Probing $b \to s$ FCNCs with EOS

Danny van Dyk

in collaboration with

Christoph Bobeth, Gudrun Hiller, Christian Wacker
and Frederik Beaujean

technische universität
dortmund

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Outline

Overview of Effective Field Theories

Probing $b \to s\{\gamma, \ell^+\ell^-\}$ with EOS

Effective Field Theory

- popular and useful tool of theoretical physics
- **separate** high-energy ($\equiv$ short-distance) from low-energy ($\equiv$ long-distance) physics
- replace Hamiltonian

$$\mathcal{H}^{\text{full}} \mapsto \mathcal{H} + \sum_i \mathcal{C}_i^{\text{eff}} \mathcal{O}_i^{\text{eff}}$$

Examples

- 4-Fermi-theory
- $g\,g \to h$
- $B_q - \bar{B}_q$ – mixing ($|\Delta B| = 2$)
- $\mathbf{b} \to \mathbf{s}\{\gamma, \ell^+\ell^-\}$ **transitions** ($|\Delta B| = 1$)

Renormalizability

- usually: mass dim. $\mathcal{O}_i^{\text{eff}} > 4 \Rightarrow$ mass dim. $\mathcal{C}_i^{\text{eff}} < 0$
- not renormalizable to all orders!
- however, works to fixed order in some smallness parameter
- expose smallness parameter, e.g. in the case of $b \to s$: G_{F}

$$\mathcal{C}_i^{\text{eff}} \mapsto \frac{4\,G_{\text{F}}}{\sqrt{2}} V_{tb} V_{ts}^* \mathcal{C}_i^{\text{b}\to\text{s}} \qquad \mathcal{O}_i^{\text{eff}} \mapsto \mathcal{O}_i^{\text{b}\to\text{s}} \text{ (def. later on)}$$

- $\mathcal{C}_i^{\text{b}\to\text{s}}$ have mass dim. 0 now!

Dropping superscript $\text{b} \to \text{s}$ **from now on.**

Separation of scales I

high energy scale $\equiv$ short distance

- $\mu = O(m_W, m_t)$: popular choice: $\mu_0 = 80\,\mathrm{GeV}$ and $\mu_0 = 120\,\mathrm{GeV}$
- reduces impact (**resummation**) of large logs: $\ln(\mu/m_W)$, $\ln(\mu/m_t)$
- calculate process in full theory
- extract $\mathcal{C}_i(\mu_0)$ (**matching**)

Separation of scales II

low energy scale $\equiv$ long distance

- calculate hadronic matrix element of $\mathcal{O}_i$

$$\langle K^* \ell^+ \ell^- | \mathcal{O}_i(\mu_b) | B_d \rangle$$

- how to choose μ_b? typical scale should be $\mu_b = m_b \simeq 4.2\mathrm{GeV}$
- reduces large logs: $\ln(\mu/m_b)$

Problem(?): scales do not match!
When calculating Observables $\sim |\sum_i \mathcal{C}_i(\mu) < \mathcal{O}_i(\mu) > |^2$ the scales must match!

Renormalization Group Equations

Enter RGE running:

$$\mathcal{C}_i(\mu_b) = \sum_j U_{ij}(\mu_b, \mu_0)\mathcal{C}_j(\mu_0)$$

Running governed by beta function and anomalous mass dimension γ of operators:

$$\ln U(\mu_b, \mu_0) \propto \int_{g(\mu_b)}^{g(\mu_0)} \mathrm{d}\, \frac{\gamma^{\mathrm{T}}(\mathrm{g}')}{2\beta(\mathrm{g})}$$

Nice! We can sensibly separate short-distance physics of the SM[1][2] from long-distance physics

[1] or the MSSM (Gudrun Hiller, Christian Gross, Stefan Schacht)

[2] or any other high energy theory

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Overview of Effective Field Theories

Probing $b \to s\{\gamma, \ell^+\ell^-\}$ with EOS

Model independent analysis of $|\Delta B| = 1$ decays

- calculate observables in terms of $\mathcal{C}_i(\mu_b)$
- fit theory pred. to exp. data and extract values of $\mathcal{C}_i(\mu_b)$
- provide posterior of $\mathcal{C}_i(\mu_b)$ (Bayesian statistics):

$$P(\text{parameters}|\text{data}) = \frac{P(\text{data}|\text{parameters})P(\text{parameters})}{P(\text{data})}$$

- iterative process: posterior of model ind. analysis is prior to parameter study in a model
- separation of scales $\mapsto$ separation of efforts

