CP Violation in *K* and B_d mesons: Exp vs Standard Model

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Summary

- ☑ On the (less than perfect) consistency between the amount of *CP* violation in the *K* and B_d systems within the Standard Model
- ☑ How Minimal Flavour Violation can help this consistency test
- ☑ What would make the MFV corrections really distinguishable from the plain SM

Based on:

Buras, DG (PRD 08 & PRD 09)

Nécessaire on *K* mesons and their *CP* violation

The d and s quarks can form, through strong interactions, the following bound states

$$|K^0\rangle \sim \begin{pmatrix} d \\ \bar{s} \end{pmatrix}$$

$$|\overline{K}^0\rangle \sim \begin{pmatrix} \bar{d} \\ s \end{pmatrix}$$

and phase conventions can be defined so that

$$\begin{cases} CP\,|K^0\rangle = -\,|\overline{K}^0\rangle \\ CP\,|\overline{K}^0\rangle = -\,|K^0\rangle \end{cases}$$

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K^0 and $\overline{K}^0$ mix into each other because of weak interactions.
However, if *CP* were a good symmetry, one would end up with the physical states:

$$|K\rangle_{\rm even} = \frac{|K^0\rangle - |\overline{K}^0\rangle}{\sqrt{2}}$$

[*CP = +1 admixture: decays into* $|\pi\pi\rangle$]

$$|K\rangle_{\rm odd} = \frac{|K^0\rangle + |\overline{K}^0\rangle}{\sqrt{2}}$$

[*CP = -1 admixture: has to decay into* $|\pi\pi\pi\rangle$]

Nécessaire 2: what is ϵ_K

However, the actual physical admixtures are (slightly) different:

$$|K_S\rangle \;\propto\; |K\rangle_{\rm even} + \bar{\epsilon}\,|K\rangle_{\rm odd}$$

$$|K_L\rangle \;\propto\; |K\rangle_{\rm odd} + \bar{\epsilon}\,|K\rangle_{\rm even}$$

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The magnitude of this *CP* violation is accessed experimentally by measuring the amplitude ratios:

$$\eta_{+-} \;=\; \frac{\langle \pi^+\pi^-|K_L\rangle}{\langle \pi^+\pi^-|K_S\rangle} \qquad\qquad \eta_{00} \;=\; \frac{\langle \pi^0\pi^0|K_L\rangle}{\langle \pi^0\pi^0|K_S\rangle}$$

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It turns out that the corresponding types of CP violation can be disentangled by the following quantities:

$$\epsilon_K = \frac{1}{3}\left(\eta_{00} + 2\eta_{+-}\right) \qquad \epsilon' = \frac{1}{3}\left(\eta_{+-} - \eta_{00}\right)$$

"Indirect" CP violation (through mixing)

"Direct" CP violation (directly in the decay)

General formula for ϵ_K

$$\epsilon_K = e^{i\phi_\epsilon} \sin\phi_\epsilon \left(\frac{\mathrm{Im}(M_{12}^K)}{\Delta M_K} + \xi \right)$$

The quantities relevant to this formula are

☞

$$\Delta M_K \equiv m_{K_L} - m_{K_S} \simeq 3.5 \times 10^{-15}\mathrm{GeV}$$

$$\Delta\Gamma_K \equiv \Gamma_{K_L} - \Gamma_{K_S} \simeq -7.4 \times 10^{-15}\mathrm{GeV}$$

Note:

$\Delta\Gamma_K \approx -2\Delta M_K$ → **numerical accident!**

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- $$M_{12}^K \equiv \langle K^0 | \mathcal{H}_{\Delta S=2} | \overline{K}^0 \rangle$$
  Amplitude for *K*-mixing: sensitive to non-SM contributions

- $$\xi \equiv \frac{\mathrm{Im}A_0}{\mathrm{Re}A_0}$$
  with A_0 the amplitude for the decay $K^0 \to \pi\pi$ (0-isospin)

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The formula typically adopted in phenomenology takes

- $\xi \to 0$
- $\phi_\epsilon = 45°$

Since both the deviations of ϕ_ϵ from 45° and ξ from zero are corrections, one can rewrite the general formula for ϵ_K as

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How close is κ_ϵ to unity?

