Phenomenology of exclusive rare semileptonic decays

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Theor. Physik 1

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Program

- concentrate on $\bar{B} \to (\bar{K}\pi)_P \ell^+\ell^-$, i.e, on the $\bar{K}^*$ resonance
- discuss influence of $\bar{B} \to (\bar{K}\pi)_S \ell^+\ell^-$ on the decay distribution
- review methods to approach theory on both sides of the narrow charmonia (J/ψ and ψ')
- constrain $\Delta B = 1$ Wilson coefficients from available data on exclusive rare semileptonic and radiative decays

Effective Field Theory for $b \to s\ell^+\ell^-$ FCNCs

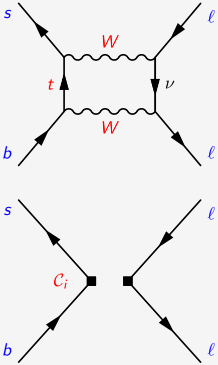
Flavor Changing Neutral Current (FCNC)

- expand amplitudes in $G_\mathrm{F} \sim 1/M_W^2$ (OPE)
- basis of operators (physics below $\mu \simeq m_b$)

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

- Wilson coefficients (physics above $\mu \simeq m_b$)

$$\mathcal{C}_i \equiv \mathcal{C}_i(M_W, M_Z, m_t, \dots)$$



Effective Hamiltonian

$$\mathcal{H} = -\frac{4G_\mathrm{F}}{\sqrt{2}}\left[V_{tb}V_{ts}^* \sum_i \mathcal{C}_i \mathcal{O}_i + O\left(V_{ub}V_{us}^*\right)\right] + \text{h.c.}$$

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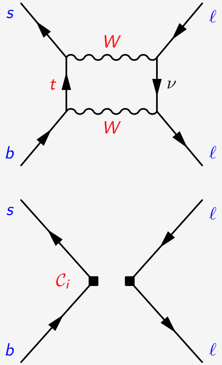


Exclusive Modes

$\bar{B}^0 \to \bar{K}^{(*)0}\ell^+\ell^-$ $\quad$ $\bar{B}_s \to \phi\ell^+\ell^-$ $\quad$ $\Lambda_b^0 \to \Lambda^0\ell^+\ell^-$

$B^- \to \bar{K}^{(*)-}\ell^+\ell^-$ $\quad$ $\Lambda_b^- \to \Lambda^-\ell^+\ell^-$

Model Independent Framework

Wilson Coefficients $\mathcal{C}_i$

- treat $\mathcal{C}_i$ as uncorrelated, generalized couplings
- constrain their values from data
- confront new physics models with constraints
- complex value, two d.o.f. per $\mathcal{C}_i$ $\Rightarrow$ BSM CPV (SM: real $\mathcal{C}_i$)

Basis of Operators $\mathcal{O}_i$

- should include all relevant $\mathcal{O}_i$, otherwise constraints are biased
- should include as few $\mathcal{O}_i$ as needed, otherwise fits are too involved
- balancing act, test statistically if choice of basis describes data well!

Basis of Operators (semileptonic)

Semileptonic Operators (SM-like: $9, 10$ chirality-flipped: $9', 10'$)

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

$+$ strong/EM penguins as in the SM

Semileptonic Operators ((pseudo-)scalar: $S('), P(')$ tensor: $T, T5$)

complete the basis of $[\bar{s}\Gamma b][\bar{\ell}\Gamma \ell]$ operators

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

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

Basis of Operators (current-current & penguins)

Current-Current

$$\mathcal{O}_1 = \left[\bar{s}\gamma_\mu P_L T^a c\right]\left[\bar{c}\gamma^\mu P_L T^a b\right] \qquad \mathcal{O}_2 = \left[\bar{s}\gamma_\mu P_L c\right]\left[\bar{c}\gamma^\mu P_L b\right]$$

SM: $\mathcal{C}_1 \simeq -0.3$, $\mathcal{C}_2 \simeq 1$

Penguins (photonic: $7(')$ gluonic: $8(')$ $\bar{q}q$: 3-6)

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

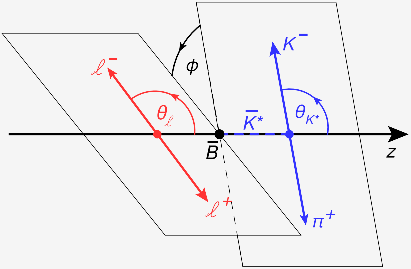
$$\mathcal{O}_3 = \left[\bar{s}\gamma_\mu P_L b\right]\left[\bar{q}\gamma^\mu q\right] \qquad \mathcal{O}_4 = \left[\bar{s}\gamma_\mu T^a P_L b\right]\left[\bar{q}\gamma^\mu T^a q\right]$$

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

$\gamma_{\mu\nu\rho} \equiv \gamma_\mu\gamma_\nu\gamma_\rho$

- $\mathcal{O}_{7(')}$ dominant when dilepton system is almost lightlike
- QED Penguins usually not included
- QCD Penguins ($\mathcal{O}_{3\ldots6}$) usually as in the SM, small Wilson coefficients

