The Decay $\bar{B} \to \bar{K}^* \ell^+ \ell^-$ at Low Recoil and its Constraints on New Physics

Danny van Dyk

Universität Siegen

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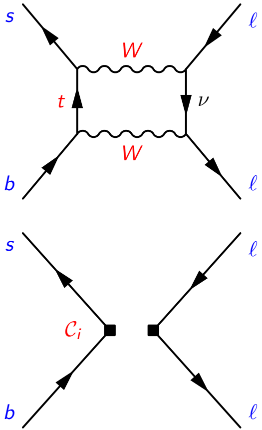
Overview

At Parton Level: $b \to s\ell^+\ell^-$

- Flavor Changing Neutral Current: change of flavor $b \to s$ in a neutral current
- in the SM W, Z, t propagators occur
- expand amplitudes in $G_\mathrm{F} \sim 1/M_W^2$ (OPE)
- find a basis of operators with b, s and two light leptons $\ell = e, \mu$

$$\mathcal{O}_i \equiv \left[\bar{s}\Gamma_i b\right] \left[\bar{\ell}\Gamma_i'\ell\right]$$

- calculate coefficients of operators $\mathcal{C}_i \equiv \mathcal{C}_i(M_W, M_Z, m_t, \dots)$



Effective Hamiltonian

- use effective Hamiltonian

$$\mathcal{H} = -\frac{4G_\mathrm{F}}{\sqrt{2}}\left[\lambda^{(t)}\mathcal{H}^{(t)} + \lambda^{(u)}\mathcal{H}^{(u)}\right], \quad \lambda^{(q)} \equiv V_{qb}V_{qs}^*$$

- make CKM unitary and hierarchy explicit:

$$\mathcal{H}^{(t)} = \sum_{i\neq 1u,2u} \mathcal{C}_i\mathcal{O}_i$$

$$\mathcal{H}^{(u)} = \mathcal{C}_1\left[\mathcal{O}_{1c} - \mathcal{O}_{1u}\right] + \mathcal{C}_2\left[\mathcal{O}_{2c} - \mathcal{O}_{2u}\right]$$

- $\lambda^{(u)}$ small and complex, important when considering CP violating observables

Operators

Semileptonic Operators (SM and χ-flipped)

$$\mathcal{O}_{9(')} = \frac{\alpha_e}{4\pi}\left[\bar{s}\gamma_\mu P_{L(R)} b\right]\left[\bar{\ell}\gamma^\mu \ell\right] \qquad \mathcal{O}_{10(')} = \frac{\alpha_e}{4\pi}\left[\bar{s}\gamma_\mu P_{L(R)} b\right]\left[\bar{q}\gamma^\mu \gamma_5 \ell\right]$$

Semileptonic Operators (extended)

$$\mathcal{O}_{S(')} = \frac{\alpha_e}{4\pi}\left[\bar{s} P_{R(L)} b\right]\left[\bar{\ell}\ell\right] \qquad \mathcal{O}_{P(')} = \frac{\alpha_e}{4\pi}\left[\bar{s} P_{R(L)} b\right]\left[\bar{\ell}\gamma_5 \ell\right]$$

$$\mathcal{O}_{T} = \frac{\alpha_e}{4\pi}\left[\bar{s}\sigma_{\mu\nu} b\right]\left[\bar{\ell}\sigma^{\mu\nu}\ell\right] \qquad \mathcal{O}_{T5} = \frac{\alpha_e}{4\pi}\left[\bar{s}\sigma_{\mu\nu} b\right]\left[\bar{\ell}\sigma_{\alpha\beta}\ell\right]\frac{i\varepsilon_{\mu\nu\alpha\beta}}{2}$$

Operators (cont.)

Radiative

$$\mathcal{O}_{7(\prime)} = \left[\bar{s}\sigma_{\mu\nu}P_{R(L)}b\right]F^{\mu\nu} \qquad \mathcal{O}_{8(\prime)} = \left[\bar{s}\sigma_{\mu\nu}P_{R(L)}b\right]G^{\mu\nu}$$

Current-Current

Fixed flavors $q = u, c$

$$\mathcal{O}_{1q} = \left[\bar{s}\gamma_\mu T^a P_L q\right]\left[\bar{q}\gamma^\mu T^a P_L b\right] \qquad \mathcal{O}_{2q} = \left[\bar{s}\gamma_\mu P_L q\right]\left[\bar{q}\gamma^\mu P_L b\right]$$