In the Standard Model, we estimated
[See: Buras, DG, PRD08]

$\kappa_\epsilon = 0.92 \pm 0.02$

Note: the corrections from $\xi \neq 0$ AND $\phi_\epsilon \neq 45°$ have like sign.

This accident builds up a **– 8 % total correction!**

How to estimate κ_ϵ

As we saw before,
κ_ϵ is defined by the relation

$$\epsilon_K = \kappa_\epsilon \times \epsilon_K(\xi = 0, \ \phi_\epsilon = 45^\circ) \quad \Rightarrow \quad \kappa_\epsilon = \frac{\sin\phi_\epsilon}{1/\sqrt{2}} \times (1 + \Delta_\epsilon)$$

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- It is dominated by QCD-penguin operator contributions to the process $K \to \pi\pi$, that are very hard to compute directly.

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However, κ_ϵ can be estimated indirectly, through ϵ' / ϵ, using the relation

$$\frac{\epsilon'}{\epsilon} = -\omega\Delta_\epsilon\,(1 - \Omega)$$

- $\omega = Re(A_2)/Re(A_0) = 0.045$ is known very precisely ("$\Delta I = ½$ rule")
- Ω represents (basically) the ratio between EW-penguin and QCD-penguin contributions to ϵ' / ϵ
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$$\Delta_\epsilon = -\frac{1}{\omega(1-\Omega)} \left[\frac{\epsilon'}{\epsilon}\right]_{\exp}$$

$$= -0.061 \pm 0.014$$

Using

- $\epsilon' / \epsilon = (1.66 \pm 0.26) \times 10^{-3}$
- $\Omega = (0.4 \pm 0.1)$ [within the SM]

See the analysis by: **Buras-Jamin, JHEP04**

Consequences of the ϵ_K^{SM} suppression factor

- Once the rest of the input is fixed, the formula for ϵ_K^{SM} allows to predict $\sin 2\beta$, that measures the amount of *CP* violation in the B_d-system.

In particular, the constraint from ϵ_K works as follows

$$|\epsilon_K^{\rm exp}| = |\epsilon_K^{\rm th, SM}| \propto \kappa_\epsilon \times \sin 2\beta$$

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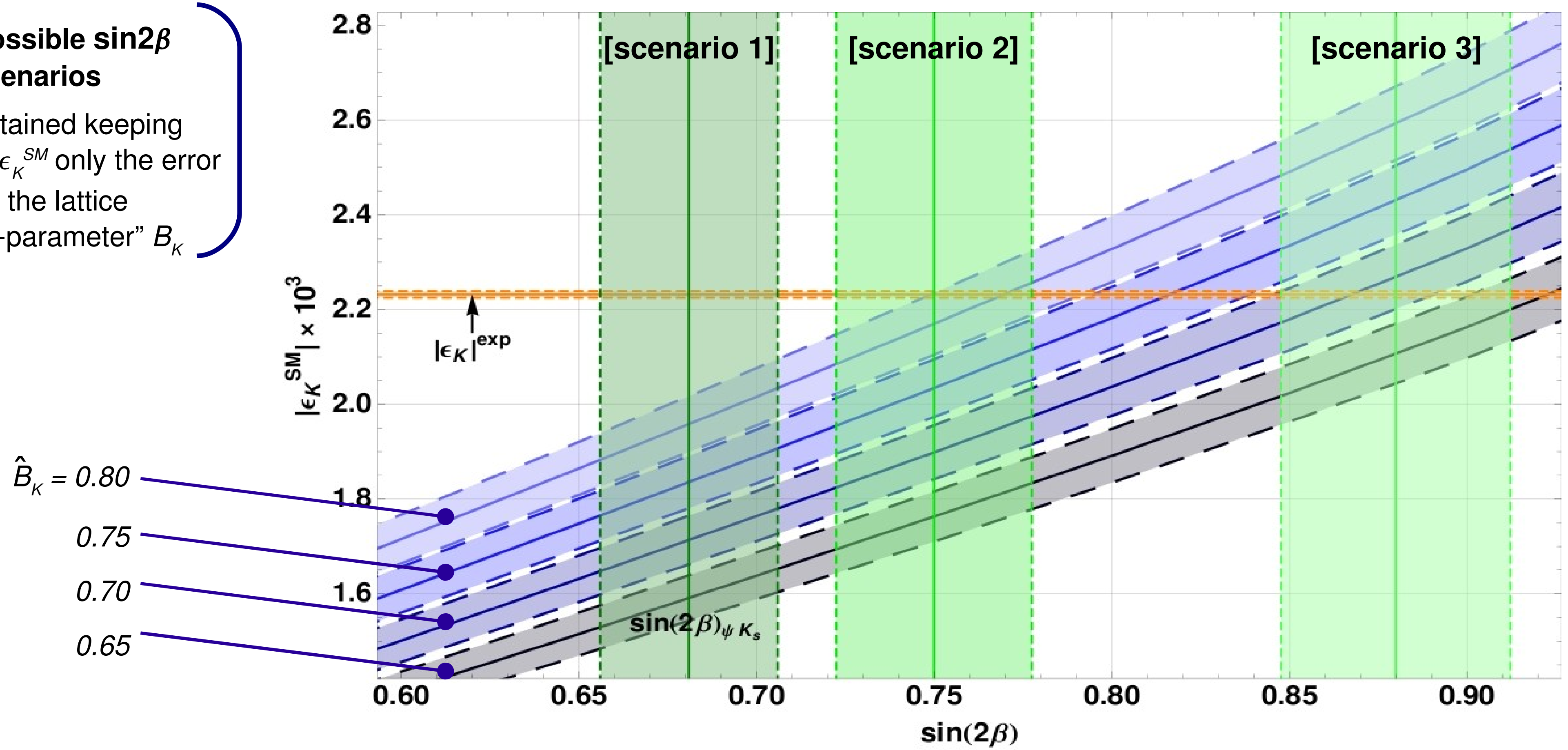
Possible sin2β scenarios