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

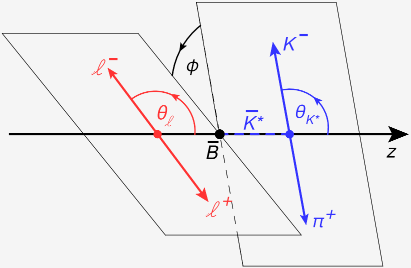


Kinematic Variables

$$4m_\ell^2 \leq q^2 \leq (M_B - M_{K^*})^2$$
$$-1 \leq \cos\theta_\ell \leq 1$$
$$-1 \leq \cos\theta_{K^*} \leq 1$$
$$0 \leq \phi \leq 2\pi$$
$$\left[(M_K + M_\pi)^2 \leq k^2 \leq (M_B - \sqrt{q^2})^2\right]$$

On-shell and S-Wave

- one usually assumes on-shell decay of P-wave K^* ($\sim \sin\theta_{K^*}, \cos\theta_{K^*}$)
- for high precision: consider width of K^*, and $J = 0$ (S-wave) ($\not\sim \theta_{K^*}$) $K\pi$-final-state from K_0^* and *non-resonant background*



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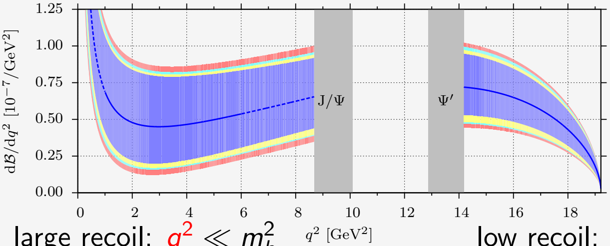
Large vs. Low Recoil (for illustration)



large recoil: $q^2 \ll m_b^2$ low recoil: $q^2 \simeq m_b^2$

Angular Distribution [Krüger/Matias '05, Altmannshofer et al. '08]

Differential Decay Rate for pure P-wave state

$$
\begin{aligned}
\frac{\mathrm{d}^4\Gamma}{\mathrm{d}q^2 \mathrm{d}\cos\theta_\ell \mathrm{d}\cos\theta_{K^*} \mathrm{d}\phi} \sim\ & J_{1s} \sin^2\theta_{K^*} + J_{1c} \cos^2\theta_{K^*} \\
& + (J_{2s} \sin^2\theta_{K^*} + J_{2c} \cos^2\theta_{K^*}) \cos 2\theta_\ell \\
& + (J_3 \cos 2\phi + J_9 \sin 2\phi) \sin^2\theta_{K^*} \sin^2\theta_\ell \\
& + (J_4 \sin 2\theta_{K^*}) \sin 2\theta_\ell \cos\phi \\
& + (J_5 \sin 2\theta_{K^*}) \sin\theta_\ell \cos\phi \\
& + (J_{6s} \sin^2\theta_{K^*} + J_{6c} \cos^2\theta_{K^*}) \cos\theta_\ell \\
& + (J_7 \sin 2\theta_{K^*}) \sin\theta_\ell \sin\phi \\
& + (J_8 \sin 2\theta_{K^*}) \sin 2\theta_\ell \sin\phi\,,
\end{aligned}
$$

$J_i \equiv J_i(q^2)$: 12 angular observables

Angular Distribution [Krüger/Matias '05, Altmannshofer et al. '08, Blake/Egede/Shires '12]

Differential Decay Rate for mixed P- and S-wave state

$$\frac{d^4\Gamma}{dq^2 d\cos\theta_\ell d\cos\theta_{K^*} d\phi} \sim J_{1s}\sin^2\theta_{K^*} + J_{1c}\cos^2\theta_{K^*} + J_{1i}\cos\theta_{K^*}$$
$$+ (J_{2s}\sin^2\theta_{K^*} + J_{2c}\cos^2\theta_{K^*} + J_{2i}\cos\theta_{K^*})\cos 2\theta_\ell$$
$$+ (J_3\cos 2\phi + J_9\sin 2\phi)\sin^2\theta_{K^*}\sin^2\theta_\ell$$
$$+ (J_4\sin 2\theta_{K^*} + J_{4i}\cos\theta_{K^*})\sin 2\theta_\ell\cos\phi$$
$$+ (J_5\sin 2\theta_{K^*} + J_{5i}\cos\theta_{K^*})\sin\theta_\ell\cos\phi$$
$$+ (J_{6s}\sin^2\theta_{K^*} + J_{6c}\cos^2\theta_{K^*})\cos\theta_\ell$$
$$+ (J_7\sin 2\theta_{K^*} + J_{7i}\cos\theta_{K^*})\sin\theta_\ell\sin\phi$$
$$+ (J_8\sin 2\theta_{K^*} + J_{8i}\cos\theta_{K^*})\sin 2\theta_\ell\sin\phi\,,$$

