Hadronic form factors for rare semi-leptonic B decays

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Overview

Rare B decays and their importance

Phenomenological motivation

Theoretical Framework

B physics on the lattice

Details of the lattice calculation

First Results

Next steps

Rare B decays and their importance

- What are they?

  Decays that do not proceed through the $b \to c$ transition.
- Why are they important?

  Contributions from NP could be significant.
  Can be used to measure CP violation.
- Interested in exclusive decays with one hadronic final state
  - $b \to u$ with pseudoscalar final state (CKM suppressed)

$$B \to \pi \ell \nu \qquad B_s \to K \ell \nu$$ Previous talk by T. Kawanai

$$B \to \pi \ell^+ \ell^- \qquad B_s \to K \ell^+ \ell^-$$

  - $b \to s(u)$ with vector final state (GIM(CKM) suppressed)

$$B_s \to \phi \ell^+ \ell^- \qquad B \to K^* \ell^+ \ell^- \qquad B_s \to K^* \ell^+ \ell^-$$

- We treat the final vector state as stable
- (Far) future simulate $K^* \to K\pi$ Lellouch, Lüsher, 2000. Hansen, Sharpe, 2013

Phenomenological motivation: Why $b \to u$

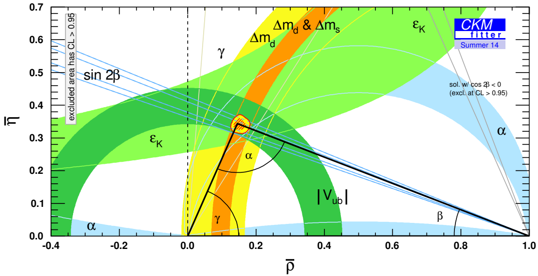
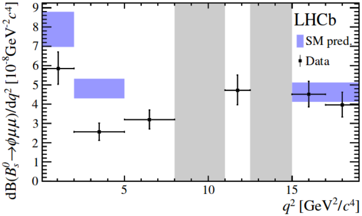


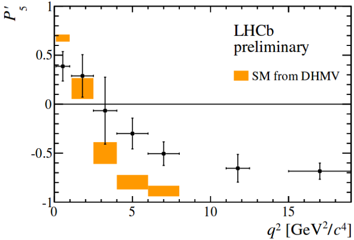
Figure from: CKMfitter Group (J. Charles et al.)

$$\frac{d\Gamma(B_s \to K^* \ell^+ \ell^-)}{dq^2} = \frac{G_F^2 |V_{ub}|^2}{192\pi^3 m_{B_s}^3} \left(\left| \frac{1}{2m_{K^*}\sqrt{q^2}} \left\{ \frac{4m_{B_s}^2 |\vec{k}|^2}{m_{B_s} + m_{K^*}} A_2(q^2) - (m_{B_s}^2 - m_{K^*}^2 - q^2)(m_{B_s} + m_{K^*}) A_1(q^2) \right\} \right|^2 + \left| (m_{B_s} + m_{K^*}) A_1(q^2) + \frac{2m_{B_s}|\vec{k}|}{m_{B_s} + m_{K^*}} V(q^2) \right|^2 + \left| (m_{B_s} + m_{K^*}) A_1(q^2) - \frac{2m_{B_s}|\vec{k}|}{m_{B_s} + m_{K^*}} V(q^2) \right|^2 \right)$$

Phenomenological motivation: Why $b \to s(d)$



$B_s^0 \to \phi\mu^+\mu^-$



$B^0 \to K^{*0}\mu^+\mu^-$

Figures from the LHCb Collaboration

- $d\Gamma(B_s \to \phi\ell^+\ell^-)/dq^2 = f(V, A_1, A_2)$
- $P'_5 = f(V, A_0, A_1, A_2, T_1, T_2, T_3)$
- Significant deviations from the Standard Model predictions
- Deviation in P'_5 suggests a new physics contribution to C_9