obtained keeping in ϵ_K^{SM} only the error on the lattice "B-parameter" B_K



More on scenario 1:

$\sin 2\beta_{J/\psi\, K_s} = \sin 2\beta$

In this case one gets $|\epsilon_K^{SM}| = (1.78 \pm 0.25) \times 10^{-3}$

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Since the SM formula for ϵ_K goes as

$$|\epsilon_K|^{SM} = [\text{const.fact.}] \times \Big(\underbrace{[\text{CKM}] \cdot S_0(m_t^2/m_W^2)}_{\approx 75\% \text{ of the total}} + \ ... \Big)$$

The simplest solution is a positive shift in the ϵ_K loop function

- *This solution is of MFV type. In fact, the CKM structure is preserved and non-SM physics only enters the short-distance S-function* [Buras et al., 00]

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Barring non-SM operators mediating mixing, the above shift would be universal, i.e. also affect B_d and B_s mass differences (and cancel in their ratio)

By demanding a 10% shift, for ϵ_K to recover 1 sigma agreement with exp, one would get

$$\Delta M_d^{\rm CMFV} \approx (0.638 \pm 20\%)/\text{ps} \quad \text{vs} \quad \Delta M_d^{\rm HFAG} = 0.507(5)\ /\text{ps}$$

$$\Delta M_s^{\rm CMFV} \approx (21.6 \pm 20\%)/\text{ps} \quad \quad \Delta M_s^{\rm HFAG} = 17.77(12)\ /\text{ps}$$

More on scenario 3:

$\sin 2\beta_{J/\psi\ Ks} = \sin 2(\beta + \phi_d)$

See also:
Lunghi, Soni, PLB08

In this case the phase β cannot be accessed directly from the J/ψ K_s mode

One possible strategy to determine β is by using ϵ_K, Δm_d and Δm_s only.

We get: $\sin 2\beta = 0.88^{+0.11}_{-0.12}$

to be compared with $\sin 2\beta_{J/\psi\ Ks} = 0.681 \pm 0.025$

At face value, this allows

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The B_d new-physics phase, negative, may be correlated (even in size) with the negative new phase in B_s hinted at by Fermilab

- HFAG average of CDF and D0 results implies $\phi_s \in [-81, -46]° \cup [-41, -7]°$ (90% CL)

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In spite of the presence of a new phase, the non-SM physics responsible for it does not need to be beyond MFV.

[D'Ambrosio et al., 02]

- *In fact, MFV is the principle of minimal breaking of the SM* $[SU(3)]^5$ *flavor group*

  The assumption that the breaking of the discrete CP symmetry be also minimal is in principle unrelated.

