CP violation in kaon mixing

towards improving its new physics reach

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LPTHE Paris and CNRS

mainly based on Ligeti, Sala 1602.08494

Les Rencontres de Physique de la Vallée d'Aoste, La Thuile, 8 March 2016

My talk in one slide

CP violation in Kaon mixing (ϵ_K)
$=$ observable sensitive to the highest flavour and CP violating scales

$\Delta\epsilon_K|_{\rm exp} \sim 0.5\%$ $\Delta\epsilon_K|_{\rm SM} \sim 15\%$ $\Rightarrow$ SM determination needs improvement!

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I'll show how to "get rid" of η_{cc}, source of the largest non-parametric error

- $\rightarrow$ $\Delta\epsilon_K|_{\rm SM}$ slightly reduced
- $\rightarrow$ Future: compute Long-Distance contribution to M_{12}

Flavour in the SM and beyond

"SM flavour problem"

$$|V_{\rm CKM}| \sim \begin{pmatrix} 1 & 0.2 & 4\cdot 10^{-3} \\ 0.2 & 1 & 4\cdot 10^{-2} \\ 9\cdot 10^{-3} & 4\cdot 10^{-2} & 1 \end{pmatrix}$$

$$(y_u, y_c, y_t) \sim (10^{-6}, 10^{-2}, 1) \qquad (y_d, y_s, y_b) \sim (10^{-5}, 10^{-3}, 10^{-2})$$

Is there a UV reason behind this pattern? Where can we test it?

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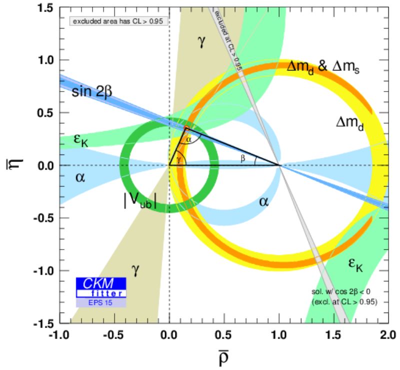

"NP flavour problem"

$$\mathcal{L}_{\rm NP} = \sum_i \frac{1}{\Lambda_i^2}\mathcal{O}_i \Rightarrow \Lambda_i \gtrsim 10^4 \div 10^5\,\mathrm{TeV}$$

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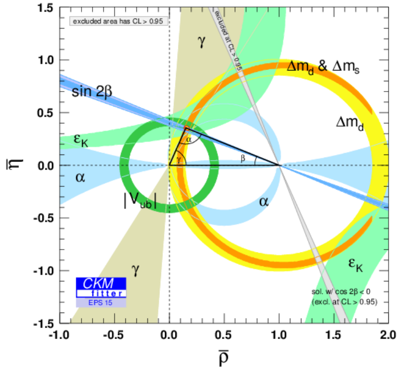

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- ☹ lowers expectations to solve SM flavour problem
- ☹ clashes with natural solution to hierarchy problem

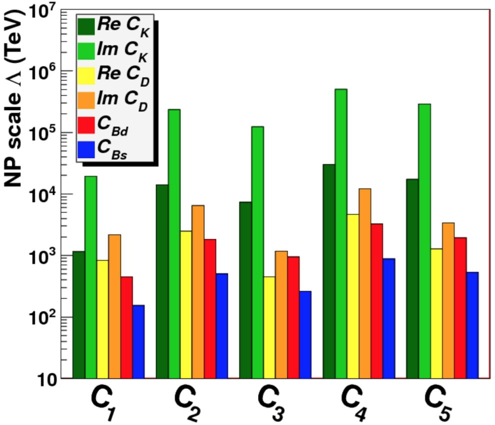
What are the most sensitive observables?

$$\mathcal{L}_{\rm NP} = \sum_i \frac{1}{\Lambda_i^2}\mathcal{O}_i$$

$$\mathcal{O}_1 = (\bar{d}_L\gamma_\mu s_L)^2,\ \mathcal{O}_2 = (\bar{d}_R s_L)^2,\ \mathcal{O}_3 = (\bar{d}_R^\alpha s_L^\beta)(\bar{d}_R^\beta s_L^\alpha)$$

$$\mathcal{O}_4 = (\bar{d}_R s_L)(\bar{d}_L s_R),\ \mathcal{O}_5 = (\bar{d}_R^\alpha s_L^\beta)(\bar{d}_L^\beta s_R^\alpha)$$

