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Estimating ε'/ε in the SM

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- The role of the $\Delta I = 1/2$ selection rule
- Phenomenological approaches: a comparative discussion
- Patterns in hadronic matrix elements
- Effects of a low m_s
- Conclusions

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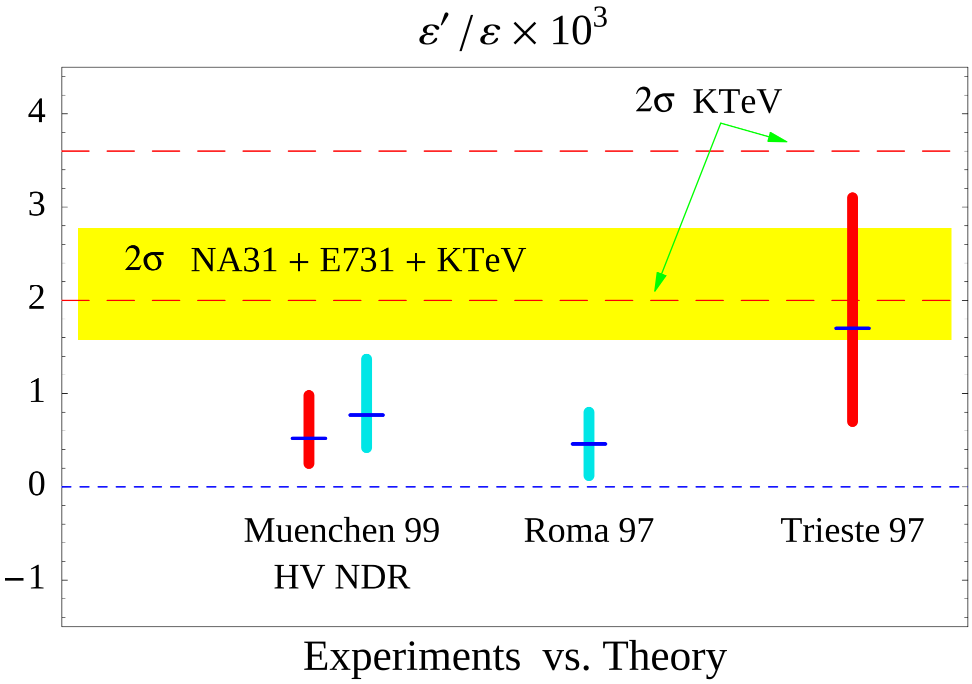
Theory vs. Experiment