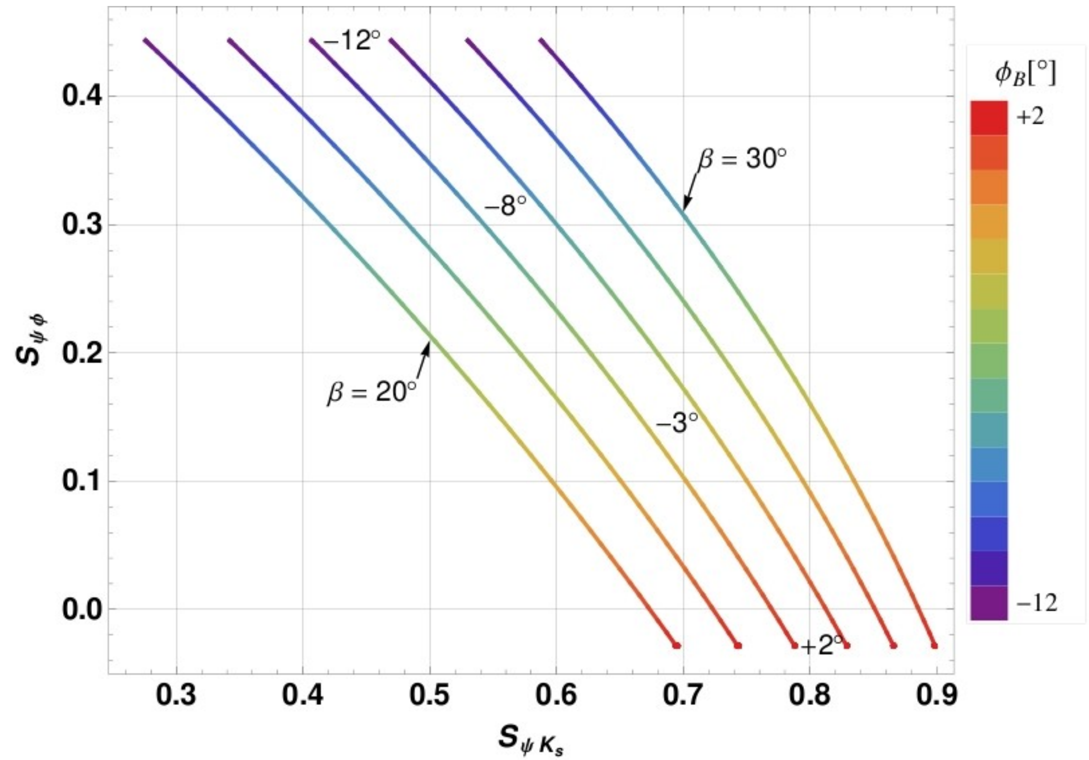
- *However, the question on the predicted amount of CPV is of course highly model-dependent in this case*

More on scenario 3:
The case of $\phi_d \approx \phi_s$

- *What if*

$$\phi_B = \phi_d \approx \phi_s \approx -9^\circ$$

$$\Rightarrow \begin{cases} \beta_{\psi K_s} < \beta \approx 30^\circ \\ S_{\psi\phi} \approx 0.4 \end{cases}$$



