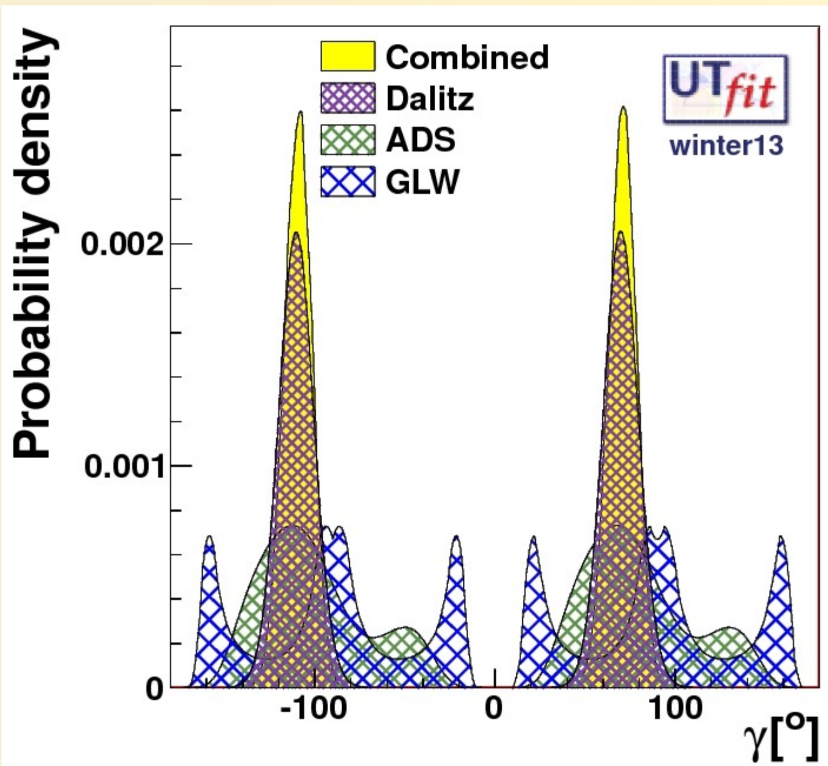
$$A(B^- \to \bar{D}^0 K^-) = A_B r_B e^{i(\delta_B - \gamma)}$$
$$A(B^+ \to D^0 K^+) = A_B r_B e^{i(\delta_B + \gamma)}$$

sensitivity to γ: the amplitude ratio r_B

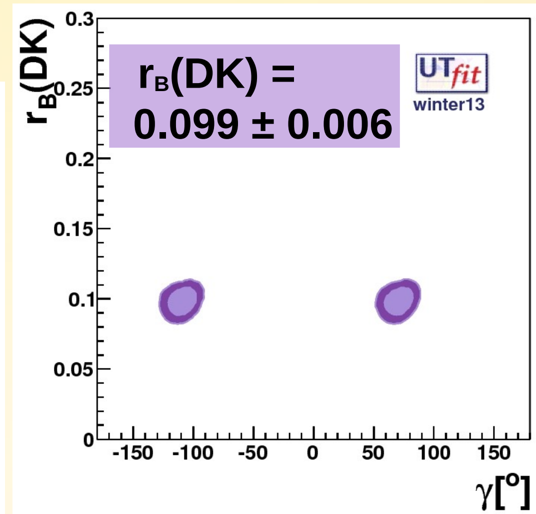
$$r_B = \left|\frac{B^- \to \bar{D}^0 K^-}{B^- \to D^0 K^-}\right| = \sqrt{\bar{\eta}^2 + \bar{\rho}^2} \times F_{CS}$$

→ hadronic contribution channel-dependent

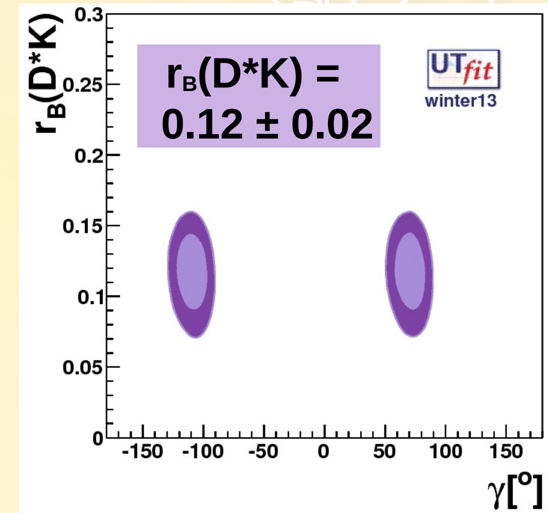
γ and DK trees



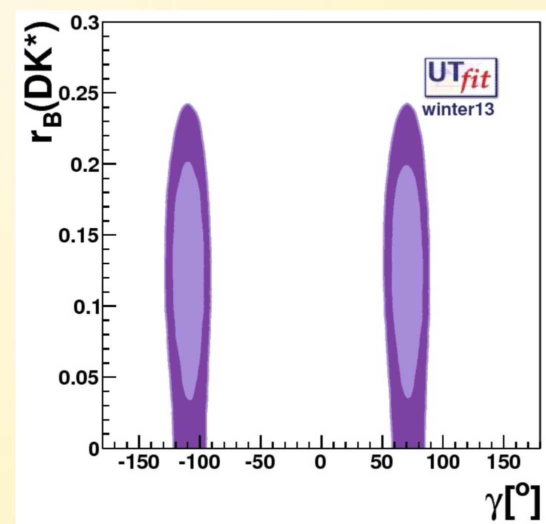
$\gamma = (71.1 \pm 7.6)^{o}$



$r_B(DK) = 0.099 \pm 0.006$

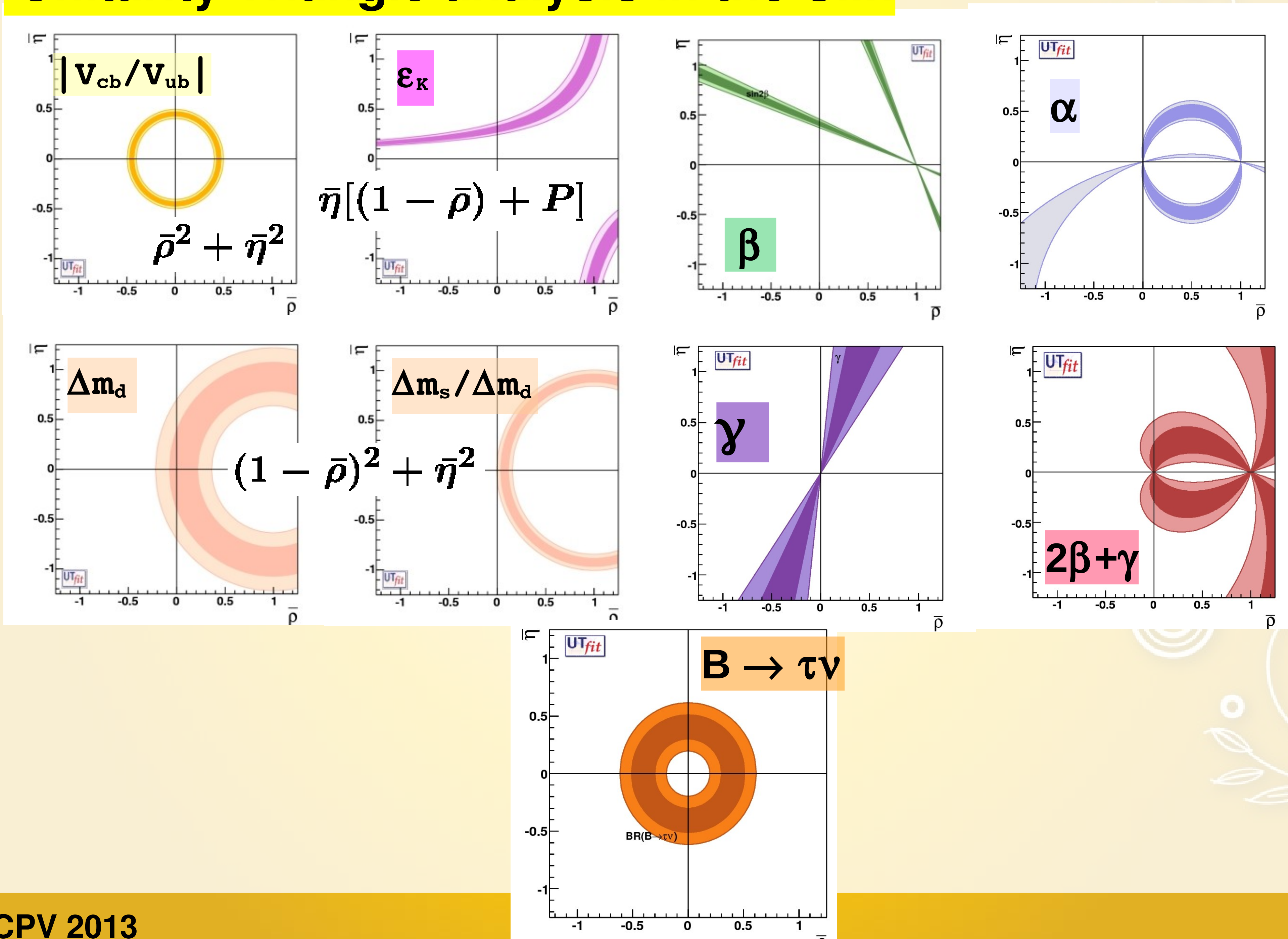


$r_B(D^*K) = 0.12 \pm 0.02$



$r_B(DK^*) = 0.12 \pm 0.06$

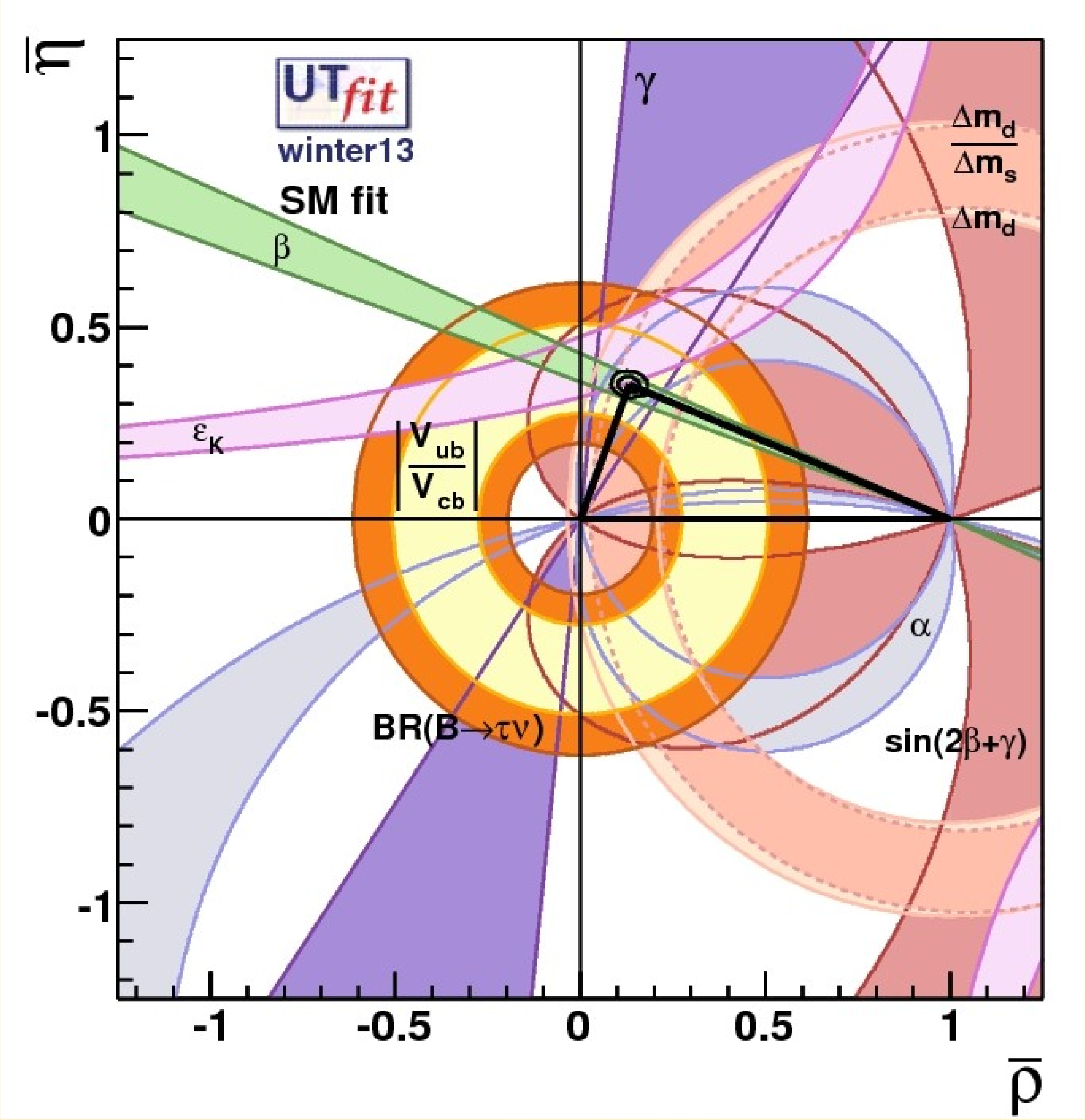
Unitarity Triangle analysis in the SM:



