Form factors for $B$ and $B_s$ semileptonic decays with NRQCD/HISQ quarks

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We discuss preliminaries of a calculation of the form factors for the semileptonic decays $B \to \pi \ell \nu$, $B_s \to K \ell \nu$, and $B \to K \ell^+ \ell^-$. We simulate with NRQCD heavy and HISQ light valence quarks on the MILC 2 + 1 dynamical asqtad configurations. The form factors are calculated over a range of momentum transfer to allow determination of their shape and the extraction of $|V_{ub}|$. Additionally, we are calculating ratios of these form factors to those for the unphysical decay $B_s \to \eta_c$. We are studying the possibility of combining these precisely determined ratios with future calculations of $B_s \to \eta_c$ using HISQ $b$-quarks to generate form factors with significantly reduced errors.
1. Motivation

We are improving upon our previous $B \to \pi \ell \nu$ calculation \cite{1} in several ways, including the use of: $b$-quark smearing; HISQ light valence-quarks with random wall sources \cite{2}; better scale-determination \cite{3}; fitting advances (e.g. simultaneous fits to multiple separation times); and the $z$-expansion \cite{4}. The calculation will also benefit from improved experimental data \cite{5} which, when combined with lattice results, determines $|V_{ub}|$.

In parallel, we are studying the $B_s \to K \ell^+ \ell^−$ decay. In combination with planned measurements \cite{6}, this will provide an additional exclusive determination of $|V_{ub}|$. Not yet studied on the lattice, this decay has a heavier spectator quark than $B \to \pi \ell \nu$ and should have reduced errors.

We are also studying $B \to K \ell^+ \ell^−$, where the flavor-changing neutral current $b \to s$ provides a probe of new physics (cf. Ref. \cite{7}). There are existing \cite{8} and promised \cite{9} experimental results for this decay, but few unquenched lattice calculations \cite{10}.

Additionally, we are investigating the possibility of using the unphysical $B_s \to \eta_s$ decay to build ratios of form factors using NRQCD $b$-quarks in which the leading sources of error largely cancel. This ratio could be combined with a future calculation of $B_s \to \eta_s$ using a HISQ $b$-quark to yield form factors with greater precision, ie.

$$\frac{f(B \to \pi \ell \nu)}{f(B_s \to \eta_s)|_{\text{NRQCD} \ b}} \times f(B_s \to \eta_s)|_{\text{HISQ} \ b},$$ (1.1)

analogous to the recent HPQCD work on $B$ and $B_s$ decay constants \cite{11}.

2. Calculation

The Standard Model $(V - A)^\mu$ weak interaction responsible for the $b \to u$ transition results in hadronic matrix elements $\langle X|V^\mu|B_q\rangle$, parameterized via form factors

$$\langle X|V^\mu|B_q\rangle = f^\mu_{+} (q^2) \left( p^\mu_B q + p^\mu_X q^2 - \frac{M^2_B - M^2_X}{q^2} q^\mu \right) + f^\mu_{0} (q^2) \frac{M^2_B - M^2_X}{q^2} q^\mu,$$ (2.1)

where $q^\mu \equiv p^\mu_B - p^\mu_X$. We recast these form factors in terms of lattice-convenient form factors,

$$\langle X|V^\mu|B_q\rangle = \sqrt{2M_{B_q}} \left[ \frac{p^\mu_B}{M_{B_q}} f^\mu_{+} (q^2) + p^\mu_X f^\mu_{0} (q^2) \right],$$ (2.2)

where $p^\mu_X \equiv p^\mu_X - (p_X \cdot p_{B_q}) p^\mu_{B_q}/M_{B_q}$. In the $B_q$-meson rest frame, the form factors are simply related to the temporal and spatial components of the hadronic vector matrix elements,

$$\langle X|V^0|B_q\rangle = \sqrt{2M_{B_q}} f^0_{\perp} (q^2)$$

$$\langle X|V^k|B_q\rangle = \sqrt{2M_{B_q}} p^k_X f^k_{\perp} (q^2).$$ (2.3)

We calculate the components of the hadronic vector matrix elements and, from them, construct the form factors $f^b_{+,0}(q^2)$ for the decays listed in Sec. 1. Ultimately, the form factors are related to
experimentally measured differential decay rates\(^1\)

\[
\frac{d\Gamma^{B_sX}}{dq^2} = \frac{G_F^2 |V_{ub}|^2}{192\pi^3 M_{B_q}^3} \left[ (M_{B_q}^2 + M_X^2 - q^2)^2 - 4M_{B_q}^2 M_X^2 \right]^{3/2} |j^{B_sX}_r(q^2)|^2, \tag{2.4}
\]

where experimental and lattice results are combined to determine $|V_{ub}|$. The Standard Model suppressed $b \to s$ transition in $B \to K\ell^+\ell^-$ opens the door for potentially discernible new physics contributions. The search for new physics in this decay requires the tensor form factor, related to the $(k0)$-component of the hadronic tensor matrix element

\[
\langle K|T^{k0}|B \rangle = \frac{2M_B M_K}{M_B + M_K} i f_T^{BK}(q^2). \tag{2.5}
\]