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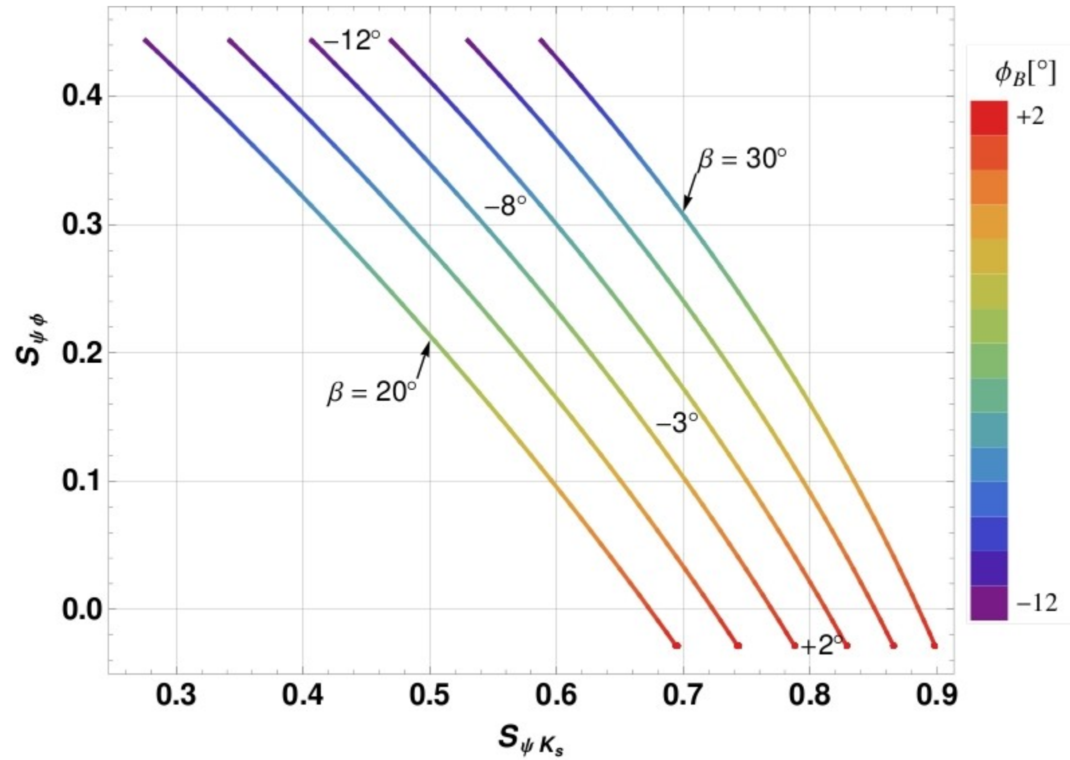

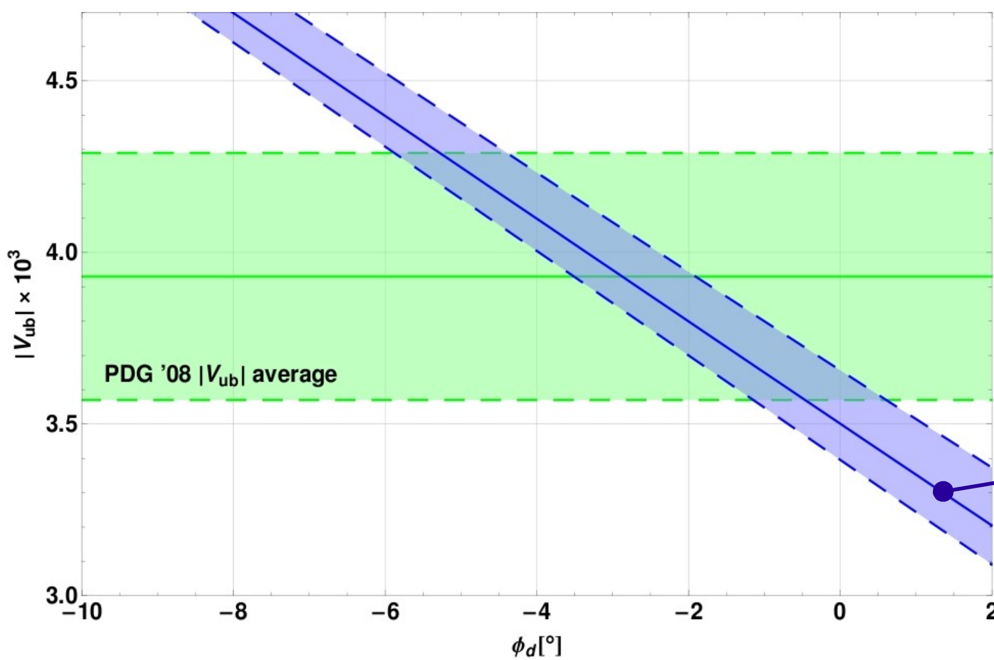

- *A crucial test of this scenario "would come" from* V_{ub}

$|V_{ub}|$ range for the case $\phi_d \approx \phi_s$

How to (more generally) estimate κ_ϵ

We saw that κ_ϵ can be estimated from $[\epsilon'/\epsilon]_{exp}$, the main theoretical input being in Ω

$$\kappa_\epsilon = \frac{\sin\phi_\epsilon}{1/\sqrt{2}} \times (1 + \Delta_\epsilon)$$

$$\Delta_\epsilon = -\frac{1}{\omega(1-\Omega)} \left[\frac{\epsilon'}{\epsilon}\right]_{\rm exp}$$

☞ Note that Ω can be affected by non-SM contributions, because EW penguins are very sensitive to new physics.