QCD Penguin

Summation over flavors $q = u, d, s, c, b$

$$\mathcal{O}_3 = \left[\bar{s}\gamma_\mu P_L b\right]\left[\bar{q}\gamma^\mu q\right] \qquad \mathcal{O}_4 = \left[\bar{s}\gamma_\mu T^a P_L b\right]\left[\bar{q}\gamma^\mu T^a q\right]$$

$$\mathcal{O}_5 = \left[\bar{s}\gamma_{\mu\nu\rho} P_L b\right]\left[\bar{q}\gamma^{\mu\nu\rho} q\right] \qquad \mathcal{O}_6 = \left[\bar{s}\gamma_{\mu\nu\rho} T^a P_L b\right]\left[\bar{q}\gamma^{\mu\nu\rho} T^a q\right]$$

$\gamma_{\mu\nu\rho} \equiv \gamma_\mu\gamma_\nu\gamma_\rho$, QED Penguins are usually neglected.

Overview

Exclusive Decays

Possible Hadronic Decays

$$\bar{B}^0 \to \bar{K}^0 \ell^+\ell^- \qquad B^- \to \bar{K}^- \ell^+\ell^- \qquad \bar{B}_s \to \eta^{(\prime)} \ell^+\ell^-$$

$$\bar{B}^0 \to \bar{K}^{*,0} \ell^+\ell^- \qquad B^- \to \bar{K}^{*,-} \ell^+\ell^- \qquad \bar{B}_s \to \phi \ell^+\ell^-$$

. . . and higher resonances

Naive Factorization

assumes

$$\langle \ell^+\ell^- V|\mathcal{H}|B\rangle = \langle \ell^+\ell^-|J^{\text{e.m.}}|0\rangle \times \langle V|J^{\text{had.}}|B\rangle$$

broken in principle by QCD: $b \to s\bar{q}q(\to \ell^+\ell^-)$, but at which order?

$B \to V$ Form Factors

Hadronic Matrix Elements

$$\langle V(k,\eta)|\bar{s}\Gamma b|B(p)\rangle$$

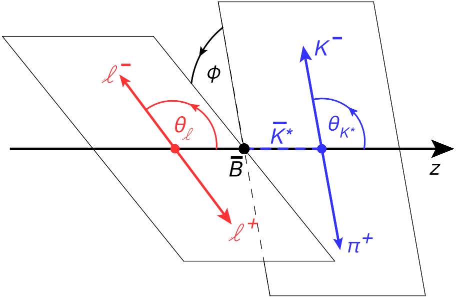
- non-perturbative quantities
- sources: Lattice QCD, Light Cone Sum Rules (LCSR)
- currently largest source of theory uncertainties

Form Factors

- 7 scalar functions, dependent on $q^2 = (p-k)^2$
- parametrize hadronic matrix elements
- make use of transformation properties
- Example

$$\langle V(k,\eta)|\bar{s}\gamma^\mu b|B(p)\rangle = \frac{2V(q^2)}{M_B + M_V}\eta_\nu^* p_\rho k_\sigma \varepsilon^{\mu\nu\rho\sigma}$$

Kinematics of $\bar{B} \to \bar{K}^*(\to \bar{K}\pi)\ell^+\ell^-$



Kinematic Variables

$$4m_\ell^2 \leq q^2 \leq (M_B - M_V)^2$$
$$-1 \leq \cos\theta_\ell \leq 1$$
$$-1 \leq \cos\theta_{K^*} \leq 1$$
$$0 \leq \phi \leq 2\pi$$

On-shell and S-Wave

- assumes on-shell decay of K^*, currently hot topic
- for high precision consider width of K^*, and $J = 0$ (S-wave) $K\pi$-final-state from K_0^* and non-resonant background

Angular Distribution [Krüger/Matias '05]

Calculate fully differential decay rate for pure P wave state

$$\frac{d^4\Gamma}{dq^2 d\cos\theta_\ell d\cos\theta_{K^*} d\phi} = \frac{3}{8\pi} J(q^2, \cos\theta_\ell, \cos\theta_{K^*}, \phi)$$

