Non-leptonic kaon decays, ChPT tests and new physics

Oscar Catà
LMU Munich

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Outline

- $\Delta S = 1$ nonleptonic weak interactions:

  (i) Recent progress in $K \to 2\pi$: $\Delta I = 1/2$ rule, $\frac{\epsilon'}{\epsilon}$.

  (ii) Experimental and theoretical status of $K \to 3\pi$

- $\Delta S = 2$ nonleptonic weak interactions: B_K and ϵ_K.
- New physics searches at low energies.
- Summary and future directions.

hadronic K decays and CP violation: a short primer

- Weak interactions induce mixing between the (strong-eigenstates) $K^0 - \bar{K^0}$. This explains why $K_L \to 3\pi$ and $K_S \to 2\pi$. However, $K_L \to 2\pi$ points at CP violation:

$$K_L = \frac{1}{\sqrt{1+|\tilde{\epsilon}|^2}}(K_2 + \tilde{\epsilon} K_1); \qquad K_{1,2} = \frac{1}{\sqrt{2}}(K^0 \mp \bar{K^0})$$

- Experimentally, access to the amplitudes

$$\eta_{+-} = \frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)}; \qquad \eta_{00} = \frac{A(K_L \to \pi^0\pi^0)}{A(K_S \to \pi^0\pi^0)}$$

- Isospin decomposition: 4 amplitudes into the ratios

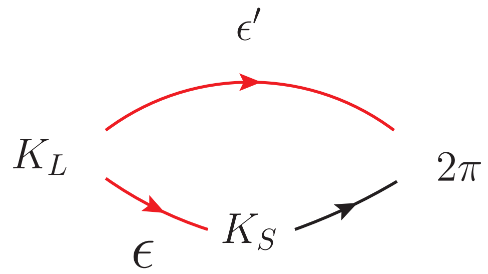
$$\epsilon = \frac{A(K_L \to (\pi\pi)_0)}{A(K_S \to (\pi\pi)_0)}; \quad \omega = \frac{A(K_S \to (\pi\pi)_2)}{A(K_S \to (\pi\pi)_0)}; \quad \chi = \frac{A(K_L \to (\pi\pi)_2)}{A(K_S \to (\pi\pi)_0)}$$

- Link to experimental amplitudes:

$$\eta_{+-} = \epsilon + \epsilon'; \qquad \eta_{00} = \epsilon - 2\epsilon'$$

hadronic K decays and CP violation: a short primer

- Direct and Indirect CP violation parametrized in terms of $\left\{ \epsilon \; ; \; \epsilon' \equiv \frac{\chi - \epsilon \cdot \omega}{\sqrt{2}} \right\}$



- Experimental determinations:

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

- Parameters from PDG:

$$|\eta_{00}| = 2.220(11) \cdot 10^{-3} \qquad |\eta_{+-}| = 2.232(11) \cdot 10^{-3}$$

$$|\epsilon_K| = 2.228(11) \cdot 10^{-3} \qquad \phi_\epsilon = (43.52 \pm 0.05)^\circ$$

$$\mathrm{Re}\left(\frac{\epsilon'}{\epsilon}\right)_K = 1.66(23) \cdot 10^{-3} \qquad \phi_{\epsilon'} = (42.3 \pm 1.5)^\circ$$

hadronic K decays and CP violation: a short primer

- **Indirect CP violation**: Neutral kaon mixing described by the matrix element

$$\mathcal{M}_{21} = \frac{1}{2m_K}\left[\langle \bar{K}^0|H_{eff}^{\Delta S=2}|K^0\rangle + \sum_n \frac{\langle \bar{K}^0|H_{eff}^{\Delta S=1}|n\rangle\langle n|H_{eff}^{\Delta S=1}|K^0\rangle}{m_K - E_n + i\epsilon}\right] \equiv M_{21} - \frac{i}{2}\Gamma_{21}$$

Long and short distances involved.