$J_i \equiv J_i(q^2, k^2)$: 12 angular observables, no further needed [Bobeth/Hiller/DvD '12]

Conclusion: remove S-wave in exp. analysis

- angular analysis [Egede/Blake/Shires '12]
- side-band analysis (for $J_{1s,1c,2s,2c}$) [Bobeth/Hiller/DvD '12]

Building Blocks of the Angular Observables (I)

Form Factors (P-Wave)

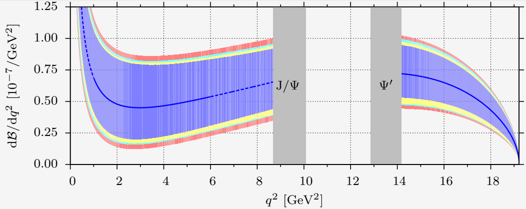
- hadronic matrix elements $\langle \bar{K}^* | \bar{s} \Gamma b | \bar{B} \rangle$ parametrized through 7 form factors:

$$\langle \bar{K}^* | \bar{s}\gamma^\mu b | \bar{B} \rangle \sim V \quad \langle \bar{K}^* | \bar{s}\gamma^\mu \gamma_5 b | \bar{B} \rangle \sim A_{0,1,2} \quad \langle \bar{K}^* | \bar{s}\sigma^{\mu\nu} b | \bar{B} \rangle \sim T_{1,2,3}$$

- form factors largest source of theory uncertainty
  amplitude $\sim 10\% - 15\% \Rightarrow$ observables: $\sim 20\% - 50\%$
  - available from Light Cone Sum Rules [Ball/Zwicky '04, Khodjamirian et al. '11]
  - Lattice QCD: work in progress [e.g. Liu et al. '11, Wingate '11]
  - extract ratios from low recoil data

    [Hambrock/Hiller '12, Beaujean/Bobeth/DvD/Wacker '12]

blue band:
form factor uncertainty



Building Blocks of the Angular Observables (II)

Transversity amplitudes A_i

- SM-like + chirality flipped: essentially four amplitudes $A_{\perp,\parallel,0,t}$ [Krüger/Matias '05]
- $\mathcal{O}_{S(')}$ give rise to A_S, $\mathcal{O}_{P(')}$ absorbed by A_t [Altmannshofer et al. '08]
- $\mathcal{O}_{T(5)}$ give rise to *6 new* amplitudes A_{ab}, (ab)=$(0t)$,$(\parallel\perp)$,$(0\perp)$,$(t\perp)$,$(0\parallel)$,$(t\parallel)$ [Bobeth/Hiller/DvD '12]
- altogether: 11 complex-valued amplitudes

Angular Observables

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

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

β_ℓ: lepton velocity in dilepton rest frame $m_\ell^2/q^2 \to 0 \Rightarrow \beta_\ell \to 1$

"Standard" Observables

considerable theory uncertainty due to form factors

Batch #1, to be extracted from CP average

$$\langle\Gamma\rangle = \langle 2J_{1s} + J_{1c} - \frac{2}{3}J_{2s} - \frac{1}{3}J_2c\rangle \qquad \langle A_{\rm FB}\rangle = \frac{\langle 2J_{6s} + J_{6c}\rangle}{2\langle\Gamma\rangle}$$

$$\langle F_L\rangle = \frac{\langle 3J_{1c} - J_2c\rangle}{\langle 3\Gamma\rangle} \qquad \langle F_T\rangle = \frac{\langle 6J_{1s} - 2J_{2s}\rangle}{\langle 3\Gamma\rangle}$$

Γ: decay width $A_{\rm FB}$: forward-backward asymm. $F_L = 1 - F_T$: long./trans. pol.

Batch #2, CP (a)symmetries [Bobeth/Hiller/Piranishvili '08, Altmannshofer et al. '08]

$$\langle A_i\rangle \sim \frac{\langle J_i - \overline{J_i}\rangle}{\langle\Gamma + \bar\Gamma\rangle} \qquad \langle S_i\rangle \sim \frac{\langle J_i + \overline{J_i}\rangle}{\langle\Gamma + \bar\Gamma\rangle}$$

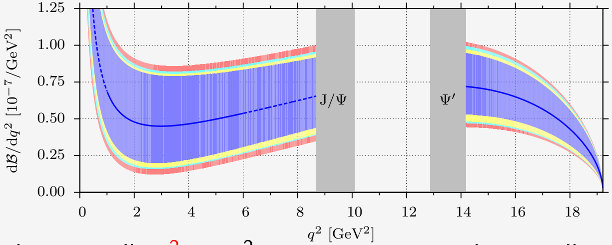
overline: CP conjugated mode, also: mixing-induced CP asymm in $B_s \to \phi\ell^+\ell^-$

$\langle X\rangle \equiv \int {\rm d}q^2\, X(q^2)$

Pollution due to Charm Resonances

Narrow Resonances: J/ψ and $\psi(2s)$

- experiments veto q^2-region of narrow charmonia J/ψ and $\psi(2s)$
- however: resonance affects observables outside the veto!