Operator Basis

SM basis + WCs in the SM

$\mathcal{O}_{1,2}$	$[\bar{s}\Gamma b]\,[\bar{c}\Gamma' c]$	$b \to s\bar{c}c$	$\mathcal{C}_2 \simeq 1$
$\mathcal{O}_{3\ldots6}$	$[\bar{s}\Gamma b]\,[\bar{q}\Gamma' q]$	$b \to s\bar{q}q$	$\mathcal{C}_{3\ldots6}$ neg.
$\mathcal{O}_7$	$\overline{m_b}(\mu)[\bar{s}\sigma^{\mu\nu}P_\mathrm{R} b]F_{\mu\nu}$	$b \to s\gamma$	$\mathcal{C}_7 \simeq -0.3$
$\mathcal{O}_8$	$\overline{m_b}(\mu)[\bar{s}\sigma^{\mu\nu}P_\mathrm{R} b]G_{\mu\nu}$	$b \to sg$	$\mathcal{C}_{1,8} = O(0.1)$
$\mathcal{O}_{9,10}$	$[\bar{s}\gamma^\mu P_\mathrm{L} b]\,[\bar{\ell}\gamma_\mu(\gamma_5)\ell]$	$b \to s\ell^+\ell^-$	$\mathcal{C}_{9,10} \simeq \pm 4.2$

Ext. basis + WCs in the SM

$\mathcal{O}_{S,P}$	$[\bar{s}(\gamma_5)b]\,[\bar{\ell}(\gamma_5)\ell]$	$b \to s\ell^+\ell^-$	$\mathcal{C}_{S,P} \simeq 0$
$\mathcal{O}_{T,T5}$	$[\bar{s}\sigma^{\mu\nu} b]\,[\bar{\ell}\sigma_{\mu\nu}(\gamma_5)\ell]$	$b \to s\ell^+\ell^-$	$\mathcal{C}_{S,P} \simeq 0$
$\mathcal{O}'_7$	$\overline{m_b}(\mu)[\bar{s}\sigma^{\mu\nu}P_\mathrm{L} b]F_{\mu\nu}$	$b \to s\gamma$	$\mathcal{C}'_i = \frac{m_s}{m_b}\mathcal{C}_i$
$\mathcal{O}'_{9,10}$	$[\bar{s}\gamma^\mu P_\mathrm{R} b]\,[\bar{\ell}\gamma_\mu(\gamma_5)\ell]$	$b \to s\ell^+\ell^-$	

Decays and Observables

Loads of decays and observables to probe $\mathcal{C}_{7,9,10}$!

Inclusive

- $B_d \to X_s\gamma$:
  $\mathcal{B}$
- $B_d \to X_s\ell^+\ell^-$:
  $\mathcal{B}$

Exclusive

- $B_{u,d} \to K^*(\to K\pi) + \ell^+\ell^-$:
  $\mathcal{B}, A_{\rm FB}, F_{\rm L}, A_{\rm T}^{(2,3,4)}, H_{\rm T}^{1,2,3}, a_{\rm CP}^{(i)}$
- $B_{u,d} \to K\ell^+\ell^-$:
  $\mathcal{B}, F_{\rm H}$
- $B_d \to K^*(\to K\pi)\gamma$:
  $\mathcal{B}, S_{K^*\gamma}$

In addition: two kinematic regions for $\to \ell^+\ell^-$: low,high dilepton mass squared.

All of the above have already been implemented in EOS.

Modeling within EOS

3 entities:

- Set of parameters: `Parameters`
- Set of kinematic variables: `Kinematics`
- Set of options, e.q B_d vs B_u, $\ell = e, \mu$: `Options`

Any `Observable` is a combination of a function with one object of `Parameters, Kinematics, Options` each.

Changes to `Parameters, Kinematics` propagate to the `Observable`

Look up via name, e.g. `B->K^*ll::BR@LowRecoil` selects the integrated branching ratio of $B \to K^*\ell^+\ell^-$.

Scan Procedure

- treat $\mathcal{C}_i(\mu_b)$ as free parameters within `Parameters`
- for each tuple $\mathcal{C}_i(\mu_b)$
  - evaluate each `Observable` for given `Kinematics` (due to binning)
  - calculate goodness-of-fit w/r to exp. measurements (BaBar'06, Belle'09, CDF'10, LHC$_b$ '11?)
- find confidence regions (CRs) in the N-dim. parameter space
- project CRs onto relevant planes for overview
- ToDo: find a fast/cheap way to provide posterior to model people.