- Real and imaginary parts correspond to

$$\mathrm{Re}\,\mathcal{M}_{21} \sim \Delta m_K \equiv m_L - m_S$$
$$\mathrm{Im}\,\mathcal{M}_{21} \sim \epsilon_K$$

- $(\Delta S = 1)^2$ piece dominated by $\pi\pi$. Define

$$A(K^0 \to (\pi\pi)_I) = A_I e^{i\delta_I}; \qquad A(\bar{K}^0 \to (\pi\pi)_I) = A_I^* e^{i\delta_I}$$

Then,

$$\Delta m_K \simeq \mathrm{Re}\langle \bar{K}^0|H_{eff}^{\Delta S=2}|K^0\rangle + \mathcal{O}(\Delta S = 1 \times \Delta S = 1)$$
$$\epsilon_K = e^{i\phi_\epsilon}\sin\phi_\epsilon\left[\frac{\mathrm{Im}\langle \bar{K}^0|H_{eff}^{\Delta S=2}|K^0\rangle}{\Delta m_K} + \frac{\mathrm{Im}A_0}{\mathrm{Re}A_0}\right]$$

hadronic K decays and CP violation: a short primer

- **Direct CP violation**:

$$\epsilon' = \frac{i}{\sqrt{2}} e^{i(\delta_2-\delta_0)} \frac{\mathrm{Re}A_2}{\mathrm{Re}A_0} \left[\frac{\mathrm{Im}A_2}{\mathrm{Re}A_2} - \frac{\mathrm{Im}A_0}{\mathrm{Re}A_0} \right]$$

- Theoretical approach:

$$H_{eff}^{\Delta S=1} = \frac{G_F}{\sqrt{2}} \lambda_u \sum_{i=1}^{10} \Big[z_i(\mu) + \tau y_i(\mu) \Big] \mathcal{Q}_i(\mu)$$

$$H_{eff}^{\Delta S=2} = \frac{G_F^2}{4\pi^2} \Big[\lambda_c^2 F_1 + \lambda_t^2 F_2 + 2\lambda_c \lambda_t F_3 \Big] \mathcal{Q}(\mu)$$

At low energies, ChPT is the right tool:

$$H_{eff}^{\Delta S=1} = \frac{G_F}{\sqrt{2}} f_0^4 \lambda_u \left\{ g_8 \mathcal{O}_8 + g_{27} \mathcal{O}_{27} + e^2 g_{ew} \mathcal{O}_{ew} \right\} + \mathrm{NLO}$$

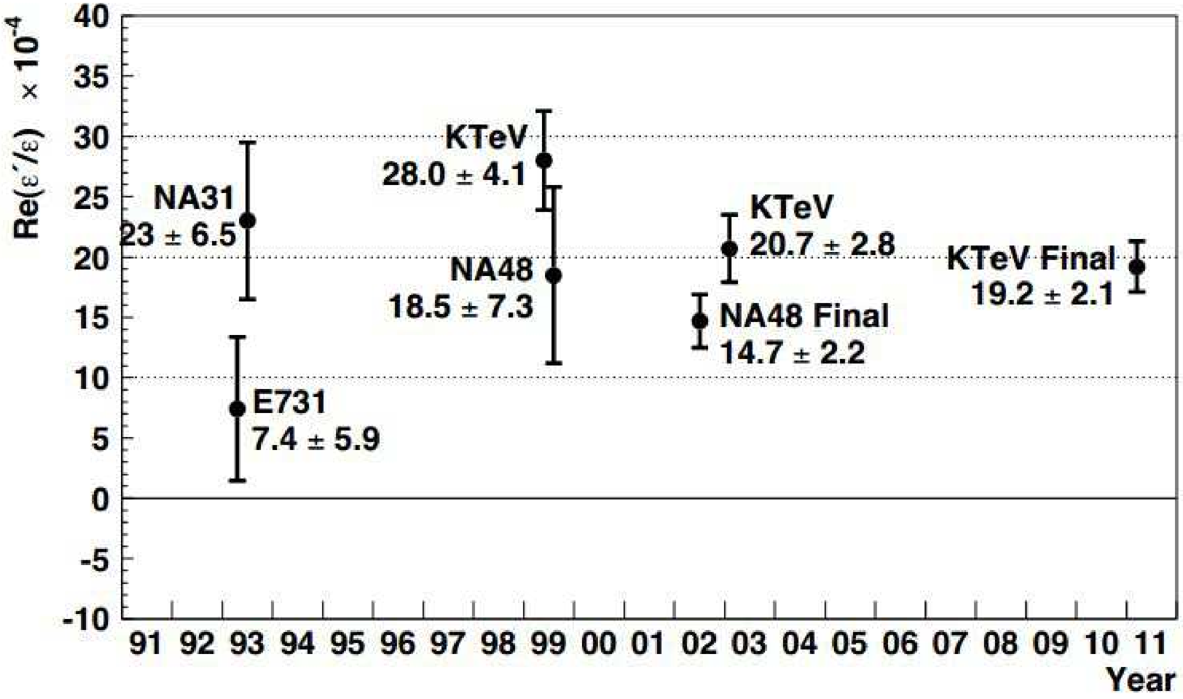
$$H_{eff}^{\Delta S=2} = -\frac{G_F^2}{16\pi^2} f_0^4 g_2 \mathcal{O}_2 + \mathrm{NLO}$$

