CP VIOLATION THEORY

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UTfit

- Introduction
- Status of CPV and SM compatibility
- CPV beyond the SM and constraints on NP
- Conclusions and Outlook

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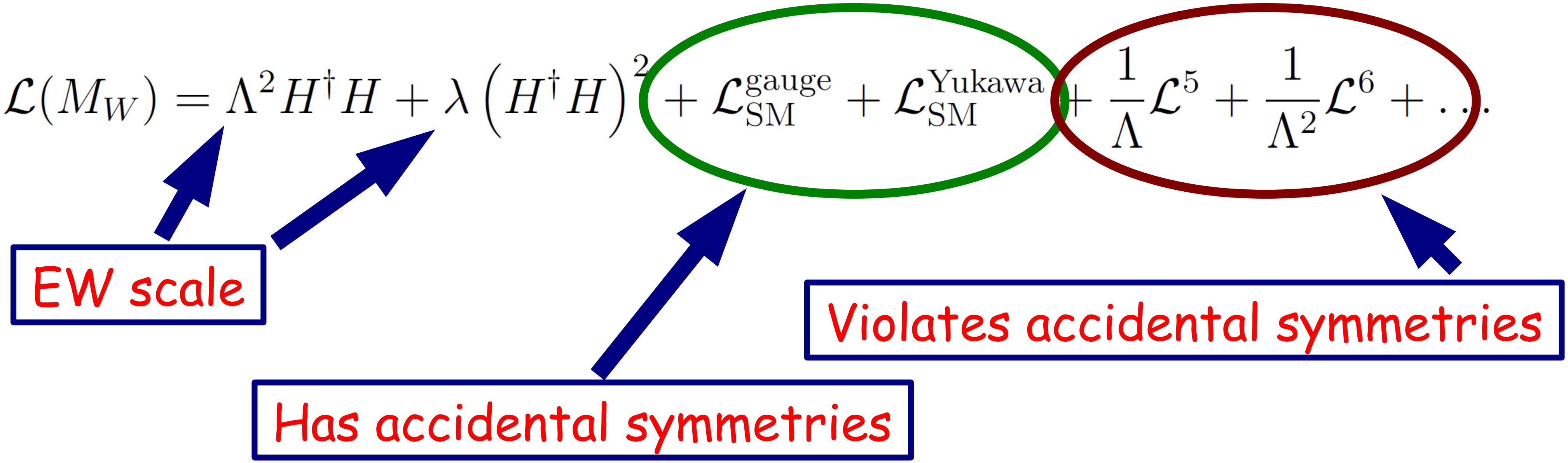
INTRODUCTION

The Standard Model works beautifully up to a few hundred GeV's, but it must be an effective theory valid up to a scale $\Lambda \leq M_{planck}$:



$$\mathcal{L}(M_W) = \Lambda^2 H^\dagger H + \lambda \left(H^\dagger H\right)^2 + \mathcal{L}_{\mathrm{SM}}^{\mathrm{gauge}} + \mathcal{L}_{\mathrm{SM}}^{\mathrm{Yukawa}} + \frac{1}{\Lambda}\mathcal{L}^5 + \frac{1}{\Lambda^2}\mathcal{L}^6 + \ldots$$

EW scale

Has accidental symmetries

Violates accidental symmetries

INTRODUCTION - II

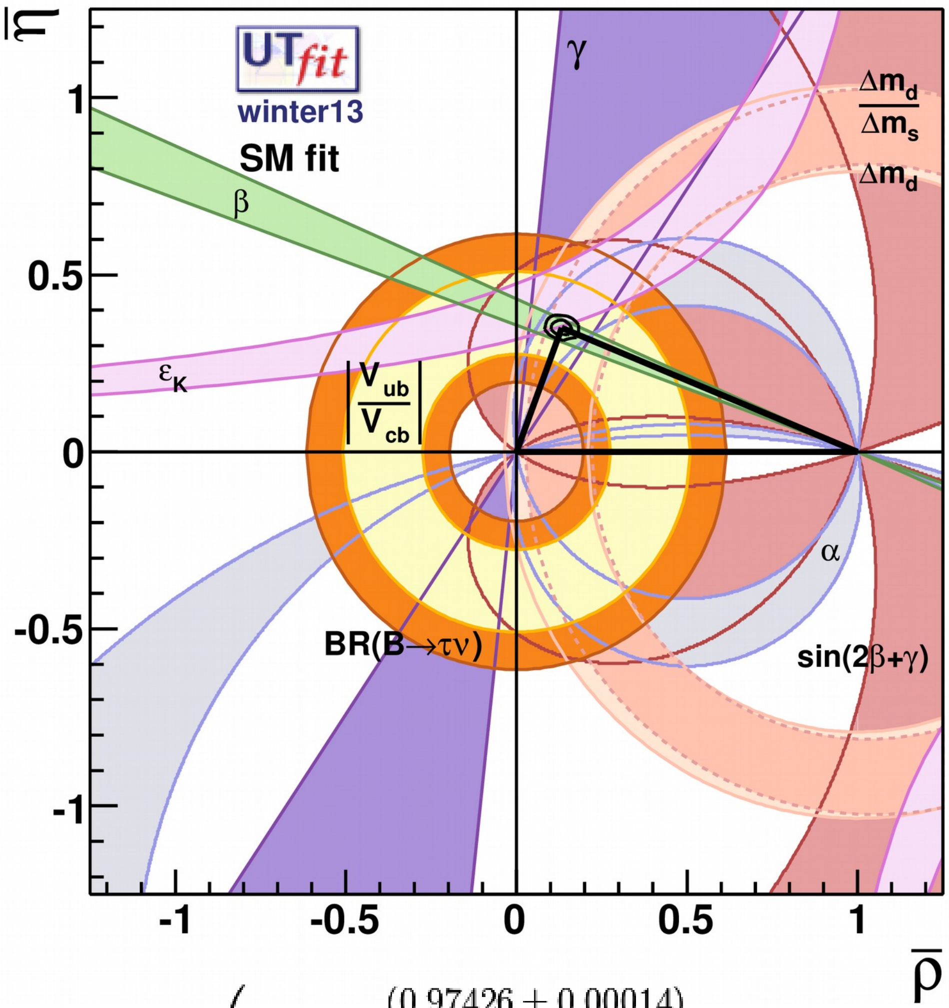
Two accidental symmetries of the SM are crucial for our discussion:

1) Absence of tree-level flavour changing neutral currents, GIM suppression of FCNC @ the loop level

2) No CP violation @ tree level

⇒ Flavour & CP physics extremely sensitive to NP!!

CPV: STATUS



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

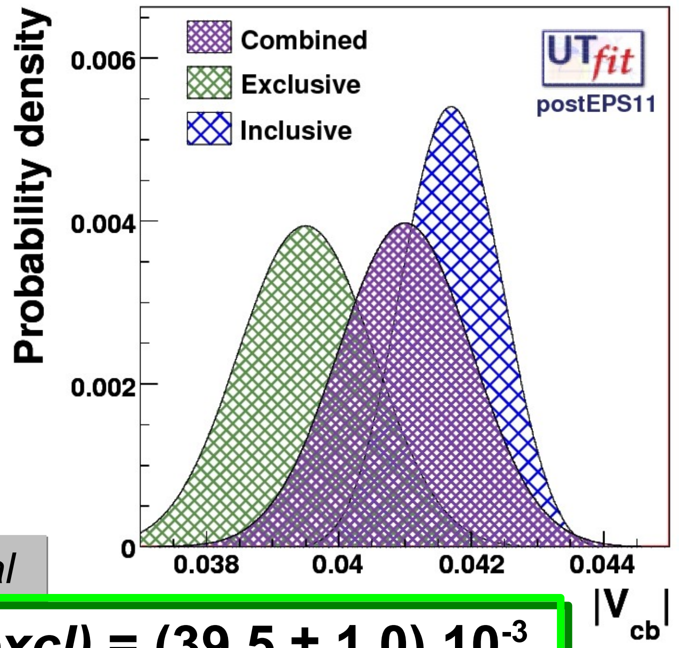
$\bar{\eta} = 0.350 \pm 0.014$

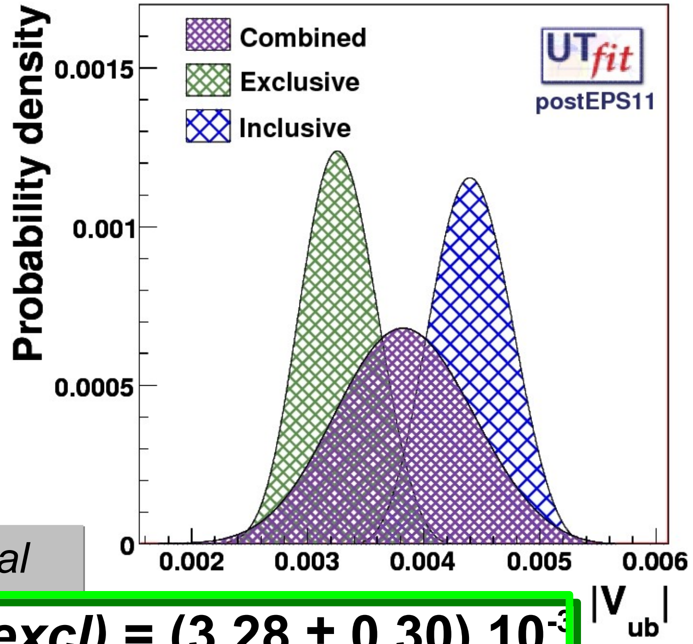
$A = 0.827 \pm 0.013$

$\lambda = 0.2254 \pm 0.0007$

$$V_{CKM} = \begin{pmatrix} (0.97426 \pm 0.00014) & (0.22545 \pm 0.00059) & (0.00365 \pm 0.00013)e^{i(-69.1\pm3.1)^\circ} \\ (-0.22525 \pm 0.00059)e^{i(0.0355\pm0.0012)^\circ} & (0.97339 \pm 0.00013)e^{i(-0.001906\pm0.000061)^\circ} & (0.04207 \pm 0.00064) \\ (0.00888 \pm 0.00020)e^{i(-21.86\pm0.80)^\circ} & (-0.04128 \pm 0.00064)e^{i(1.064\pm0.043)^\circ} & (0.999106 \pm 0.000024) \end{pmatrix}$$