$$\begin{aligned}
J(q^2, \theta_\ell, \theta_{K^*}, \phi) = {} & J_{1s}\sin^2\theta_{K^*} + J_{1c}\cos^2\theta_{K^*} \\
& + (J_{2s}\sin^2\theta_{K^*} + J_{2c}\cos^2\theta_{K^*})\cos 2\theta_\ell \\
& + J_3 \sin^2\theta_{K^*}\sin^2\theta_\ell\cos 2\phi \\
& + (J_4 \sin 2\theta_{K^*})\sin 2\theta_\ell\cos\phi \\
& + (J_5 \sin 2\theta_{K^*})\sin\theta_\ell\cos\phi \\
& + (J_{6s}\sin^2\theta_{K^*} + J_{6c}\cos^2\theta_{K^*})\cos\theta_\ell \\
& + (J_7 \sin 2\theta_{K^*})\sin\theta_\ell\sin\phi \\
& + (J_8 \sin 2\theta_{K^*})\sin 2\theta_\ell\sin\phi \\
& + J_9 \sin^2\theta_{K^*}\sin^2\theta_\ell\sin 2\phi,
\end{aligned}$$

Angular Distribution [Krüger/Matias '05, Blake/Egede/Shires '12]

Calculate fully differential decay rate for mixed P and S wave state

$$\frac{d^4\Gamma}{dq^2 d\cos\theta_\ell d\cos\theta_{K^*} d\phi} = \frac{3}{8\pi} J(q^2, \cos\theta_\ell, \cos\theta_{K^*}, \phi)$$

$$\begin{aligned}
J(q^2, \theta_\ell, \theta_{K^*}, \phi) = & \, J_{1s} \sin^2\theta_{K^*} + J_{1c} \cos^2\theta_{K^*} + J_{1i} \cos\theta_{K^*} \\
& + (J_{2s} \sin^2\theta_{K^*} + J_{2c} \cos^2\theta_{K^*} + J_{2i} \cos\theta_{K^*}) \cos 2\theta_\ell \\
& + J_3 \sin^2\theta_{K^*} \sin^2\theta_\ell \cos 2\phi \\
& + (J_4 \sin 2\theta_{K^*} + J_{4i} \cos\theta_{K^*}) \sin 2\theta_\ell \cos\phi \\
& + (J_5 \sin 2\theta_{K^*} + J_{5i} \cos\theta_{K^*}) \sin\theta_\ell \cos\phi \\
& + (J_{6s} \sin^2\theta_{K^*} + J_{6c} \cos^2\theta_{K^*}) \cos\theta_\ell \\
& + (J_7 \sin 2\theta_{K^*} + J_{7i} \cos\theta_{K^*}) \sin\theta_\ell \sin\phi \\
& + (J_8 \sin 2\theta_{K^*} + J_{8i} \cos\theta_{K^*}) \sin 2\theta_\ell \sin\phi \\
& + J_9 \sin^2\theta_{K^*} \sin^2\theta_\ell \sin 2\phi,
\end{aligned}$$

Angular Observables

Helicity Decomposition

$$g_{\mu\nu} = \sum_{n,m} g_{nm} \varepsilon^\dagger_\mu(n) \varepsilon_\nu(m) \qquad n, m = t, 0, +, -$$

$$-g_{\mu\nu} + \frac{k_\mu k_\nu}{k^2} = \sum_{n,m} \delta_{mn} \eta^\dagger_\mu(n) \eta_\nu(m) \qquad n, m = 0, +, -$$

Transversity Amplitudes (SM)

- first use helicity amplitudes

$$H_{ab} = \eta^\dagger_\mu(a) \mathcal{M}^{\mu\nu} \varepsilon^\dagger_\nu(b)$$

- four non-vanishing amp. $H_{\pm\pm}, H_{00}, H_{0t}$
- transversity basis: $A_{\perp,\parallel} = (H_{++} \mp H_{--})/\sqrt{2}$, $A_0 = H_0$, $A_t = H_{0t}$
- extended opterator basis $\rightarrow$ more amplitudes

Angular Observables (cont')

Transversity Amplitudes (extended basis) [Bobeth/Hiller/DvD '12]

- extended opterator basis → more amplitudes
- S('): A_S, P('): absorbed by A_t [Altmannshofer et al. '08]
- T(5): 6 new amps A_{ab} $(ab) = (0t), (\parallel\perp), (0\perp), (t\perp), (0\parallel), (t\parallel)$
  $H_{abc} = \eta^\dagger_\mu(a)\mathcal{M}^{\mu\nu\rho}\varepsilon^\dagger_\nu(b)\varepsilon^\dagger_\rho(c)$

$$A_{ab} = \text{linear com. of}\,(H_{xyz}) \quad a, b = t, 0, \parallel, \perp \quad x, y, z = t, 0, +, -$$

