Rare decays and CP violation in systems of *B* and *K* mesons

Christoph Bobeth
TU Munich

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Outline

- Motivation
- $B_{s,d} \to \mu\bar{\mu}$ and $B_{s,d}$-mixing
- $K \to \pi\nu\bar{\nu}$, ε_K and ε'/ε

→ only Standard Model: CKM from FCNCs

→ recent developments in theory (lattice, perturbation theory)

→ experimental situtation

Motivation for FCNC processes

SM-CPV in quark flavour sector given by CKM mechanism $\Rightarrow$ only 4 parameters: $\lambda, A, \bar{\rho}, \bar{\eta}$

CC decays = tree	$\Leftrightarrow$	FCNC decays = loop
$V_{ud,us}, V_{cd,cs}, V_{ub,cb}$		V_{td}, V_{ts}, V_{tb}

Consistency tests of SM CKM paradigm

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Consistency tests of SM CKM paradigm

Determination of $V_{td,ts,tb}$ in FCNC decays require **high control of hadronic input** for theory

!!! Lattice (QCD) calculations provide only **simple hadronic quantities** f_{B_q}, B_K, B_{B_q}, $F_{B\to K}(q^2)$

$\Rightarrow$ only a few $s \to d$, $b \to d$, s FCNC processes with accuracy at **percent level**

- leptonic $B_{s,d} \to \ell\bar{\ell}$ ($K_{L,S} \to \ell\bar{\ell}$ suffers from long-distance contributions)
- semi-leptonic $K^+ \to \pi^+\nu\bar{\nu}$ and $K_L \to \pi^0\nu\bar{\nu}$ future: $B \to K^{(*)}\nu\bar{\nu}$
- mass differences of neutral $B_{d,s}$: $\Delta M_{d,s}$
- ε_K

??? conceptually very challenging to go below 1% hadronic uncertainty

$\Rightarrow$ requires **control over QED effects** (virtual, real, Coulomb)

$B_{s,d} \to \ell\bar{\ell}$ – theory status

Branching ratio ($q = d, s$)

$$Br(B_q \to \ell\bar{\ell}) \propto \left(\frac{2m_\ell}{m_{B_q}}\right)^2 \times \boxed{|V_{tb}V_{tq}^*|^2} \boxed{\left(f_{B_q}^{(0)}\right)^2} \times \left|\boxed{\mathcal{A}_{\text{LO}}} + \frac{\alpha_e}{4\pi}\boxed{\mathcal{A}_{\text{NLO}}}\right|^2$$

- helicity suppression
- **CKM** to be determined
- ***B_q* decay constant** in pure QCD from lattice $f_{B_{u,d}} = (189.4 \pm 1.4)$ MeV $f_{B_s} = (230.7 \pm 1.2)$ MeV
  [FNAL/MILC 1712.09262]
- **LO amplitude** $\propto C_{10}$ at NNLO QCD & NLO EW
  [Hermann/Misiak/Steinhauser 1311.1347, CB/Gorbahn/Stamou 1311.1348]
- **NLO QED amplitude** $\propto C_{7,9}^{\text{eff}}$!!! restricted to $\ell = \mu$, assuming $m_\mu \sim \Lambda_{\text{QCD}}$

$\Rightarrow$ power-enhanced m_b/Λ_{QCD} from spectator-quark dynamics [Beneke/CB/Szafron 1708.09157]

$\Rightarrow$ factorization in SCET$_{1+2}$ and resummation between $\mu \sim m_b \to \mu \sim m_\mu, \Lambda_{\text{QCD}}$

+ $f_{B_q}^{(0)}$ sufficient for power-enhanced $\mathcal{A}_{\text{NLO}}$, beyond new $f_{B_q}^{(n)}$ required

+ combination with soft real-radiation for $\Delta E \ll m_\mu, \Lambda_{\text{QCD}}$ [Beneke/CB/Szafron 1908.07011]

$B_s \to \mu\bar{\mu}$ – uncertainty budget

Non-radiative rate time-integrated, use $|V_{cb}|_{\text{incl}}$ [Beneke/CB/Szafron 1908.07011]

$N_f = 2 + 1 + 1$ [FLAG 1902.08191]

$$\overline{\text{Br}}^{(0)}_{s\mu} = 3.660 \left(1 \pm 1.1\%\big|_{f_{B_s}} \pm 3.1\%\big|_{\text{CKM}} \pm 1.1\%\big|_{m_t} \pm 0.6\%\big|_{\text{pmr}} \pm 1.2\%\big|_{\text{non-pmr}} {}^{+0.3}_{-0.5}\%\big|_{\text{LCDA}}\right) \cdot 10^{-9}$$