where

$$\mathcal{O}_8 = \langle L_\mu L^\mu \rangle_{23}; \quad \mathcal{O}_{27} = \langle L_\mu \rangle_{23} \langle L^\mu \rangle_{11} + \frac{2}{3} \langle L_\mu \rangle_{21} \langle L^\mu \rangle_{13}; \quad \mathcal{O}_2 = \langle L_\mu \lambda_{23} L^\mu \lambda_{23} \rangle$$

Direct CP violation in $K_L \to 2\pi$

- Experimentally established after KTeV and NA48 measurements



(figure from E. Worcester)

- Present world average:

$$\mathrm{Re}\left(\frac{\epsilon'}{\epsilon}\right)_K = 1.66(23)\cdot 10^{-3}$$

Direct CP violation in $K_L \to 2\pi$

- Theoretical efforts boil down to an understanding of $\Delta I = 1/2$ rule, Q_6 and Q_8 matrix elements.

$$\epsilon' = \frac{i}{\sqrt{2}} e^{i(\delta_2 - \delta_0)} \frac{\text{Re}A_2}{\text{Re}A_0} \left[\frac{\text{Im}A_2}{\text{Re}A_2} - \frac{\text{Im}A_0}{\text{Re}A_0} \right]$$

- The long-standing $\Delta I = 1/2$ rule puzzle: $\dfrac{\text{Re}A_0}{\text{Re}A_2} \simeq 22.5$, at odds with naive factorization (~ 1).

- Qualitative understanding:

  (i) RG-mixing of current-current operators ($\sim 10\%$)

  (ii) Huge nonperturbative enhancement: Hadronic matrix elements ($\sim 90\%$)

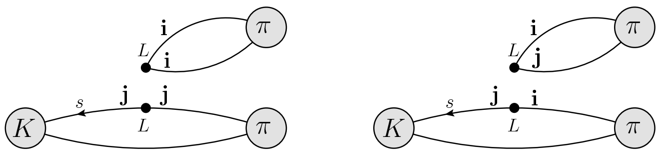
  (iii) Penguin contributions suppressed (penguins do not fly).

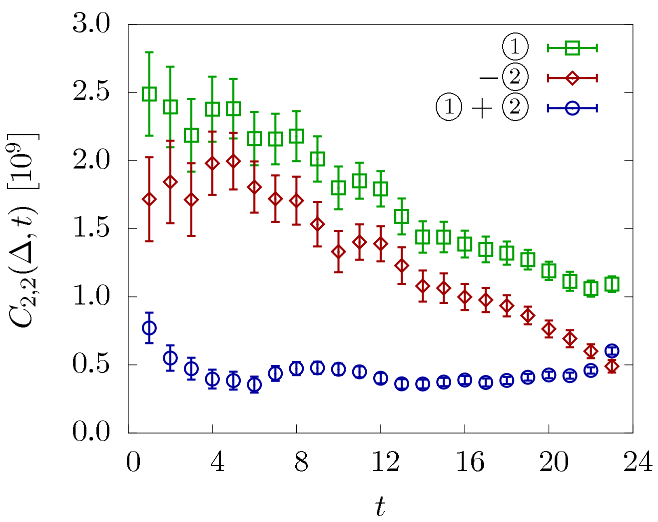
All contributions point in the same direction, but quantitative improvement of hadronic matrix elements is extremely challenging.

$\Delta I = 1/2$ *rule*

- Some progress by combining different nonperturbative methods with the large-Nc expansion [Bardeen et al'87;Bijnens et al'00; Hambye et al'03]. Non-factorizable contributions sizeable and pointing in the right direction. However, we still fall short of a quantitative analytic understanding. Considerable progress but no solid (and competitive) predictions for $\mathrm{Re}(\epsilon'/\epsilon)$.