large recoil: $q^2 \ll m_b^2$ low recoil: $q^2 \simeq m_b^2$

Approach by Theorists: Divide and Conquer

- treat region below J/ψ (aka *large recoil*) differently than above $\psi(2s)$
- design combinations of J_i which have reduced theory uncertainty in only one kinematic region

Large Recoil (I)

QCD Factorization (QCDF) + Soft Collinear Effective Theory (SCET)

- calculate $\bar{q}q$ loops perturbatively, expand in $1/m_b$, $1/E_{K^*}$
- relate matrix elements to universal hadronic quantities:
  - Light Cone Distribution Amplitudes (LCDAs)
  - form factors
  - decay constants

[Beneke/Feldmann '00, Beneke/Feldmann/Seidel '01 & '04]

Light Cone Sum Rules (LCSR)

- calculate $\langle \bar{c}c \rangle$, $\langle \bar{c}cG \rangle$ on the light cone for $q^2 \ll 4m_c^2$
- achieves resummation of soft gluon effects
- use analycity of amplitude to relate results to $q^2 < M_{\psi'}^2$
- uses many of the same inputs as QCDF+SCET
- includes parts of QCDF+SCET results

[Khodjamirian/Mannel/Pivovarov/Wang '11]

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QCD Factorization (QCDF) + Soft Collinear Effective Theory (SCET)

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- relate matrix elements to universal hadronic quantities:
  - Light Cone Distribution Amplitudes (LCDAs)
  - form factors
  - decay constants

[Beneke/Feldmann '00, Beneke/Feldmann/Seidel '01 & '04]

Combination of QCDF+SCET and LCSR Results

- not yet!
  - no studies yet to find impact on optimized observables at large recoil!
  - LCSR results are not included in following discussion

Large Recoil (II)

SM + chirality flipped

- transversity amplitudes factorize up to power supressed terms

$$A_\perp^{L,R} \sim X_\perp^{L,R} \times \xi_\perp \qquad A_\parallel^{L,R} \sim X_\parallel^{L,R} \times \xi_\perp \qquad A_0^{L,R} \sim X_0^{L,R} \times \xi_\parallel$$

$\xi_{\perp,\parallel}$: soft form factors $\qquad X_i^{L,R}$: combinations of Wilson coefficients

[Beneke/Feldmann/Seidel '01 & '04, Bobeth/Hiller/Piranishvili '08, Altmannshofer et al. '08]

Optimized Observables

enhanced sensitivity to right-handed currents, reduced form factor dependence

[Krüger/Matias '05, Egede et al. '08 & '10]

$$A_T^{(2)} = \frac{|A_\perp|^2 - |A_\parallel|^2}{|A_\perp|^2 + |A_\parallel|^2} \sim J_3 \qquad A_T^{(3)} = \frac{|A_0^L A_\parallel^{L*} + A_0^{R*} A_\parallel^R|}{\sqrt{|A_0|^2 |A_\parallel|^2}} \sim J_4, J_7$$

$$A_T^{(4)} = \frac{|A_0^L A_\perp^{L*} - A_0^{R*} A_\perp^R|}{\sqrt{|A_0|^2 |A_\perp|^2}} \sim J_5, J_8 \qquad A_T^{(5)} = \frac{|A_\perp^L A_\parallel^{R*} + A_\perp^{R*} A_\parallel^L|}{|A_\perp|^2 + |A_\parallel|^2}$$

Large Recoil (II)

SM + chirality flipped

- transversity amplitudes factorize up to power supressed terms

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[Beneke/Feldmann/Seidel '01 & '04, Bobeth/Hiller/Piranishvili '08, Altmannshofer et al. '08]

Further Optimized Observables

enhanced sensitivity to right-handed currents, reduced form factor dependence

[Becirevic/Schneider '11]

$$A_T^{(\mathrm{re})} \propto \frac{J_{6s}}{J_{2s}} \qquad A_T^{(\mathrm{im})} \propto \frac{J_9}{J_{2s}}$$

Low Recoil

SM basis [Bobeth/Hiller/DvD '10] + chirality flipped [Bobeth/Hiller/DvD '12]

- transversity amplitudes factorize

$$A_{\perp,\parallel,0}^{L,R} \sim C_{\pm}^{L,R} \times f_{\perp,\parallel,0} + O\left(\frac{\alpha_s \Lambda}{m_b}, \frac{\mathcal{C}_7 \Lambda}{\mathcal{C}_9 m_b}\right) \quad \text{SM:} \quad C_{+}^{L,R} = C_{-}^{L,R}$$

f_i: helicity form factors $\qquad C_{\pm}^{L,R}$: combinations of Wilson coeff.