- **main parametric** long-distance (f_{B_q}) and short-distance (CKM and m_t)
- **non-QED:** parametric (Γ_q, α_s) and non-parametric (μ_W, μ_b and higher order)
- ***B*-meson LCDA:** λ_B and $\sigma_{1,2}$ entering power-enhanced QED crr'n

World average: $\overline{\text{Br}}^{(0)}_{s\mu}\big|_{\text{exp}} = \left(2.67^{+0.45}_{-0.35}\right) \cdot 10^{-9}$ [Aebischer et al. 1903.10434: LHCb, CMS, ATLAS Run 1+2]

[see talk by Aidan Grummer]

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Sensitivity to $|V_{tb}V^*_{ts}|$ with $N_f = 2+1+1$ & assuming **LHCb:** 4% uncertainty with 300/fb

[A. Puig @ LHCb Upgrade WS, LAPP, Annecy, 03/2018, LHCb 1208.3355]

$$\delta\overline{\text{Br}}^{(0)}_{s\mu}\Big|_{\text{theory}} \approx 2.1\% \quad + \quad \delta\overline{\text{Br}}^{(0)}_{s\mu}\Big|_{\text{LHCb 300/fb}} \approx 4.0\% \quad \Rightarrow \quad \delta\left|V_{tb}V^*_{ts}\right| \approx 2.5\%$$

for comparison from $b \to c\ell\bar{\nu}_\ell$: $\delta|V_{cb}|_{\text{incl}} = 1.5\%$ [Gambino/Healey/Turczyk 1606.06174]

[see talks by Nico Gubernari and Mirco Dorigo →] $\delta|V_{cb}|_{\text{excl}} = 2.2\%$ [Bordone/Jung/van Dyk 1908.09398]

$\Delta M_{s,d}$ – Mass difference of neutral B_q-mesons

$$\Delta M_q \;\propto\; \boxed{\left|V_{tb} V_{tq}^*\right|^2} \; \boxed{\left(f_{B_q}^{(0)}\right)^2 B_{B_q}} \times \boxed{\hat{\eta}_B S_0(x_t)}$$

- **CKM** to be determined
- **$|\Delta B| = 2$ matrix element** as (decay constant) $\times$ (bag factor)
- **short-distance** $\propto \hat{\eta}_B S_0(x_t)$ including NLO QCD & NLO EW

[Buras/Jamin/Weisz NPB347(1990)491, Gambino/Kwiatkowski/Pott hep-ph/9810400]

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⇒ from Lattice first high-precision B_{B_q} [FNAL/MILC 1602.03560, RBC/UKQCD 1812.08791, HPQCD 1907.01025]

⇒ averages from several Lattice and Sum rule results [Di Luzio/Kirk//Rauh 1909.11087]

⇒ udpated predictions [Lenz/Tetlalmatzi-Xolocotzi 1912.07621]

$$\Delta M_s|_{\rm SM} = 18.77 \left(1 \pm 3.1\%|_{B_{B_q}} \pm 3.4\%|_{\rm CKM}\right) {\rm ps}^{-1} \qquad \Delta M_s|_{\rm exp} = (17.757 \pm 0.021)\, {\rm ps}^{-1}$$

$$\Delta M_d|_{\rm SM} = 0.543 \left(1 \pm 3.6\%|_{B_{B_q}} \pm 3.4\%|_{\rm CKM}\right) {\rm ps}^{-1} \qquad \Delta M_d|_{\rm exp} = (0.5064 \pm 0.0019)\, {\rm ps}^{-1}$$

Sensitivity to $|V_{tb} V_{tq}^*|$ $\delta|V_{tb} V_{ts}^*| \approx 1.5\%$ and $\delta|V_{tb} V_{td}^*| \approx 1.8\%$ ⇐ TODAY as for $|V_{cb}|$ from $b \to c\ell\bar{\nu}_\ell$

$K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L \to \pi^0 \nu\bar{\nu}$

$$Br(K^+ \to \pi^+ \nu\bar{\nu}) = \tilde{\kappa}_+ \times X_t^2 \times \left\{ \frac{\mathrm{Im}^2 \lambda_t}{\lambda^{10}} + \left(\frac{\mathrm{Re}\,\lambda_t}{\lambda^5} + \frac{\mathrm{Re}\,\lambda_c}{\lambda} \times \overbrace{\frac{P_c}{X_t}}^{\approx 0.25\,(1 \pm 20\%)} \right)^2 \right\}$$

$$Br(K_L \to \pi^0 \nu\bar{\nu}) = \kappa_L \times X_t^2 \times \frac{\mathrm{Im}^2 \lambda_t}{\lambda^{10}} \qquad \lambda_U \equiv V_{Ud} V_{Us}^* \qquad \lambda = V_{us}$$

- **matrix element** from $K \to \pi e \bar{\nu}_e$ + QED real radiation [Mescia/Smith 0705.2025]