### 2.1 Generating Correlator Data

Ensemble averages are performed using the MILC $2 + 1$ asqtad gauge configurations [12] listed in Table 1. The valence quarks in our simulation are NRQCD [13] $b$-quarks, tuned in Ref. [11], and HISQ [14] light and strange quarks, whose propagators were generated in previous works [2, 15]. Working in the parent meson rest frame, a sequential propagator is built from NRQCD $b$-quark smearings function $\phi(y' - y)$ is either a delta function or Gaussian, specified by indices $\alpha, \beta$ in Eqs. (2.6 - 2.8), and is introduced by the replacement $\sum_y \rightarrow \sum_{x,y} \phi(y' - y)$. The spectator source includes a $U(1)$ phase $\xi(x')$. The daughter quark, with $U(1)$ phase and momentum insertion at $x$, is tied to the sequential quark propagator, with $\sum_x$ in Eqs. (2.6 - 2.8) accomplished via random wall sources, i.e. $\sum_x \rightarrow \sum_{xx'} \xi(x)\xi(x')$.

\[
C^\alpha_{B_q}(t_0, t) = \frac{1}{L^3} \sum_{x,y} \langle \Phi^\beta_{B_q}(t, y) \Phi^{\alpha \dag}_{B_q}(t_0, x) \rangle \tag{2.6}
\]

\[
C_{X}(t_0, t; \mathbf{p}) = \frac{1}{L^3} \sum_{x,y} e^{i \mathbf{p} \cdot (x-y)} \langle \Phi_{X}(t, y) \Phi^{\dag}_{X}(t_0, x) \rangle \tag{2.7}
\]

\[
C^{\alpha}_{B_sX}(t_0, t; T; \mathbf{p}) = \frac{1}{L^3} \sum_{x,y,z} e^{i \mathbf{p} \cdot (x-y)} \langle \Phi_{X}(t_0 + T, y) J(t, z) \Phi^{\alpha \dag}_{B_q}(t_0, x) \rangle \tag{2.8}
\]

\(^1\)Eq. (2.4) neglects final state lepton masses.
In three-point correlator data the parent meson is created at time-slice $t_0$, the daughter meson is annihilated at $t_0 + T$, and a flavor-changing current $J(t, z)$ is inserted at intermediate times $t_0 \leq t \leq t_0 + T$, where $t_0$ is chosen at random to reduce auto-correlations. This three-point correlator setup is depicted in Fig. 1. Data are generated over the ranges of parent and daughter meson temporal separations listed in Table 1. Prior to fitting, all data are shifted to a common $t_0 = 0$. 

Figure 1: Setup for three-point correlator data generation.

Figure 2: From ensemble C2: (a) and (b) show the improvement from simultaneous fits to local (“l”) and smeared (“s”) source-sink combinations; (c) and (d) display stability of fit results.

(a) Fits to $aM_{B_s}^{(0)}$ for various source-sink combinations.

(b) Fits to $b^{(1)}_{B_s}$ for various source-sink combinations.

(c) $aM_{B_s}^{(0)}$ vs. the number of states $N_{l/a}$, with $t_{l/a}=2$. 

(d) $aM_{B_s}^{(0)}$ versus $t_{l/a}$, with $N = 10$. 

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Figure 1: Setup for three-point correlator data generation.
shows the improvement observed from simultaneously fitting data for multiple two-point, the daughter two-point, and three-point correlator data sets for multiple values of $T$. We perform a simultaneous, Bayesian fit to the four local and smeared combinations of the parent two-point, the daughter two-point, and three-point correlator data sets for multiple values of $T$. The improvement from simultaneously fitting data for multiple $T$ is shown in Fig. 4.

2.2 Fitting Correlator Data

Two-point correlator data for parent mesons are fit to the ansatz

$$C_{B_q}^{\alpha\beta}(t) = \sum_{n=0}^{N-1} b_q^{\alpha(n)} b_q^{\beta(n)} (-1)^n e^{-M_{B_q}^{(n)} t},$$

where $b_q^{\alpha(n)} = \frac{\langle \Phi^{\alpha}_B | B_q^{(n)} \rangle}{\sqrt{2 M_{B_q}^{(n)}}}$.