- Recent progress from the lattice (RBC-UKQCD): accidental cancellations in A_2 [Boyle et al'12] (talk by Norman Christ)





$\Delta I = 1/2$ *rule*

- Cancellation of the effect due to apparent (and dramatic) failure of factorization:

$$t_2 \simeq -0.7 t_1 \qquad vs \qquad t_2 \simeq \frac{1}{3} t_1$$

- A_2 successfully reproduced for physical masses [Blum et al'12]

$$\mathrm{Re}A_2 = 1.381(46)(258)\cdot 10^{-8}\,\mathrm{GeV}; \qquad \mathrm{Im}A_2 = -6.54(46)(120)\cdot 10^{-13}\,\mathrm{GeV}$$

  to be compared to $\mathrm{Re}A_2 = 1.479(4)\cdot 10^{-8}\,\mathrm{GeV}$.

- A_0 more challenging, and so far still at unphysical masses. However, mild mass dependence expected.

	a^{-1} [GeV]	m_π [MeV]	m_K [MeV]	ReA_2 [10^{-8} GeV]	ReA_0 [10^{-8} GeV]	$\frac{\mathrm{Re}A_0}{\mathrm{Re}A_2}$	notes
16^3 Iwasaki	1.73(3)	422(7)	878(15)	4.911(31)	45(10)	9.1(2.1)	threshold calculation
24^3 Iwasaki	1.73(3)	329(6)	662(11)	2.668(14)	32.1(4.6)	12.0(1.7)	threshold calculation
IDSDR	1.36(1)	142.9(1.1)	511.3(3.9)	1.38(5)(26)	-	-	physical kinematics
Experiment	–	135 - 140	494 - 498	1.479(4)	33.2(2)	22.45(6)	

- Overall picture: $\dfrac{\mathrm{Re}A_0}{\mathrm{Re}A_2} \sim \dfrac{2t_2 - t_1}{t_1 + t_2}$, with very small penguin contributions.

- Lattice will soon assemble all the pieces for $\mathrm{Re}(\epsilon'/\epsilon)$.

Indirect CP violation: B_K *and* ϵ_K

- Experimentally,

$$|\epsilon_K| = \left| \frac{A(K_L \to (\pi\pi)_0)}{A(K_S \to (\pi\pi)_0)} \right| = \frac{1}{3}(2|\eta_{+-}| + |\eta_{00}|) = 2.228(11) \cdot 10^{-3}$$

- Theoretically, ϵ_K given by $\Delta S = 2$ box diagrams.

$$\epsilon_K = e^{i\phi_\epsilon} \sin\phi_\epsilon \left[\frac{\mathrm{Im}\langle \bar{K}^0 | H_{eff}^{\Delta S=2} | K^0 \rangle}{\Delta m_K} + \frac{\mathrm{Im} A_0}{\mathrm{Re} A_0} \right]$$

$\mathcal{H}_{eff}^{\Delta S=2}$ given by a single (multiplicatively renormalizable) operator $\mathcal{O}^{\Delta S=2} = (\bar{s}_L \gamma_\mu d_L)(\bar{s}_L \gamma^\mu d_L)$:

$$\mathcal{H}_{\mathrm{eff}}^{\Delta S=2} = \frac{G_F^2 m_W^2}{16\pi^2} \Big[\lambda_c^2 S_0(x_c)\eta_1 + \lambda_t^2 S_0(x_t)\eta_2 + 2\lambda_c\lambda_t S_0(x_c, x_t)\eta_3 \Big] c_i(\mu) \mathcal{O}^{\Delta S=2}(\mu)$$

$$\langle K^0 | \mathcal{O}^{\Delta S=2}(\mu) | \bar{K^0} \rangle = \frac{8}{3} f_K^2 m_K^2 B_K(\mu)$$

- Latest theoretical result (NNLO) [Brod et al'10]

$$|\epsilon_K| = 1.90(26) \cdot 10^{-3}$$

Compared to experiment, it falls a bit short.