SEMILEPTONIC DECAYS





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

UTfit input value:
average à la PDG

V_{cb} **= (41.0 ± 1.0)** 10^{-3}

uncertainty ~ 2.4%

Laiho *et al*

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

UTfit from HFAG

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

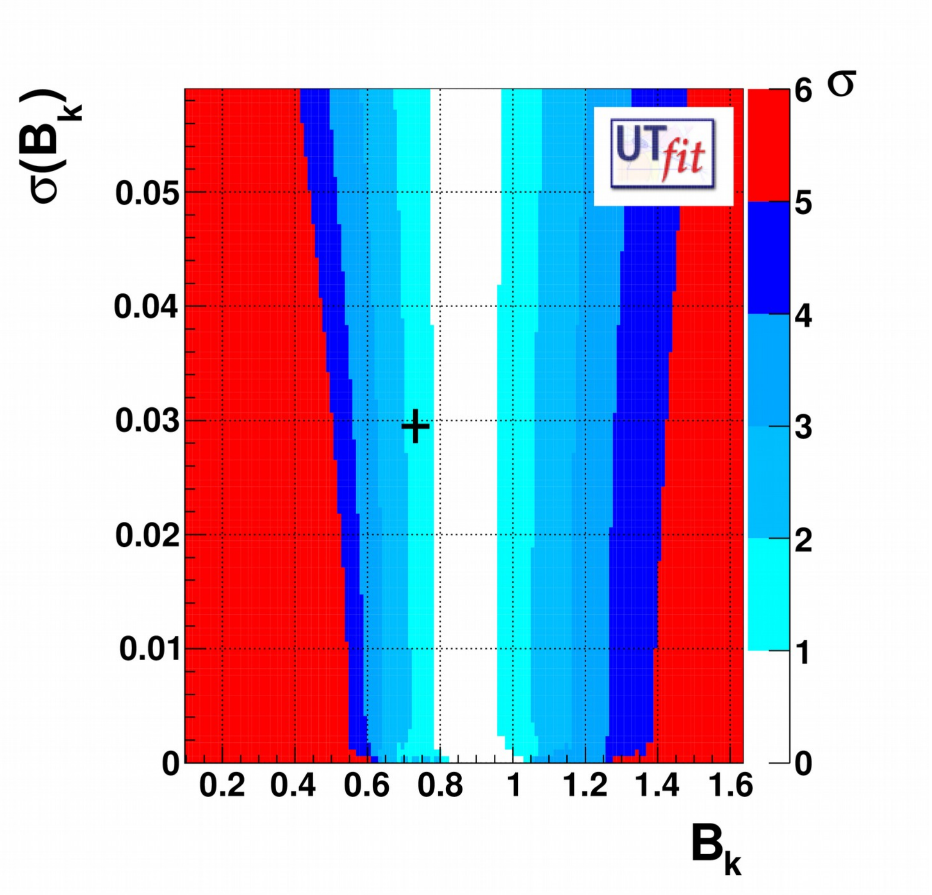
~2.6σ discrepancy

UTfit input value:
average à la PDG

V_{ub} **= (3.82 ± 0.56)** 10^{-3}

uncertainty ~ 15%

CPV IN KAONS: ε_K

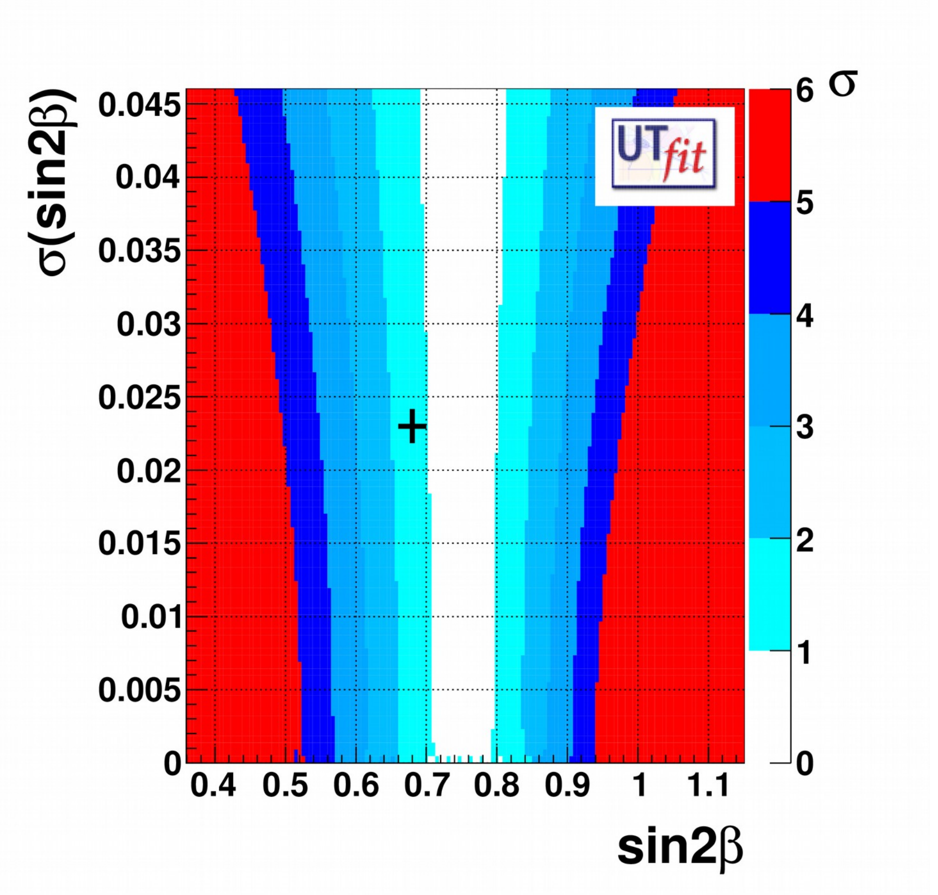


- Including ImA_0 contribution & LD à la Buras-Guadagnoli-Isidori
- Contribution of D=8 operators in the OPE under evaluation Cata & Peris; Ciuchini et al
- B_k^{input} = 0.733±0.029

$B_k^{prediction}$ = 0.866±0.086

compatibility: 1.5σ

CPV IN B_d: sin2β



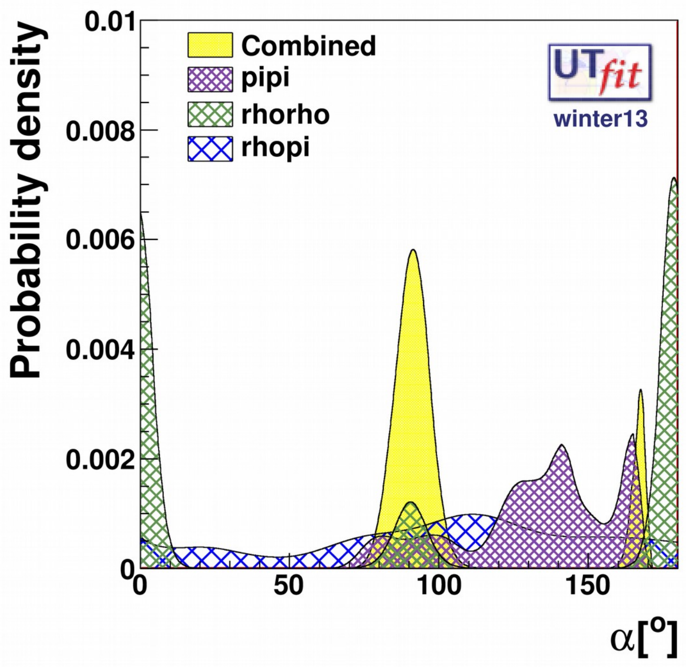
- Including theory error on the extraction of sin2β from $B_d \to J/\psi K_S$

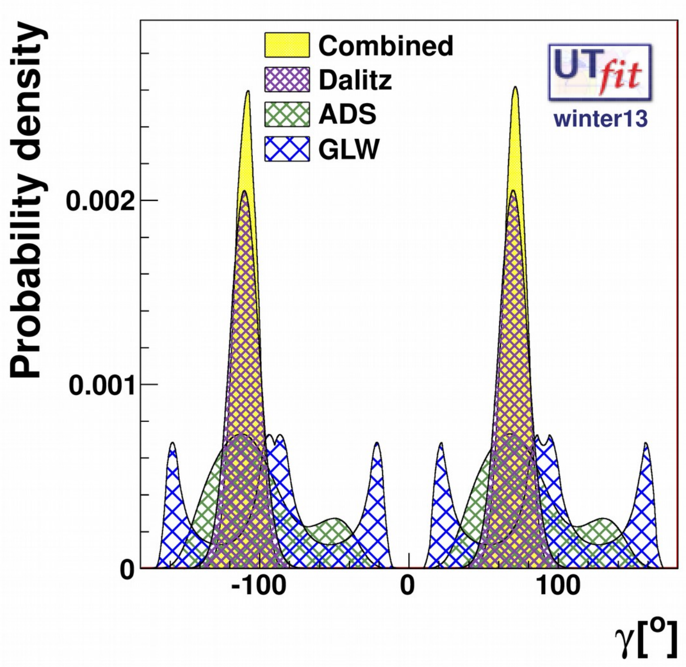
Ciuchini, Pierini, LS '05,'11;
Faller et al '09; De Bruyn et al '10;
Jung '12; Fleischer '12; ...

