

CP violation in kaon mixing towards a better precision?

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RPP, Annecy, 26 Jan 2016

- CP violation in Kaon mixing (ϵ_K)
= observable sensitive to the highest CP and flavour violating scales
- $\Delta\epsilon_K|_{\text{exp}} < 1\%$ $\Delta\epsilon_K|_{\text{theory}} > 10\%$
we have to improve the SM determination!
the importance of η_{cc} is somehow overlooked in the community:
what are the prospects for improvement? **feedback encouraged**

Flavour in the SM and beyond

"SM flavour problem" $|V_{\text{CKM}}| \sim \begin{pmatrix} 1 & 0.2 & 4 \cdot 10^{-3} \\ 0.2 & 1 & 4 \cdot 10^{-2} \\ 9 \cdot 10^{-3} & 4 \cdot 10^{-2} & 1 \end{pmatrix}$

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

Is there a UV reason behind this pattern?

Where can we test it?

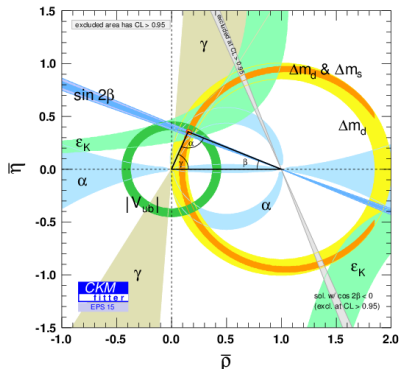
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"NP flavour problem"

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

CP violation in kaon mixing

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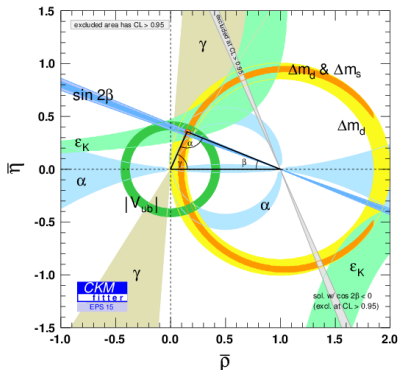
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$$\mathcal{L}_{NP} = \sum_i \frac{1}{\Lambda_i^2} \mathcal{O}_i \Rightarrow \Lambda_i \gtrsim 10^4 \div 10^5 \text{ TeV}$$

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

CP violation in kaon mixing

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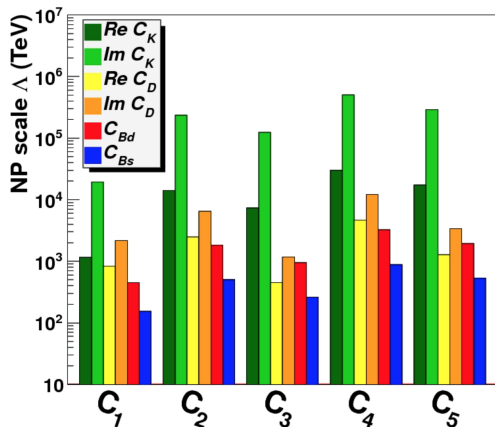
What are the most sensitive observables?*

*besides electric dipole moments

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

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

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



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

General Message:
intensity (flavour) frontier
probes scales \gg TeV

Higher energies are 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:

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

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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_{CKM} elements related to quark masses:

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

Kaplan 1991, Contino et al 2006, ...

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Only those \mathcal{O}_i present in the SM
[e.g. NO $\mathcal{O}_i = (\bar{s}_L d_R)(\bar{s}_R d_L)$]

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

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

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

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

others have $\xi \sim y_i y_j / V_{CKM}^{2-4}$

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

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

Partial compositeness $\Lambda \simeq m_{\rho, \tau}$ $\Lambda \gtrsim 15$ or 3 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

Flavour scale and new resonances at the LHC

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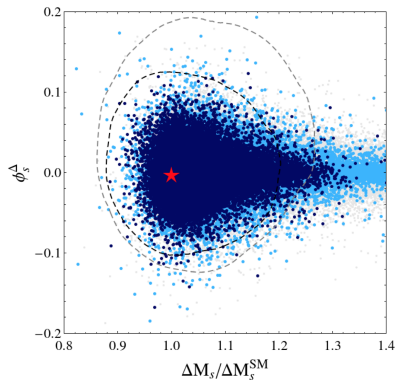
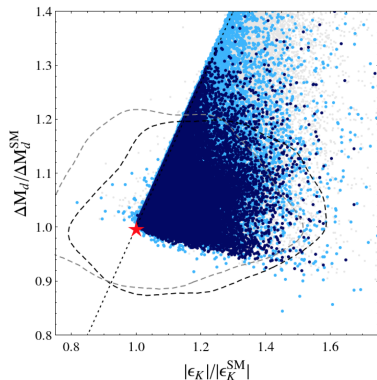
Flavour and CP violation best protected in SUSY- $U(2)^3$: sparticles at the LHC?