Angular Observables

- J_i functionals of A_S, A_a, A_{ab}, $a, b = t, 0, \parallel, \perp$
- example

$$J_3(q^2) = \frac{3\beta_\ell}{4}\left[|A_\perp|^2 - |A_\parallel|^2 + 16\left(|A_{t\parallel}|^2 + |A_{0\parallel}|^2 - |A_{t\perp}|^2 - |A_{0\perp}|^2\right)\right]$$

Further Observables

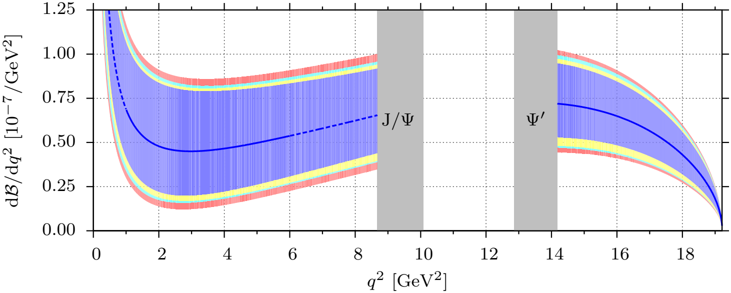
CP Conserving

- decay width
$$d\Gamma/dq^2 = \frac{6J_{1s} + 3J_{1c} - 2J_{2s} + J_{2c}}{3}$$
- forward-backward asymmetry
$$A_{\mathrm{FB}}(q^2) = \frac{2J_{6s} + J_{6c}}{2d\Gamma/dq^2}$$
- longitudinal/transversal polarization
$$F_{\mathrm{L}} = \frac{3J_{1c} - J_{2c}}{3d\Gamma/dq^2} \qquad F_{\mathrm{T}} = \frac{3J_{1s} - J_{2s}}{6d\Gamma/dq^2} \qquad F_{\mathrm{L}} + F_{\mathrm{T}} = 1$$

Further

- CP asymmetries of the angular observables
- isospin asymmetries of the angular observables

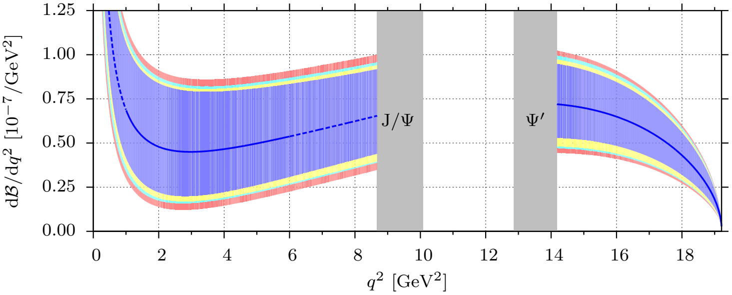
q^2 Spectrum of the Branching Ratio $\mathcal{B} = \tau_B \Gamma$



$\bar{q}q$ Pollution

- 4-quark operators like $\mathcal{O}_{1c,2c}$ induce $b \to s\bar{c}c(\to \ell^+\ell^-)$ via loops
- hadronically $B \to K^* J/\psi(\to \ell^+\ell^-)$ or higher charmonia
- experiment: cut narrow resonances $J\psi \equiv \psi(1S)$ and $\psi' = \psi(2S)$
- theory: handle non-resonant quark loops/broad resonances $> 2S$

q^2 Spectrum of the Branching Ratio $\mathcal{B} = \tau_B \Gamma$



Large Recoil $E_{K^*} \sim m_b$ QCDF,SCET

- expand in $1/m_b$, $1/E_{K^*}$, α_s
- symmetry: $7 \to 2$ form factors

[Beneke/Feldmann/Seidel '01 & '04]

[Egede et al. '08 & '10]

Low Recoil $q^2 \sim m_b^2$ OPE,HQET

- expand in $1/m_b$, $1/\sqrt{q^2}$, α_s
- symmetry: $7 \to 4$ form factors

[Grinstein/Pirjol '04], [Beylich/Buchalla/Feldmann '11]

[Bobeth/Hiller/DvD '10 & '11]

Overview

Improved Isgur-Wise Relations

Operator Identity

$$i\partial^\nu [\bar{s} i \sigma_{\mu\nu} b] = -(m_b + m_s)[\bar{s}\gamma_\mu b] + i\partial_\mu [\bar{s} b] - 2[\bar{s} i \overleftarrow{D}_\mu b]$$