UTfit 2013



[Disclaimer: focus on $\Delta F = 2$ processes]

General Message:

Intensity (flavour) frontier probes scales $\gg$ TeV

Highest energies probed by ϵ_K (= CP violation in Kaon mixing)

Interplay with energy frontier (LHC)? Needs specification of new physics models

Two (most popular) flavour pictures

Assume New Physics at scale $\Lambda \sim 1 - 10$ TeV:

$\mathcal{L}_{\rm NP} = \sum_i \xi_i \frac{c_i}{\Lambda^2} \mathcal{O}_i$ $\quad c_i \sim O(1)$ $\quad \xi_i$ small due to some “feature”

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CKM-like symmetries

Flavour symmetry ($U(3)^3$ or $U(2)^3$) controls NP effects

SM understanding only parametrical ($U(3)^3$) or partly addressed ($U(2)^3$)

D'Ambrosio et al. 2002, Barbieri et al. 2011

Partial compositeness

SM quarks mix with composite operators + anarchic flavour in composite sector

$V_{\rm CKM}$ elements related to quark masses:

$$y_i \sim \epsilon_i^L \epsilon_i^R, \qquad (V_{\rm CKM})_{ij} \sim \epsilon_i^L / \epsilon_j^L$$

Kaplan 1991, Contino et al 2006, ...

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SM understanding only parametrical ($U(3)^3$) or partly addressed ($U(2)^3$)

Only those $\mathcal{O}_i$ present in the SM

[e.g. NO $\mathcal{O}_4 = (\bar{s}_L d_R)(\bar{s}_R d_L)$]

Same SM suppression, i.e. $\xi \sim V_{CKM}^{2-4}$

$\Lambda \gtrsim 3$ TeV ($\epsilon_K \sim B - \bar{B}$)

D'Ambrosio et al. 2002, Barbieri et al. 2011
Barbieri Buttazzo Sala Straub 2012, 2014

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$$y_i \sim \epsilon_i^L \epsilon_i^R, \qquad (V_{\rm CKM})_{ij} \sim \epsilon_i^L / \epsilon_j^L$$

All $\mathcal{O}_i$ allowed: SM ones have $\xi \sim V_{CKM}^{2-4}$

(some) others have $\xi \sim y_i y_j$

$\Lambda \gtrsim 15$ TeV (ϵ_K), 3 TeV ($B - \bar{B}$)

Kaplan 1991, Contino et al 2006, ...
Barbieri Buttazzo Sala Straub Tesi 2012

Flavour scale and new resonances at the LHC

Partial compositeness $\Lambda \simeq m_{\rho,T}$ $\Lambda \gtrsim 15 \text{ or } 3 \text{ TeV} \rightarrow$ No NP at the LHC.

CKM-like symmetries

- implement in composite models (flavour violation at tree level)

  $\rightarrow$ if $U(2)^3$ then $m_T \sim 1$ TeV, if $U(3)^3$ then $m_T \gg 1$ TeV

- implement in supersymmetry (flavour violation at loop level)

  $\rightarrow$ both $U(2)^3$ and $U(3)^3$: stops and gluinos within LHC8-13 reach

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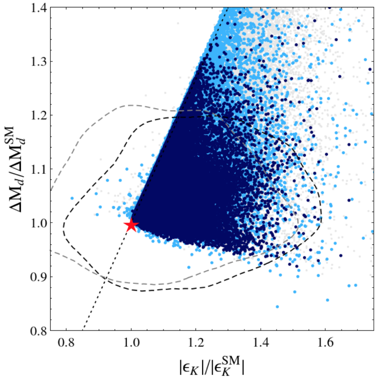
Flavour and CP violation best protected in SUSY-$U(2)^3$: sparticles at the LHC?

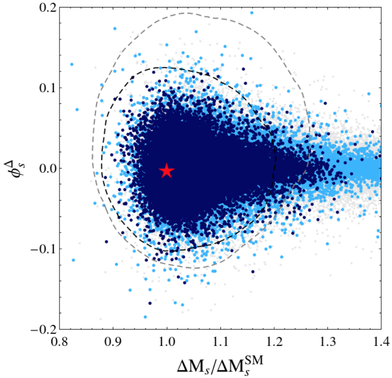
All points allowed by LHC8 sparticle searches

Dark: conservative exclusions

Light: compressed spectra, ...