- 4 combinations of Wilson coefficients enter observables:

$$\rho_1^{\pm} \sim |C_{\pm}^{R}|^2 + |C_{\pm}^{L}|^2$$

$$\text{Re}\left(\rho_2\right) \sim \text{Re}\left(C_{+}^{R} C_{-}^{R*} - C_{-}^{L} C_{+}^{L*}\right) \quad \text{and } \text{Re}\left(\cdot\right) \leftrightarrow \text{Im}\left(\cdot\right)$$

Tensor operators [Bobeth/Hiller/DvD '12]

- 6 new transversity amplitudes, still factorize!

$$A_{ab} \sim \mathcal{C}_{T(T5)} \times f_{\perp,\parallel,0} + O\left(\frac{\Lambda}{m_b}\right)$$

- 3 new combinations of Wilson coefficients

$$\rho_1^{T} \sim |\mathcal{C}_T|^2 + |\mathcal{C}_{T5}|^2 \qquad \text{Re}\left(\rho_2^{T}\right) \sim \text{Re}\left(\mathcal{C}_T \mathcal{C}_{T5}^{*}\right) \quad \text{and } \text{Re}\left(\cdot\right) \leftrightarrow \text{Im}\left(\cdot\right)$$

Optimized Observables at Low Recoil

"Form Factor Free" Observables

- optimized for low recoil: $H_T^{(1,2,3,4,5)}$ [Bobeth/Hiller/DvD '10 & '12]
- $H_T^{(1)}$: probes low-recoil framework before new physics
- $H_T^{(2,3,4,5)}$: access to combination of Wilson coefficients

$$\rho_2 / \sqrt{\rho_1^+ \rho_1^-} \quad \underset{\text{SM basis}}{\longrightarrow} \quad \frac{\mathcal{C}_9 \mathcal{C}_{10}}{|\mathcal{C}_9|^2 + |\mathcal{C}_{10}|^2}$$

up to $O\left(\frac{\alpha_s \Lambda}{m_b}, \frac{\mathcal{C}_7 \Lambda}{\mathcal{C}_9 m_b}\right)$ corrections, complementary to large recoil

"Short-Distance Free" Observables

- form factor ratios, relevant for comparison with lattice
- SM: all ratios f_i / f_j available, chirality-flipped: only $f_0 / f_\parallel$

CP Asymmetries at Low Recoil

Optimized CP Asymmetries (SM-like and chirality-flipped basis)

$$a_{\rm CP}^{(1,\pm)} = \frac{\rho_1^\pm - \bar\rho_1^\pm}{\rho_1^\pm + \bar\rho_1^\pm} \xrightarrow[\text{SM basis}]{} A_{\rm CP} \qquad a_{\rm CP}^{(2,\pm)} = \frac{\frac{\rho_2}{\rho_1^\pm} - \frac{\bar\rho_2}{\bar\rho_1^\pm}}{\frac{\rho_2}{\rho_1^\pm} + \frac{\bar\rho_2}{\bar\rho_1^\pm}} \xrightarrow[\text{SM basis}]{} A_{\rm CP,FB}$$

$$a_{\rm CP}^{(3)} = \frac{\mathrm{Re}\,(\rho_2 - \bar\rho_2)}{\sqrt{(\rho_1^+ + \bar\rho_1^+)(\rho_1^- + \bar\rho_1^-)}} \sim H_T^{(2,3)} \qquad a_{\rm CP}^{(4)} = \frac{\mathrm{Im}\,(\rho_2 - \bar\rho_2)}{\sqrt{(\rho_1^+ + \bar\rho_1^+)(\rho_1^- + \bar\rho_1^-)}} \sim H_T^{(4,5)}$$

- driven by strong phase $\mathrm{Im}\,(Y)$

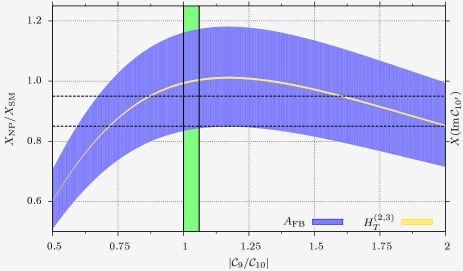
$$\mathrm{Im}\,(Y) = \mathrm{Im}\left(Y_9 + \frac{2m_b M_B}{q^2} Y_7\right) \qquad Y_i \equiv \mathcal{C}_i^{\rm eff} - \mathcal{C}_i$$

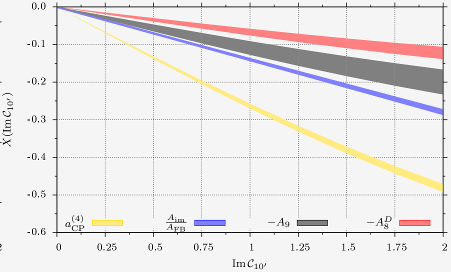
  low recoil OPE predicts $\mathrm{Im}\,(Y) \simeq 0.2$ for $q^2 \geq 14\mathrm{GeV}^2$

- also: $A_{\rm im}/A_{\rm FB} = J_9/J_{6s} = \mathrm{Im}\,(\rho_2)\,/\,\mathrm{Re}\,(\rho_2)$
  both $A_{\rm im}$ and $A_{\rm FB}$ measured, but error on ratio not known