- $\sin 2\beta^{exp} = 0.680 \pm 0.023$
  $\sin 2\beta^{prediction} = 0.755 \pm 0.044$
  compatibility: 1.5 σ

- Compatibility strongly depends on input for V_{ub}:
  $\sin 2\beta^{excl} = 0.723 \pm 0.036$
  compatibility: 1 σ
  $\sin 2\beta^{incl} = 0.781 \pm 0.034$
  compatibility: 2.5 σ

CPV IN B_d: α and γ





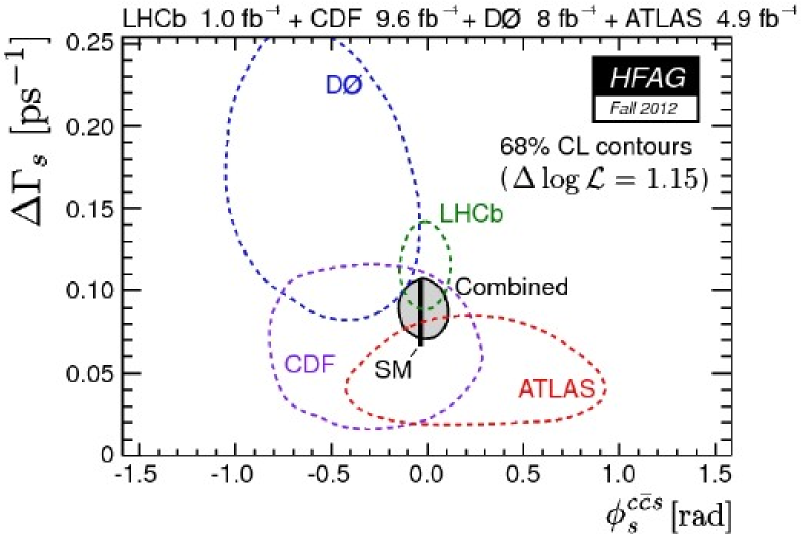
- Will implement combined $B_{d,s} \to KK, \pi\pi$ analysis in the UT fit

Fleischer '99, '07, '11; Ciuchini et al '12

- Excellent compatibility: $\alpha^{exp} = (91 \pm 8)^\circ$ $\alpha^{ind} = (88 \pm 4)^\circ$ $\gamma^{exp} = (71 \pm 8)^\circ$ $\gamma^{ind} = (69 \pm 4)^\circ$

CPV IN B_s

	Measurement	%	Prediction	Pull (σ)
$\Delta m_s\,[ps^{-1}]$	17.72±0.04	0.2	17.5±1.3	< 1
$2\beta_s$	(0.3±2.5)°	120	(2.13±0.09)°	< 1
$\Delta\Gamma_s/\Gamma_s$	0.137±0.016	12	0.147±0.014	< 1
$A_{SL}^{s}\cdot 10^4$	-109±40	37	-3.3±6.8	+2.6



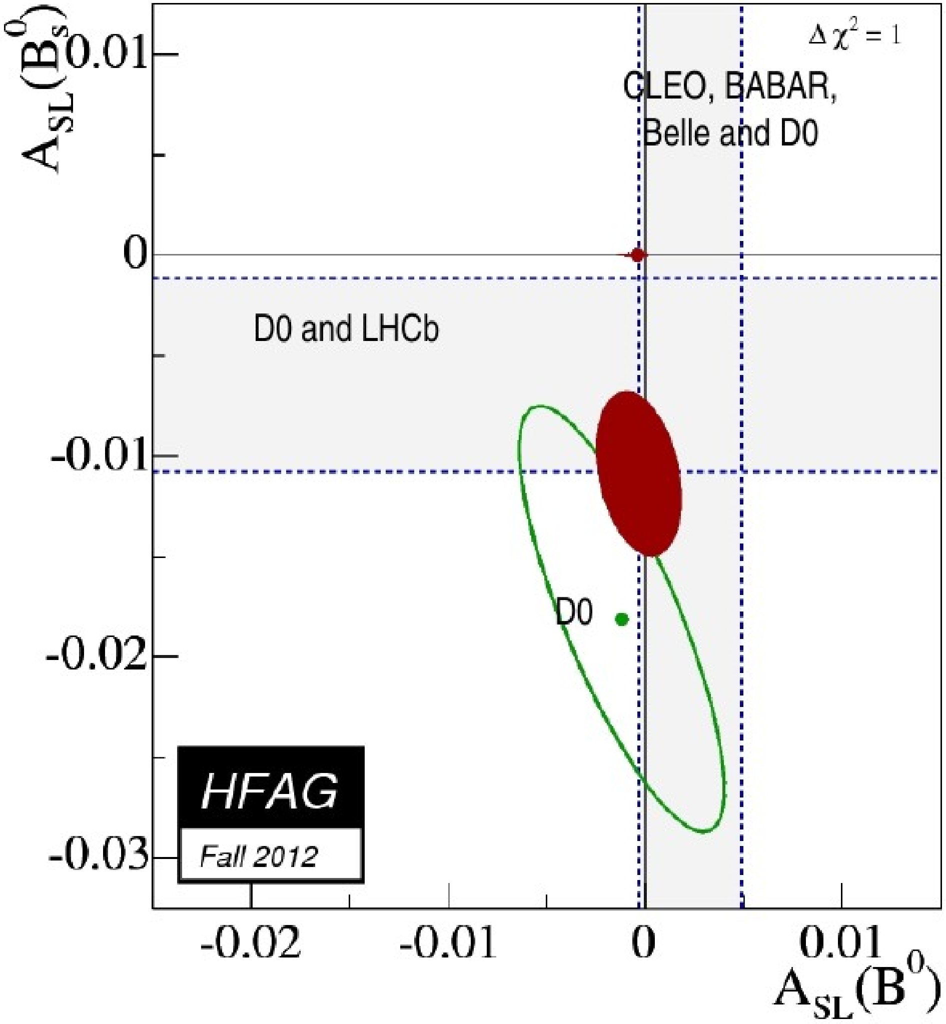
See also: Lenz & Nierste '07;
Lenz et al. '11, '12; UTfit '07;...

Semileptonic asymmetries

$A_{SL}{}^{d} = -0.0003 \pm 0.0021$

$A_{SL}{}^{s} = -0.0109 \pm 0.0040$

$r = -0.309$



Discrepancy driven by the D0 like-sign dimuon asymmetry

$A_{SL}{}^{b} = (-0.787 \pm 0.172 \pm 0.093)\%$

UTfit beyond the Standard Model

1. fit simultaneously for the CKM and the NP parameters (generalized UT fit)
   - add most general NP to all sectors
   - use all available experimental info
   - find out how much room is left for NP in $\Delta F=2$ transitions

Soares, Wolfenstein; Deshpande, Dutta, Oh; Silva, Wolfenstein; Cohen et al.; Grossman, Nir, Worah; Laplace et al; Ciuchini et al; Ligeti; CKMFitter; UTfit; Botella et al.; Agashe et al.; ...

2. perform an $\Delta F=2$ EFT analysis to put bounds on the NP scale
   - consider different choices of the FV and CPV couplings

1. Parameterization of generic NP contributions to the mixing amplitudes

K mixing amplitude (2 real parameters):

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

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

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

Observables:

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

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

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

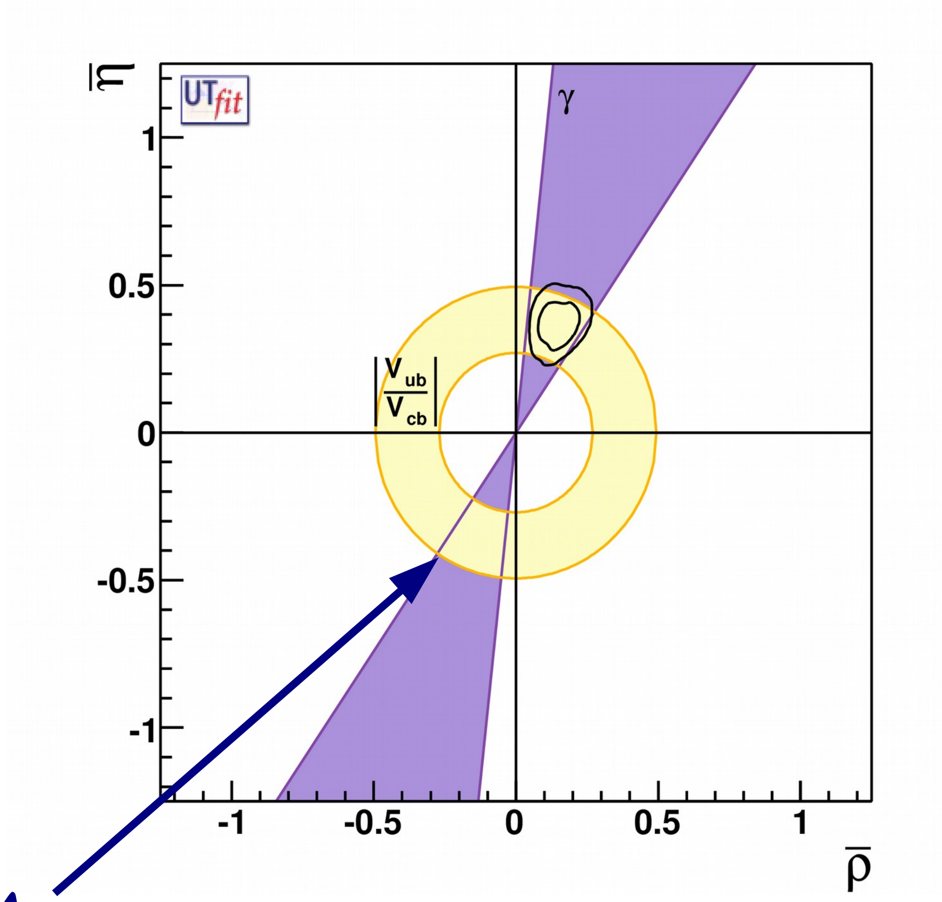
UT parameters in the presence of NP

Model-independent determination of the CKM parameters

(no NP in tree-level decays)