All points allowed by LHC8 sparticle searches

Dark: conservative exclusions

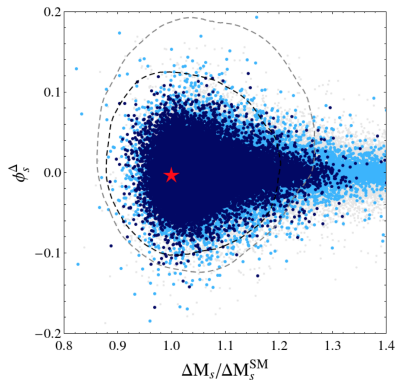
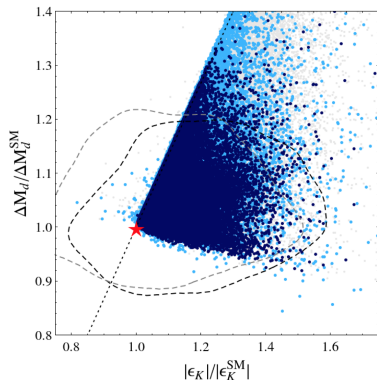
Light: compressed spectra, ...

[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
$ V_{ud} $	0.9738 ± 0.0004	$0.97425 \pm 0 \pm 0.00022$	id	id
$ V_{us} (K_{\ell 3})$	$0.2228 \pm 0.0039 \pm 0.0018$	$0.2258 \pm 0.0008 \pm 0.0012$	0.22494 ± 0.0006	id
$ \epsilon_K $	$(2.282 \pm 0.017) \times 10^{-3}$	$(2.228 \pm 0.011) \times 10^{-3}$	id	id
$\Delta m_d [\text{ps}^{-1}]$	0.502 ± 0.006	0.507 ± 0.004	id	id
$\Delta m_s [\text{ps}^{-1}]$	$> 14.5 [95\% \text{ CL}]$	17.768 ± 0.024	id	id
$ V_{cb} \times 10^3 (b \rightarrow 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
$ V_{ub} \times 10^3 (b \rightarrow 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
$\alpha (\text{mod } \pi)$	—	$(85.4^{+4.0}_{-3.8})^\circ$	$(91.5 \pm 2)^\circ$ [17]	$(91.5 \pm 1)^\circ$
$\gamma (\text{mod } \pi)$	—	$(68.0^{+8.0}_{-8.5})^\circ$	$(67.1 \pm 4)^\circ$ [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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Till now ϵ_K played a leading role, both in general and in specific models!

What about the future of ϵ_K ?

ϵ_K = CP violation in Kaon mixing

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

$$|\epsilon_K|_{\text{exp}} = (2.228 \pm 0.011) \times 10^{-3} \quad |\epsilon_K|_{\text{SM}} = (2.0^{(*)} \pm 0.3) \times 10^{-3}$$

(*) inputs from CKM fit without ϵ_K

Progress is needed in the SM determination of ϵ_K !

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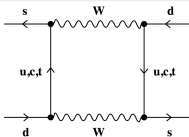
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Master formula for ϵ_K

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



k_ϵ summarises long distance and absorptive contribution

Buras Guadagnoli Isidori 1002.3612

Budget error of ϵ_K in the Standard Model

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$\left \frac{\Delta \epsilon_K}{\epsilon_K} \right _{X=}$	$ V_{cb} $	η_{cc}	η_{ct}	m_t	k_ϵ^{obs}	k_ϵ^{lat}	$\bar{\eta}$	$\bar{\rho}$	$\left \frac{\Delta \epsilon_K}{\epsilon_K} \right _{\text{total}}$
$ V_{cb} _{\text{comb}}$	11.1%	7.4%	4.1%	2.0 %	1.7%	1.1%	4.7%	2.5%	15%
$ V_{cb} _{\text{incl}}$	6.5%	7.1%	3.9%	2.0 %	1.7%	1.1%	4.7%	2.6%	12%

$$|V_{cb}|_{\text{comb}} = (41.1 \pm 1.3) \times 10^{-3} \quad |V_{cb}|_{\text{incl}} = (42.21 \pm 0.78) \times 10^{-3}$$

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

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Future?

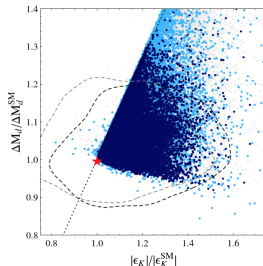
$$\Delta V_{cb} \longrightarrow 0.3 \times 10^{-3} \Rightarrow \Delta \epsilon_K / \epsilon_K \sim 2.5\% \quad \text{then } \eta_{cc} \text{ even more important!}$$

Stay tuned: a way to get rid of η_{cc} uncertainty **Ligeti Sala to appear**

Take-home message

based on work in SM to appear soon w/Ligeti
and on completed works in NP, w/Barbieri Buttazzo and Straub

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what are the prospects for improvement? **feedback encouraged**

Back up