[Dashed: $\Delta F = 2$ fit]





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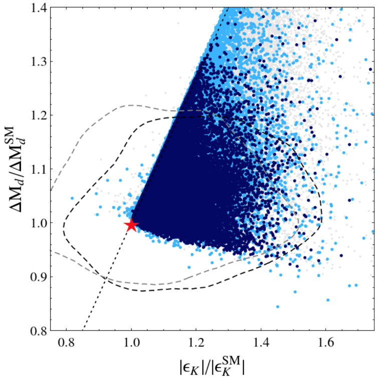

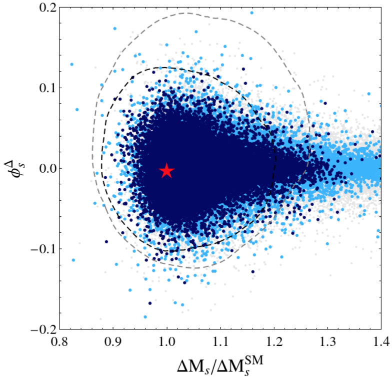

What if no sparticles at LHC14?

ϕ_s LHCb aims at $\pm 0.01 \div 0.03$ [now ± 0.07]

$\Delta M_{d,s}$ expected lattice improvements

ϵ_K how will it progress?

Impact of flavour on future of particle physics?

Some expected progresses in flavour:

CKMfitter + Ligeti, Papucci 1309.2293

	2003	2013	Stage I		Stage II
$\lvert V_{ud}\rvert$	0.9738 ± 0.0004	$0.97425 \pm 0 \pm 0.00022$	id		id
$\lvert V_{us}\rvert$ $(K_{\ell 3})$	$0.2228 \pm 0.0039 \pm 0.0018$	$0.2258 \pm 0.0008 \pm 0.0012$	0.22494 ± 0.0006		id
$\lvert \epsilon_K\rvert$	$(2.282 \pm 0.017) \times 10^{-3}$	$(2.228 \pm 0.011) \times 10^{-3}$	id		id
Δm_d [ps^{-1}]	0.502 ± 0.006	0.507 ± 0.004	id		id
Δm_s [ps^{-1}]	> 14.5 [95% CL]	17.768 ± 0.024	id		id
$\lvert V_{cb}\rvert \times 10^3$ $(b \to c\ell\bar{\nu})$	$41.6 \pm 0.58 \pm 0.8$	$41.15 \pm 0.33 \pm 0.59$	42.3 ± 0.4	[17]	42.3 ± 0.3
$\lvert V_{ub}\rvert \times 10^3$ $(b \to u\ell\bar{\nu})$	$3.90 \pm 0.08 \pm 0.68$	$3.75 \pm 0.14 \pm 0.26$	3.56 ± 0.10	[17]	3.56 ± 0.08
$\sin 2\beta$	0.726 ± 0.037	0.679 ± 0.020	0.679 ± 0.016	[17]	0.679 ± 0.008
α (mod π)	—	$(85.4^{+4.0}_{-3.8})^\circ$	$(91.5 \pm 2)^\circ$	[17]	$(91.5 \pm 1)^\circ$
γ (mod π)	—	$(68.0^{+8.0}_{-8.5})^\circ$	$(67.1 \pm 4)^\circ$	[17, 18]	$(67.1 \pm 1)^\circ$
β_s	—	$0.0065^{+0.0450}_{-0.0415}$	0.0178 ± 0.012	[18]	0.0178 ± 0.004

Stage I = 7 fb^{-1} LHCb + 5 fb^{-1} Belle-II, Stage II = 50 fb^{-1} LHCb + Belle-II

Example: $\phi_s = \phi_s^\Delta - 2|\beta_s|$ of SUSY slide

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ϵ_K: till now played a leading role, both in general and in specific models!

What about its future?