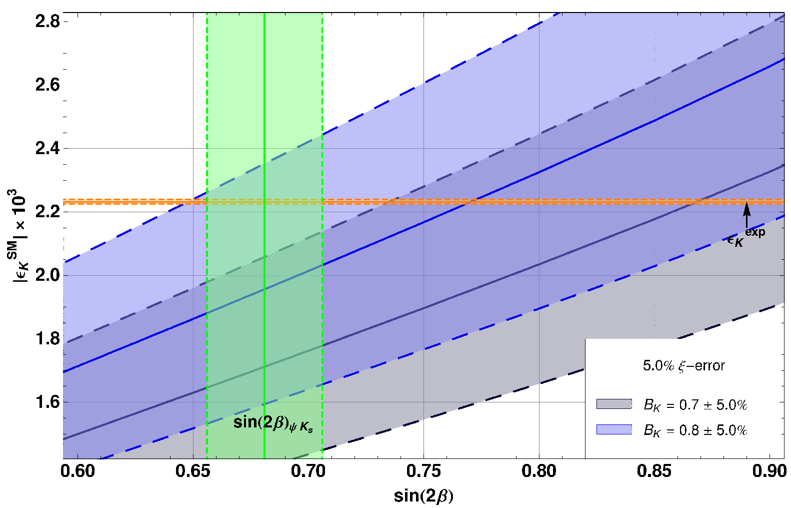
Nonperturbative contributions and new physics

New CP violation phases? Tension between K and B systems [Buras et al'10]

$$\epsilon_K = e^{i\phi_\epsilon}\sin\phi_\epsilon\left[\frac{\mathrm{Im}M_{12}}{\Delta m_K}+\rho\frac{\mathrm{Im}A_0}{\mathrm{Re}A_0}\right]\equiv\kappa_\epsilon\frac{e^{i\phi_\epsilon}}{\sqrt{2}}\left[\frac{\mathrm{Im}M_{12}}{\Delta m_K}\right]$$

Subleading long-distance effects considered in ϵ_K. Overall effect in terms of a prefactor $\kappa_\epsilon \sim 0.92(2)$. This combined with lower values of B_K would require a slightly too large $\sin 2\beta$, which would 'conflict' with B_s data. New phases, *e.g.* $S_{\psi K_s} = \sin(2\beta + 2\phi_d)$?

$$|\epsilon_K| \sim \kappa_\epsilon f_K^2 \hat{B}_K |V_{cb}|^4 \xi_s^2 \frac{C_s}{C_d}\sin 2\beta$$



Nonperturbative contributions and new physics

- The effect should however be smaller once long-distances in the dispersive part are included [Bijnens et al'91].

$$\epsilon_K = e^{i\phi_\epsilon} \sin\phi_\epsilon \left[\frac{\mathrm{Im} M_{12}}{\Delta m_K} + \rho \frac{\mathrm{Im} A_0}{\mathrm{Re} A_0} \right]$$

$$\rho = 1 \ \ \text{(only absorptive)}; \qquad \rho = 0.6(3) \ \ \text{(dispersive included)}$$

In the end one finds [Buras et al'10]

$$\kappa_\epsilon = 0.94(2)$$

- The effect is reduced (less compelling for NP scenarios) but the important message is that (subleading) long-distance effects are relevant at the present precision. In particular [Blum et al'12]

$$(\kappa_\epsilon)_{\mathrm{abs}} = 0.924(6)$$

Good handle on κ_ϵ.

Determination of B_K (analytical methods)

- Naive estimates:

$$B_K^{VS} = 1; \qquad B_K^{N_c,p^2} = 0.75$$

- Computations beyond factorization ($1/N_c$ corrected, scale-sensitive):

$$B_K = 0.70(10)$$

[Bardeen et al'87]

- Not fully clarified: Triple expansion $\mathcal{O}(p^n, m, 1/N_c)$ with tricky features: $\mathcal{O}(1/N_c)$ sizeable and negative, $\mathcal{O}(p^4)$ sizeable and positive.

- Most worrisome, from chiral symmetry [Donoghue et al'82]