Probing BSM Physics at Low Recoil

Sensitivity Studies for NP only in $\mathcal{C}_{9,10(\prime)}$





Results [Bobeth/Hiller/DvD '12]

- $H_T^{2,3}$ probe $|\mathcal{C}_9/\mathcal{C}_{10}|$ better than $A_{\rm FB}$
- $a_{\rm CP}^{(4)}$ probes $\mathrm{Im}\left(\mathcal{C}_{10'}\right)$ better than other CP asymm.

$$\left\langle a_{\rm CP}^{(4)} \right\rangle \simeq (-0.240 \pm 0.005)\,\mathrm{Im}\left(\mathcal{C}_{10'}\right)$$

Global Analyis of Exclusive Decays

Global Analyis of Exclusive Decays

- following results from [Beaujean/Bobeth/DvD/Wacker '12]
- see also further analyses [Altmannshofer/Straub '12, Descotes-Genon et al. '12]

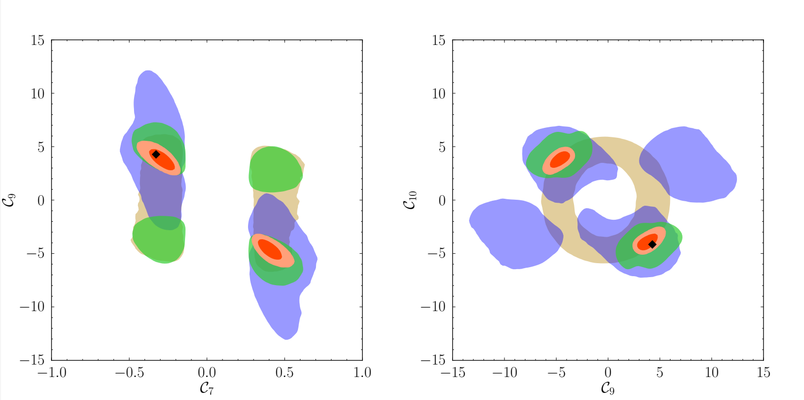
Available Data for Exclusive Processes

$\bar{B} \to \bar{K}^* \ell^+ \ell^-$	$\mathcal{B}, A_{\rm FB}, S_3, A_T^{(2)}, A_I$	BaBar,Belle,CDF,LHCb
$\bar{B} \to \bar{K} \ell^+ \ell^-$	$\mathcal{B}, A_{\rm FB}, F_H, A_I$	BaBar,Belle,CDF,LHCb
$\bar{B} \to \bar{K}^* \gamma$	$\mathcal{B}, S_{K^*\gamma}$	CLEO,BaBar,Belle
$\bar{B}_s \to \mu^+ \mu^-$	upper bound on $\mathcal{B}$	LHCb

blue observables: used in following analysis
orange:new data available since analysis

Global Analysis of Exclusive $b \to s\{\ell^+\ell^-, \gamma\}$

95% credibility regions: Two Solutions



all regions include $B \to K^*\gamma$ inputs

brown incl. $B \to K\ell^+\ell^-$ (high + low)

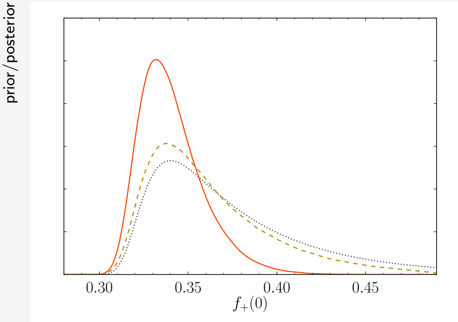
blue incl. $B \to K^*\ell^+\ell^-$ (low)

green incl. $B \to K^*\ell^+\ell^-$ (high)

light red all data + $B_s \to \mu^+\mu^-$ (dark red 68%)

◆ SM value

What We Also Learn from Data



dotted: prior [Khodjamirian et al. '11]

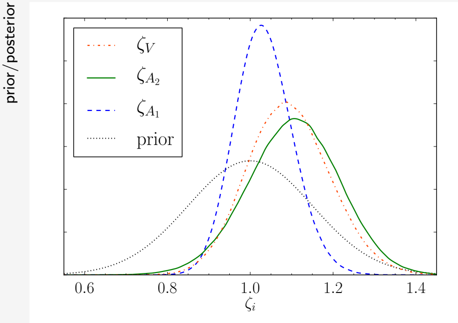
dashed: posterior w/ $B \to K\ell^+\ell^-$ data

solid: posterior w/ all data

$B \to K$ form factor: f_+

- $B \to K\ell^+\ell^-$ data and prior agree well
- $B \to K^*\ell^+\ell^-$ data has strong impact on posterior

What We Also Learn from Data



$V(q^2) \to \zeta_V V(q^2)$, similar for $A_{1,2}$

ζ_i: common gauss prior

V, A_1, A_2: [Ball/Zwicky '04]-results

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

- prior/posterior agree well for ζ_{A_1}
- considerable shifts in posterior ($\sim 10\%$) for ζ_V and ζ_{A_2}!
- agrees with findings by [Hambrock/Hiller '12]