Unitarity Triangle analysis in the SM:

Observables	Accuracy
$\lvert V_{ub}/V_{cb} \rvert$	~ 15%
ε_K	~ 0.5%
Δm_d	~ 1%
$\lvert \Delta m_d/\Delta m_s \rvert$	~ 1%
$\sin 2\beta$	~ 3%
$\cos 2\beta$	~ 15%
α	~ 7%
γ	~ 10%
$BR(B \to \tau\nu)$	~ 25%

Unitarity Triangle analysis in the SM:



levels @
95% Prob

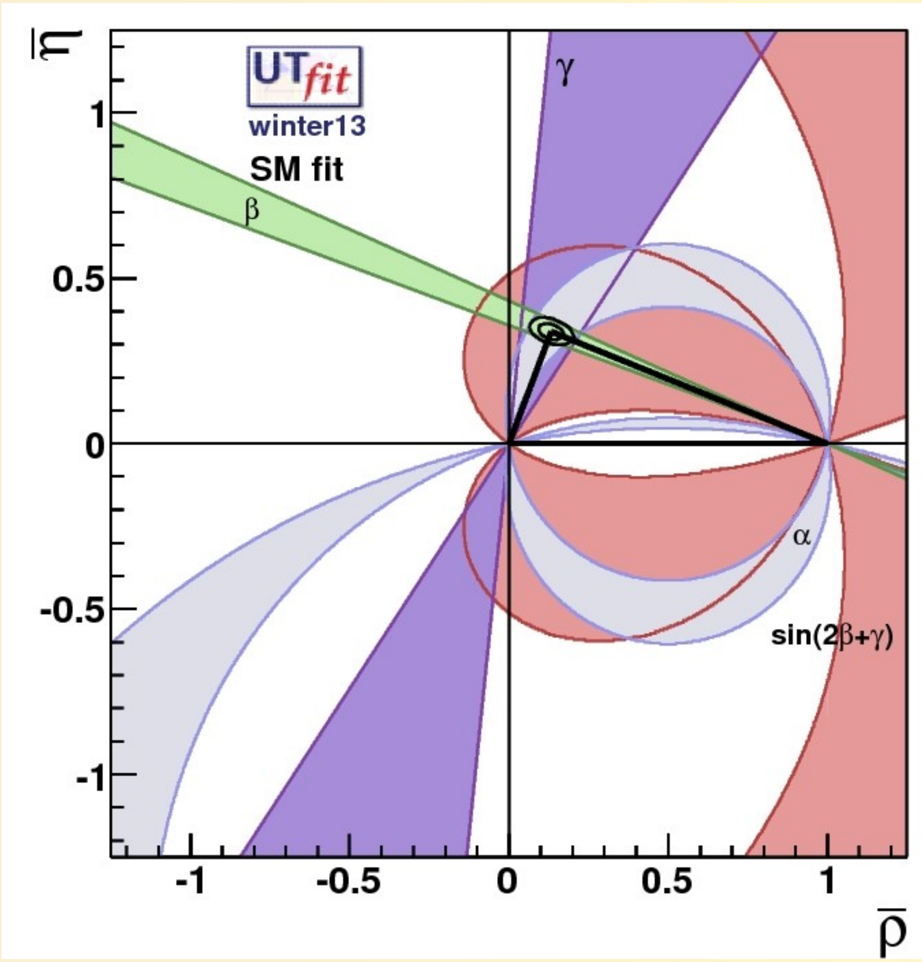
$\bar{\rho} = 0.132 \pm 0.021$
$\bar{\eta} = 0.349 \pm 0.015$

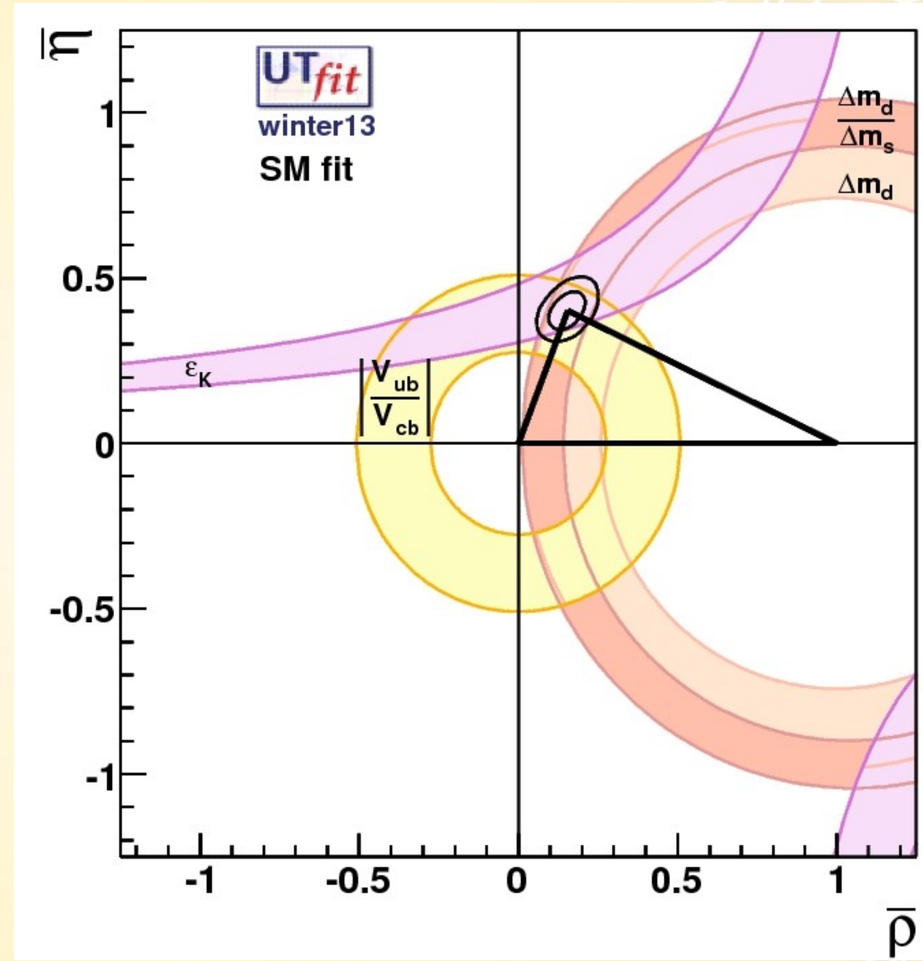
home-made
BaBar+Belle average:
$BR(B \to \tau\nu) = (0.99 \pm 0.25)\ 10^{-4}$

- Data in agreement
- NP, if any, seems not to introduce additional CP or flavour violation in $b \leftrightarrow d$ transitions at current experimental precision

angles vs the others

levels @ 95% Prob





$\bar{\rho} = 0.130 \pm 0.027$
$\bar{\eta} = 0.338 \pm 0.016$

$\bar{\rho} = 0.163 \pm 0.038$
$\bar{\eta} = 0.394 \pm 0.035$

Unitarity Triangle analysis in the SM:

obtained excluding the given constraint from the fit

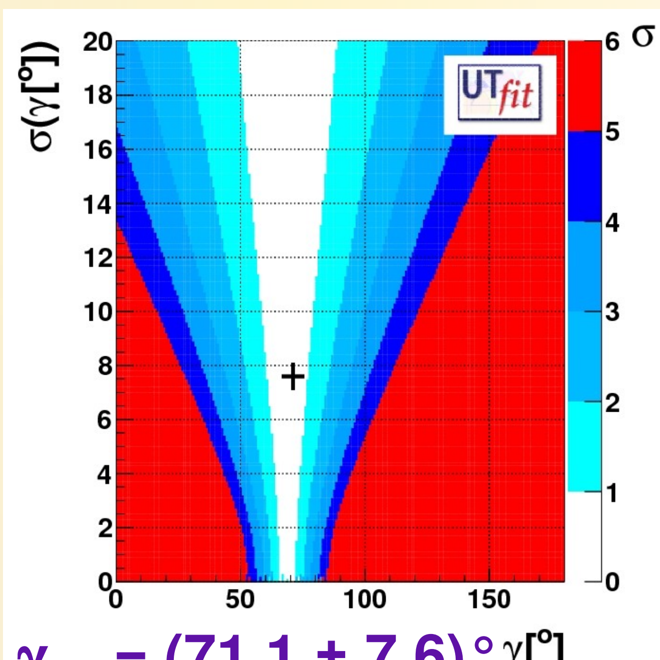
Observables	Measurement	Prediction	Pull (#σ)
$\sin 2\beta$	0.665 ± 0.024	0.757 ± 0.045	~ 1.7
γ	71.1 ± 7.6	68.6 ± 3.3	< 1
α	91.1 ± 6.7	87.4 ± 3.6	< 1
$\|V_{ub}\| \cdot 10^3$	3.82 ± 0.56	3.60 ± 0.14	< 1
$\|V_{ub}\| \cdot 10^3$ (incl)	4.40 ± 0.31	–	~ 2.2
$\|V_{ub}\| \cdot 10^3$ (excl)	3.28 ± 0.30	–	~ 1.1
$\|V_{cb}\| \cdot 10^3$	41.0 ± 1.0	42.8 ± 0.79	~ 1.3
B_K	0.730 ± 0.30	0.866 ± 0.086	< 1
$BR(B \to \tau\nu)$	0.99 ± 0.25	0.826 ± 0.077	< 1
$BR(B \to \tau\nu)$(old)	1.67 ± 0.30	–	~ 2.6