Tensor Form Factors

- apply op.id. to hadronic matrix elements
- left-hand side

$$\langle V(k,\eta)|\bar{s}\sigma_{\mu\nu} q^\nu b|B(p)\rangle \sim T_1, T_2, T_3$$

- right-hand side

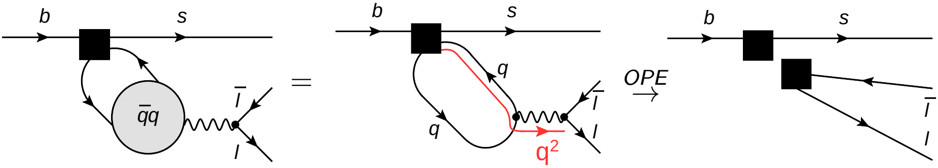
$$\langle V(k,\eta)|\bar{s}\gamma_\mu(\gamma_5) b|B(p)\rangle \sim V(A_0, A_1, A_2)$$

- read off improved Isgur-Wise relations $(\kappa(m_b) = 1 + O(\alpha_s^2))$

$$T_1 = \kappa V \qquad T_2 = \kappa A_1 \qquad T_3 = \kappa \frac{M_B^2}{q^2} A_2$$

Local OPE [Grinstein/Pirjol '04, Beylich/Buchalla/Feldmann '11]

$$i \int \mathrm{d}^4 x e^{iqx} \langle \bar{K}^* | T\{\mathcal{O}_i(0), j_\mu^{\mathrm{e.m.}}(x)\} | \bar{B} \rangle = \sum_{j,k} \mathcal{C}_{i,j,k}(q^2/m_b^2, \mu) \langle \mathcal{O}_j^{(k)} \rangle_\mu$$



Operators

$k = 3$ form factors, α_s corrections known, absorbed into effective Wilson coefficients $\mathcal{C}_{7,9} \to \mathcal{C}_{7,9}^{\mathrm{eff}}$

$k = 4$ absent

$k = 5$ $\Lambda^2/m_b^2 \sim 2\%$ corrections, first new had. matrix elements explicitly: $< 1\%$ for $q^2 = 15\mathrm{GeV}^2$ [Beylich/Buchalla/Feldmann]

$k = 6$ first isospin breaking correction, Λ^3/m_b^3 suppressed

Low Recoil Framework Put Together

SM Basis

- TA factorize to $O\big(\alpha_s \Lambda / m_b, \mathcal{C}_7 \Lambda / (\mathcal{C}_9 m_b)\big)$ [Grinstein/Pirjol '04, Bobeth/Hiller/DvD '10]

$$A_{0,\perp,\parallel}^{L(R)} = N C^{L(R)} f_{0,\perp,\parallel}$$

- f_i: helicity form factors [Bharucha/Feldmann/Wick '10]
- in spin-averaged decays: only two short-distance coefficients

$$2\rho_1 = |C^L|^2 + |C^R|^2 \qquad 4\rho_2 = |C^L|^2 - |C^R|^2$$

- all observables are either [Bobeth/Hiller/DvD '10]
  - ρ_1 dependent
  - ρ_2/ρ_1 dependent
  - free of short-distance coefficients

$$\Gamma \sim \rho_1 \qquad A_{\mathrm{FB}} \sim \frac{\rho_2}{\rho_1} \qquad F_{\mathrm{L}} : \text{SD free}$$

Optimized Observables

- no form factor dependence by design

$$H_T^{(1)} \equiv \frac{\sqrt{2} J_4}{\sqrt{-J_{2c}(2J_{2s} - J_3)}} = \mathrm{sgn}\,(f_0)$$

$$H_T^{(2)} \equiv \frac{\beta_\ell J_5}{\sqrt{-J_{2c}(2J_{2s} + J_3)}} = 2\frac{\rho_2}{\rho_1}$$

$$H_T^{(3)} \equiv \frac{\beta_\ell J_{6s}}{2\sqrt{(2J_{2s}^2 - J_3^2}} = 2\frac{\rho_2}{\rho_1}$$

- $H_T^{(1)}$ probes the OPE
- $H_T^{(2,3)}$ sensitive to $\mathcal{C}_9/\mathcal{C}_{10}$

[Bobeth/Hiller/DvD '10]

Beyond the SM [Bobeth/Hiller/DvD '12]

Amplitudes (extended basis)