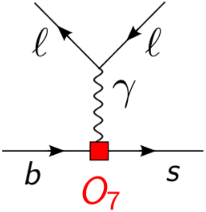
Descotes-Genon, et. al. 2013

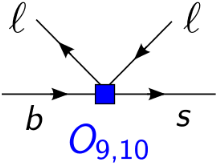
- Most calculations performed in the high recoil region
- Only one unquenched lattice QCD calculation of

$B \to K^*\ell^+\ell^-$ and $B_s \to \phi\ell^+\ell^-$ Horgan et. al. 2014

Theoretical framework: Effective Hamiltonian

$$\mathcal{H}_{\text{eff}}^{b\to s} = -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \sum_i C_i O_i$$





$$O_7^{(\prime)} = \frac{m_b e}{16\pi^2} \bar{s}\sigma^{\mu\nu} P_{R(L)} b \; F_{\mu\nu}$$

$$O_9^{(\prime)} = \frac{e^2}{16\pi^2} \bar{s}\gamma^{\mu} P_{L(R)} b \; \bar{\ell}\gamma_\mu \ell$$

$$O_{10}^{(\prime)} = \frac{e^2}{16\pi^2} \bar{s}\gamma^{\mu} P_{L(R)} b \; \bar{\ell}\gamma_\mu \gamma^5 \ell$$

Theoretical framework: Form factors

$$\langle \phi(k,\varepsilon)|\bar{\psi}\gamma^\mu b|B_s(p)\rangle = V(q^2)\frac{2i\varepsilon^{\mu\nu\rho\sigma}\varepsilon^*_\nu k_\rho p_\sigma}{m_{B_s}+m_\phi}$$

$$\begin{aligned}\langle \phi(k,\varepsilon)|\bar{\psi}\gamma^\mu\gamma_5 b|B_s(p)\rangle &= A_0(q^2)\frac{2m_\phi\varepsilon^*\cdot q}{q^2}q^\mu \\ &+ A_1(q^2)(m_{B_s}+m_\phi)\left[\varepsilon^{*\mu} - \frac{\varepsilon^*\cdot q}{q^2}q^\mu\right] \\ &- A_2(q^2)\frac{\varepsilon^*\cdot q}{m_{B_s}+m_\phi}\left[k^\mu + p^\mu - \frac{m^2_{B_s}-m^2_\phi}{q^2}q^\mu\right]\end{aligned}$$

$$q_\nu\langle \phi(k,\varepsilon)|\bar{\psi}\sigma^{\nu\mu} b|B_s(p)\rangle = T_1(q^2)4\varepsilon^{\mu\rho\tau\sigma}\varepsilon^*_\rho k_\tau p_\sigma$$

$$\begin{aligned}q_\nu\langle \phi(k,\varepsilon)|\bar{\psi}\sigma^{\nu\mu}\gamma^5 b|B_s(p)\rangle &= T_2(q^2)2i\left[\varepsilon^{*\mu}(m^2_{B_s}-m^2_\phi) - (\varepsilon^*\cdot q)(p+k)^\mu\right] \\ &+ T_3(q^2)2i(\varepsilon^*\cdot q)\left[q^\mu - \frac{q^2}{m^2_{B_s}-m^2_\phi}(p+k)^\mu\right]\end{aligned}$$

Theoretical framework: Obtaining the V form factor for $B \to \phi l^+ l^-$

Taking the ratio of three to two point functions:

$$R^{\mu\nu}_{V\mathcal{J}B}(t,T,\vec{p}_V) = \frac{C^{\mu\nu}_{VVB}(t,T,\vec{p}_V)}{\sqrt{\frac{1}{3}\sum_i C^{ii}_{VV}(t,\vec{p}_V) \times C_{BB}(T-t)}} \sqrt{\frac{4E_V m_B}{e^{-E_V t} e^{-m_B(T-t)}}}$$

$$\xrightarrow{t,T\to\infty} \sum_\lambda \epsilon_\mu(p_V,\lambda)\langle V(p_V,\lambda)|\bar{\psi}\gamma^\nu b|B(p_B)\rangle$$

and using the relation

$$\sum_\lambda \epsilon^\mu(k,\lambda)\epsilon^{\nu *}(k,\lambda) = \frac{k^\mu k^\nu}{m_V^2} - g^{\mu\nu}$$

it can be shown that in the B-meson rest frame

$$V(q^2) = \frac{i\mathcal{R}^{ji}_{VVB}(\vec{k})(m_B + m_V)}{2m_B \epsilon^{0ijk} k_k} \quad (\text{no } i,j \text{ sum})$$