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 flavor physics

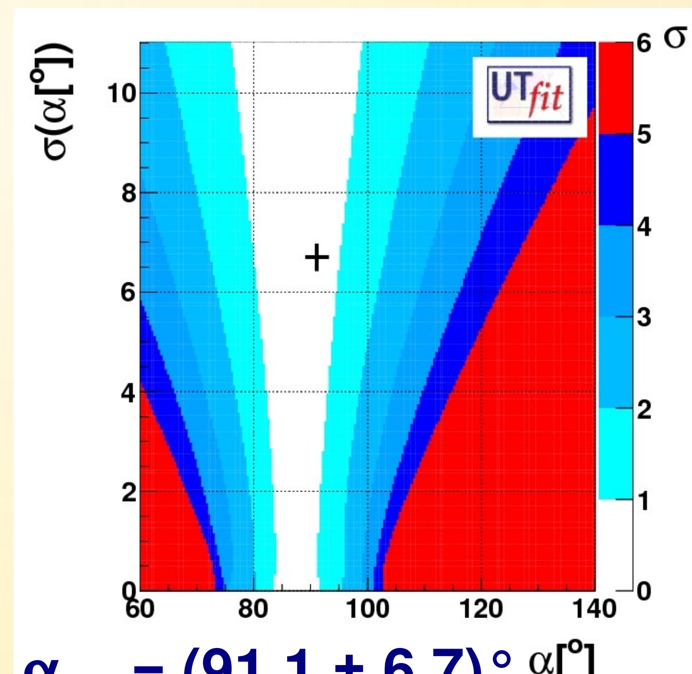
Color code: agreement between the predicted values and the measurements at better than 1, 2, ...nσ

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



γ_{exp} = (71.1 ± 7.6)°

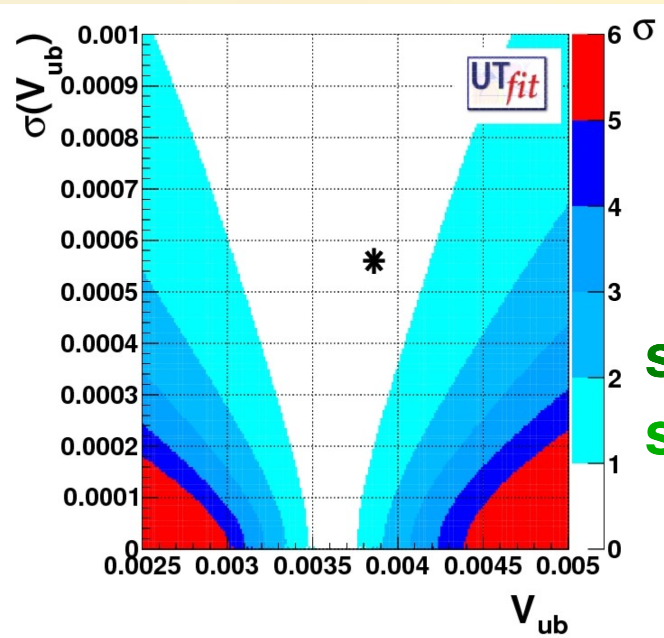
γ_{UTfit} = (68.6 ± 3.3)°



α_{exp} = (91.1 ± 6.7)°

α_{UTfit} = (87.4 ± 3.6)°

tensions (or used-to-be tensions)



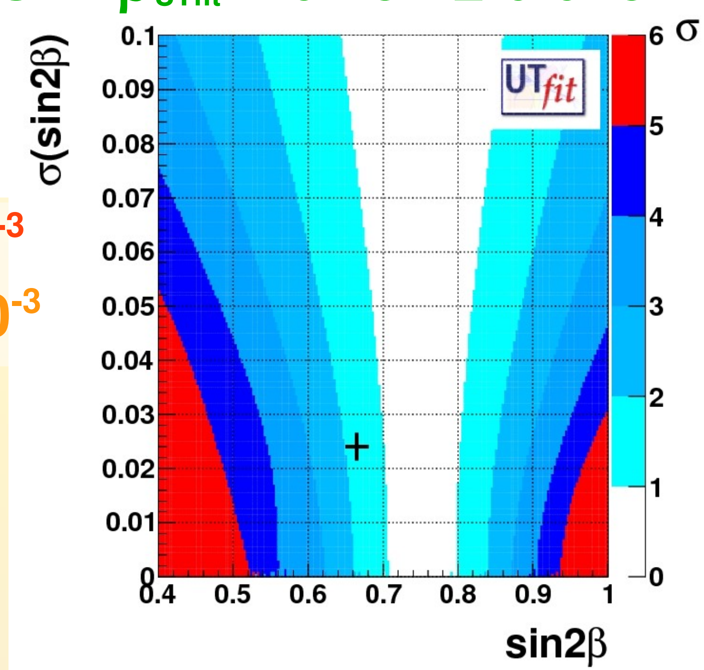
$Vub_{exp} = (3.82 \pm 0.56) \cdot 10^{-3}$

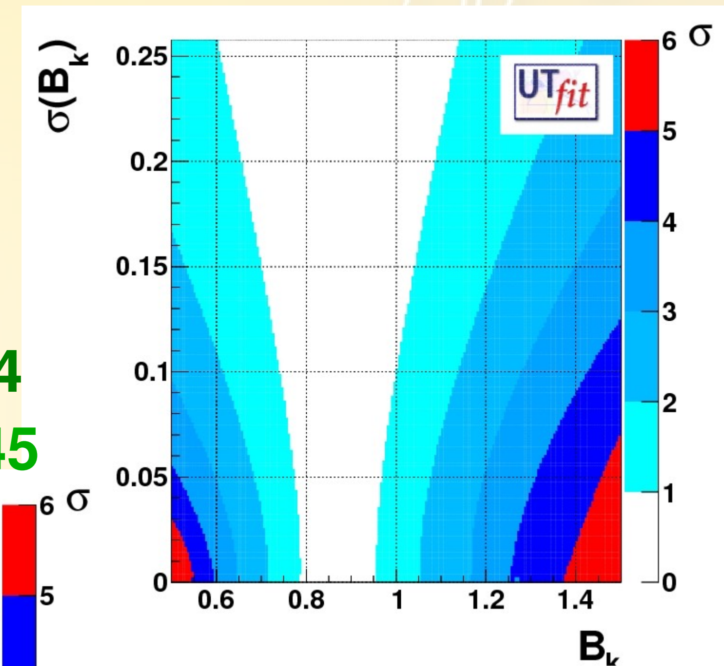
$Vub_{UTfit} = (3.60 \pm 0.14) \cdot 10^{-3}$

~1.7σ

$\sin 2\beta_{exp} = 0.665 \pm 0.024$

$\sin 2\beta_{UTfit} = 0.757 \pm 0.045$

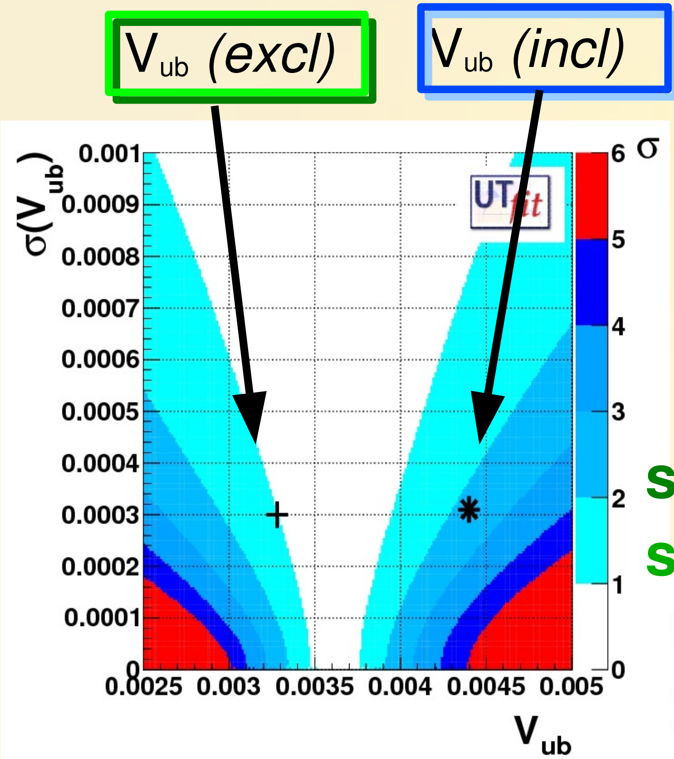




$B_{Kexp} = 0.730 \pm 0.030$

$B_{KUTfit} = 0.826 \pm 0.077$

tensions (or used-to-be tensions)



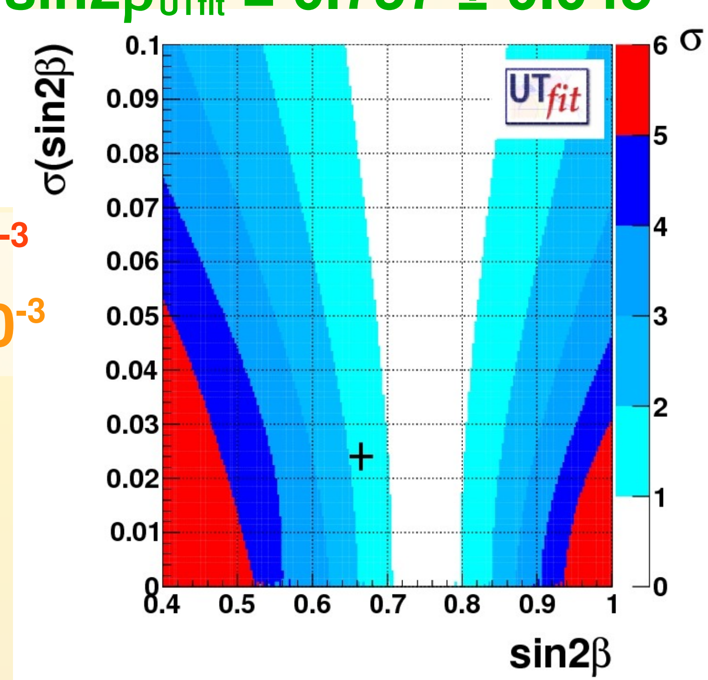
$Vub_{exp} = (3.82 \pm 0.56) \cdot 10^{-3}$

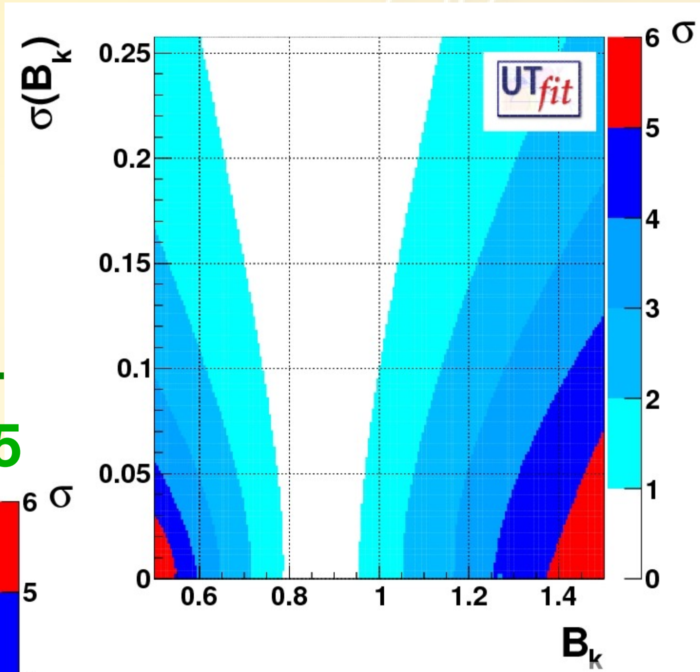
$Vub_{UTfit} = (3.60 \pm 0.14) \cdot 10^{-3}$