- all TA factorize for $\ell = e, \mu$ and in absence of scalar operators

$$A_{0,\parallel}^{L(R)} = -N C_-^{L(R)} f_{0,\parallel} \qquad A_\perp^{L(R)} = +N C_+^{L(R)} f_\perp$$

$$A_{0(t)\perp} \sim C_{T(5)} f_\perp \qquad A_{0(t)\parallel} \sim C_{T(5)} f_\parallel \qquad A_{\parallel\perp(t0)} \sim C_{T(5)} f_0$$

$$\rho_1 \to \rho_1^\pm = \frac{1}{2}(|C_\pm^R|^2 + |C_\pm^L|^2) \quad \rho_2 \to \frac{1}{4}(C_+^R C_-^{R*} - C_-^L C_+^{L*})$$

More Optimized Observables

- existing observables

$$H_T^{(2)} = H_T^{(3)} = 2\,\mathrm{Re}\,(\rho_2)\,/\sqrt{\rho_1^- \rho_1^+}$$

- new observables

$$H_T^{(4)} \equiv \frac{\sqrt{2} J_8}{\sqrt{-J_{2c}(2J_{2s} + J_3)}} = 2\,\mathrm{Im}\,(\rho_2)\,/\sqrt{\rho_1^- \rho_1^+}$$

$$H_T^{(5)} \equiv \frac{-J_9}{\sqrt{(2J_{2s})^2 - J_3^2)}} = 2\,\mathrm{Im}\,(\rho_2)\,/\sqrt{\rho_1^- \rho_1^+}$$

Beyond the SM (cont') [Bobeth/Hiller/DvD '12]

Relations at Low Recoil

Scenario	$\lvert H_T^{(1)} \rvert = 1$	$H_T^{(2)} = H_T^{(3)}$	$H_T^{(4)} = H_T^{(5)}$	$J_7 = 0$	$J_{8,9} = 0$
SM	✓	✓	(✓)	✓	✓
SM ⊗ S, P	✓	$\frac{m_\ell}{Q}$ Re $\left(\mathcal{C}_-^{\mathrm{L,R}} \Delta_S^*\right)$	(✓)	$\frac{m_\ell}{Q}$ Im $\left(\mathcal{C}_+^{\mathrm{L,R}} \Delta_S^*\right)$	✓
SM ⊗ T, T5	$\frac{M_{K^*}^2}{Q^2} \rho_1^T$	$\frac{m_\ell}{Q}$ Re $\left(\rho_2^T\right)$	$\frac{M_{K^*}}{Q}$ Im $\left(\rho_2^T\right)$	$\frac{m_\ell}{Q}$ Im $(\mathcal{C}_i \mathcal{C}_{T5}^*)$	Im $\left(\rho_2^T\right)$
SM ⊗ SM'	✓	✓	✓	✓	Im (ρ_2)
all	$\frac{M_{K^*}^2}{Q^2} \rho_1^T$	Re $(\mathcal{C}_{T5} \Delta_S^*)$	$\frac{M_{K^*}}{Q}$ Im $\left(\rho_2^{(T)}\right)$	Im $(\mathcal{C}_{T5} \Delta_S^*)$	Im $\left(\rho_2^{(T)}\right)$

$$\rho_1^T \sim |\mathcal{C}_T|^2 + |\mathcal{C}_{T5}|^2 \qquad \rho_2^T \sim \mathrm{Re}\,(\mathcal{C}_T \mathcal{C}_{T5})$$

$$\Delta_S = \mathcal{C}_S - \mathcal{C}_{S'} \qquad Q = m_b, \sqrt{q^2}$$

Factorization

Scenario	$H_T^{(1)}$	$H_T^{(2)}$	$H_T^{(3)}$	$H_T^{(4)}$	$H_T^{(5)}$
SM	✓	✓	✓	—	—
SM $\otimes$ S, P	✓	A_0	✓	—	—
SM $\otimes$ T, T5	✓	✓	✓	✓	✓
SM $\otimes$ SM'	✓	✓	✓	✓	✓
all	✓	A_0	✓	✓	✓

—: vanishes in that scenario

✓: form factor free up to m_ℓ / Q

A_0: factorization broken by terms $\propto A_0$

Overview

Global Fit [Beaujean/Bobeth/DvD/Wacker '12]

Method [see also Dissertation Beaujean '12]

Black Box!