Conclusion/Further Works

Conclusion

- systematic framework for exclusive $b \to s\ell^+\ell^-$ at large *and* low recoil
- rich phenomenology of $\bar{B} \to \bar{K}^*(\to K\pi)\ell^+\ell^-$
  - large recoil: rich spectrum of observables, good (B)SM sensitivity
  - low recoil: framework/OPE can be probed
  - low recoil: (B)SM sensitivity complementary to large recoil, very small theory uncertainty
- data also allows inference of hadronic quantities
- looking forward to LHCb analyses and the prospects of Belle II

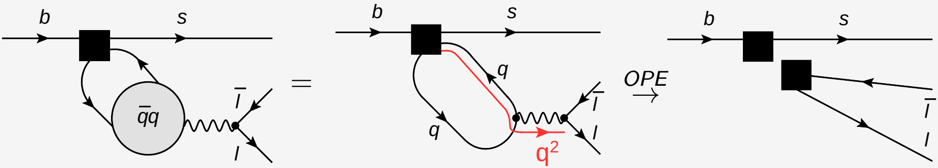
Omissions due to Time Constraints

- very large recoil: $4m_e^2 \leq q^2 \leq 1\text{GeV}^2$ [Camalich/Jäger '12]
- symmetry relations between transversity amplitudes, how to build basis of observables [Descotes-Genon et al. '13]

Backup Slides

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

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



Operators

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

$k = 4$ absent

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

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

Details on Calculation of Angular Observables

Helicity Decomposition

Use polarization vectors η (of K^*) and ε (of $\ell^+\ell^-$ state)

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

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

Transversity Amplitudes (SM-like and chirality flipped)

- introduce helicity amplitudes $H_{ab} = \eta^\dagger_\mu(a)\mathcal{M}^{\mu\nu}\varepsilon^\dagger_\nu(b)$
- four non-vanishing amplitudes: $H_{\pm\pm}, H_{00}, H_{0t}$
- switch to transversity basis:

$$\sqrt{2}A_{\perp,\parallel} = H_{++} \mp H_{--} \qquad A_0 = H_0 \qquad A_t = H_{0t}$$

- extended opterator basis $\rightarrow$ more amplitudes

Details on Calculation of Angular Observables

(Pseudo)Scalar Operators

- introduce additional form factor
- $\Rightarrow$ breaks form factor free ratios involving $J_{1c,2c}$
- only $\Delta_{S,P} \equiv \mathcal{C}_{S,P} - \mathcal{C}_{S',P'}$ enter
- $\mathcal{O}_{S(')}$ give rise to A_S, $\mathcal{O}_{P(')}$ absorbed by A_t [Altmannshofer et al. '08]

Tensor Operators

- $\mathcal{O}_{T(5)}$ give rise to *6 new* amplitudes A_{ab}, $(ab)=(0t),(\|\perp),(0\perp),(t\perp),(0\|),(t\|)$

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

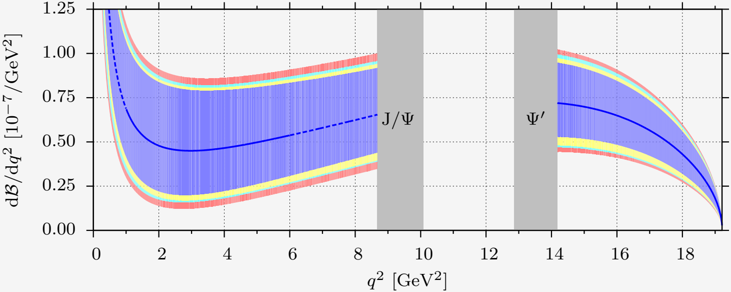
$$A_{0\perp} \sim H_{+0+} + H_{-0-} \qquad A_{0\|} \sim H_{+0+} - H_{-0-}$$

$$A_{t\perp} \sim H_{-t-} - H_{+t+} \qquad A_{t\|} \sim H_{-t-} + H_{+t+}$$

$$A_{\|\perp} \sim H_{0-+} \qquad A_{t0} \sim H_{0t0}$$

- all other H_{abc} vanish [Bobeth/Hiller/DvD '12]

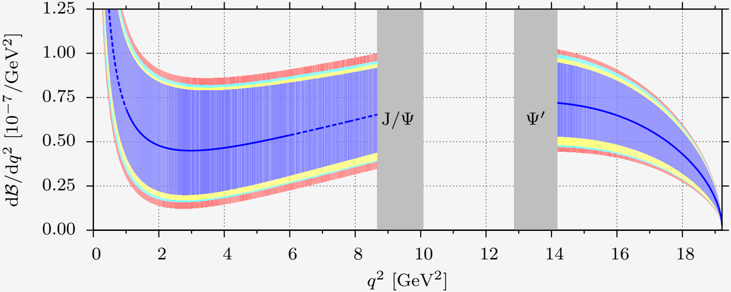
q^2 Spectrum of the Branching Ratio $\mathcal{B} = \tau_B \Gamma$