~1.7σ

$\sin2\beta_{exp} = 0.665 \pm 0.024$

$\sin2\beta_{UTfit} = 0.757 \pm 0.045$



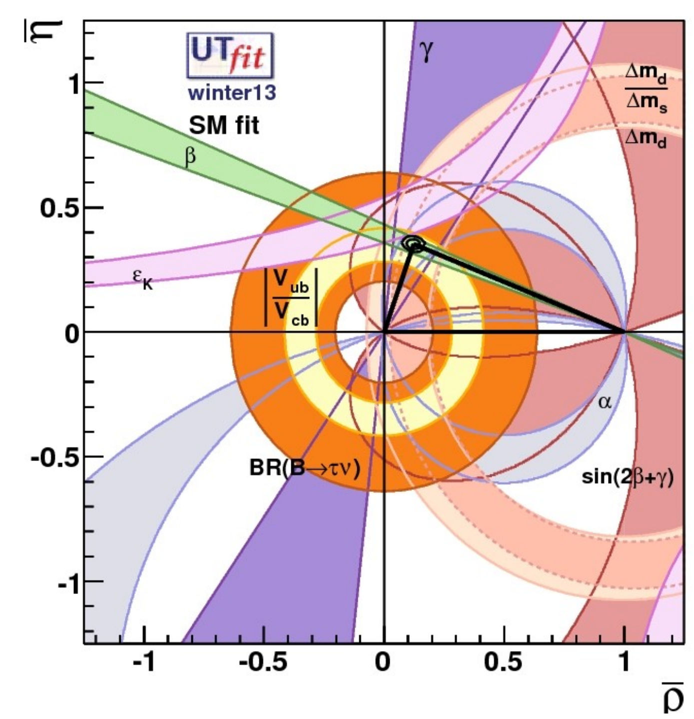


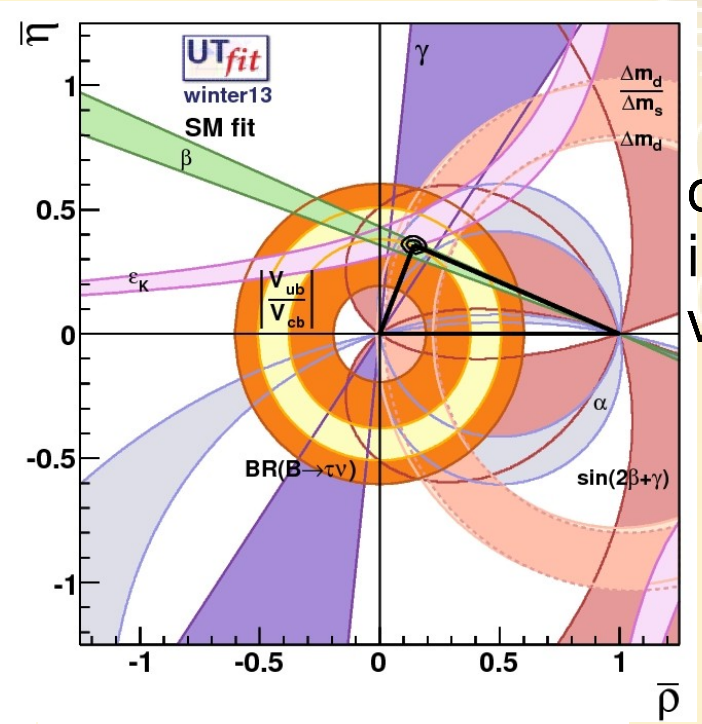
$B_{Kexp} = 0.730 \pm 0.030$

$B_{KUTfit} = 0.826 \pm 0.077$

inclusives vs exclusives

only exclusive values

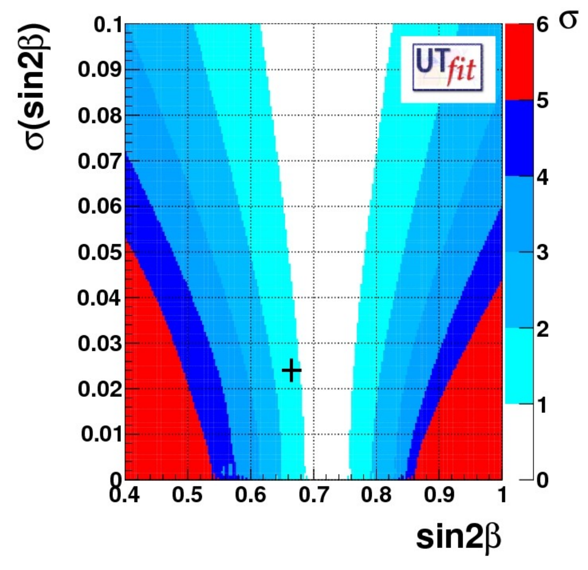


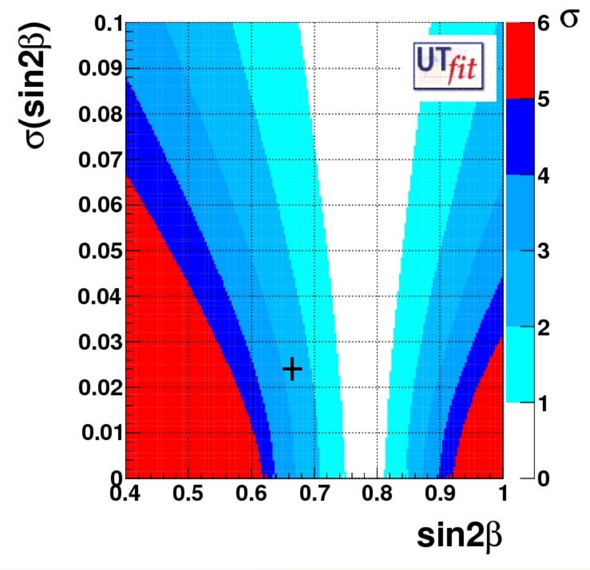


only inclusive values

$\sin 2\beta_{UTfit}$ = 0.723 ± 0.036

~1.3σ

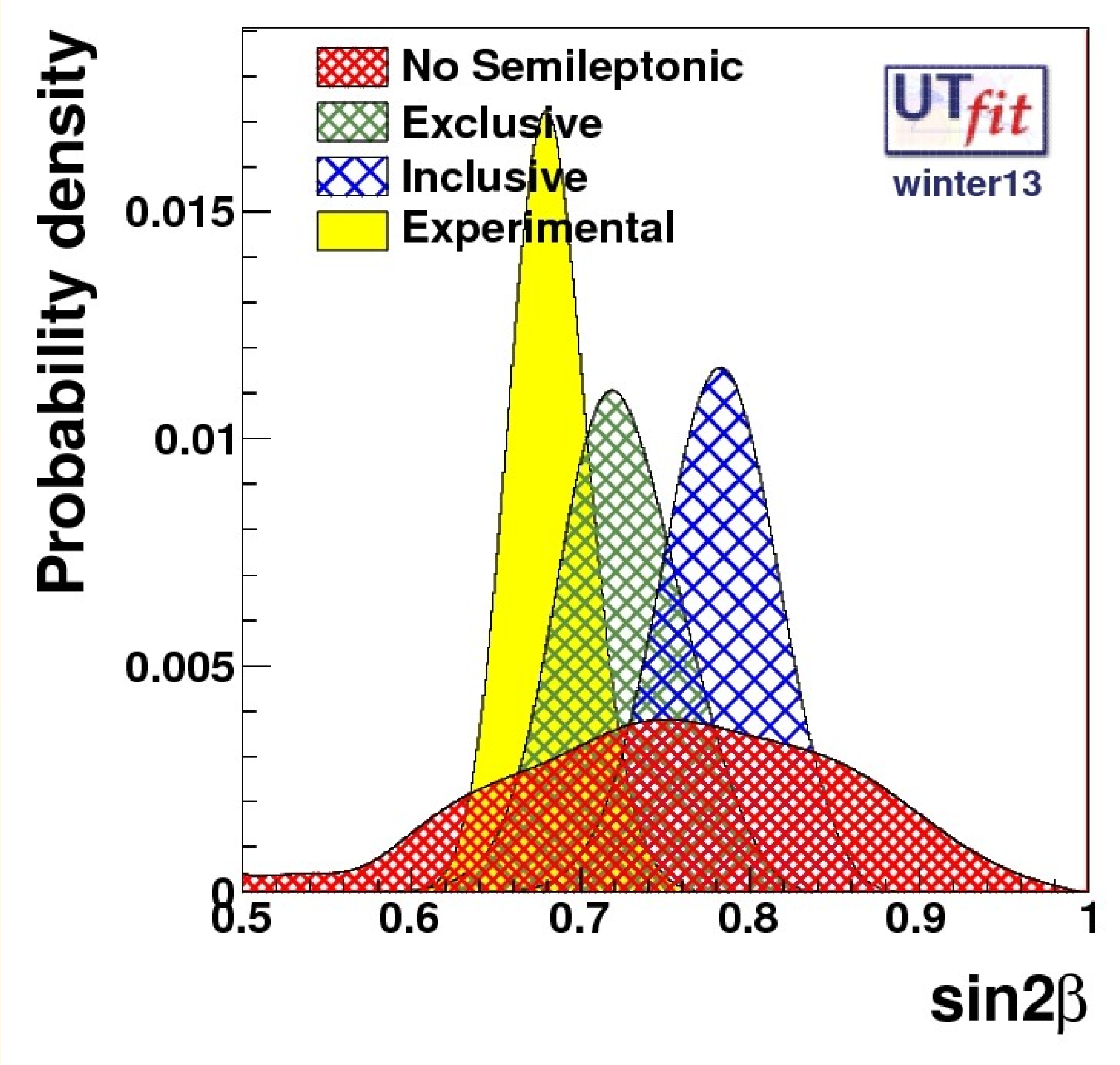




$\sin 2\beta_{UTfit}$ = 0.781 ± 0.034

~2.6σ

inclusives vs exclusives



only exclusive values

$\sin 2\beta_{UTfit}$ = 0.723 ± 0.036

~1.3σ

only inclusive values

$\sin 2\beta_{UTfit}$ = 0.781 ± 0.034

~2.6σ

$\sin 2\beta_{UTfit}$ = 0.76 ± 0.10 ¬ ***no semileptonic***

~0.9σ

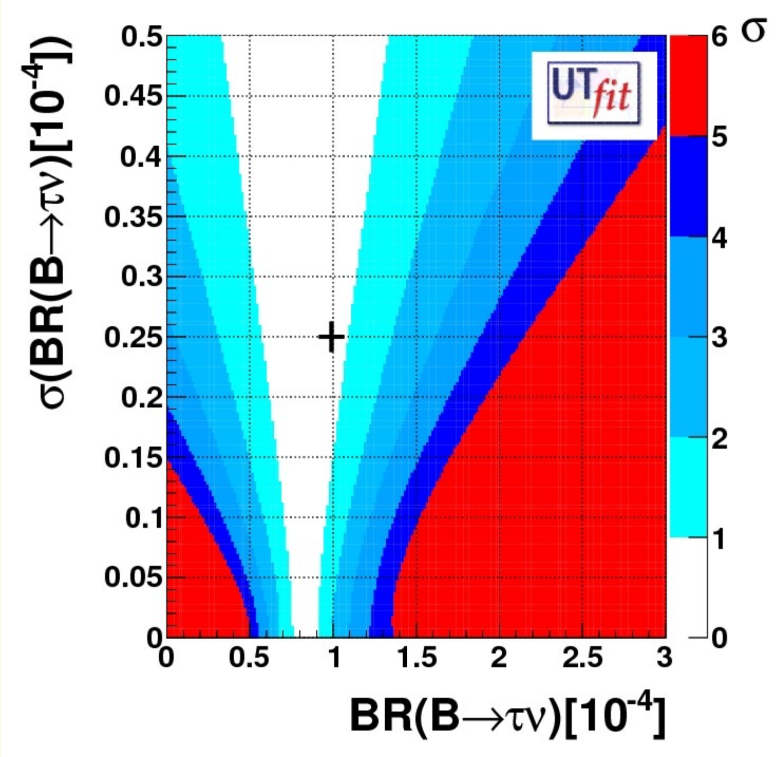
more standard model predictions:

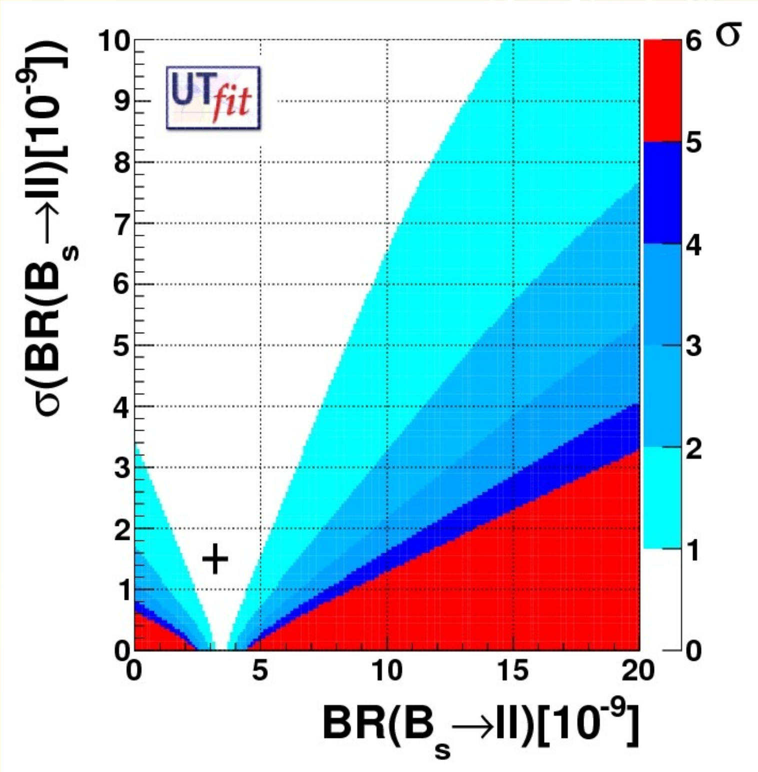
our home-made average:

BR(B→τν) = (0.99 ± 0.25) 10^{-4}

from LHCb evidence

BR(B_s→μμ) = 3.2 ± 1.5 10^{-9}





indirect determinations from UT

BR(B→τν) = (0.826 ± 0.077) 10^{-4}

BR(B_s→ll) = (3.47 ± 0.26) 10^{-9}

M.Bona et al, 0908.3470 [hep-ph]

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 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):

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

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

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

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

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

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

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

new-physics-specific constraints

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

Laplace et al. Phys.Rev.D 65: 094040,2002

semileptonic asymmetries:
sensitive to NP effects in both size and phase
2D constraints a la HFAG for A^s_{sl} and A^d_{sl}

CDF + D0 + LHCb

same-side dilepton charge asymmetry:
admixture of B_s and B_d so sensitive to NP effects in both systems

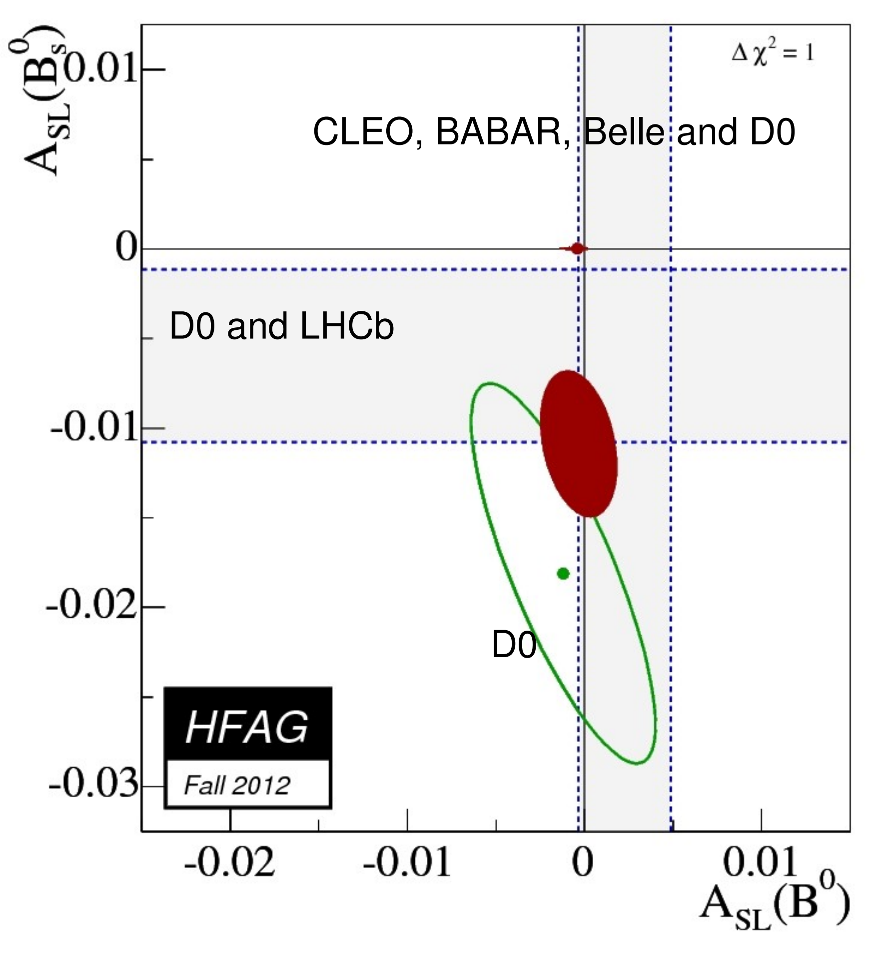
$$A^{\mu\mu}_{SL} \times 10^3 = -7.9 \pm 2.0$$

D0 arXiv:1106.6308

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

new-physics-specific constraints

semileptonic asymmetries



new-physics-specific constraints

$$\tau_{B_s}^{FS} = \frac{1}{\Gamma_s} \frac{1 - \left(\frac{\Delta\Gamma_s}{2\Gamma_s}\right)^2}{1 + \left(\frac{\Delta\Gamma_s}{2\Gamma_s}\right)^2}$$

Dunietz et al., hep-ph 0012219

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

$$\tau_{B_s}^{\mathrm{FS}}\ [\mathrm{ps}] = 1.417 \pm 0.042$$

HFAG

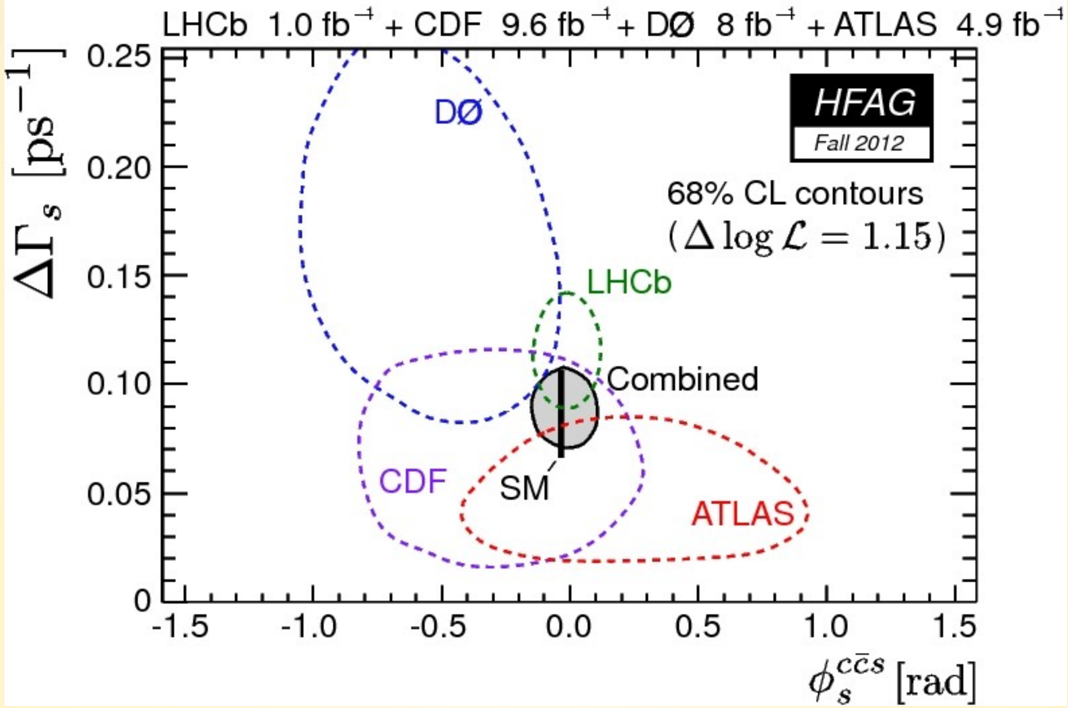
$\phi_s = 2\beta_s$ vs $\Delta\Gamma_s$ from $B_s \to J/\psi\phi$

angular analysis as a function of proper time and b-tagging
additional sensitivity from the $\Delta\Gamma_s$ terms

ϕ_s and $\Delta\Gamma_s$:
2D experimental likelihood from CDF and D0

ϕ_s and $\Delta\Gamma_s$:
central values with gaussian errors from LHCb

new-physics-specific constraints



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new-physics-specific constraints

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

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

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

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

angular analysis as a function of proper time and b-tagging
additional sensitivity from the $\Delta\Gamma_s$ terms

ϕ_s and $\Delta\Gamma_s$:
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central values with gaussian errors from LHCb