- explore with Markov Chain Monte Carlo
- group samples with Hierarchical Clustering
- sample efficiently with Population Monte Carlo [Kilbinger et al. '09]

see also talk on sampling in high-dimensional spaces (informal seminar)

Implementation

- EOS: C++, open source GPLv2
- programs for evaluation of observables, uncertainties, fits
- available via

  `http://project.het.physik.tu-dortmund.de/eos/source`

Inputs

Exclusive Decays

- $\bar{B} \to \bar{K}^* \ell^+ \ell^-$, large & low recoil
  observables: $\mathcal{B} = \tau_B \Gamma$, A_{FB}, F_{L}, $A_T^{(2)}$, S_3
  experiments: BaBar, Belle, CDF, LHCb, several bins each
- $\bar{B} \to \bar{K} \ell^+ \ell^-$, large & low recoil
  observables: $\mathcal{B}$ several bins each experiments: BaBar, Belle, CDF (LHCb is now available!)
- $B_s \to \mu^+ \mu^-$
  observable: $\mathcal{B}(t = 0)$ (see [de Bruyn et al. '12]) experiment: combination ATLAS+CMS+LHCb (best upper bound to date)
- $B^0 \to K^{*0} (\to K_S \pi^0) \gamma$
  observable: $\mathcal{B}, S_{K^*\gamma}, C_{K^*\gamma}$
  experiment: CLEO, BaBar, Belle

Parameters

Interest: $\mathcal{C}_{7,9,10}$

3 real valued parameters, flat prior

Nuisance: Subleading Contributions

one factor per amplitude (6) per kinematic region (12 altogether), gaussian prior

Nuisance: Hadronic Parameters

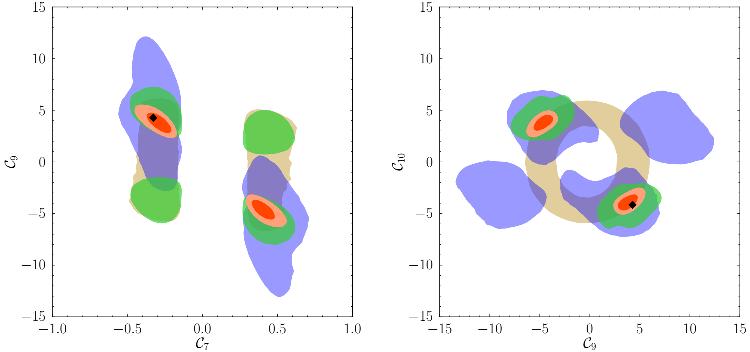
- $B \to K^*$ form factors (BZ2004: V, A_1, A_2), gaussian prior
- $B \to K$ form factors (KMPW2010: f_+), gaussian prior
- decay constant f_{B_s}, gaussian prior

Nuisance: CKM Wolfenstein Parameters

input from UTfit, tree level results, **uncorrelated** gaussian prior

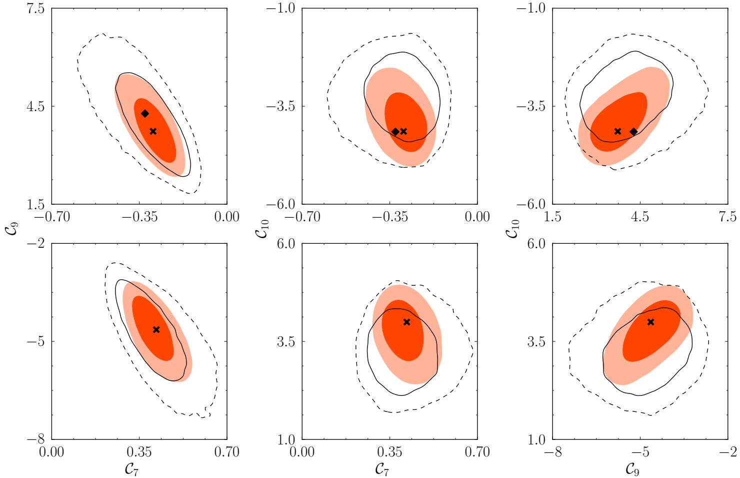
Results for Parameters of Interest

95% credibility regions



all regions include $B \to K^*\gamma$ inputs brown incl. $B \to K\ell^+\ell^-$ (high + low)
blue incl. $B \to K^*\ell^+\ell^-$ (low) green incl. $B \to K^*\ell^+\ell^-$ (high)
light red all data + $B_s \to \mu^+\mu^-$ dark red same at 65%

Results for Different Sets of Priors



color: normal priors (dark: 68%, light: 95%)
lines: wide priors (solid: 68%, dashed: 95%) diamond: SM, cross: MAP