B physics in the lattice

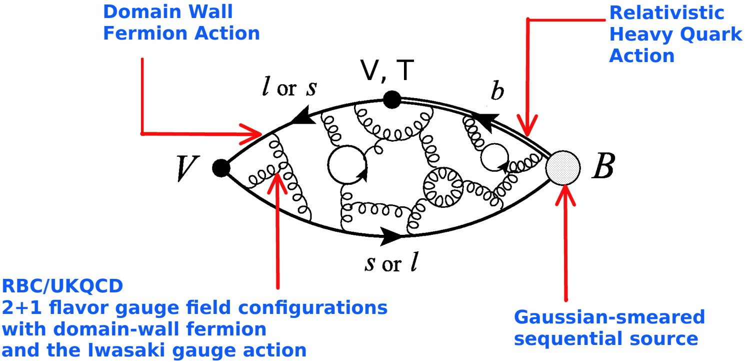
- Problem: $ma > 1$
- Solution: Adapt the lattice to describe heavy quark physics in a carefully circumscribed kinematic range El-Khadra, et. al., 1997
- How?:

The relativistic heavy quark action

$$S = \sum_n \overline{\psi}_n \left(m_0 + \gamma_0 D_0 + \zeta \vec{\gamma} \cdot \vec{D} - \frac{a}{2}(D_0)^2 - \frac{a}{2}\zeta(\vec{D})^2 + \sum_{\mu,\nu} \frac{ia}{4} c_p \sigma_{\mu\nu} F_{\mu\nu} \right) \psi_n$$

- By tuning m_0, ζ and c_p all discretization errors of order $O(|p|a)$ and $O(ma)^n$ can be removed El-Khadra, et al., 1997; S. Aoki, et al., 2001; Christ, et. al., 2006; Lin and Christ, 2006
- Nonperturbative tuning performed following Y. Aoki et al. 2012

Details of the lattice calculation

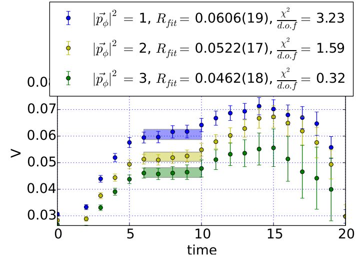


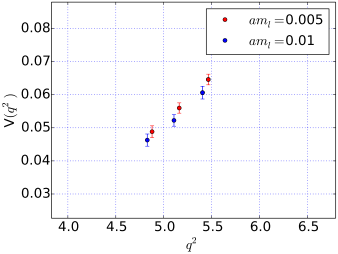
Parameters of the calculation

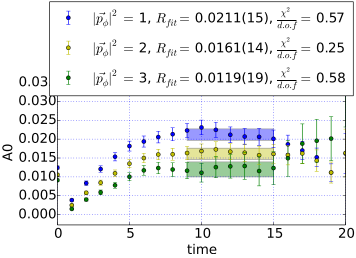
$L^3\times T$	a^{-1} [GeV]	am_l	am'_s	M_π [MeV]	total # of configs
$24^3\times 64$	1.785(5)	0.005	0.0343	338	1636
$24^3\times 64$	1.785(5)	0.01	0.0343	434	1419

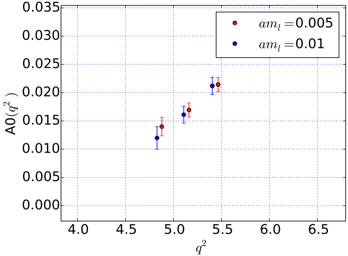
a^{-1} taken from T. Blum et. al. 2014 am'_s close to the physical strange quark mass