ϵ_K = CP violation in Kaon mixing

$$\epsilon_K = \frac{\mathcal{A}(K_L \to (\pi\pi)_{I=0})}{\mathcal{A}(K_S \to (\pi\pi)_{I=0})}\left(1 + O(10^{-4})\right) \text{ with respect to measurement}$$

$|\epsilon_K|_{\rm exp} = (2.228 \pm 0.011) \times 10^{-3}$ $\quad |\epsilon_K|_{\rm SM} = (2.16^{(*)} \pm 0.22) \times 10^{-3}$

$^{(*)}$ inputs from CKM fit without ϵ_K

Progress is needed in the SM determination of ϵ_K!

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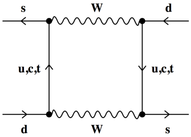
Usual evaluation of ϵ_K

$$|\epsilon_K|_{\rm SM} = \kappa_\epsilon C_\epsilon \hat{B}_K |V_{cb}|^2 \lambda^2 \bar{\eta} \left(|V_{cb}|^2 (1-\bar{\rho})\eta_{tt} S_0(x_t) + \eta_{ct} S_0(x_t, x_c) - \eta_{cc} x_c\right)$$



κ_ϵ summarises long distance and absorptive contribution

Buras Guadagnoli Isidori 1002.3612

Error budget of ϵ_K in the Standard Model

$$|\epsilon_K|_{\mathrm{SM}} = \kappa_\epsilon C_\epsilon \hat{B}_K |V_{cb}|^2 \lambda^2 \bar{\eta} \left[|V_{cb}|^2 (1-\bar{\rho}) \eta_{tt} S_0(x_t) + \eta_{ct} S_0(x_t, x_c) - \eta_{cc} x_c \right]$$

CKM inputs	η_{cc}	η_{ct}	$\kappa_\epsilon^{(\prime)}$	m_t	m_c	$\widehat{B}_K$	$\lvert V_{cb}\rvert$	$\bar{\eta}$	$\bar{\rho}$	$\lvert\Delta\epsilon_K/\epsilon_K\rvert_{\mathrm{tot.}}$
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CKM parameters	SM CKM fit [5]	tree-level only
λ	0.22543 ± 0.00037	0.2253 ± 0.0008
$\lvert V_{cb}\rvert (= A\lambda^2)$	$(41.80 \pm 0.51) \times 10^{-3}$	$(41.1 \pm 1.3) \times 10^{-3}$
$\bar{\eta}$	0.3540 ± 0.0073	0.38 ± 0.04
$\bar{\rho}$	0.1504 ± 0.0091	0.115 ± 0.065

$\eta_{cc} = 1.87 \pm 0.76$ NNLO in Brod Gorbhan 1008.2036 series converges badly!

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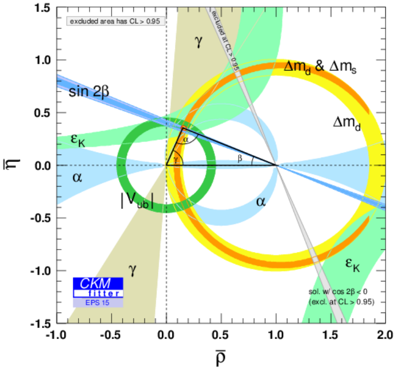
Future?

$\Delta V_{cb} \longrightarrow 0.3 \times 10^{-3} \Rightarrow \Delta\epsilon_K/\epsilon_K \sim 2.5\%$ (similarly for $\bar{\eta}, \bar{\rho}$)

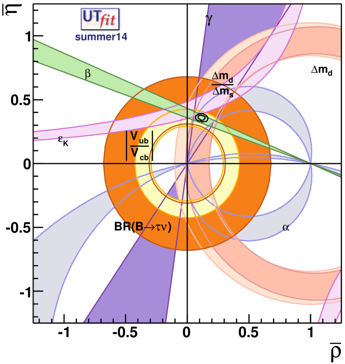
then η_{cc} even more important!

$$\eta_{cc} = 1\,(\mathrm{LO}) + 0.38\,(\mathrm{NLO}) + 0.49\,(\mathrm{NNLO})$$

Treated differently by different groups (see widths of ϵ_K bands):