$$B_K^{\chi} = \frac{5}{4} g_{27} \sim 0.37$$

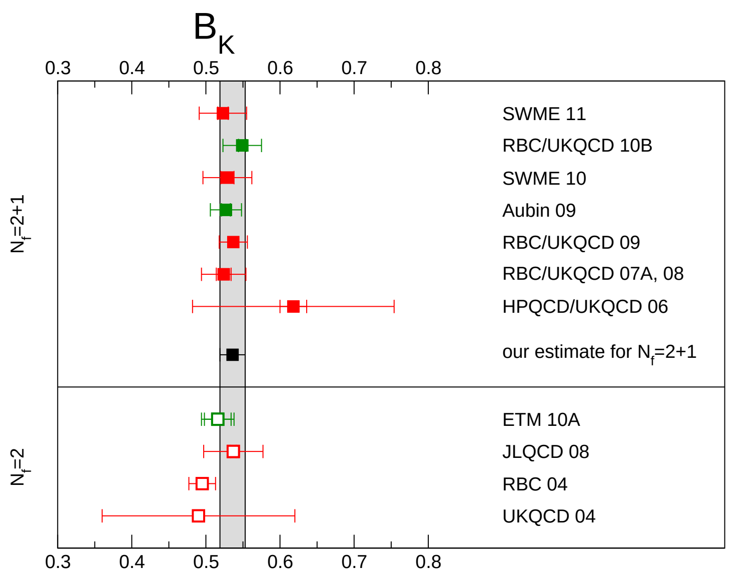
Understood at $\mathcal{O}(p^4, 0, 1/N_c)$ [Bijnens et al'95,06; Peris et al'01; O.C. et al'03]. Huge chiral corrections not fully understood. Theoretical rollercoaster...

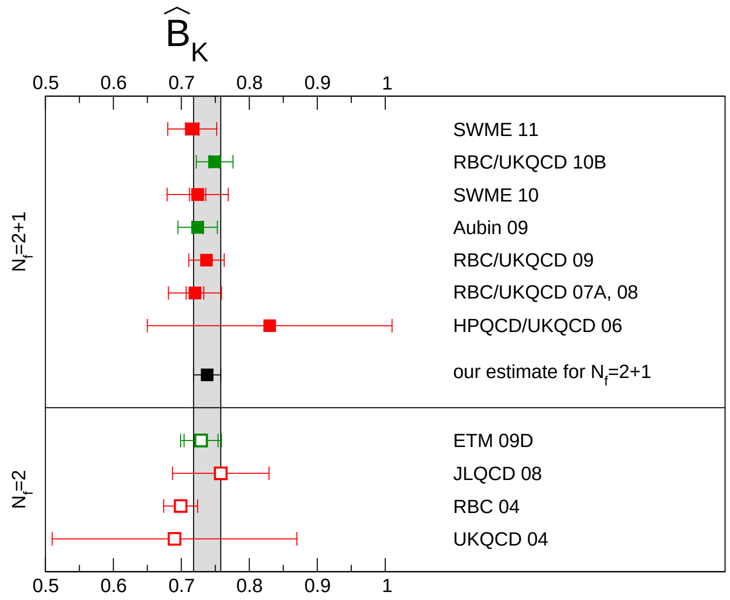
Determination of B_K (lattice QCD)

Collaboration	Ref.	N_f	publication status	continuum extrapolation	chiral extrapolation	finite volume	renormalization	running	B_K	$\hat{B}_K$
SWME 11	[281]	2+1	P	★	●	●	■	–	0.523(7)(26)	0.716(10)(35)
RBC/UKQCD 10B	[282]	2+1	P	●	●	★	★	a	0.549(5)(26)	0.749(7)(26)
SWME 10	[283]	2+1	A	★	●	●	■	–	0.529(9)(32)	0.724(12)(43)
Aubin 09	[269]	2+1	A	●	★□	●	★	–	0.527(6)(21)	0.724(8)(29)
RBC/UKQCD 07A, 08	[108, 284]	2+1	A	■	●	★	★	–	0.524(10)(28)	0.720(13)(37)
HPQCD/UKQCD 06	[285]	2+1	A	■	●*	★	■	–	0.618(18)(135)	0.83(18)
ETM 10A	[286]	2	A	★	●	●	★	b	0.516(18)(12)	0.729(25)(17)
JLQCD 08	[280]	2	A	■	●	■	★	–	0.537(4)(40)	0.758(6)(71)
RBC 04	[287]	2	A	■	■	■†	★	–	0.495(18)	0.699(25)
UKQCD 04	[288]	2	A	■	■	■†	■	–	0.49(13)	0.69(18)

[FLAG'11] (details on Jack Laiho's talk)

FLAG averages (2011):





$$N_f = 2+1: \qquad B_K^{\overline{\rm MS}}(2{\rm GeV}) = 0.536(17) \qquad \hat{B}_K = 0.738(20)$$

$$N_f = 2: \qquad B_K^{\overline{\rm MS}}(2{\rm GeV}) = 0.516(18)(12) \qquad \hat{B}_K = 0.729(25)(17)$$