First results: $B_s \to \phi\ell^+\ell^-$









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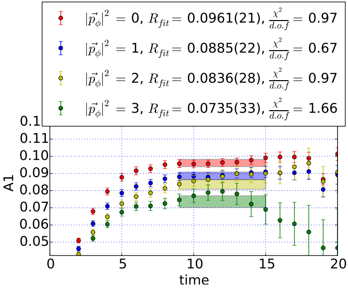

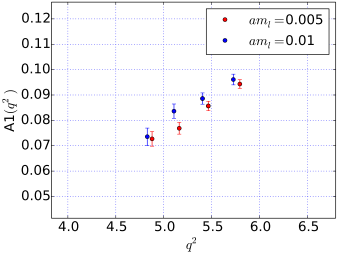

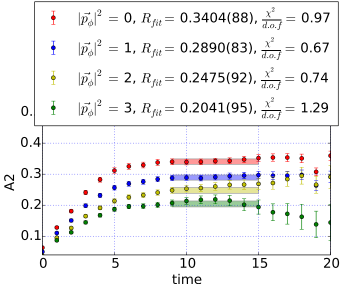

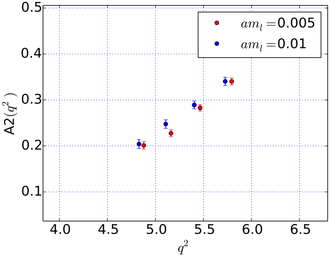

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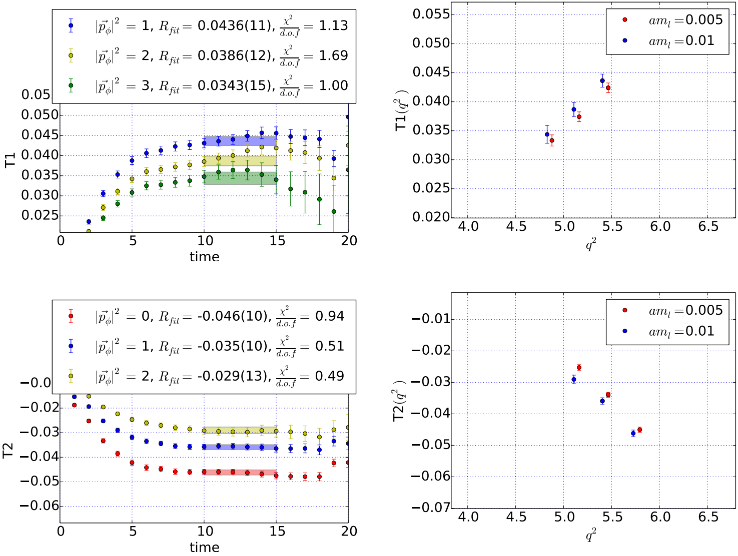

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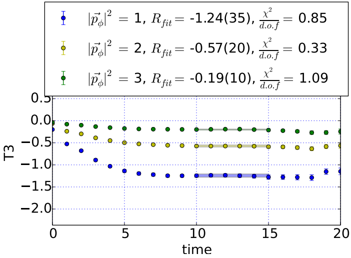

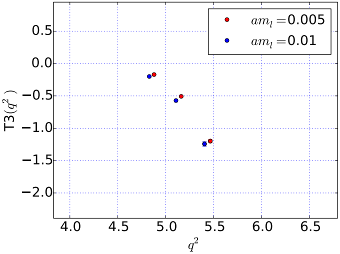

Next steps

- Implement O(a) improvement.
- Obtain results for all ensembles (finer lattice spacing, physical pions).
- Perturbative computation of heavy-light renormalization factors and coefficients for O(a) improvement.
- Combined chiral-continuum extrapolation.
- Kinematic extrapolation to low q^2 using the z-expansion.

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