Data are generated and analyzed for the $B$ and $B_s$ mesons and all four combinations of local and Gaussian smeared sources and sinks. Fig. 2 shows the improvement observed from simultaneously fitting multiple source-sink smearing combinations and the stability of fit results with respect to changes in $N$ and $t_{\text{min}}$. Two-point correlator data for the daughter mesons are fit to

$$C_X(t) = \sum_{n=0}^{N-1} |d_X^{(n)}|^2 (-1)^n \left( e^{-E_X^{(n)} t} + e^{-E_X^{(n)} (T-t)} \right),$$

where $d_X^{(n)} = \frac{\langle \Phi_X | X^{(n)} \rangle}{\sqrt{2 E_X^{(n)}}}$.

We generate and analyze data for the $\pi$, $K$, and $\eta_s$ daughter mesons, each at momenta $p \in 2\pi L \times \{(0,0,0),(1,0,0),(1,1,0),(1,1,1)\}$. These fit results satisfy the dispersion relation as shown in Fig. 3. At each momentum, three-point correlator data are fit to

$$C_{B_q X}^{\alpha\beta}(t,T) = \sum_{m,n=0}^{N-1} b_q^{\alpha(m)} A_{B_q X}^{(m,n)} d_X^{(n)\dagger} (-1)^m (-n) e^{-M_{B_q}^{(m)} t} e^{-E_X^{(n)} (T-t)},$$

where the three-point amplitude is related to the lattice matrix element by

$$A_{B_q X}^{(n,m)} = \frac{\langle X | J | B_q \rangle}{2 \sqrt{M_{B_q}^{(m)} E_X^{(n)}}}.$$

We perform a simultaneous, Bayesian fit to the four local and smeared combinations of the parent two-point, the daughter two-point, and three-point correlator data sets for multiple values of $T$.
2.3 Matching and Preliminary Results

The lattice vector current \( J = \gamma_\mu \) is matched to the continuum at one-loop using massless HISQ lattice perturbation theory [1, 16]

\[
\langle V_\mu \rangle_{\text{cont}} = (1 + \alpha_s D_\mu^{(0)}) \langle \gamma_\mu^{(0)} \rangle + \langle \gamma_\mu^{(1), \text{sub}} \rangle
\]

(2.13)

where \( \langle \gamma_\mu^{(1), \text{sub}} \rangle \equiv \langle \gamma_\mu^{(1)} \rangle - \alpha_s \zeta_{10,\mu} \langle \gamma_\mu^{(0)} \rangle \). Currents contributing through \( O(\alpha_s, \Lambda_{\text{QCD}}/M, \alpha_s/\lambda M) \) are

\[
\gamma_\mu^{(0)} = b \gamma_\mu \tilde{q} \quad \text{and} \quad \gamma_\mu^{(1)} = -\frac{1}{2M} b \gamma_\mu \gamma \cdot \nabla \tilde{q}
\]

(2.14)

where \( q \) is the daughter quark in Fig. 1. For the lattice tensor current \( J = T_{\mu \nu} \),

\[
\langle T_{\mu \nu} \rangle_{\text{cont}} = (1 + \alpha_s \rho_T) \langle T_{\mu \nu}^{(0)} \rangle + \langle T_{\mu \nu}^{(1), \text{sub}} \rangle
\]

(2.15)

where \( \langle T_{\mu \nu}^{(1), \text{sub}} \rangle = (\bar{T}_{\mu \nu}^{(1)} - \alpha_s \zeta_{10}^{T} \bar{T}_{\mu \nu}^{(0)}) \). Heavy-quark symmetry of the NRQCD \( b \)-quark allows the tensor current renormalization to be recast in terms of vector current quantities: \( T_{\mu \nu}^{(0)} = V_{\mu \nu}^{(0)} \), \( T_{\mu \nu}^{(1)} = -V_{\mu \nu}^{(1)} \), and \( \zeta_{10}^{T} = -\zeta_{10}^{T} \).

For the ensembles analyzed, preliminary results for form factors are shown in Fig. 5. The form factors \( f_{+,0}(q^2) \) are calculated for all decay channels and \( i f_T(q^2) \) is calculated for \( B \to K \ell^+ \ell^- \).
3. Next Steps

Once data generation and correlator fitting is complete, we will extract the physical values of the form factors. The kinematic dependence of the form factors over the full range of physical $q^2$ can be written in a model-independent way via the $z$-expansion [4]. We plan to incorporate the chiral and continuum extrapolations in the $z$-expansion as in [2, 15]. The resultant modified $z$-expansion permits the use of data over the full range of $q^2$, including data at daughter momenta for which chiral perturbation theory is expected to break down. We plan to cross-check these results against those obtained by separately performing the chiral and continuum extrapolation and then the $z$-expansion.

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