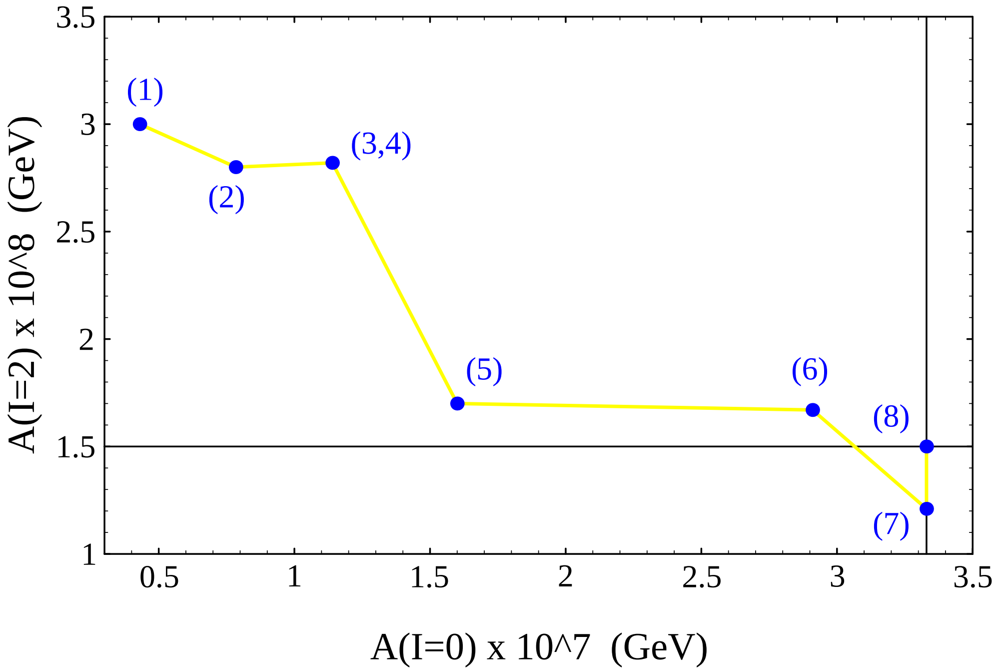


$$\frac{\varepsilon'}{\varepsilon} = \frac{1}{\sqrt{2}}\left\{\frac{\langle(\pi\pi)_{I=2}|\mathcal{H}_W|K_L\rangle}{\langle(\pi\pi)_{I=0}|\mathcal{H}_W|K_L\rangle} - \frac{\langle(\pi\pi)_{I=2}|\mathcal{H}_W|K_S\rangle}{\langle(\pi\pi)_{I=0}|\mathcal{H}_W|K_S\rangle}\right\}$$

The $\Delta I = 1/2$ selection rule in $K \to \pi\pi$ decays

$$\boxed{|\mathcal{A}_0|/|\mathcal{A}_2| = 22.2}$$

Anatomy of the $\Delta I = 1/2$ rule in the χQM



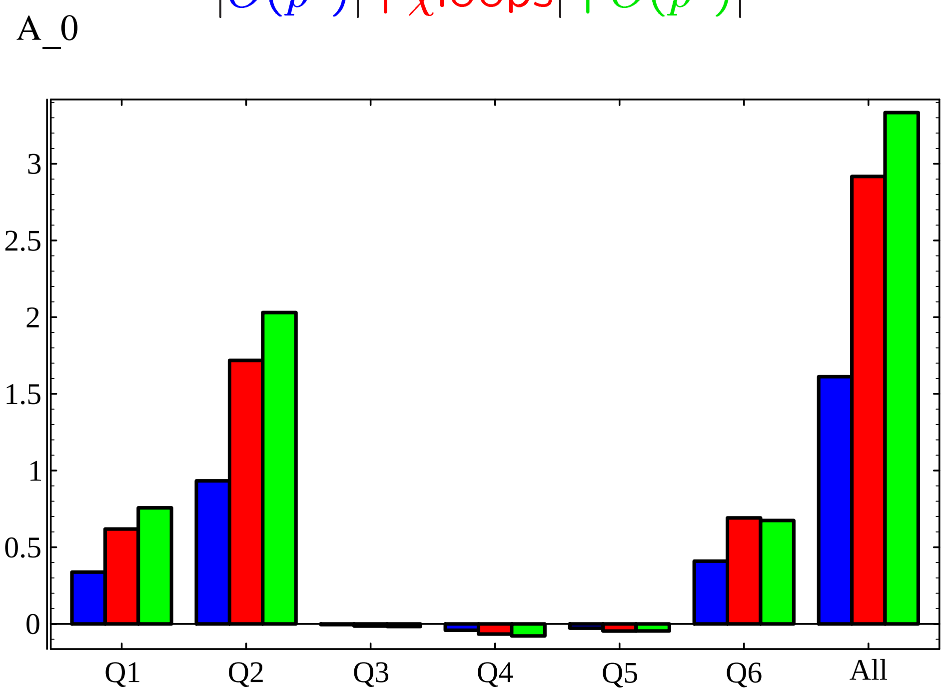
Requiring that the selection rule is reproduced with a 20% accuracy gives

$$\begin{aligned}
\langle \alpha_s GG/\pi \rangle &= (334 \pm 4 \text{ MeV})^4 \\
\langle \bar{q}q \rangle &= -\left(240 \,{}^{+30}_{-10} \text{ MeV}\right)^3 \\
M &= 200 \,{}^{+5}_{-3} \text{ MeV}
\end{aligned}$$

in terms of which ALL matrix elements are computed.