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

$\bar{\eta} = 0.370 \pm 0.057$



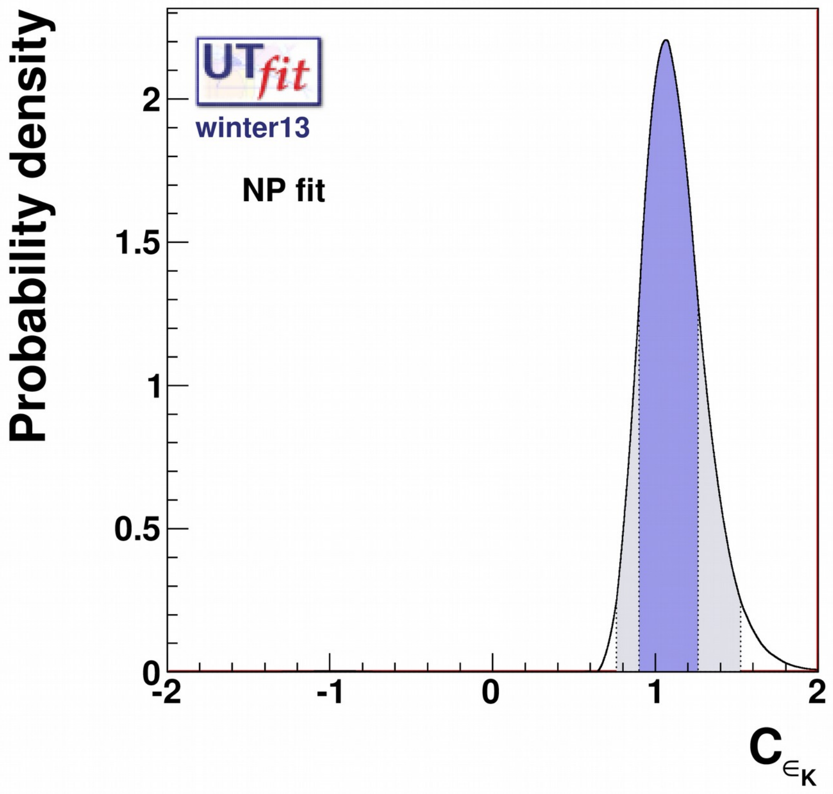
degeneracy of γ broken by A_{SL}

In the SM was:

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

$\bar{\eta} = 0.350 \pm 0.014$

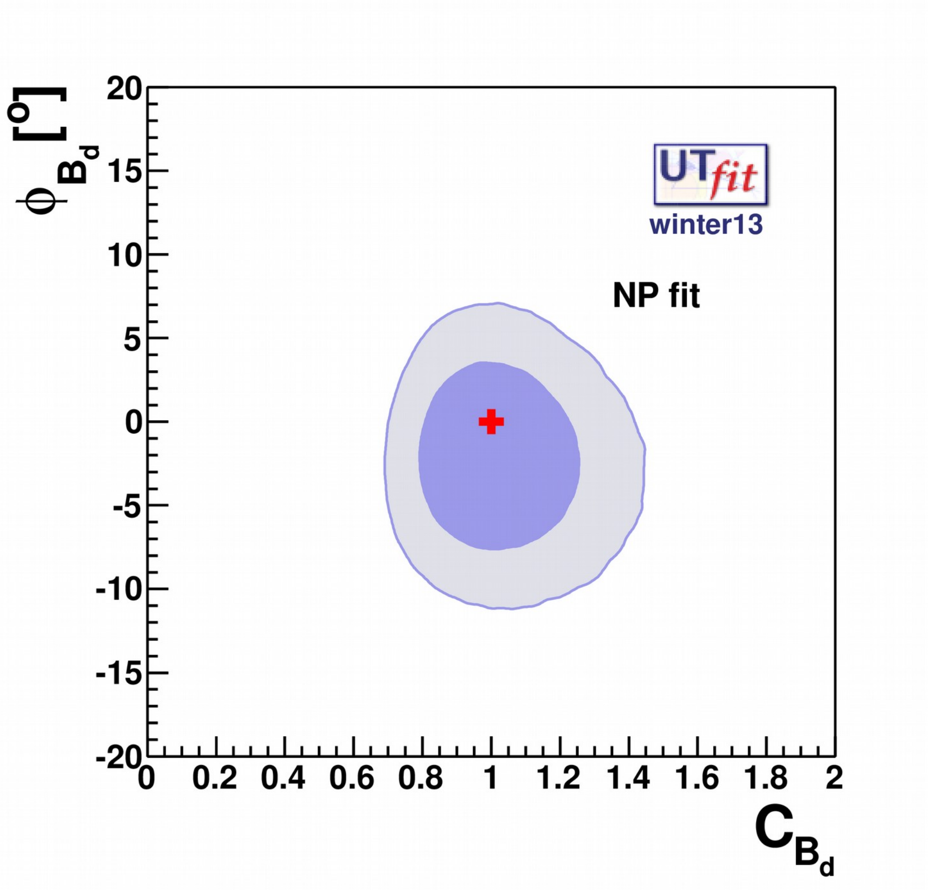
NP FIT RESULTS



- $C_{\varepsilon K}$ = 1.08 ± 0.18

([0.76,1.52] @ 95% probability)

NP IN B_d MIXING



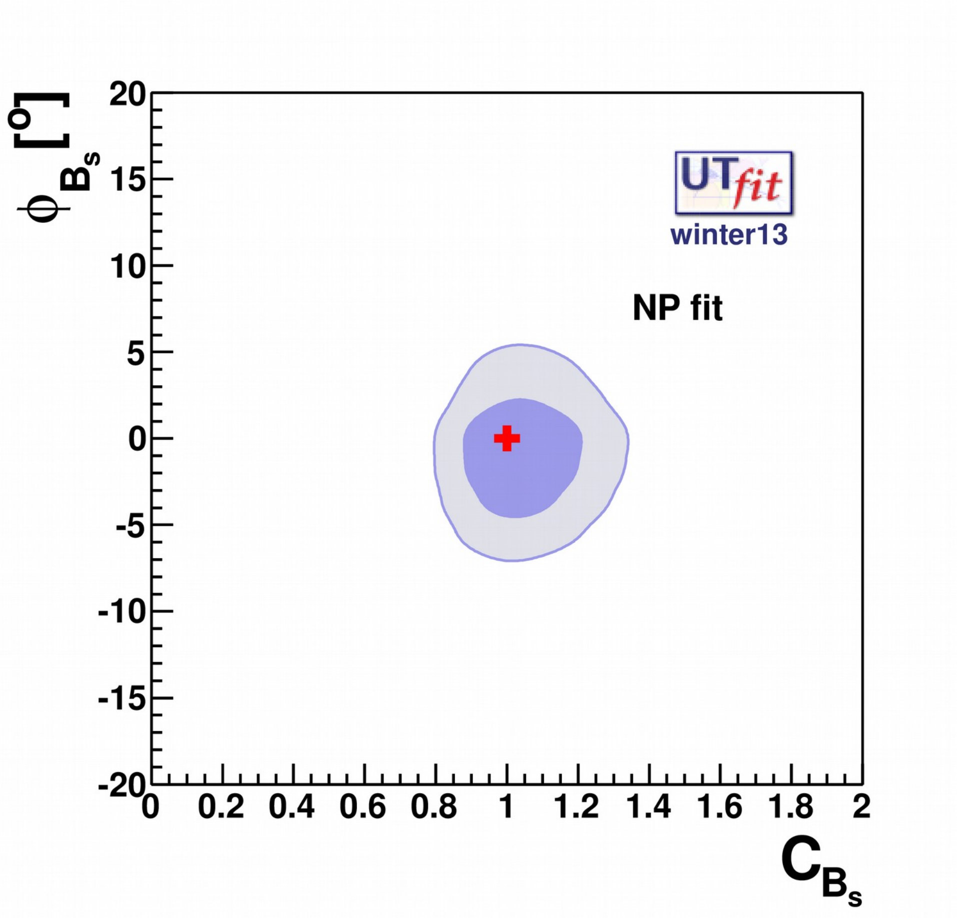
- C_{Bd} = 1.01 ± 0.15

  ([0.73,1.35] @ 95% probability)

- ϕ_{Bd} = (-2.2 ± 3.7)°

  ([-9,5.2]° @ 95% probability)

NP IN B_s MIXING



- C_{Bs} = 1.03 ± 0.10

  ([0.84,1.26] @ 95% probability)

- $\phi_{Bs} = (-0.8 \pm 2.5)°$

  ([-5,3.8]° @ 95% probability)

The D0 dimuon asymmetry remains unexplained

$D\text{-}\bar{D}$ MIXING

- Established experimentally only in 2007
- Great experimental progress recently
- SM long distance contributions difficult to estimate, but solid prediction: no CPV in mixing
- Direct CPV possible in SCS decays; experimental situation unclear

BASIC FORMULAE

- All mixing-related observables can be expressed in terms of $x=\Delta m/\Gamma$, $y=\Delta\Gamma/2\Gamma$ and $|q/p|$, or better in terms of M_{12}, Γ_{12} and $\Phi_{12}=\arg(\Gamma_{12}/M_{12})$:

Ciuchini et al; Kagan & Sokoloff

$$|M_{12}| = \frac{1}{\tau_D}\sqrt{\frac{x^2+\delta^2 y^2}{4(1-\delta^2)}}\,, \quad |\Gamma_{12}| = \frac{1}{\tau_D}\sqrt{\frac{y^2+\delta^2 x^2}{1-\delta^2}}\,, \quad \sin\Phi_{12} = \frac{|\Gamma_{12}|^2+4|M_{12}|^2-(x^2+y^2)|q/p|^2/\tau_D^2}{4|M_{12}\Gamma_{12}|}$$

$$\delta = \frac{1-|q/p|^2}{1+|q/p|^2}\,, \quad \phi = \arg(q/p) = \arg(y+i\delta x)\,, \quad A_M = \frac{|q/p|^4-1}{|q/p|^4+1}\,, \quad R_M = \frac{x^2+y^2}{2}\,, \qquad (1)$$

$$\begin{pmatrix} x'_f \\ y'_f \end{pmatrix} = \begin{pmatrix} \cos\delta_f & \sin\delta_f \\ -\sin\delta_f & \cos\delta_f \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}\,, \quad (x'_\pm)_f = \left|\frac{q}{p}\right|^{\pm1}(x'_f\cos\phi \pm y'_f\sin\phi)\,, \quad (y'_\pm)_f = \left|\frac{q}{p}\right|^{\pm1}(y'_f\cos\phi \mp x'_f\sin\phi)\,,$$

$$y_{\rm CP} = \left(\left|\frac{q}{p}\right|+\left|\frac{p}{q}\right|\right)\frac{y}{2}\cos\phi - \left(\left|\frac{q}{p}\right|-\left|\frac{p}{q}\right|\right)\frac{x}{2}\sin\phi\,, \quad A_\Gamma = \left(\left|\frac{q}{p}\right|-\left|\frac{p}{q}\right|\right)\frac{y}{2}\cos\phi - \left(\left|\frac{q}{p}\right|+\left|\frac{p}{q}\right|\right)\frac{x}{2}\sin\phi\,,$$

$$R_D = \frac{\Gamma(D^0\to K^+\pi^-)+\Gamma(\bar D^0\to K^-\pi^+)}{\Gamma(D^0\to K^-\pi^+)+\Gamma(\bar D^0\to K^+\pi^-)}\,, \quad A_D = \frac{\Gamma(D^0\to K^+\pi^-)-\Gamma(\bar D^0\to K^-\pi^+)}{\Gamma(D^0\to K^+\pi^-)+\Gamma(\bar D^0\to K^-\pi^+)}\,,$$

A REMARK ON x',y' @ HC's

- LHCb recently improved the measurement of y' and x'^2 from $D \to K\pi$ decays
- We interpret this result, and the previous CDF one, as a CP average as follows:

$$y' \to (y'_+ + y'_-)/2$$

$$x'^2 \to (x'^2_+ + x'^2_- + y'^2_+ + y'^2_-)/2 - y'^2$$

CPV IN D MIXING

- updating the UTfit average we obtain:
    - $x = (4.2 \pm 1.8)\ 10^{-3}$, $y = (6.4 \pm 0.8)\ 10^{-3}$, $|q/p|-1 = (2 \pm 8)\ 10^{-2}$, $\phi = (0.3 \pm 2.6)^{\circ}$
    - $\Phi_{12} = (2 \pm 11)^{\circ}$
- impressive improvement, CPV now very well measured
- more stringent constraints on CP-violating NP

2. EFT analysis of ΔF=2 transitions

The mixing amplitudes $A_q e^{2i\phi_q} = \langle \bar{M}_q | H_{eff}^{\Delta F=2} | M_q \rangle$

$$H_{eff}^{\Delta B=2} = \sum_{i=1}^{5} C_i(\mu) Q_i(\mu) + \sum_{i=1}^{3} \tilde{C}_i(\mu) \tilde{Q}_i(\mu)$$

$$Q_1 = \bar{q}_L^\alpha \gamma_\mu b_L^\alpha \, \bar{q}_L^\beta \gamma^\mu b_L^\beta \qquad \text{(SM/MFV)}$$

$$Q_2 = \bar{q}_R^\alpha b_L^\alpha \, \bar{q}_R^\beta b_L^\beta \qquad Q_3 = \bar{q}_R^\alpha b_L^\beta \, \bar{q}_R^\beta b_L^\alpha$$

$$Q_4 = \bar{q}_R^\alpha b_L^\alpha \, \bar{q}_L^\beta b_R^\beta \qquad Q_5 = \bar{q}_R^\alpha b_L^\beta \, \bar{q}_L^\beta b_R^\alpha$$

$$\tilde{Q}_1 = \bar{q}_R^\alpha \gamma_\mu b_R^\alpha \, \bar{q}_R^\beta \gamma^\mu b_R^\beta$$

$$\tilde{Q}_2 = \bar{q}_L^\alpha b_R^\alpha \, \bar{q}_L^\beta b_R^\beta \qquad \tilde{Q}_3 = \bar{q}_L^\alpha b_R^\beta \, \bar{q}_L^\beta b_R^\alpha$$

7 new operators beyond MFV involving quarks with different chiralities

H_{eff} can be recast in terms of the $C_i(\Lambda)$ computed at the NP scale

- $C_i(\Lambda)$ can be extracted from the data (one by one)
- the associated NP scale Λ can be defined from

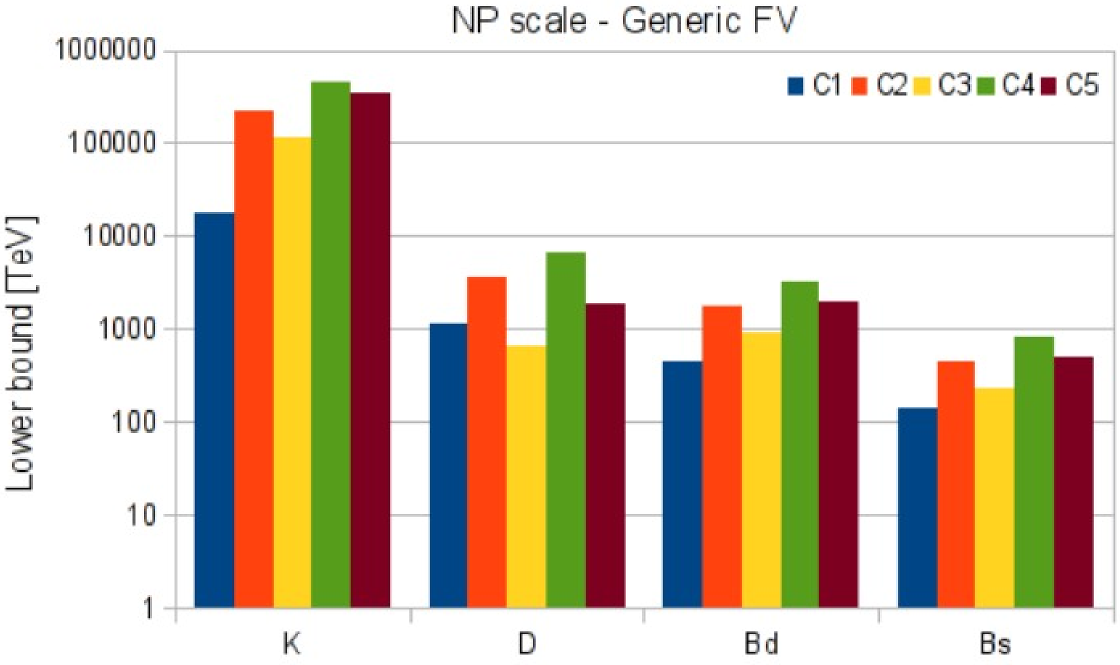
$$C_i(\Lambda) = \frac{L F_i}{\Lambda^2}$$

tree/strong interact. NP: $L \sim 1$

perturbative NP: $L \sim \alpha_s^2, \alpha_W^2$

Flavour structures:

MFV	next-to-MFV	generic
- $F_1 = F_{SM} \sim (V_{tq} V_{tb}^*)^2$	- $\lvert F_i \rvert \sim F_{SM}$	- $\lvert F_i \rvert \sim 1$
- $F_{i \neq 1} = 0$	- arbitrary phases	- arbitrary phases