New Physics Searches

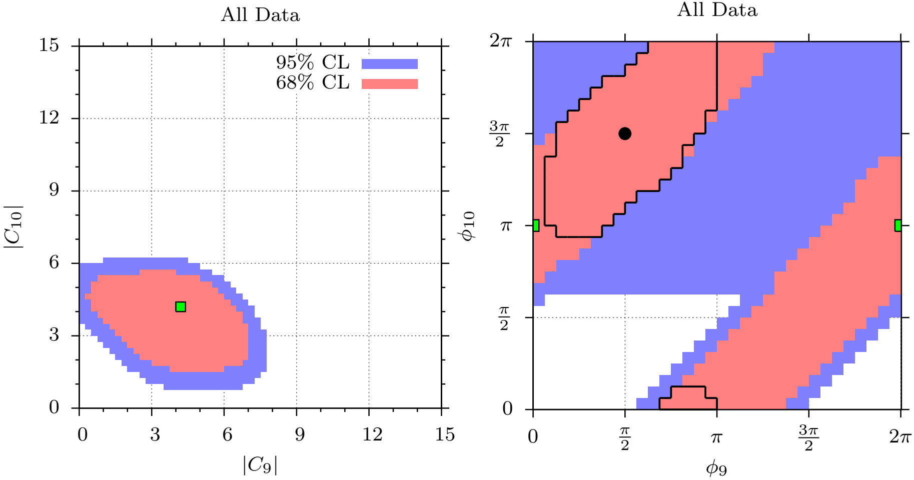
so far

- lattice scan for real $\mathcal{C}_{9,10}$ using inclusive decays + $B \to K^*\ell^+\ell^-$
  C. Bobeth, G. Hiller, DvD '10
- lattice scan for complex $\mathcal{C}_{7,9,10}$ using inclusive decays + $B \to K^*\ell^+\ell^-$
  C. Bobeth, G. Hiller, DvD '11

in preparation

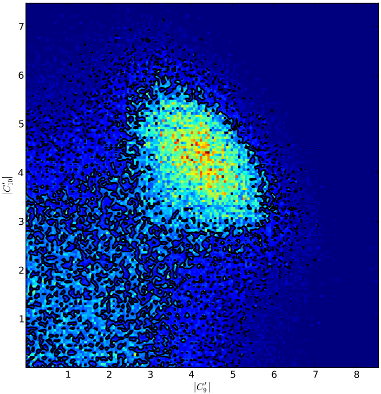
- lattice scan for complex $\mathcal{C}_{7,9,10}$ with above + $B \to K\ell^+\ell^-$ C. Bobeth, G. Hiller, DvD, C. Wacker
- bayesian monte carlo fit for complex $\mathcal{C}_{7,9,10}$ and chirality flipped operators F. Beaujean, C. Bobeth, DvD, C. Wacker

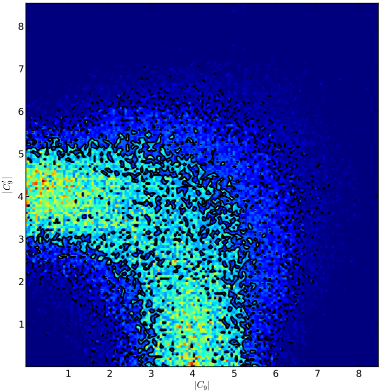
Results for complex-valued $\mathcal{C}_{9,10}$



C. Bobeth, G. Hiller, DvD '11

Preliminary Results (Monte Carlo)





F. Beaujean, C. Bobeth, DvD, C. Wacker in prep.

References

- EOS (DvD, C. Wacker, F. Beaujean, C. Bobeth): `http://project.het.physik.tu-dortmund.de/eos/`
- NLO calculation at Large Recoil (M.Beneke, T.Feldmann, D.Seidel '01 and '04): `arxiv:hep-ph/0106067` and `arxiv:hep-ph/0412400`
- Expansion in Λ/Q, $Q = m_b, \sqrt{q^2}$ (B.Grinstein, D.Pirjol '04): `arxiv:hep-ph/0404250`
- Low Recoil observables and model independent analysis (C.Bobeth, G.Hiller, DvD '10): `arxiv:1006.5013 [hep-ph]`
- CP-Asymmetries at Low Recoil (C. Bobeth, G. Hiller, DvD): `arxiv:1105.0376 [hep-ph]`

Outline

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