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Structure of ϵ'/ϵ

Buras, Lautenbacher, 93
Buras, Jamin, 03

A convenient formula to evaluate ϵ'/ϵ and to understand its structure is provided by

the so-called Penguin-Box expansion $$\epsilon'/\epsilon = {\rm Im}(V_{ts}^* V_{td}) \sum_i P_i \times X_i$$

where

- X_i = Inami-Lim functions
- $P_i = r_i^{(0)} + r_i^{(6)} R_6 + r_i^{(8)} R_8$

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Encode the info on the matrix elements $\langle Q_6 \rangle_0$ and $\langle Q_8 \rangle_2$ with

$$Q_6 = (\bar{s}_\alpha d_\beta)_{V-A} \sum_q (\bar{q}_\beta q_\alpha)_{V+A}$$

leading QCD penguin

$$Q_8 = \frac{3}{2} (\bar{s}_\alpha d_\beta)_{V-A} \sum_q e_q (\bar{q}_\beta q_\alpha)_{V+A}$$

leading EW penguin

How to (more generally) estimate κ_ϵ : continued

Therefore, ϵ'/ϵ has the structure

$$\epsilon'/\epsilon = c_0 + c_6 R_6 + c_8 R_8 = [\epsilon'/\epsilon](\text{NP shifts}, R_6, R_8)$$

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Procedure

- ☑ Evaluate c_0, c_6, c_8, <u>including non-SM contributions</u>, by appropriate shifts of the Inami-Lim functions
- ☑ Take for R_8 the range $R_8 = 1.0 \pm 0.2$ [see analysis by Buras-Jamin, 03]
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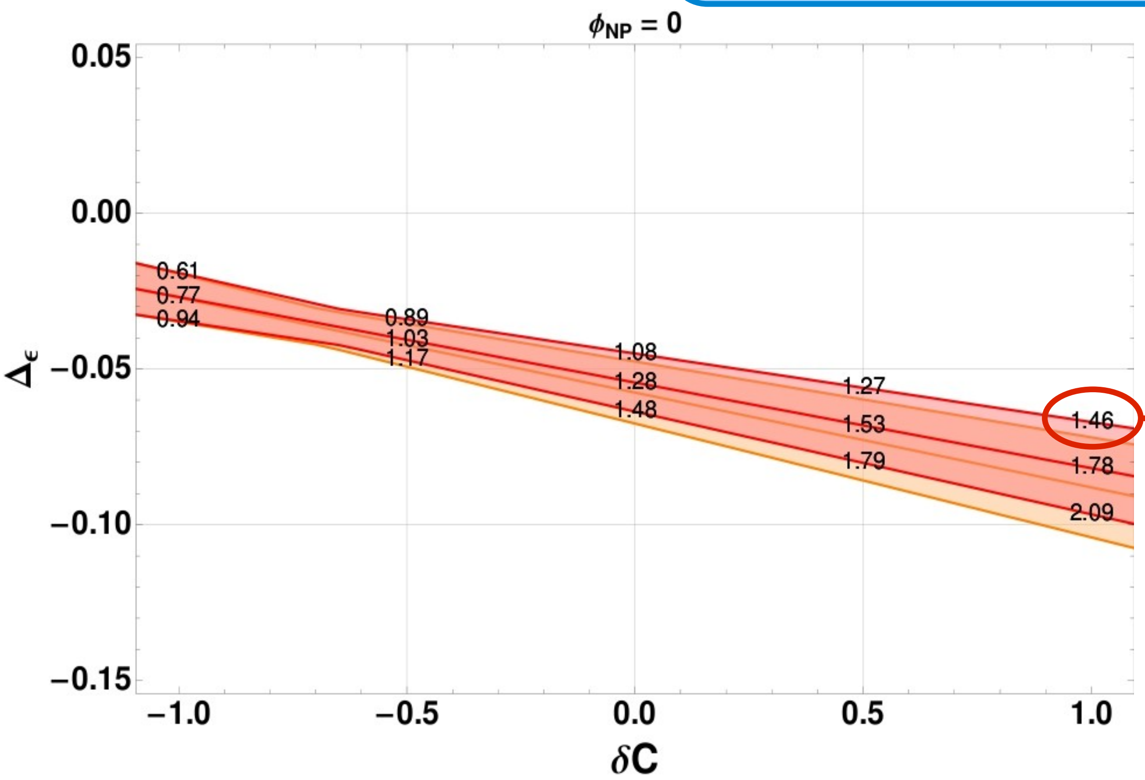
- Estimate R_6 by demanding equality of the above formula with $[\epsilon'/\epsilon]_{exp}$
- Since
  - $c_6 R_6$ has only a $\Delta I = 1/2$ component
  - $c_8 R_8$ has only a $\Delta I = 3/2$ component
  - $-\omega \Delta_\epsilon$ is by definition the sum of the $\Delta I = 1/2$ contributions