Penguins and $\Delta I = 1/2$ rule

$|O(p^2)| + \chi\text{loops}| + O(p^4)|$



The Q_6 contribution to $A(K \to \pi\pi)_{I=0}$ (in GeV $\times 10^7$) is about 20% of the total !

How does this information feed into the determination of the whole set of $\Delta S = 1$ (and 2) matrix elements ?

Summary of B_i factors

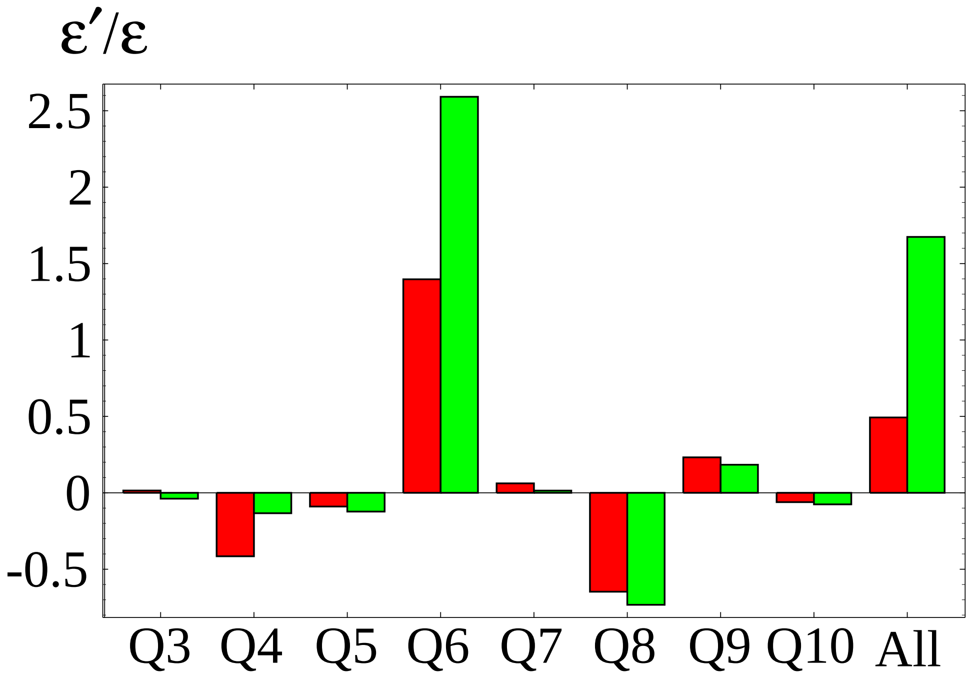
$$B_i^{(0,2)} \equiv |\langle Q_i \rangle_{0,2}^{\text{model}}| / \langle Q_i \rangle_{0,2}^{\text{VSA}}$$

B_i	Muenchen 99 $\mu = 1.3$ GeV	Roma 97 $\mu = 2.0$ GeV	Trieste 97 $\mu = 0.8$ GeV
$B_1^{(0)}$	13 (†)	–	9.5
$B_2^{(0)}$	6.1 ± 1.0 (†)	–	2.9
$B_1^{(2)} = B_2^{(2)}$	0.48 (†)	–	0.41
B_3	1 (*)	1 (*)	-2.3
B_4	5.2 (* †)	$1 \div 6$ (*)	1.9
$B_5 \simeq B_6$	1.0 ± 0.2 (*)	1.0 ± 0.2	1.6 ± 0.3
$B_7^{(0)} \simeq B_8^{(0)}$	1 (*)	1 (*)	2.5 ± 0.1
$B_9^{(0)}$	7.0 (* †)	1 (*)	3.6
$B_{10}^{(0)}$	7.5 (* †)	1 (*)	4.4
$B_7^{(2)}$	1 (*)	0.6 ± 0.1	0.92 ± 0.02
$B_8^{(2)}$	0.8 ± 0.2 (*)	0.8 ± 0.15	0.92 ± 0.02
$B_9^{(2)}$	0.48	0.62 ± 0.10	0.41
$B_{10}^{(2)}$	0.48	1 (*)	0.41
$\hat{B}_K$	0.80 ± 0.15	0.75 ± 0.15	1.1 ± 0.2