UT analysis including NP

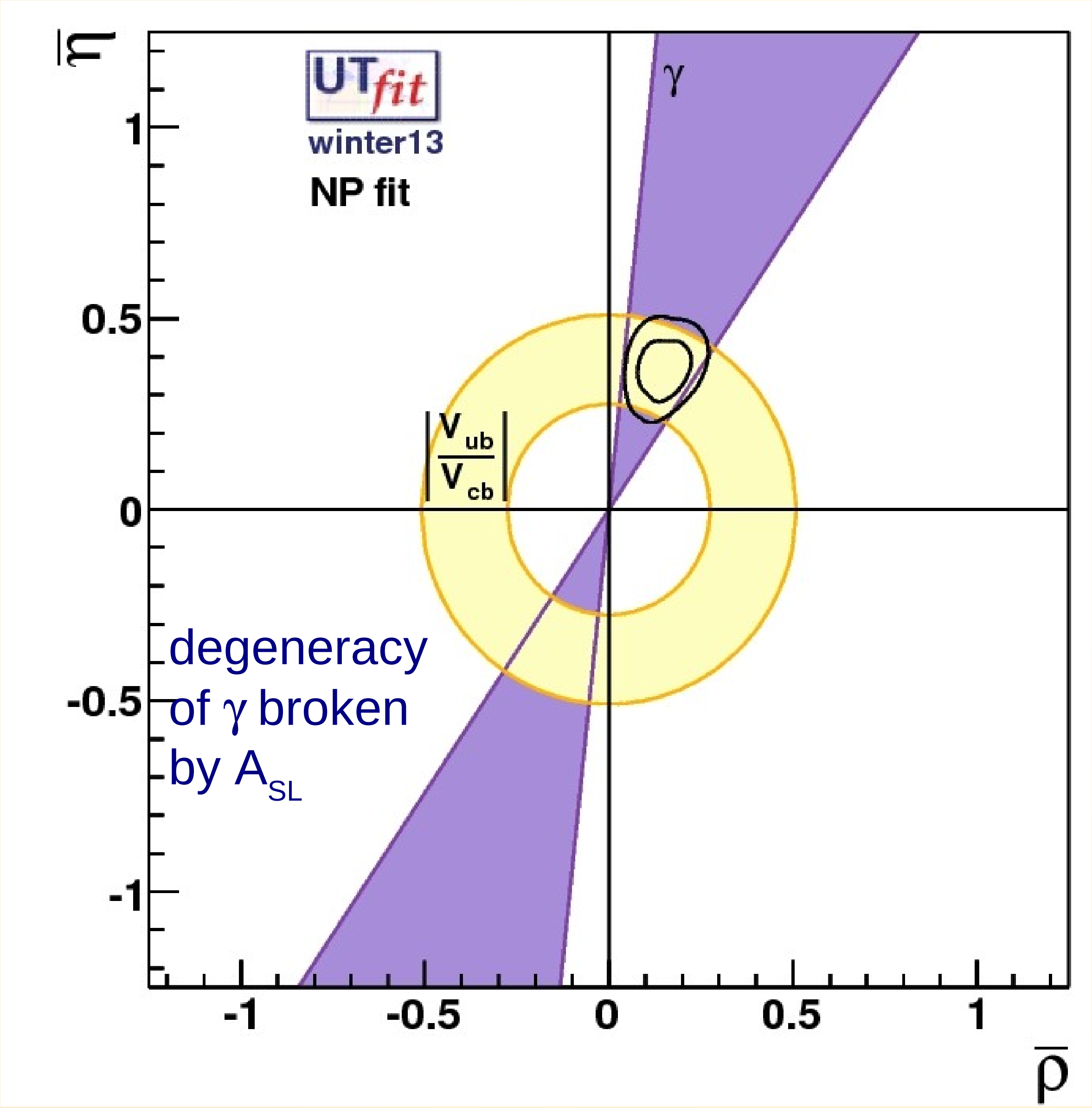
M.Bona *et al* (UTfit)
Phys.Rev.Lett. 97:151803,2006

	ρ, η	C_{Bd}, ϕ_{Bd}	$C_{\varepsilon K}$	C_{bs}, ϕ_{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	
$(V_{ub}/V_{cb})^{SM}$	$(V_{ub}/V_{cb})^{SM}$
γ^{SM}	γ^{SM}
Bd Mixing	
β^{SM}	$\beta^{SM}+\phi_{Bd}$
α^{SM}	$\alpha^{SM}-\phi_{Bd}$
Δm_d	$C_{Bd}\Delta m_d$
Bs Mixing	
Δm_s^{SM}	$C_{Bs}\Delta m_s^{SM}$
β_s^{SM}	$\beta_s^{SM}+\phi_{Bs}$
K Mixing	
ε_K^{SM}	$C\varepsilon_K\ \varepsilon_K^{SM}$

NP analysis results



$\bar{\rho} = 0.147 \pm 0.048$

$\bar{\eta} = 0.370 \pm 0.056$

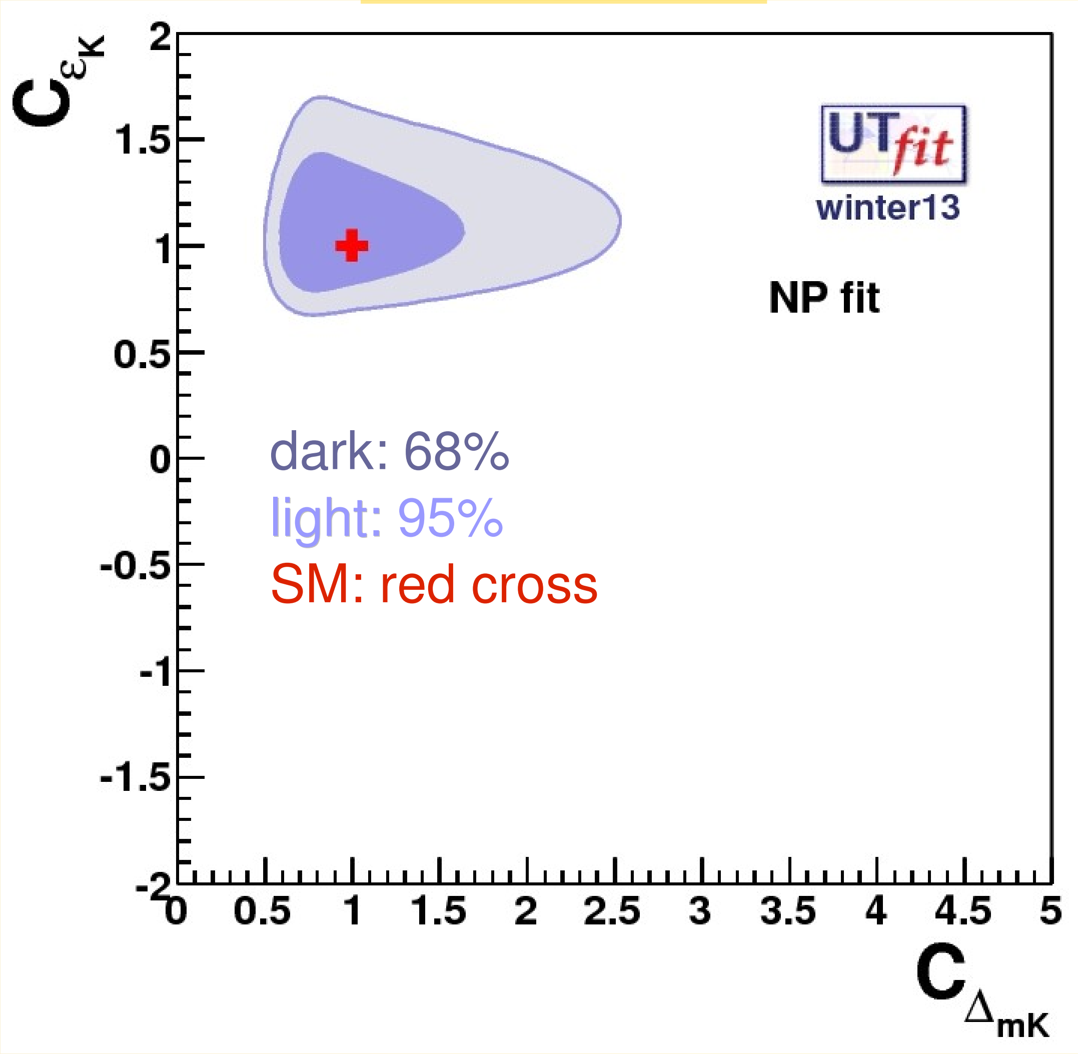
SM is

$\bar{\rho} = 0.132 \pm 0.021$

$\bar{\eta} = 0.349 \pm 0.015$

NP parameter results

$C_{\Delta mK}$ vs $C_{\varepsilon K}$



$C_{\varepsilon_K} = 1.08 \pm 0.18$

$C_{\Delta mK} = 0.98 \pm 0.33$

$$\mathrm{Im}\, A_K = C_{\varepsilon} \mathrm{Im}\, A_K^{SM}$$

$$\mathrm{Re}\, A_K = C_{\Delta m_K} \mathrm{Re}\, A_K^{SM}$$

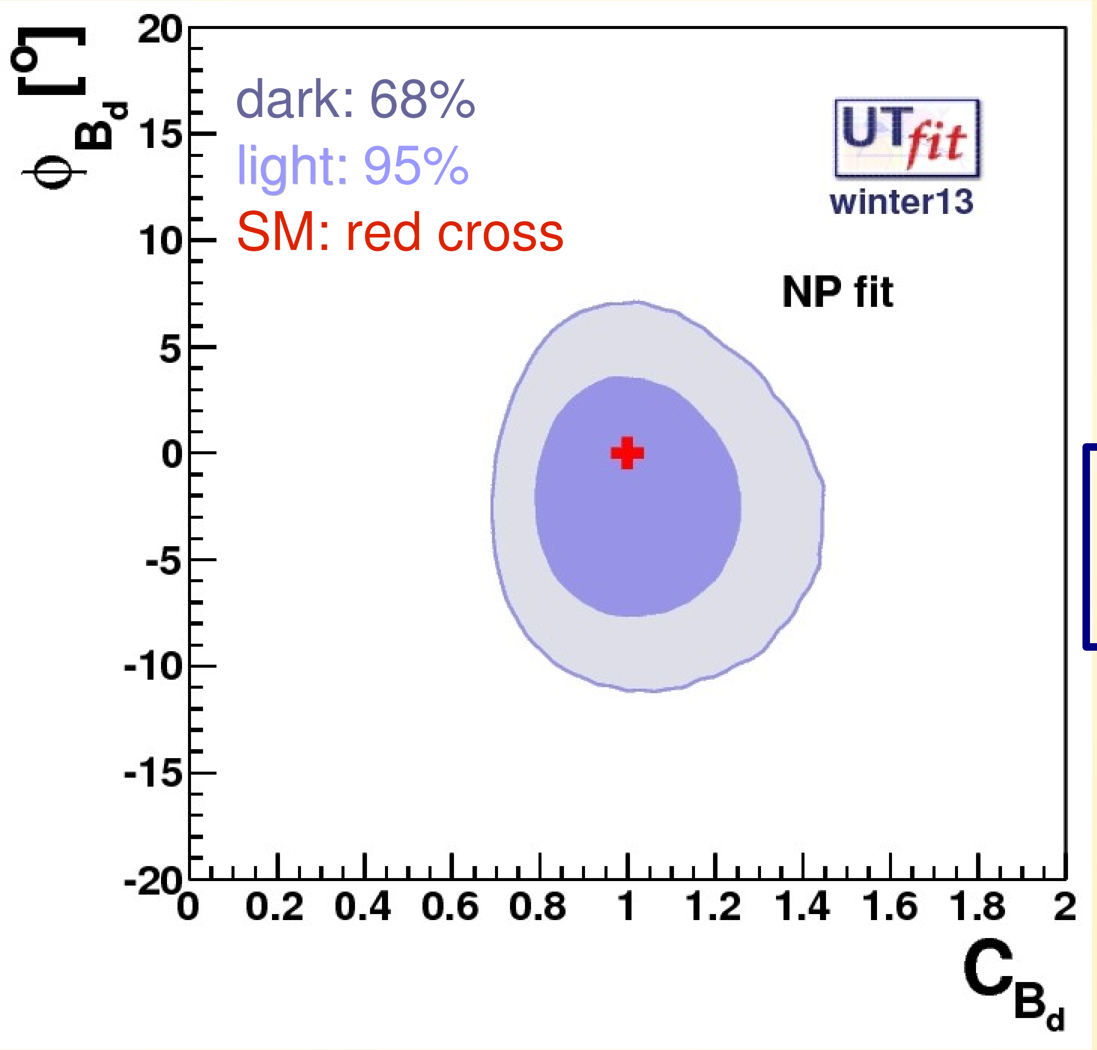
$$\Delta m_K = C_{\Delta m_K} (\Delta m_K)^{SM}$$

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

NP parameter results

$$C_{B_q}\, e^{2i\phi_{B_q}} = \frac{\langle B_q | H_{\rm eff}^{\rm full} | \bar{B}_q \rangle}{\langle B_q | H_{\rm eff}^{\rm SM} | \bar{B}_q \rangle}$$