  $\tilde{\kappa}_+ = 5.072\,(1 \pm 0.5\%) \cdot 10^{-11}$, $\kappa_L = 2.194\,(1 \pm 0.6\%) \cdot 10^{-10}$

- **short-distance (SD)** $\propto X_t = 1.481(1 \pm 0.9\%|_{\text{th+exp}})$ at NLO QCD & EW

  [Buchalla/Buras NPB400 (1993) 225, Misiak/Urban 9901278, Brod/Gambino/Stamou 1009.0947]

- **charm SD + LD** $P_c = X_c \pm \delta P_{c,u}$ with $X_c = 0.365\,(1 \pm 3.3\%)$, $\delta P_{c,u} = 0.04 \pm 0.02$

  [Buras/Gorbahn/Haisch/Nierste 0508165 & 0603079] [Isidori/Mescia/Smith 0503107]

  lattice studies of $\delta P_{c,u}$ → [Christ/Feng/Portelli/Sachrajda 1910.10644]

$K^+ \to \pi^+\nu\bar\nu$ and $K_L \to \pi^0\nu\bar\nu$

$$Br(K^+ \to \pi^+\nu\bar\nu) = \tilde\kappa_+ \times X_t^2 \times \left\{ \frac{\mathrm{Im}^2\lambda_t}{\lambda^{10}} + \left(\frac{\mathrm{Re}\,\lambda_t}{\lambda^5} + \frac{\mathrm{Re}\,\lambda_c}{\lambda} \times \overbrace{\frac{P_c}{X_t}}^{\approx 0.25\,(1\pm 20\%)} \right)^2 \right\}$$

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Sensitivity to λ_t

A) $\delta\,\mathrm{Im}\,\lambda_t \approx 2\%|_{\text{th}} + \delta Br(K_L \to \pi^0\nu\bar\nu)|_{\text{exp}}$ ⇐ exp: future KOTO, (KLEVER)

B) $\delta|\lambda_t| \approx 4\%|_{\text{th}} + \delta Br(K^+ \to \pi^+\nu\bar\nu)|_{\text{exp}}$ ⇐ exp: NA62 (2016-18)

NA62: 2016+17 → 3 evts. ⇒ $Br < 1.85 \cdot 10^{-10}$ @ 90% CL (2018 not yet analysed, but 2 × 2017 data sample)

2021-23 (LHC Run 3) (higher beam intensity, suppressed upstream bkg) **with aim $\delta Br|_{\text{exp}} \sim 10\%$**

ε_K – CPV in $|\Delta S| = 2$

Rearranged PT series from $\lambda_u = -\lambda_c - \lambda_t \;\rightarrow\; \lambda_c = -\lambda_u - \lambda_t$ [Brod/Gorbahn/Stamou 1911.06822]

$\Rightarrow$ improves SD accuracy

$$|\varepsilon_K| \;\propto\; \boxed{F_K^2 \widehat{B}_K} \times \boxed{|V_{cb}|^2 \lambda^2 \bar{\eta}} \times \left(\boxed{|V_{cb}|^2 (1-\bar{\rho})} \times \boxed{\eta_{tt}\, \mathcal{S}(x_t)} - \boxed{\eta_{ut}\, \mathcal{S}(x_c, x_t)} \right)$$

- **CKM** to be determined
- **$|\Delta S = 2|$ matrix element** as (decay constant) × (bag factor) $\Rightarrow$ Lattice $\widehat{B}_K = 0.7625(97)$
- **short-distance** $\eta_{tt}^{\rm NLL} = 0.55\,(1 + 0.042|_\mu)$ and $\eta_{ut}^{\rm NNLL} = 0.402\,(1 + 0.013|_\mu)$

  previously dominant uncertainty from η_{ct} [Brod/Gorbahn 1007.0684, 1108.2036]

  now from η_{tt} [Brod/Gorbahn/Stamou 1911.06822]

$$|\varepsilon_K|_{\rm SM} = 2.161\left(1 + 3.0\%|_{\rm pert} + 3.5\%|_{\text{non-pert}}\right)\cdot 10^{-3} \qquad |\varepsilon_K|_{\rm exp} = \left(2.228 \pm 0.011\right)\cdot 10^{-3}$$

$\Rightarrow$ very sensitive $|\varepsilon_K| \propto \bar{\eta}\,|V_{cb}|^2$, top-contribution even $\propto |V_{cb}|^4$

ε'/ε – CPV in $|\Delta S| = 1$

Direct CPV in $K^0 \to \pi\pi$ tiny in SM $\quad\Rightarrow\quad \varepsilon'/\varepsilon \propto \text{Im}\left(V_{td}V_{ts}^*\right) \sim \lambda^5 \sim 10^{-4}$

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

RBC-UKQCD Lattice Collab. **no IB** (isospin breaking)