(*) educated guess (†) input

ε'/ε: a (Penguin) Comparative Anatomy

|Muenchen|Trieste| $(\times 10^3)$



- $\left\langle Q_{9,10} \right\rangle_2 = \frac{3}{2} \langle Q_1 \rangle_2$: from $\Delta I = 1/2$ rule

- $\langle Q_8 \rangle_2$ moderately smaller than VSA

- Largest deviations: $\langle Q_6 \rangle$ and $\langle Q_4 \rangle$!

$\boxed{\langle Q_4 \rangle}$

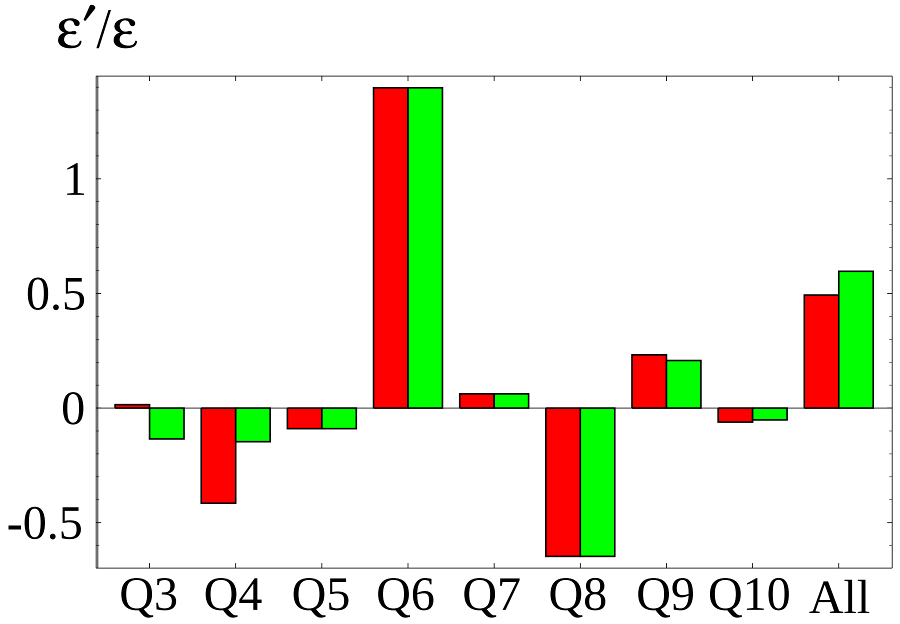
$$\langle Q_4 \rangle = \langle Q_2 \rangle_0 - \langle Q_1 \rangle_0 + \langle Q_3 \rangle \;\Rightarrow$$

$$B_4 = \frac{1}{9} B_2^{(0)} + \frac{5}{9} B_1^{(0)} + \frac{1}{3} B_3$$

The $\Delta I = 1/2$ rule requires a large value of $\langle Q_2 \rangle_0 - \langle Q_1 \rangle_0$. On the other hand that does not necessarily implies a correspondingly large value of B_4 (see the χQM result).