C_{B_d} vs ϕ_{B_d}



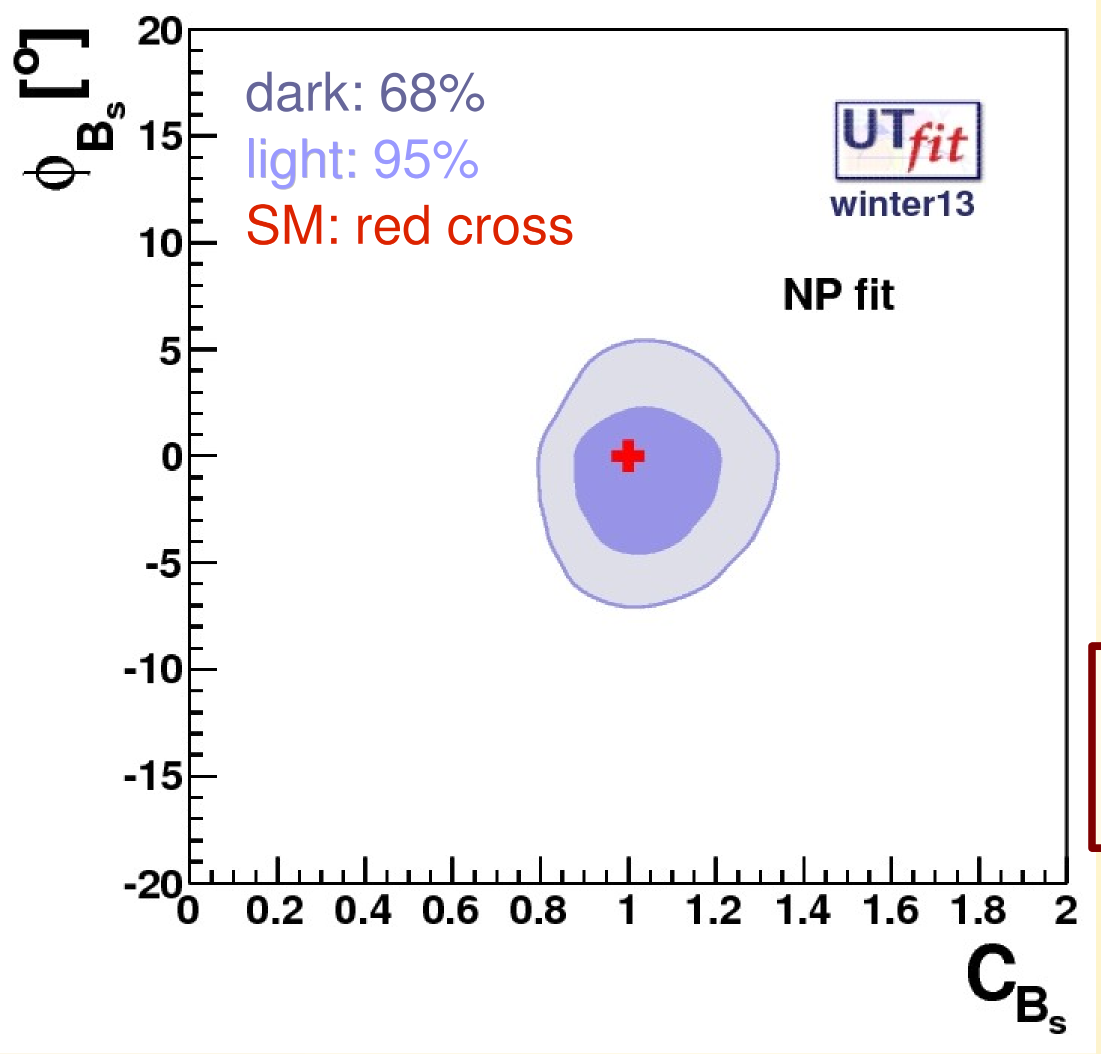
$C_{B_d} = 1.01 \pm 0.15$

$\phi_{B_d} = (-2.2 \pm 3.7)°$

NP parameter results

$$C_{B_q}\, e^{2i\phi_{B_q}} = \frac{\langle B_q | H_{\mathrm{eff}}^{\mathrm{full}} | \bar{B}_q \rangle}{\langle B_q | H_{\mathrm{eff}}^{\mathrm{SM}} | \bar{B}_q \rangle}$$

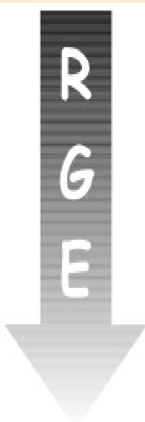
C_{Bs} vs ϕ_{Bs}



$C_{B_s} = 1.03 \pm 0.10$

$\phi_{B_s} = (-1.1 \pm 2.2)°$

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

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

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

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.

testing the TeV scale

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

The dependence of C on Λ changes on flavor 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

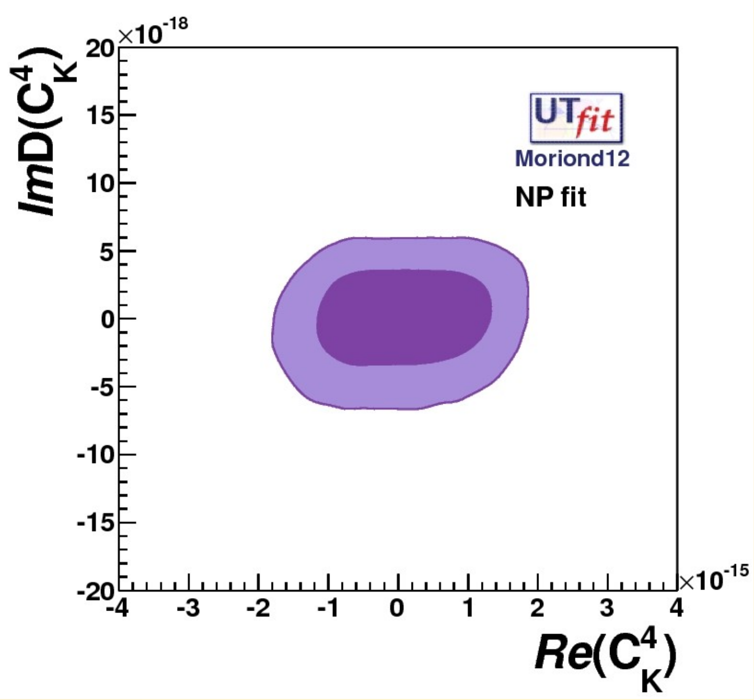
- $\alpha \sim 1$ for strongly coupled NP
- $\alpha \sim \alpha_W$ (α_S) in case of loop coupling through weak (strong) interactions

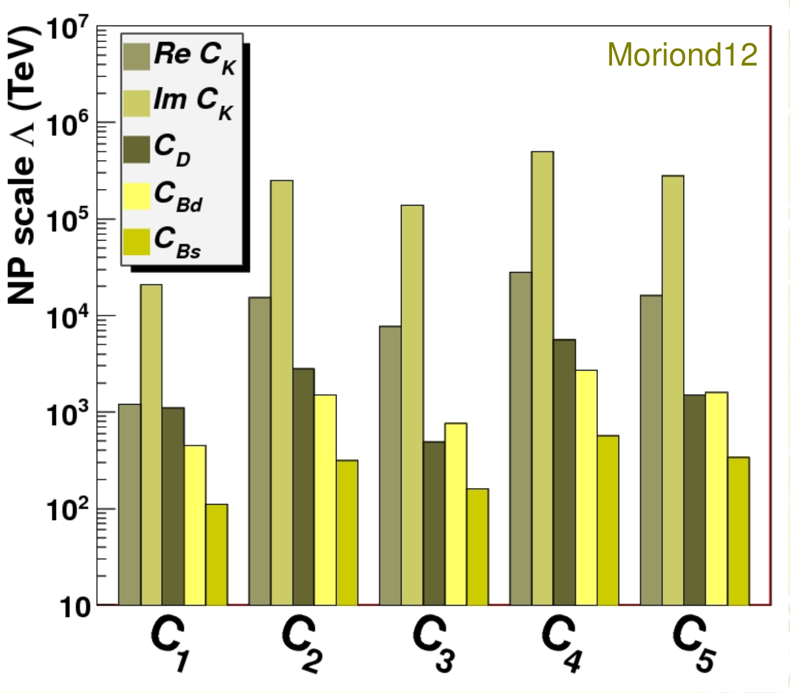
If no NP effect is seen
lower bound on NP scale Λ
if NP is seen
upper bound on NP scale Λ

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

results from the Wilson coefficients

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.





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).

Scenario	strong/tree	α_s loop	α_W loop
NMFV	19	1.9	0.6
General	$2.7 \cdot 10^5$	$2.7 \cdot 10^4$	$9 \cdot 10^3$

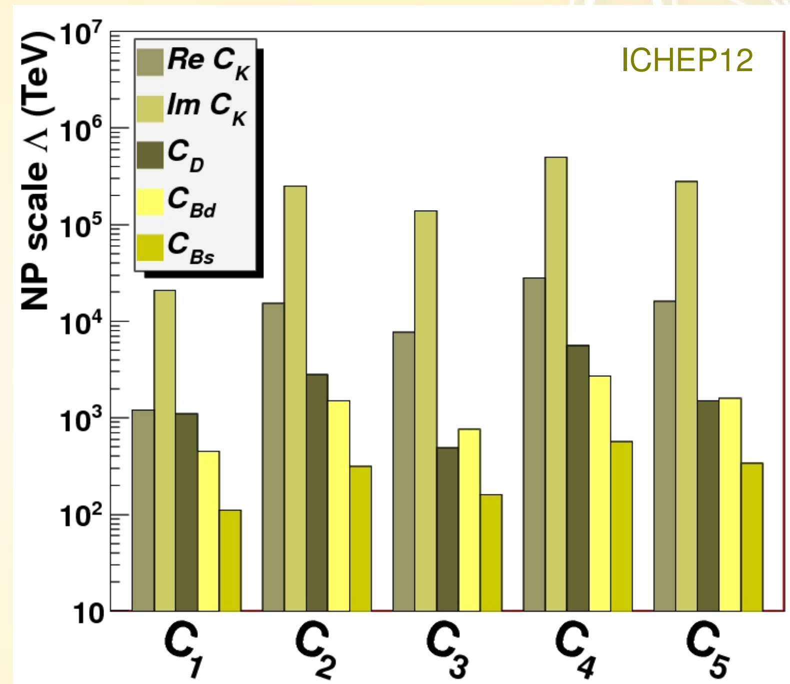
Lower bounds on NP scale (in TeV at 95% prob.)

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.

L. Silvestrini

present lower bound on the NP scale for $L=1$ and $F_i = 1$:
from ε_K: $4.9\ 10^5$ TeV
from D mixing: $1.3\ 10^4$ TeV
from B_d mixing: $3\ 10^3$ TeV
from B_s mixing: $8\ 10^2$ TeV



V. Bertone et al.
arXiv:1207.1287 [hep-lat], 2012

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

conclusions

- SM analysis displays very good overall consistency
- Still open discussion on semileptonic inclusive vs exclusive
- UTA provides determination also of NP contributions to $\Delta F=2$ amplitudes and currently leaves very little space for NP
- So the scale analysis points to high scales for the generic scenario and even above LHC reach for weak coupling.
- For finding some deviations we need to look closer at some 2-3σ level effects: sin2β, ΔA_{CP} in charm.. However these are not easily accomodated in simple NP models and direct searches are also indicating that simple NP models are unnatural.
- So, as usual, we need more data..