Results for Parameters of Interest

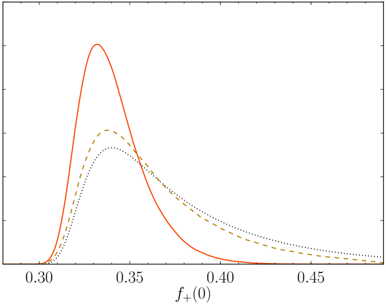
	$\mathcal{C}_7$	$\mathcal{C}_9$	$\mathcal{C}_{10}$
68%	$[-0.34, -0.23] \cup [0.35, 0.45]$	$[-5.2, -4.0] \cup [3.1, 4.4]$	$[-4.4, -3.4] \cup [3.3, 4.3]$
95%	$[-0.41, -0.19] \cup [0.31, 0.52]$	$[-5.9, -3.5] \cup [2.6, 5.2]$	$[-4.8, -2.8] \cup [2.7, 4.7]$
max	$-0.28 \cup 0.40$	$-4.56 \cup 3.64$	$-3.92 \cup 3.86$
68%	$[-0.39, -0.19] \cup [0.30, 0.48]$	$[-5.6, -3.8] \cup [2.9, 5.1]$	$[-4.0, -2.5] \cup [2.6, 3.9]$
95%	$[-0.53, -0.13] \cup [0.24, 0.61]$	$[-6.7, -3.1] \cup [2.2, 6.2]$	$[-4.7, -1.9] \cup [2.0, 4.6]$
max	$-0.30 \cup 0.38$	$-4.64 \cup 3.84$	$-3.24 \cup 3.30$

upper: normal priors
lower: wide priors

Very good agreement with the SM!
From 59 exper. inputs, only one pull $> 2\sigma$! ($\mathcal{B}[B \to K^* \ell^+ \ell^-]_{>16}$ Belle)

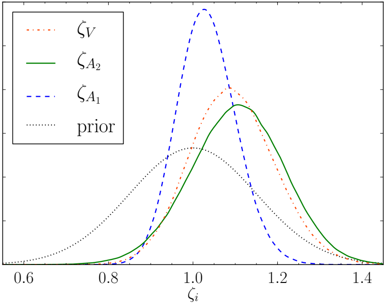
Results for Nuisance Parameters

$B \to K\ell^+\ell^-$



$f_+(q^2)$ form factor, two parameters, z parametrisation
dotted: prior
dashed: only $B \to K\ell^+\ell^-$ data
solid: all data

$B \to K^*\ell^+\ell^-$



$V(q^2) \to \zeta_V V(q^2)$, etc.
considerable shifts ($\sim 10\%$) in V and A_2!

Conclusion

Low Recoil

- systematic framework, rich phenomenology
- large number of stable relations between $H_T^{(i)}$
- framework/OPE can be probed
- LHCb providing more data, looking forward to Super Flavor Factories

Global Fit

- best fit close to SM, within 1σ, SM wins over model-independent fit
- extract information about form factors, subleading contributions
- slight tension between $B \to K$ and $B \to K^*$ form factors $\sim 10\%$
- inclusive decays $B \to X_s \ell^+ \ell^-$, $B \to X_s \gamma$ w.i.p.

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CP Asymmetries at Low Recoil

Optimized CP Asymmetries

$$a_{\mathrm{CP}}^{(1)} = A_{\mathrm{CP}} = \frac{\rho_1 - \bar{\rho}_1}{\rho_1 + \bar{\rho}_1} \qquad a_{\mathrm{CP}}^{(2)} = A_{\mathrm{CP,FB}} = \frac{\frac{\rho_2}{\rho_1} - \frac{\bar{\rho}_2}{\bar{\rho}_2}}{\frac{\rho_2}{\rho_1} + \frac{\bar{\rho}_2}{\bar{\rho}_2}}$$

$$a_{\mathrm{CP}}^{(3)} = \frac{\mathrm{Re}\left(\rho_2 - \bar{\rho}_2\right)}{\rho_1 + \bar{\rho}_1} \sim H_T^{(2,3)} \qquad a_{\mathrm{CP}}^{(4)} = \frac{\mathrm{Im}\left(\rho_2 - \bar{\rho}_2\right)}{\rho_1 + \bar{\rho}_1} \sim H_T^{(4,5)}$$

driven by

$$\mathrm{Im}\,(Y) = \mathrm{Im}\left(Y_9 + \kappa \frac{2 m_b M_B}{q^2} Y_7\right)$$

compare

$$\mathcal{C}_{7,9}^{\mathrm{eff}} = \mathcal{C}_{7,9} + Y_{7,9}$$

Y at Low Recoil