CKMfitter: η_{cc}@NNLO



UTfit: η_{cc}@NLO

A step back: (usual) evaluation of ϵ_K

$$\epsilon_K = \frac{\mathcal{A}(K_L \to (\pi\pi)_{I=0})}{\mathcal{A}(K_S \to (\pi\pi)_{I=0})}$$

$$|K_{S,L}\rangle = p|K^0\rangle \pm q|\bar{K^0}\rangle, \quad i\frac{d}{dt}\begin{pmatrix} K^0 \\ \bar{K^0} \end{pmatrix} = \left(M - i\frac{\Gamma}{2}\right)\begin{pmatrix} K^0 \\ \bar{K^0} \end{pmatrix}$$

$$|\epsilon_K| = \frac{\sin\phi_\epsilon}{2} \arg\left(-\frac{M_{12}}{\Gamma_{12}}\right) \qquad \Delta m \simeq 2|M_{12}| \quad \Delta\Gamma \simeq -2|\Gamma_{12}|$$

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$|\epsilon_K|$ independent of Kaon phases but: M_{12} and Γ_{12} computed in different ways...

$2m_K M_{12} = \langle \bar{K}^0|\mathcal{H}|K_0\rangle^* =$ short- plus long- distance contributions,

$\Gamma_{12} = \sum_f \mathcal{A}(K^0 \to f)^* \mathcal{A}(\bar{K}^0 \to f)$ dominated by $f = (\pi\pi)_{I=0}$, on the lattice

...so final result depends on phase convention:

$$|\epsilon_K| = \sin\phi_\epsilon \left(\frac{\mathrm{Im} M_{12}^{\mathrm{SD}}}{\Delta m} - \frac{\mathrm{Im}\Gamma_{12}}{2\mathrm{Re}\Gamma_{12}} + \frac{\mathrm{Im} M_{12}^{\mathrm{LD}}}{\Delta m}\right) = \frac{\kappa_\epsilon}{\sqrt{2}} \frac{\mathrm{Im} M_{12}^{\mathrm{SD}}}{\Delta m}$$

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Our evaluation of ϵ_K

Rephase Kaons to take advantage of this phase dependence!

$$|K^0\rangle \to |K^0\rangle' = e^{i\lambda_c/|\lambda_c|}|K^0\rangle, \qquad |\bar{K}^0\rangle \to |\bar{K}^0\rangle' = e^{-i\lambda_c/|\lambda_c|}|\bar{K}^0\rangle$$

$$\lambda_c = V_{cd}V_{cs}^* \simeq -\lambda(1+\bar{\eta}|V_{cb}|^2)$$

"charm box" becomes real $\Rightarrow$ no η_{cc} term in $\mathrm{Im}M_{12}^{SD}$ $\Rightarrow$ $\mathrm{Im}M_{12}^{SD}$ increases, κ_ϵ decreases

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	SM CKM fit	—	3.4%	5.9%	1.5%	1.3%	1.3%	3.6%	1.7%	0.7%	8.3%

...so final result depends on phase convention:

$$|\epsilon_K| = \sin\phi_\epsilon\left(\frac{\mathrm{Im}M_{12}^{\mathrm{SD}}}{\Delta m} - \frac{\mathrm{Im}\Gamma_{12}}{2\mathrm{Re}\Gamma_{12}} + \frac{\mathrm{Im}M_{12}^{\mathrm{LD}}}{\Delta m}\right) = \frac{\kappa_\epsilon}{\sqrt{2}}\frac{\mathrm{Im}M_{12}^{\mathrm{SD}}}{\Delta m}$$

$$|\epsilon_K|_{\mathrm{SM}} = \kappa_\epsilon C_\epsilon \hat{B}_K |V_{cb}|^2\lambda^2\bar{\eta}\left[|V_{cb}|^2(1-\bar{\rho})\eta_{tt}S_0(x_t) + \eta_{ct}S_0(x_t,x_c)\right]$$

Conclusion and Outlook

CP violation in Kaon mixing (ϵ_K)
= observable sensitive to the highest flavour and CP violating scales

$\Delta\epsilon_K|_{\rm exp} \sim 0.5\%$ $\quad \Delta\epsilon_K|_{\rm SM} \sim 15\%$ $\Rightarrow$ SM determination needs improvement!

the importance of η_{cc} is somehow overlooked in the community

This talk: η_{cc} can be "removed" via a rephasing

Implications:

→ $\Delta\epsilon_K|_{\rm SM}$ slightly reduced

→ Future: compute Long-Distance contribution to M_{12} →

Back up

$$|\epsilon_K|_{\rm SM} = k_\epsilon^{(\prime)} C_\epsilon \hat{B}_K |V_{cb}|^2 \lambda^2 \bar{\eta} \left(|V_{cb}|^2 (1-\bar{\rho}) \eta_{tt} S_0(x_t) + \eta_{ct} S_0(x_t, x_c) \right)$$

Parameter	value
Δm	$3.484(6) \times 10^{-12}$ MeV
m_{K^0}	$497.614(24)$ MeV
$\Delta\Gamma$	$7.3382(33) \times 10^{-12}$ MeV
$\|\epsilon_K\|$	$(2.228 \pm 0.011) \times 10^{-3}$
ϕ_ϵ	$(43.52 \pm 0.05)^\circ$
$\|\epsilon'/\epsilon\|$	$(1.66 \pm 0.23) \times 10^{-3}$
$\|A_0/A_2\|$	$22.45(6)$
$\|A_0\|$	$3.32(2) \times 10^{-7}$ GeV
η_{cc}	$1.87(76)$
η_{ct}	$0.496(47)$
η_{tt}	$0.5765(65)$
$\overline{m}_t(\overline{m}_t)$	$162.3(2.3)$ GeV
$\overline{m}_c(\overline{m}_c)$	$1.275(25)$ GeV
$\hat{B}_K$	$0.7661(99)$
f_K	$156.3(0.9)$ MeV
$\mathrm{Im}\,(A_2 e^{-i\delta_2})$	$-6.99(0.20)(0.84) \times 10^{-13}$ GeV
$\mathrm{Im}\,(A_0 e^{-i\delta_0})$	$-1.90(1.22)(1.04) \times 10^{-11}$ GeV

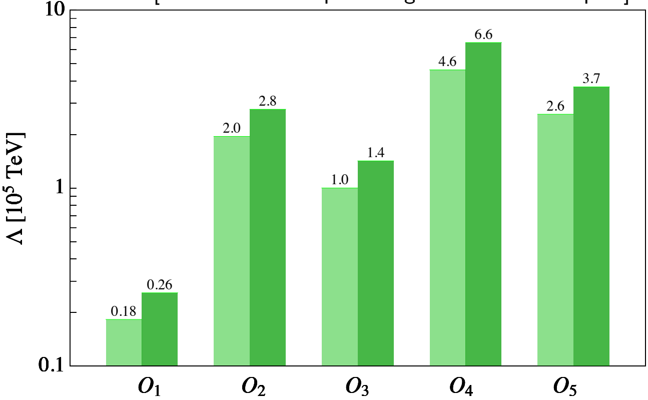
	CKM inputs	$\|\epsilon_K\| \times 10^3$	$\kappa_\epsilon^{(\prime)}$	$\xi^{(\prime)} \times 10^4$
Usual evaluation	tree-level	2.30 ± 0.42	0.963 ± 0.010	-0.57 ± 0.48
	SM CKM fit	2.16 ± 0.22	0.943 ± 0.016	-1.65 ± 0.17
Our evaluation	tree-level	2.38 ± 0.37	0.844 ± 0.044	-6.99 ± 0.92
	SM CKM fit	2.24 ± 0.19	0.829 ± 0.049	-7.83 ± 0.26

Bounds on New Physics

$$\mathcal{L}_{\rm NP} = \sum_i \frac{1}{\Lambda^2}\mathcal{O}_i$$

$$\mathcal{O}_1 = (\bar{d}_L\gamma_\mu s_L)^2,\ \mathcal{O}_2 = (\bar{d}_R s_L)^2,\ \mathcal{O}_3 = (\bar{d}_R^\alpha s_L^\beta)(\bar{d}_R^\beta s_L^\alpha)$$
$$\mathcal{O}_4 = (\bar{d}_R s_L)(\bar{d}_L s_R),\ \mathcal{O}_5 = (\bar{d}_R^\alpha s_L^\beta)(\bar{d}_L^\beta s_R^\alpha)$$

[Dark: CKM-fit inputs   Light: "tree-level" inputs]



*Generic but well defined bounds, and actually directly valid for some models (e.g. fermion resonances in CHM, now $m_T > 30$ TeV)