- Re A_2, Im A_2 and δ_2 [RBC-UKQCD 1502.00263]
- Re A_0, Im A_0 and δ_0 [RBC-UKQCD 2004.09440]

New result for A_0 in 2020: $\varepsilon'/\varepsilon|_{\text{SM}} = 21.7\left(1 \pm 12\%|_{\text{stat}} \pm 29\%|_{\text{syst}} \pm 23\%|_{\text{IB}}\right) \cdot 10^{-4}$

- agrees with experiment $\varepsilon'/\varepsilon|_{\text{exp}} = (16.6 \pm 2.3) \times 10^{-4}$
- good agreement for $\pi\pi$-phase shifts $\delta_{0,2}$ with chiral limit
- $\Delta I = 1/2$ rule: $\dfrac{\text{Re}\,A_0}{\text{Re}\,A_2} = 19.9(2.3)(4.4)$ agrees with experiment 22.45(6)

!!! huge shift w.r.t. 2015: $\varepsilon'/\varepsilon = 1.4\left(1 \pm 370\%|_{\text{stat}} \pm 330\%|_{\text{syst}}\right) \cdot 10^{-4}$ [RBC-UKQCD 1505.07863]

ε'/ε – CPV in $|\Delta S| = 1$

Direct CPV in $K^0 \to \pi\pi$ tiny in SM $\quad \Rightarrow \quad \varepsilon'/\varepsilon \;\propto\; \mathrm{Im}\left(V_{td} V_{ts}^*\right) \sim \lambda^5 \sim 10^{-4}$

Leading IB in QCD penguins from ChPT → $\hat{\Omega}_{\rm eff}$

[Cirigliano/Ecker/Neufeld/Pich hep-ph/0310351, 0307030 ↑]

$$\frac{\varepsilon'}{\varepsilon} = -\frac{\omega_+}{\sqrt{2}\,|\varepsilon|}\left[\frac{\mathrm{Im}\,\widetilde{A}_0}{\mathrm{Re}\,A_0}\left(1-\hat{\Omega}_{\rm eff}\right) - \frac{1}{a}\frac{\mathrm{Im}\,A_2}{\mathrm{Re}\,A_2}\right]$$

[Buras/Gorbahn/Jäger/Jamin 1507.06356 ↑]

$\omega_+ = a\ \mathrm{Re}\,A_2\,/\,\mathrm{Re}\,A_0 = (4.53 \pm 0.02) \times 10^{-2}$ from experiment

- **octet scheme:** $\hat{\Omega}_{\rm eff}^{(8)} = 0.17 \pm 0.09$
  ChPT with octet of light pseudoscalars

  [Cirigliano/Gisbert/Pich/Rodríguez-Sánchez 1911.01359]

- **nonet scheme:** $\hat{\Omega}_{\rm eff}^{(9)} = 0.29 \pm 0.07$
  include effects of $\eta_8 - \eta_0$ mixing

  [Buras/Gérard 2005.08976]

⇒ inclusion of IB to RBC-UKQCD result leads to suppression of ε'/ε:

$\varepsilon'/\varepsilon^{(8)} = (17.4 \pm 6.1) \cdot 10^{-4}$

$\varepsilon'/\varepsilon^{(9)} = (13.9 \pm 5.2) \cdot 10^{-4}$

[Aebischer/CB/Buras 2005.05978]

Also **“ChPT-only” prediction** including IB (does not use RBC-UKQCD matrix elements)

$\varepsilon'/\varepsilon^{\rm ChPT} = (14 \pm 5) \cdot 10^{-4}$

[Cirigliano/Gisbert/Pich/Rodríguez-Sánchez 1911.01359]

Summary

Rare decays and mixing in B- and K-meson systems are

- **valueable** FCNC probes of CKM elements $V_{ts,td}$
- only **very few** observables with theory accuracy **at percent level**
- short-distance at NLO QCD & EW, in many cases also NNLO QCD,
  but still room for improvements: $|\Delta S| = 2$ in ε_K (η_{tt}), $|\Delta S| = 1$ in ε'/ε
- **progress from Lattice QCD**, and more to come:
  $\Rightarrow$ $V_{ts,td}$ from $\Delta M_{s,d}$ with similar precision as $|V_{cb}|_{\text{incl}}$ from $b \to c\ell\bar{\nu}_\ell$!!!
- **experimentally challenging** to reach percent level
  $\Rightarrow$ $B_s \to \mu\bar{\mu}$ at LHCb 300/fb after 2030?
  $\Rightarrow$ $K^+ \to \pi^+\nu\bar{\nu}$ at NA62, next run 2021-2023
  $\Rightarrow$ $K_L \to \pi^0\nu\bar{\nu}$ at KOTO, (KLEVER) around 2030?

!!! **beyond SM,** theoretical accuracy can be much lower, depending on observable,
because additional hadronic parameters can enter