Test $B_4 = O(1)$ in the Muenchen approach:

$$|B_3 = 1 | B_4 = O(1)|$$

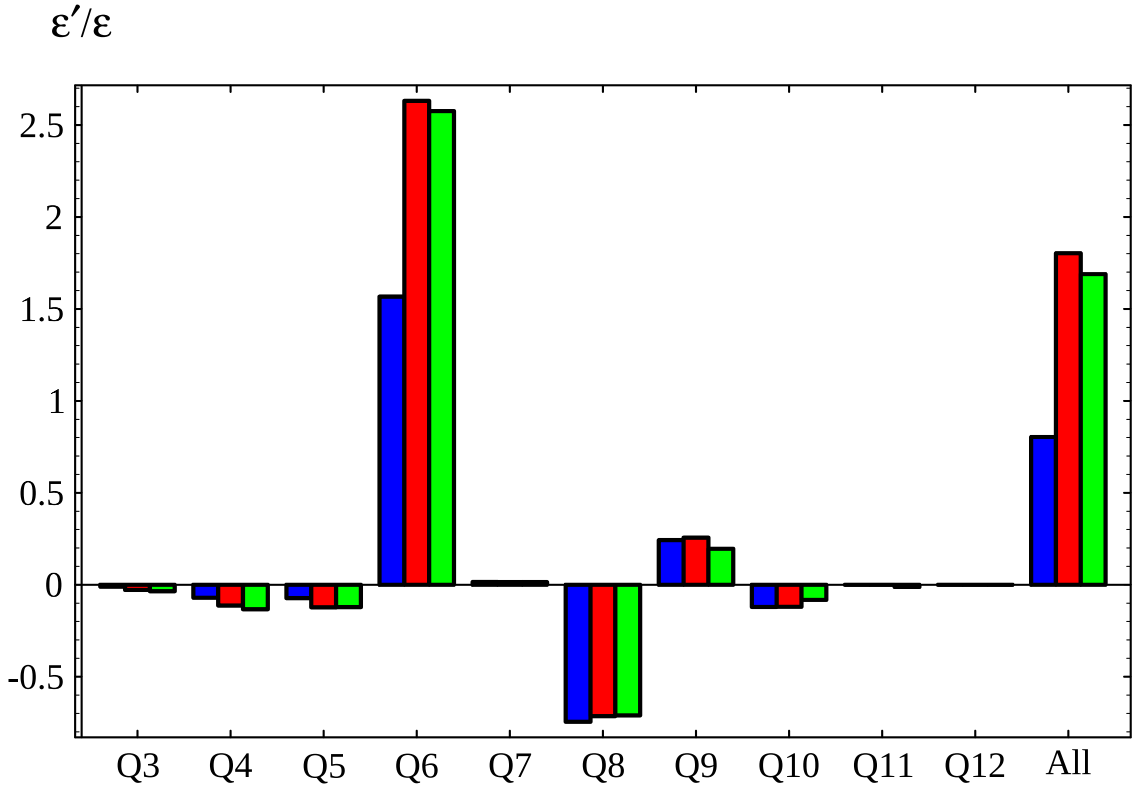


A moderate enhancement (20%) due to the feedback of a large negative B_3 ($\langle Q_2 \rangle_0 - \langle Q_1 \rangle_0$ is larger than in the χQM due to the absence of penguins at $\mu = m_c$.)

$\langle Q_6 \rangle$

ε'/ε in the χQM at $O(p^4)$

$|O(p^2)|+\chi$loops$|O(p^4)|$



At the LO the pattern of hadronic matrix elements would not differ much from other current estimates.

Chiral corrections "concentrate" on $\langle Q_6 \rangle \Rightarrow B_6/B_8^{(2)} \approx 2$ (non-trivial consequence of the $\Delta I = 1/2$ fit !)

Role of NLO order chiral corrections and unquenching in lattice calculations ?