Generic Flavor Violation

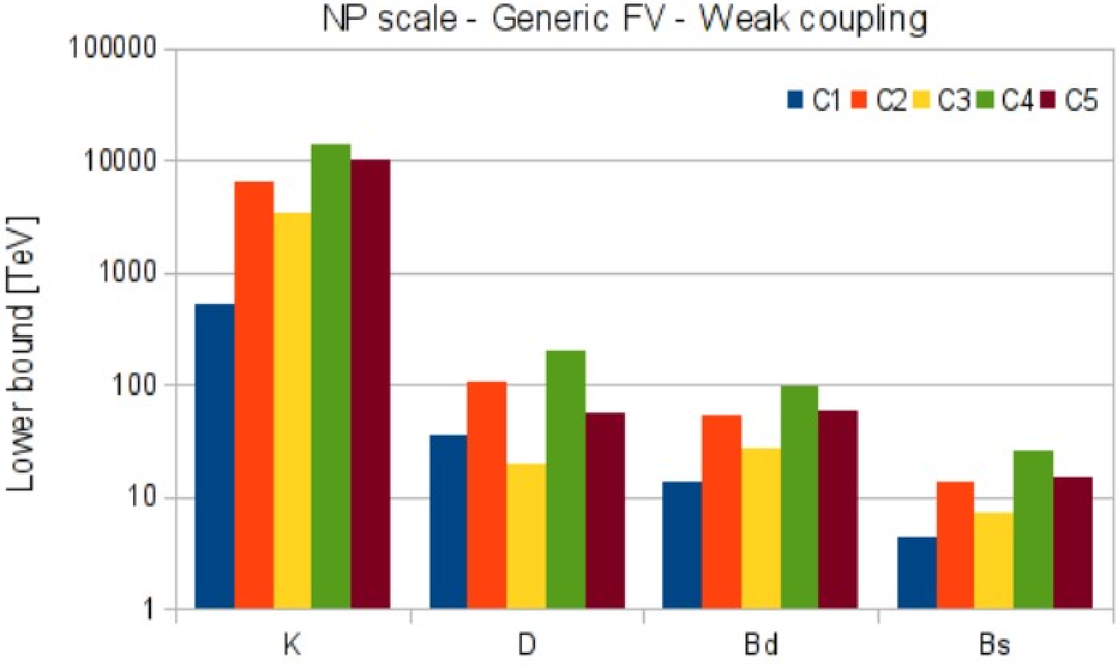
Non-perturbative NP

$\Lambda > 4.6\ 10^5$ TeV

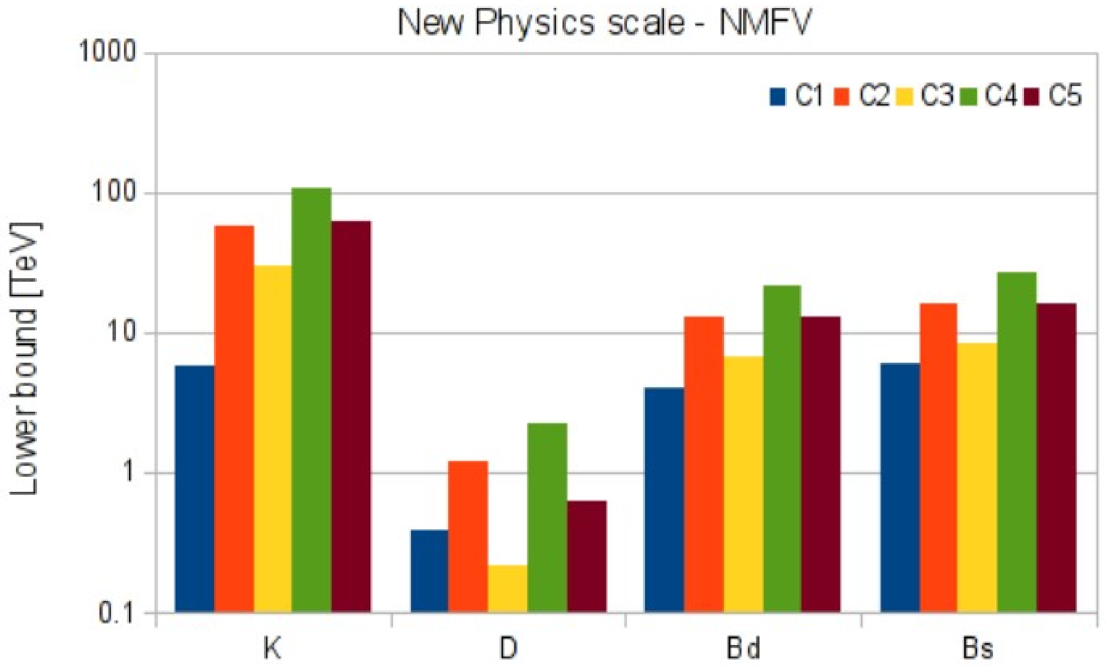
NP in α_W loops

$\Lambda > 1.4\ 10^4$ TeV

preliminary results

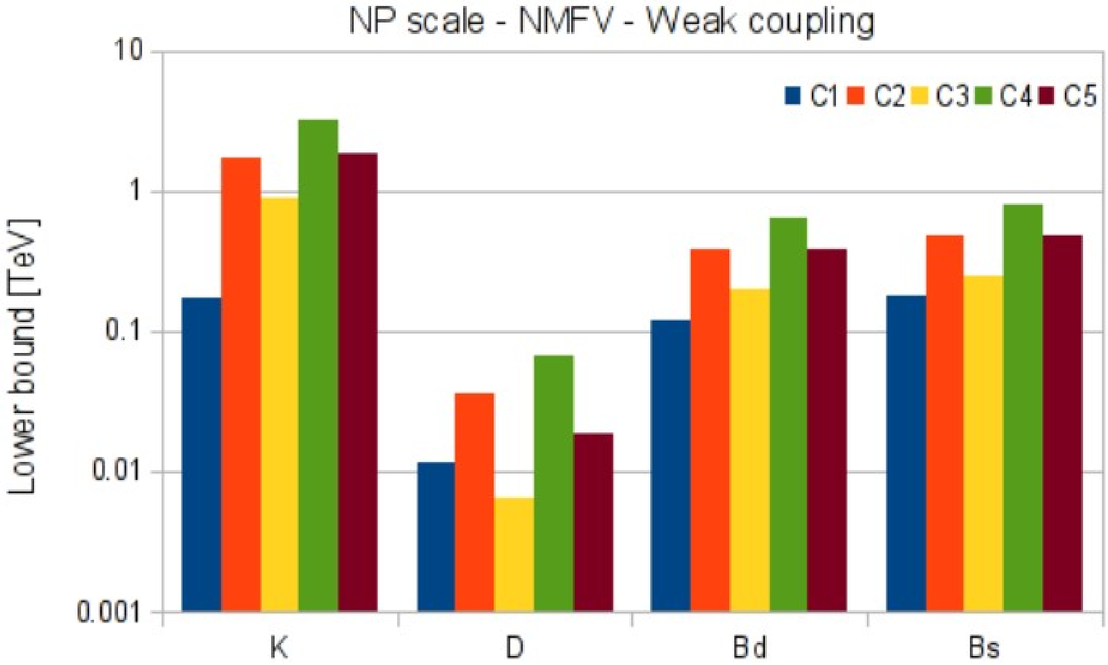


NMFV: SM-like Flavor Couplings



Non-perturbative NP

$\Lambda > 105$ TeV



NP in α_W loops

$\Lambda > 3.2$ TeV

preliminary results

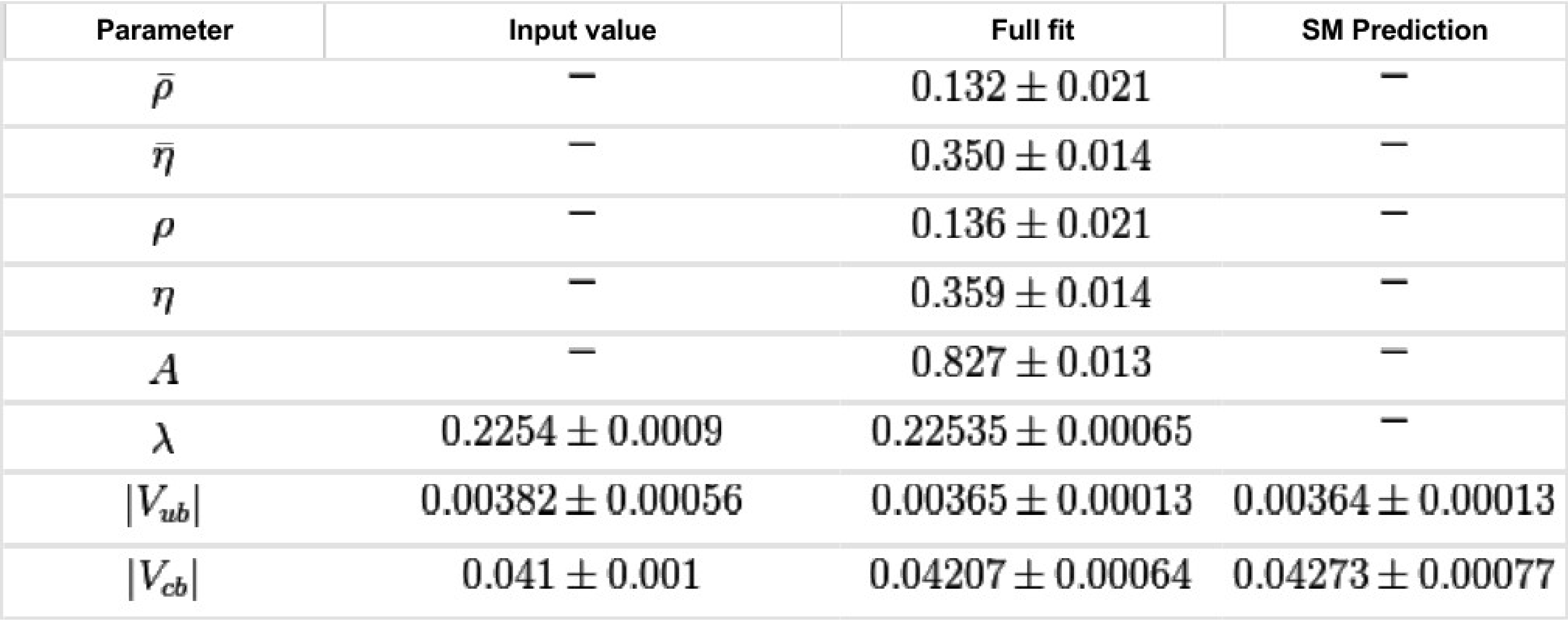
CONCLUSIONS

- The SM UTA has reached high precision and redundancy, allowing to test the SM and search for NP
- Overall picture consistent with the SM, with nonstandard CPV in $\Delta F=2$ possible at the few degrees level in all sectors
- Stringent bounds on the NP scale from $\Delta F=2$ processes