Status of $K \to 3\pi$ decays

- General decomposition (dominant octet contributions): [Devlin et al'78]

$$\begin{aligned}
\mathcal{M}(K_L \to \pi^+\pi^-\pi^0) &= \alpha_1 - \beta_1 u + (\zeta_1 + \xi_1)u^2 + \frac{1}{3}(\zeta_1 - \xi_1)v^2 \ , \\
\mathcal{M}(K_L \to \pi^0\pi^0\pi^0) &= -3\alpha_1 - \zeta_1(3u^2 + v^2) \ , \\
\mathcal{M}(K^+ \to \pi^+\pi^+\pi^-) &= 2\alpha_1 + \beta_1 u + (2\zeta_1 - \xi_1)u^2 + \frac{1}{3}(2\zeta_1 + \xi_1)v^2 \ , \\
\mathcal{M}(K^+ \to \pi^+\pi^0\pi^0) &= -\alpha_1 + \beta_1 u - (\zeta_1 + \xi_1)u^2 - \frac{1}{3}(\zeta_1 - \xi_1)v^2
\end{aligned}$$

where

$$u = \frac{s_3 - s_0}{m_\pi^2} \ , \qquad v = \frac{s_1 - s_2}{m_\pi^2} \ , \qquad s_i = (p_K - p_{\pi_i})^2 \ , \qquad s_0 = \frac{1}{3}\sum_{i=1}^{3} s_i$$

- $K \to 3\pi$ amplitudes computed to NLO in [Kambor et al'91] and recomputed in [Bijnens et al'03-05] including isospin and electromagnetic corrections.

Counterterms in $K \to 3\pi$

$$
\begin{aligned}
\alpha_1 &= \alpha_1^{(0)} - \frac{2g_8}{27 f_K f_\pi} m_K^4 \left\{ (k_1 - k_2) + 24\mathcal{L}_1 \right\} \;, \\
\beta_1 &= \beta_1^{(0)} - \frac{g_8}{9 f_K f_\pi} m_\pi^2 m_K^2 \left\{ (k_3 - 2k_1) - 24\mathcal{L}_2 \right\} \;, \\
\zeta_1 &= -\frac{g_8}{6 f_K f_\pi} m_\pi^4 \left\{ k_2 - 24\mathcal{L}_1 \right\} \;, \\
\xi_1 &= -\frac{g_8}{6 f_K f_\pi} m_\pi^4 \left\{ k_3 - 24\mathcal{L}_2 \right\}
\end{aligned}
$$

- Structure of the counterterms:

$$
\begin{aligned}
&\mathcal{L}_1 = \mathcal{L}_2 + 3L_2 = 2L_1 + 2L_2 + L_3 \\
&k_1 = 9(-N_5 + 2N_7 - 2N_8 - N_9) \\
&k_2 = 3(N_1 + N_2 + 2N_3) \\
&k_3 = 3(N_1 + N_2 - N_3)
\end{aligned}
$$

strong amplitudes with weak external vertices and direct weak terms.

- Including corrections, good overall fit to data. [Bijnens et al'05]

Counterterms in $K \to 3\pi$

- Theoretical calculations with factorization models [Isidori et al'91,Ecker et al'92, D'Ambrosio et al'97]. Main idea: same underlying physics (resonance exchange) dominates both strong and electroweak LECs. This leads to relations between N_i and L_i and makes the electroweak sector predictable.

- Main results:

  (i) k_1 dominated by scalar meson sector.

  (ii) k_2, k_3 affected by vector meson exchange:

$$k_2 = 24\mathcal{L}_1 \ ,$$
$$k_3 = 24\left(\mathcal{L}_2 + \frac{3}{4}L_9\right)$$

  (iii) Strong cancellations between strong and weak diagrams.

- Puzzle: failure of vector meson dominance: $k_2 = 0 = k_3$ identically cancelled, in contradiction with fits to experimental data.

Counterterms in $K \to 3\pi$

- Skyrme structure of the $\mathcal{O}(p^4)$ Lagrangian dictates

$$k_2 = 0; \qquad k_3 = 24\left(L_3 + \frac{3}{4}L_9\right)$$

which entails the predictions $\alpha_1^V = \zeta_1 = 0$ and $\beta_1, \xi_1 \sim (k_3 - 24L_3)$.