it follows that Δ_ϵ can be estimated through $-1/\omega \cdot [\epsilon'/\epsilon](\text{NP shifts}, R_6, R_8 \to 0)$ (with a small caveat on c_0)

More quantitatively:
case of EW-penguin NP phase = 0



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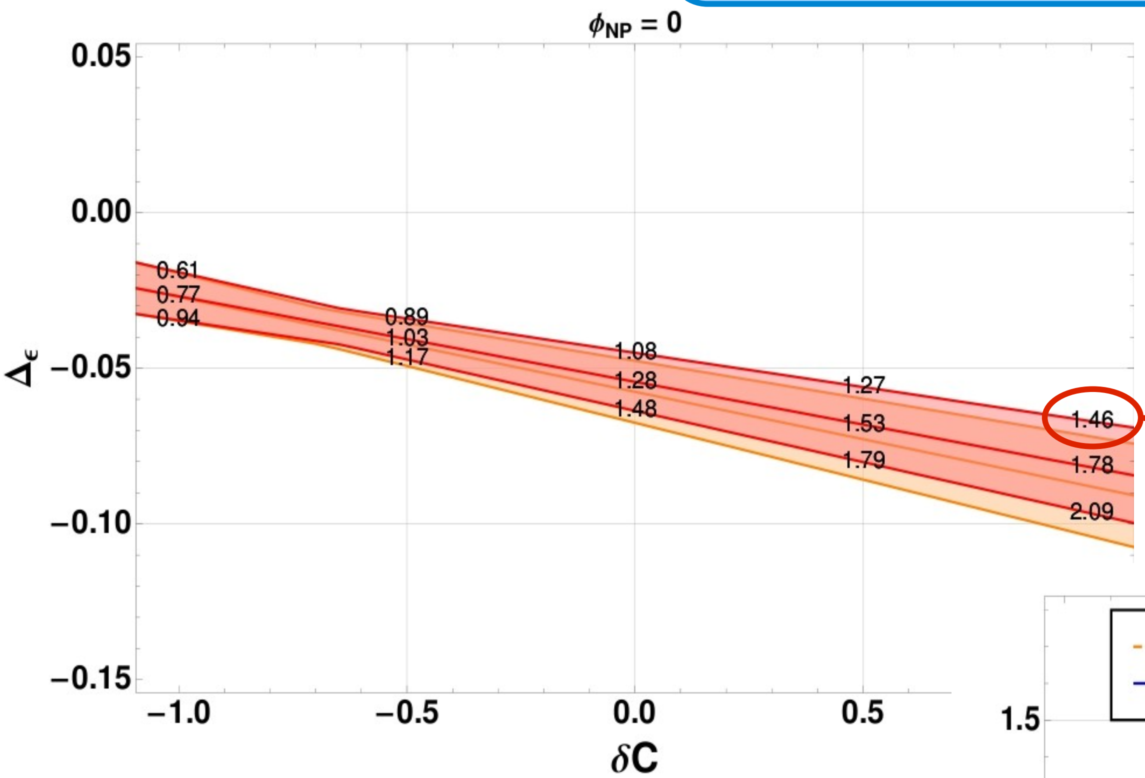