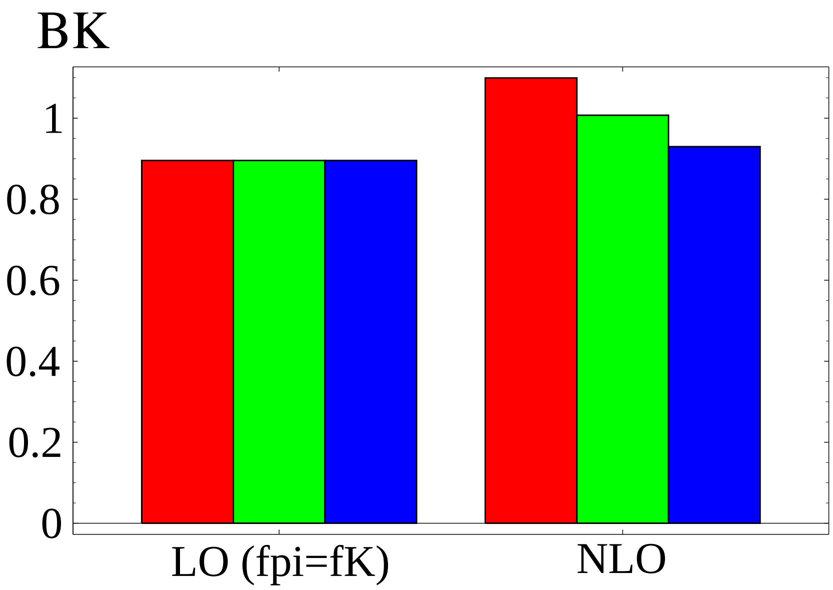
Low m_s and ε'/ε in the χQM

In the Chiral Quark Model approach the explicit dependence on m_s appears at the NLO in the chiral expansion.

Varying the central value of $m_s(m_c)$ from 150 MeV to 130 MeV affects $\langle Q_6 \rangle$ and $\langle Q_8 \rangle$ at the few percent level.

A more sensitive quantity is $\hat{B}_K$

$m_s(m_c)$ |150|130|110| MeV



Varying $m_s(m_c) = 130 \pm 20$ MeV, $\Lambda^{(4)}_{\rm QCD} = 340 \pm 40$ MeV and all relevant paramaters the updated χQM result is:

$$\boxed{\hat{B}_K = 1.0 \pm 0.2}$$

This increases the previous determination of $\mathrm{Im}\,\lambda_t$ by roughly 10% and correspondingly ε'/ε (an update of the ε'/ε estimate with gaussian treatment of experimental inputs is in progress)

Conclusions

- Phenomenological approaches which fit the $\Delta I = 1/2$ selection rule in $K \to \pi\pi$ decays, generally agree in the pattern and size of the $I = 2$ components of the $\Delta S = 1$ hadronic matrix elements with the lattice calculations.

- Concerning the crucial $I = 0$ matrix elements, where lattice calculations presently suffer from large sistematic uncertainties, the $\Delta I = 1/2$ rule forces upon us large deviations from the naive VSA: $B-$factors of $O(10)$ for $\langle Q_{1,2} \rangle_0$!

- In the Chiral Quark Model calculation, the fit of the CP conserving $K \to \pi\pi$ amplitudes, which determines the three basic parameters of the model, feeds down to the penguin sectors showing a substancial enhancement of the Q_6 matrix element, such that $B_6/B_8^{(2)} \approx 2$. This is what leads to the ε'/ε prediction in the 10^{-3} ballpark.

- Up to 40% of the present uncertainty in the ε'/ε prediction arises from the uncertainty in the CKM elements $\text{Im}(V_{ts}^* V_{td})$ which is presently controlled by the $\Delta S = 2$ parameter B_K. A better determination of the unitarity triangle from B-physics is expected from the B-factories and hadronic colliders. From K-physics: $K_L \to \pi^0 \nu \bar{\nu}$ cleanest "theoretical" determination of $\text{Im}\,\lambda_t$.

- It is premature to interpret the present theoretical-experimental "disagreement" on ε'/ε as a signal of physics beyond the SM. A number of ungauged systematic uncertainties affect presently all theoretical estimates. And what about the long-standing puzzle of the $\Delta I = 1/2$ rule? Perhaps an "anomalously" large ε'/ε is the CP violating image of $A_0/A_2 \approx 20$.