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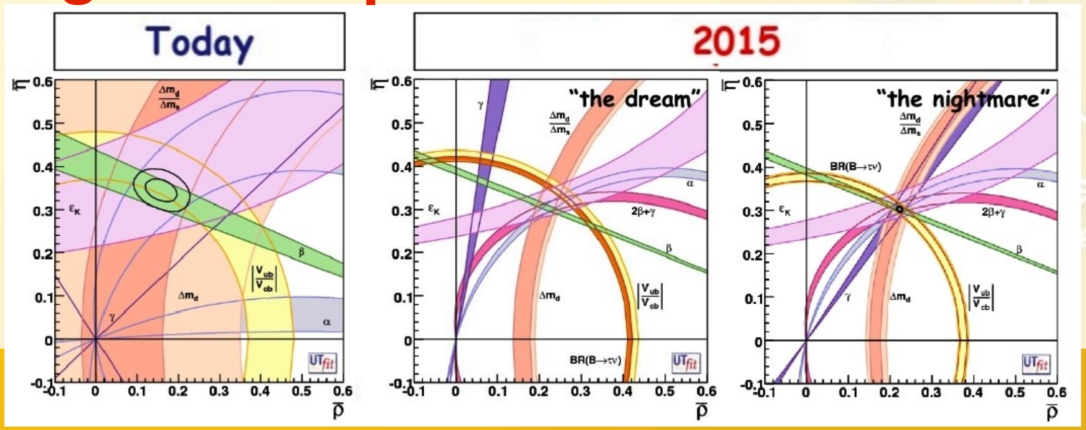
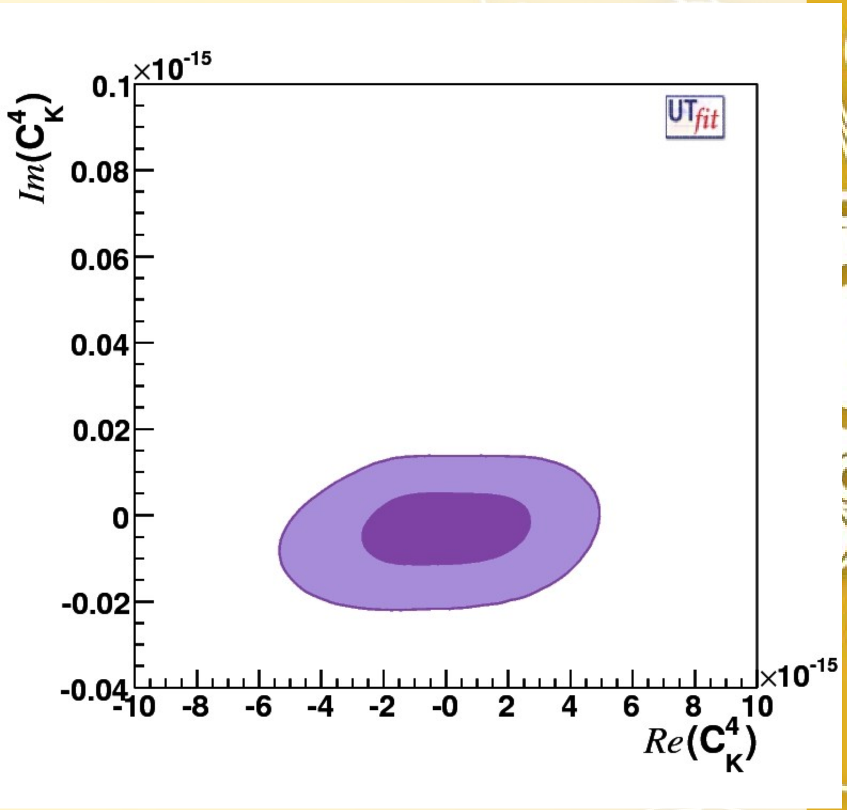


Back up slides

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

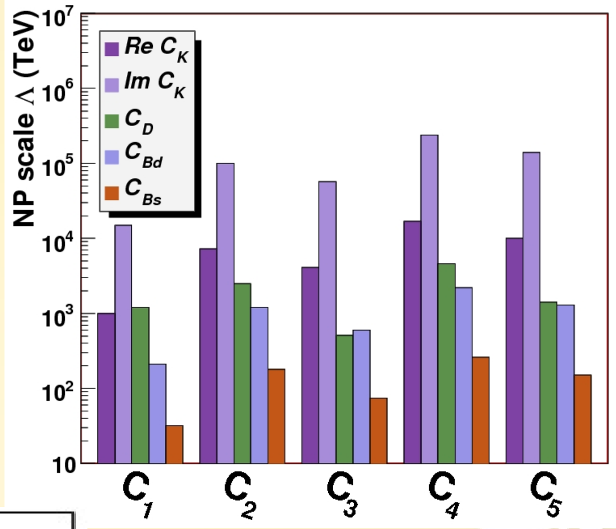


To obtain the lower bound for loop-mediated contributions, one simply multiplies the bounds by α_s ~ 0.1 or by α_W ~ 0.03.

Upper and lower bound on the scale

Lower bounds on NP scale from K and B_d physics (TeV at 95% prob.)

Scenario	strong/tree	α_s loop	α_W loop
MFV	5.5	0.5	0.2
NMFV	62	6.2	2
General	24000	2400	800



Upper bounds on NP scale from B_s:

Scenario	strong/tree	α_s loop	α_W loop
NMFV	35	4	2
General	800	80	30

- the general case was already problematic (well known flavour puzzle)
- NMFV has problems with the size of the B_s effect vs the (insufficient) suppression in B_d and (in particular) K mixing
- MFV is OK for the size of the effects, but the B_s phase cannot be generated

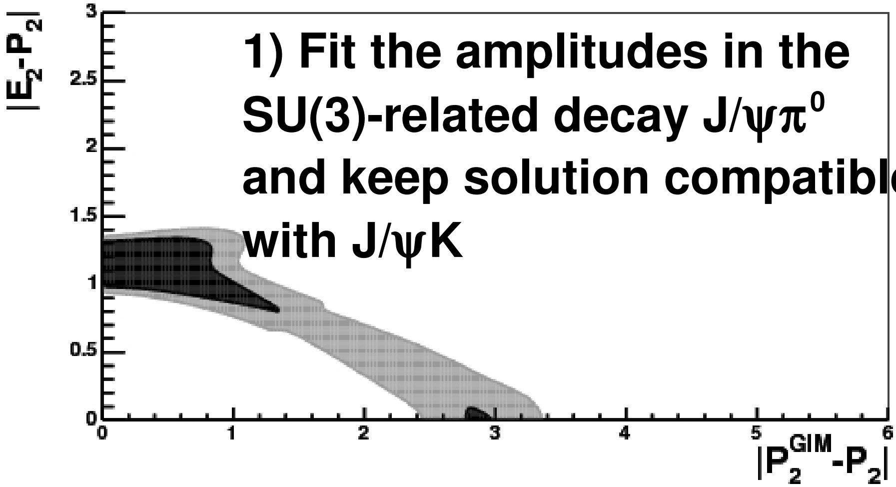
Data suggest some hierarchy in NP mixing which is stronger than the SM one

Theory error on sin2β:

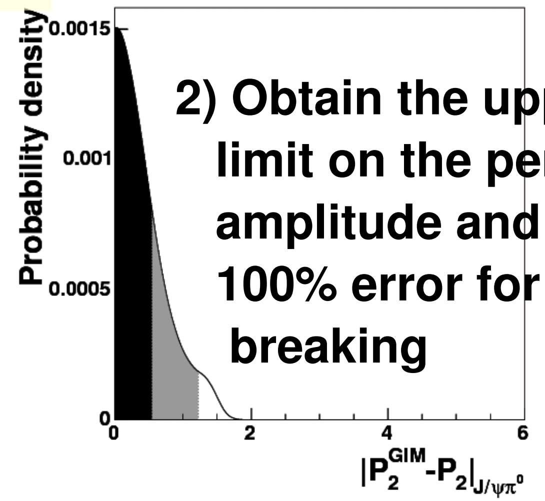
A.Buras, L.Silvestrini
Nucl.Phys.B569:3-52(2000)

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}
			$\frac{1}{N}$	$\frac{1}{N^2}$	$\frac{1}{N}$	$\frac{1}{N}$	$\frac{1}{N^2}$	$\frac{1}{N}$	$\frac{1}{N}$	$\frac{1}{N^2}$	[illegible]	[illegible]	$\frac{1}{N^3}$
$B_d \to J/\psi K^0$	C	–	λ^2	–	–	–	λ^2	–	–	λ^4	–	–	–
$B_d \to \pi^0 J/\psi$	D	–	λ^3	λ^3	–	–	λ^3	–	–	λ^3	–	$[\lambda^3]$	$[\lambda^3]$

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

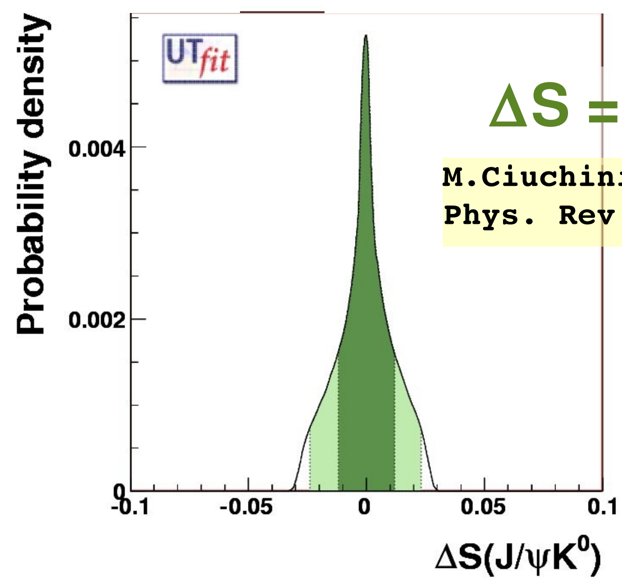


1) Fit the amplitudes in the SU(3)-related decay $J/\psi\pi^0$ and keep solution compatible with $J/\psi K$



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



$\Delta S = 0.000 \pm 0.012$

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

The future of CKM fits

LHCb reach from: O. Schneider, 1st LHCb Collaboration Upgrade Workshop

SuperB reach from: SuperB Conceptual Design Report, arXiv:0709.0451

	LHCb 2015 10/fb (5 years)	SuperB 1/ab (1 month at Y(5S))
Δm_s	0.07%(+0.5%)	no
A^s_{SL}	?	0.006
ϕ_s ($J/\psi\ \phi$)	0.01+syst	0.14
		75/ab (5 years)
$\sin 2\beta$ ($J/\psi\ K_s$)	0.010	0.005
γ (all methods)	2.4°	1-2°
α (all methods)	4.5°	1-2°
$\lvert V_{cb}\rvert$ (all methods)	no	< 1%
$\lvert V_{ub}\rvert$ (all methods)	no	1-2%

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Hadronic matrix element	Current lattice error	60 TFlop Year [2011 LHCb]	1-10 PFlop Year [2015 SuperB]
$f_+^{K\pi}(0)$	0.9% (22% on 1-f_+)	0.4% (10% on 1-f_+)	< 0.1% (2.4% on 1-f_+)
$\hat{B}_K$	11%	3%	1%
f_B	14%	2.5 - 4.0%	1 – 1.5%
$f_{B_s}B_{B_s}^{1/2}$	13%	3 - 4%	1 – 1.5%
ξ	5% (26% on ξ-1)	1.5 - 2 % (9-12% on ξ-1)	0.5 – 0.8 % (3-4% on ξ-1)
$\mathcal{F}_{B\to D/D^*l\nu}$	4% (40% on 1-$\mathcal{F}$)	1.2% (13% on 1-$\mathcal{F}$)	0.5% (5% on 1-$\mathcal{F}$)
$f_+^{B\pi}, \ldots$	11%	4 - 5%	2 – 3%
$T_1^{B\to K^*/\rho}$	13%	----	3 – 4%

S. Sharpe @ Lattice QCD: Present and Future, Orsay, 2004 and report of the U.S. Lattice QCD Executive Committee