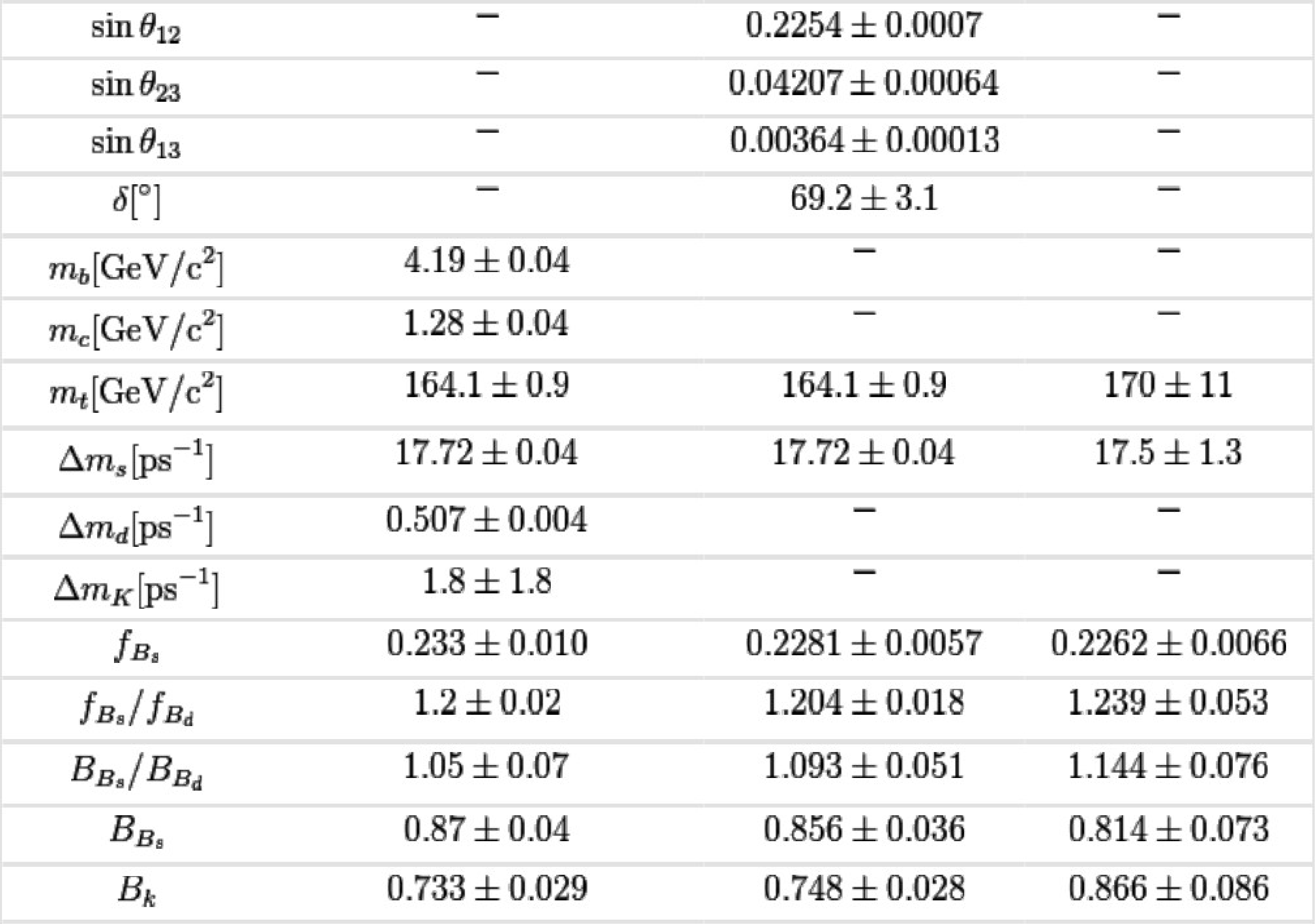
DEPRESSED?

- I still think scale separation is a valid principle
- The physics stabilizing the EW scale might be more complicated than the simple benchmark models commonly used
- Experimental & theoretical progress expected in the next few years
- With a little help from our experimentalist friends, look forward to a bright future!

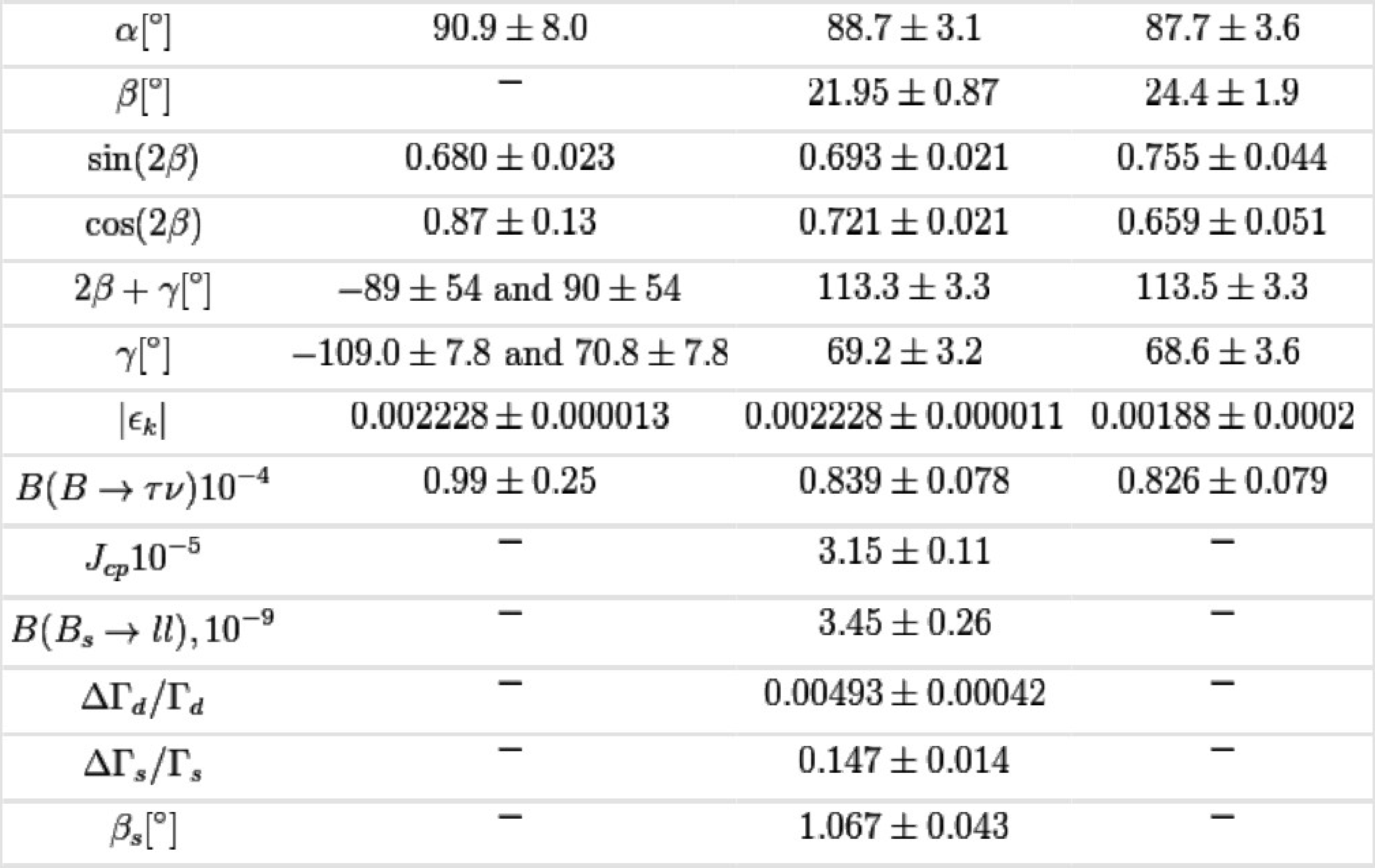
BACKUP SLIDES



Parameter	Input value	Full fit	SM Prediction
$\bar{\rho}$	$-$	0.132 ± 0.021	$-$
$\bar{\eta}$	$-$	0.350 ± 0.014	$-$
ρ	$-$	0.136 ± 0.021	$-$
η	$-$	0.359 ± 0.014	$-$
A	$-$	0.827 ± 0.013	$-$
λ	0.2254 ± 0.0009	0.22535 ± 0.00065	$-$
$\|V_{ub}\|$	0.00382 ± 0.00056	0.00365 ± 0.00013	0.00364 ± 0.00013
$\|V_{cb}\|$	0.041 ± 0.001	0.04207 ± 0.00064	0.04273 ± 0.00077