$\bar{q}q$ 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]

Beyond the SM

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	$\frac{\Lambda^2}{Q^2}\rho_1^T$	$\frac{m_\ell}{Q}$ Re $\left(\rho_2^T\right)$	$\frac{\Lambda}{Q}$ 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	$\frac{\Lambda^2}{Q^2}\rho_1^T$	Re $(\mathcal{C}_{T5}\Delta_S^*)$	$\frac{\Lambda}{Q}$ Im $\left(\rho_2^{(T)}\right)$	Im $(\mathcal{C}_{T5}\Delta_S^*)$	Im $\left(\rho_2^{(T)}\right)$

Probing the Low Recoil OPE

- deviations form $H_T^{(2)} = H_T^{(3)}$, $J_7 = 0$ signal OPE breaking
- deviations from $J_{8,9} = 0$ signal of NP (CPV right-handed current, tensors)

Beyond the SM

Status of Optimized Observables

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

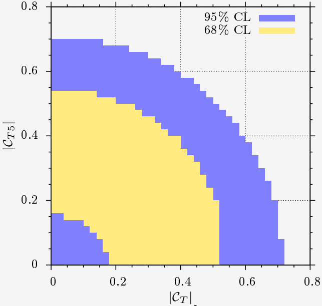
A_0 factorization broken by terms $\propto A_0$

$B \to K\ell^+\ell^-$ at Low Recoil

Observables

- $\mathcal{B}^K$, $A_{\rm FB}^K$, F_H^K (flat term)
- F_H^K sensitive to (pseudo)scalar ops. complementary to $B \to K^*\ell^+\ell^-$ and $B_s \to \ell^+\ell^-$
- correlations between $B \to K^*\ell^+\ell^- \leftrightarrow B \to K\ell^+\ell^-$, common SD factors ρ_1^+, ρ_1^T

Fit Results

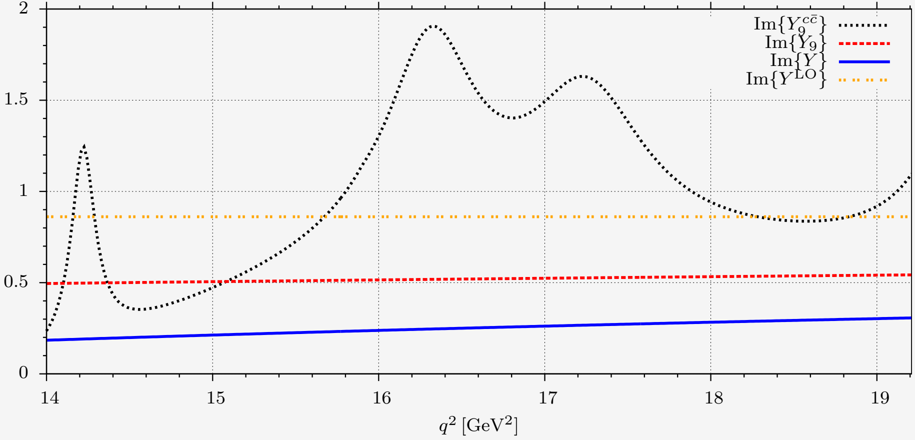


strongest constraints on $|\mathcal{C}_{T,T5}|$ to date, based on 2012 LHCb data [arXiv:1209.4284]

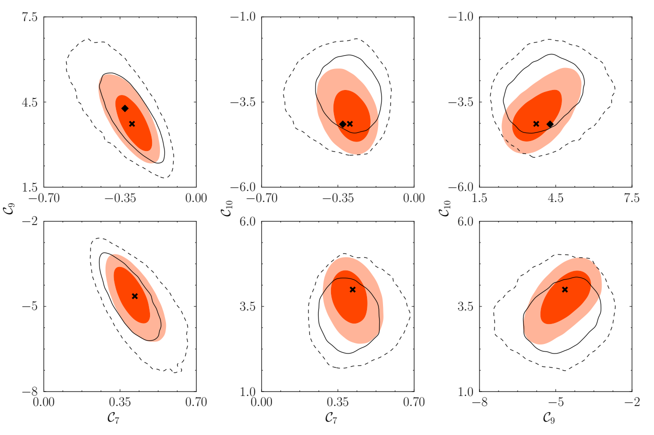
Constraints

$$|\mathcal{C}_{T,T5}| \leq 0.55\ (0.70)\ @\ 68\%\ (95\%)\ \text{CL}$$

Y at Low Recoil



Check stability for different choices of priors:



color: normal priors (dark: 68%, light: 95%)

lines: wide priors (solid: 68%, dashed: 95%)

diamond: SM, cross: MAP

[Beaujean/Bobeth/DvD/Wacker '12]

Global Analysis of Exclusive $b \to s\{\ell^+\ell^-, \gamma\}$

	$\mathcal{C}_7$	$\mathcal{C}_9$	$\mathcal{C}_{10}$
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

What We Learn

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