- Experimentally, $\zeta_1 \sim 0$ but $\beta_1, \xi_1 \neq 0$ (charged and neutral channels). Final state interactions still a problem, but $k_3 \sim 5 \cdot 10^{-9}$ seems plausible.
- Failure of VMD not generic but a model-dependent artifact [Cappiello et al'12]

$$L_3 = -\frac{3}{4}L_9 \qquad\qquad k_3 = 0$$

$$L_3 = -\frac{11}{24}L_9 \qquad\qquad k_3 \sim 3 \cdot 10^{-9}$$

- **CP violation in $K \to 3\pi$ decays**

(i) Direct CP violation: theory ahead of experiment. Predicted slope asymmetries [Gámiz et al'03] one order of magnitude smaller than NA48/2 (so far compatible with no signal).

(ii) Indirect CP violation: New bound from KLOE[Talk by Patrizia De Simone]

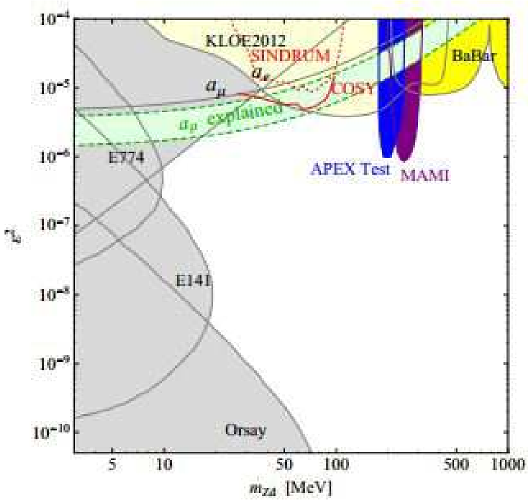
$$\mathrm{Br}(K_s \to 3\pi^0) < 2.8 \cdot 10^{-8} \qquad (\mathrm{SM\ at\ } 1.9 \cdot 10^{-9})$$

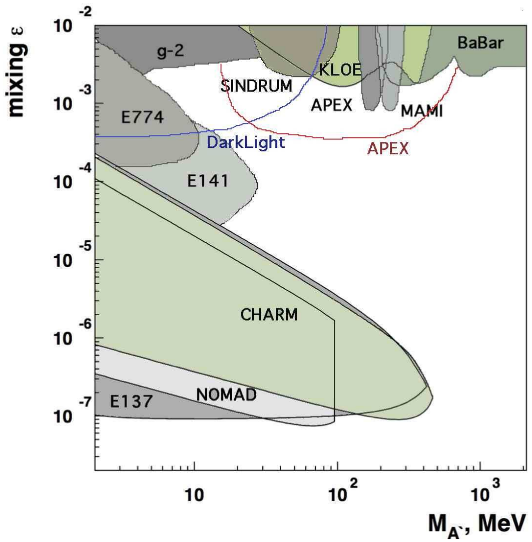
New physics searches at low energies

- Light dark matter, dark photons, dark light, A', U boson... Coming from Dark sector connected to the SM through an extra $U(1)_D$ (massless or massive)

$$\mathcal{L} = \frac{\epsilon}{2} F^D_{\mu\nu} F^{\mu\nu}$$

- Possible origin of anomalies in astrophysical observations and $(g-2)_\mu$. Ubiquitous in BSM extensions.
- Suited for kaon experiments: low-energy search in radiative processes. (talks by M. Moulson and S. Strauch). KTeV-E779, TREK, NA62, KLOE (K decays or pion tagging).





[Davoudiasl et al'13, Gninenko'13]

Conclusions

- $K \to 2\pi$:

  (i) $\mathrm{Re}(\epsilon'/\epsilon)$: experiment ahead of theory.

  (ii) Silver lining: remarkable progress in the quantitative understanding of the $\Delta I = 1/2$ rule (RBC-UKQCD). Determination of $\mathrm{Re}(\epsilon'/\epsilon)$ in coming years feasible.

  (iii) ϵ_K: with inclusion of nonperturbative effects and NNLO perturbative corrections, $|\epsilon_K|_{exp} > |\epsilon_K|_{th}$.

- $K \to 3\pi$:

  (i) CP conserving part well fitted by ChPT expressions.

  (ii) Alleged failure of VMD to saturate the counterterms understood.

  (iii) CP violation: direct (slope asymmetries so far compatible with 0), indirect (too small to be detected).