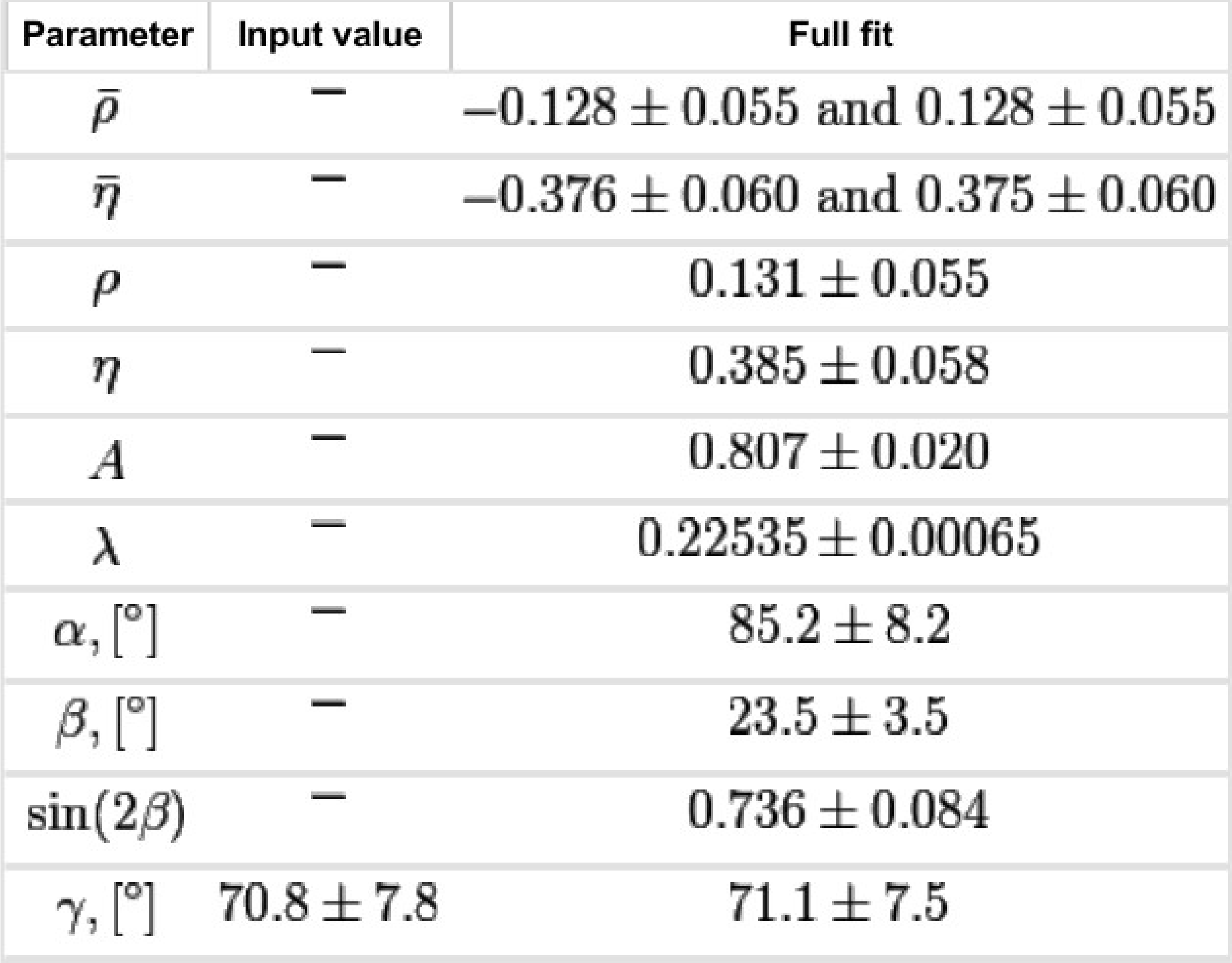


$\sin\theta_{12}$	$-$	0.2254 ± 0.0007	$-$
$\sin\theta_{23}$	$-$	0.04207 ± 0.00064	$-$
$\sin\theta_{13}$	$-$	0.00364 ± 0.00013	$-$
$\delta[^\circ]$	$-$	69.2 ± 3.1	$-$
$m_b[\mathrm{GeV/c^2}]$	4.19 ± 0.04	$-$	$-$
$m_c[\mathrm{GeV/c^2}]$	1.28 ± 0.04	$-$	$-$
$m_t[\mathrm{GeV/c^2}]$	164.1 ± 0.9	164.1 ± 0.9	170 ± 11
$\Delta m_s[\mathrm{ps}^{-1}]$	17.72 ± 0.04	17.72 ± 0.04	17.5 ± 1.3
$\Delta m_d[\mathrm{ps}^{-1}]$	0.507 ± 0.004	$-$	$-$
$\Delta m_K[\mathrm{ps}^{-1}]$	1.8 ± 1.8	$-$	$-$
f_{B_s}	0.233 ± 0.010	0.2281 ± 0.0057	0.2262 ± 0.0066
f_{B_s}/f_{B_d}	1.2 ± 0.02	1.204 ± 0.018	1.239 ± 0.053
B_{B_s}/B_{B_d}	1.05 ± 0.07	1.093 ± 0.051	1.144 ± 0.076
B_{B_s}	0.87 ± 0.04	0.856 ± 0.036	0.814 ± 0.073
B_k	0.733 ± 0.029	0.748 ± 0.028	0.866 ± 0.086



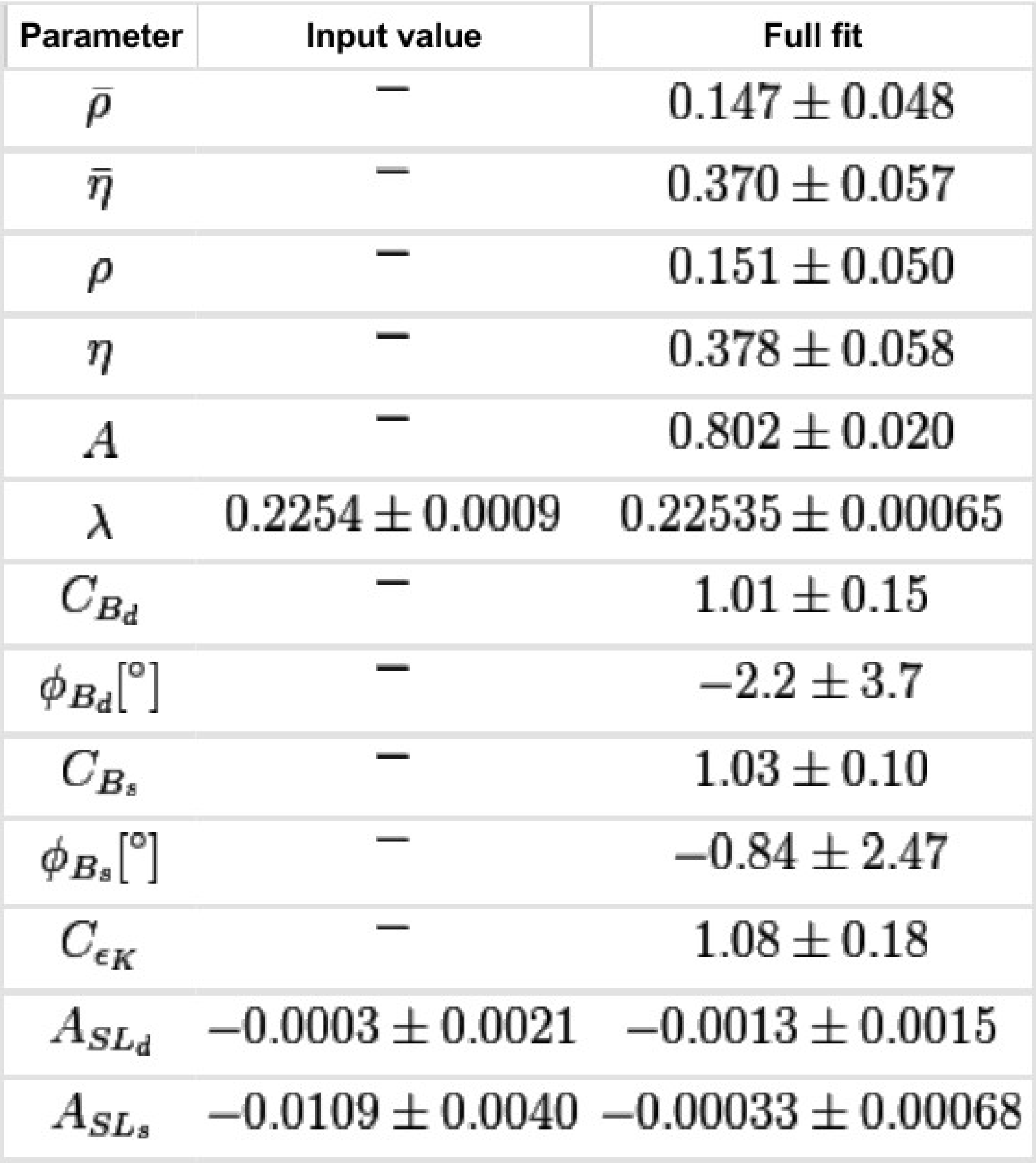
$\alpha[^\circ]$	90.9 ± 8.0	88.7 ± 3.1	87.7 ± 3.6
$\beta[^\circ]$	$-$	21.95 ± 0.87	24.4 ± 1.9
$\sin(2\beta)$	0.680 ± 0.023	0.693 ± 0.021	0.755 ± 0.044
$\cos(2\beta)$	0.87 ± 0.13	0.721 ± 0.021	0.659 ± 0.051
$2\beta + \gamma[^\circ]$	-89 ± 54 and 90 ± 54	113.3 ± 3.3	113.5 ± 3.3
$\gamma[^\circ]$	-109.0 ± 7.8 and 70.8 ± 7.8	69.2 ± 3.2	68.6 ± 3.6
$\lvert\epsilon_k\rvert$	0.002228 ± 0.000013	0.002228 ± 0.000011	0.00188 ± 0.0002
$B(B \to \tau\nu)10^{-4}$	0.99 ± 0.25	0.839 ± 0.078	0.826 ± 0.079
$J_{cp}10^{-5}$	$-$	3.15 ± 0.11	$-$
$B(B_s \to ll), 10^{-9}$	$-$	3.45 ± 0.26	$-$
$\Delta\Gamma_d/\Gamma_d$	$-$	0.00493 ± 0.00042	$-$
$\Delta\Gamma_s/\Gamma_s$	$-$	0.147 ± 0.014	$-$
$\beta_s[^\circ]$	$-$	1.067 ± 0.043	$-$

TREE LEVEL FIT



Parameter	Input value	Full fit
$\bar{\rho}$	$-$	-0.128 ± 0.055 and 0.128 ± 0.055
$\bar{\eta}$	$-$	-0.376 ± 0.060 and 0.375 ± 0.060
ρ	$-$	0.131 ± 0.055
η	$-$	0.385 ± 0.058
A	$-$	0.807 ± 0.020
λ	$-$	0.22535 ± 0.00065
$\alpha, [^\circ]$	$-$	85.2 ± 8.2
$\beta, [^\circ]$	$-$	23.5 ± 3.5
$\sin(2\beta)$	$-$	0.736 ± 0.084
$\gamma, [^\circ]$	70.8 ± 7.8	71.1 ± 7.5

NP FIT



Parameter	Input value	Full fit
$\bar{\rho}$	$-$	0.147 ± 0.048
$\bar{\eta}$	$-$	0.370 ± 0.057
ρ	$-$	0.151 ± 0.050
η	$-$	0.378 ± 0.058
A	$-$	0.802 ± 0.020
λ	0.2254 ± 0.0009	0.22535 ± 0.00065
C_{B_d}	$-$	1.01 ± 0.15
$\phi_{B_d}[^\circ]$	$-$	-2.2 ± 3.7
C_{B_s}	$-$	1.03 ± 0.10
$\phi_{B_s}[^\circ]$	$-$	-0.84 ± 2.47
C_{ϵ_K}	$-$	1.08 ± 0.18
A_{SL_d}	-0.0003 ± 0.0021	-0.0013 ± 0.0015
A_{SL_s}	-0.0109 ± 0.0040	-0.00033 ± 0.00068