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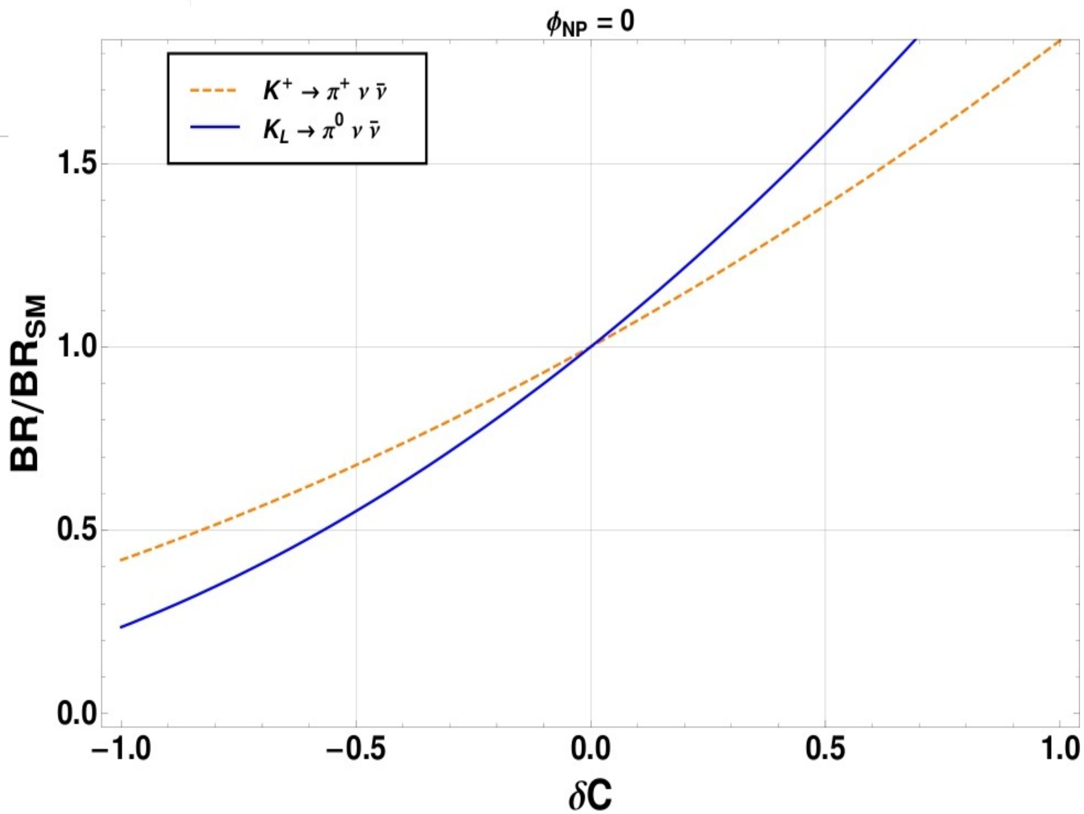
The shift predicts a very defined pattern of enhancement for rare *K* decays



Conclusions

- ☑ *The correlation ϵ_K – $\sin 2\beta$ is a fundamental consistency check of SM CP violation. With regards to CP violation, it is the only one available at present.*

- ☑ *Our analysis shows that a (more) accurate SM formula for ϵ_K implies a – 8% shift in the central value.*

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- ☑ *Reaching firm(er) conclusions about the tension requires improvement in the theoretical input. To get an idea, the leading top-top contribution (≈ 75%) to ϵ_K^{SM} goes as:*

$$|\epsilon_K|^{\rm SM} \propto \kappa_\epsilon \hat{B}_K |V_{cb}|^4 |V_{us}|^2 R_t^2 \sin 2\beta$$

$$\Rightarrow \quad \frac{\delta|\epsilon_K|^{\rm SM}}{|\epsilon_K|^{\rm SM}} \approx \sqrt{\underbrace{\left(\frac{\delta \hat{B}_K}{\hat{B}_K}\right)^2}_{5\%} + \underbrace{\left(4\frac{\delta|V_{cb}|}{|V_{cb}|}\right)^2}_{11\%} + \underbrace{\left(2\frac{\delta R_t}{R_t}\right)^2}_{8\%}} \approx 15\%$$

- ☑ *If the tension becomes an inconsistency, scenarios providing a solution can be searched for already within MFV*