

Letter of Interest for RF1: Weak decays of b and c quarks

Peter A. Boyle,^{a,b} Mattia Bruno,^c Luigi Del Debbio,^b Felix Erben,^b Jonathan M. Flynn,^{d*}
Davide Giusti,^e Maxwell Hansen,^c Ryan C. Hill,^{d,f} Taku Izubuchi,^{g,a} Andreas Jüttner,^{d,h}
Christoph Lehner,^{e,a} Michael Marshall,^b Antonin Portelli,^b Amarjit Soni,^a Masaaki Tomii,ⁱ
J. Tobias Tsang,^j and Oliver Witzel^{k**} (RBC and UKQCD collaborations)

August 31, 2020

Tree- and loop-level decays of bottom and charm quarks provide a plethora of channels to test and constrain the Standard Model (SM). Tensions between experimental measurements and theoretical predictions, e.g. in ratios testing lepton flavor universality, are exciting possible signs of New Physics. To fully leverage the ongoing experimental research programs by Belle II, LHCb, ATLAS, CMS and BES III, it is essential to improve theoretical predictions to achieve uncertainties of similar size. To compute the effects of the strong force in flavor changing weak processes demands that we use a non-perturbative and systematically improvable method like lattice quantum chromodynamics (QCD). For more than ten years, the RBC and UKQCD collaborations have actively contributed to the world-wide effort by pursuing state-of-the-art calculations for flavor physics phenomenology as well as by improving simulation techniques and tackling new processes. The importance of physics involving charm and bottom quarks will be reflected in the next-generation dynamical gauge field configurations [1], with chiral domain-wall fermions at physical up/down, strange and charm quark masses at a range of different lattice spacings ($a^{-1} = 3\text{--}5\text{ GeV}$) which will allow a benign extrapolation to reach valence bottom quark masses using data points with “heavier than charm” quark masses. In addition we will significantly extend the range in momentum transfer directly covered in our nonperturbative simulations and, depending on the process considered, should be able to obtain results at percent, if not sub-percent, precision. Processes of interest are briefly discussed below.

Neutral meson mixing, meson lifetimes, and leptonic decays

Although a loop-level process, neutral B_s and B meson mixing is the preferred channel to determine the Cabibbo–Kobayashi–Maskawa (CKM) matrix elements $|V_{ts}|$ and $|V_{td}|$. The SU(3) breaking ratio ξ (ratio of B_s over B meson mixing) [2] is an important input for global CKM triangle fits [3, 4]. Both mixing processes also play an important role in constraining models of New Physics. Global averages of experimental measurements of oscillation frequencies [5], dominated by the latest LHCb results [6, 7], show sub-percent level uncertainties. We recently achieved percent-level precision for the SU(3) breaking ratios [8] and work is in progress to calculate the bag parameters for individual mixing processes at the few percent-level. In the future, using the next generation of gauge field ensembles, we intend to obtain sub-percent level predictions for the bag parameters as well as their ratio ξ . At this level of precision effects due to electromagnetism will also need to be accounted for. Similar progress is intended for the determination of leptonic decay constants of $D_{(s)}$, B and B_c mesons. Given corresponding experimental measurements these allow the CKM matrix elements $|V_{cd}|$, $|V_{cs}|$, $|V_{ub}|$ and $|V_{cb}|$ to be determined. In addition we plan to use state-of-the-art lattice QCD methods to determine $B_{(s)}$ lifetimes, to verify predictions based on QCD sum-rules [9, 10] and other analytic methods to further test the SM.

*j.m.flynn@soton.ac.uk

**oliver.witzel@colorado.edu

Exclusive semileptonic decays at tree- and loop-level

In the SM, charged weak currents allow tree-level flavor-changing decays, but the absence of tree-level flavor-changing neutral currents (FCNC) means that FCNC decays provide stringent tests of the SM. The large masses of $B_{(s)}$ and $D_{(s)}$ mesons make many such decays energetically possible, providing excellent tests or determinations of CKM matrix elements. Decays with the same hadronic final state but different generations of final-state leptons test the universality of lepton flavor couplings in the SM and have attracted substantial attention. Several experiments have reported such ratios for tree-level (e.g. $B \rightarrow D^{(*)}\ell\nu$ [11–14] or $B_c \rightarrow J/\psi\ell\nu$ [15]) as well as rare loop-level $b \rightarrow \{s, d\}\ell\ell$ decays (e.g. $B \rightarrow K^{(*)}\ell^+\ell^-$ [16–21] or $B_s \rightarrow \phi\ell^+\ell^-$ [22]) including also baryonic initial and final states. The tensions between experiment and theory vary for different processes/measurements, but theory predicts in all cases a smaller value than experimentally observed.

To confirm or refute the observed deviations, higher-precision semileptonic form factor calculations are needed which directly cover most or all of the allowed physical range of momentum transfer q^2 to the leptons for both pseudoscalar and vector hadronic final states. Building upon our experience of $B \rightarrow \pi\ell\nu$ and $B_s \rightarrow K\ell\nu$ decays [23] we are currently working on $B_{(s)} \rightarrow D_{(s)}\ell\nu$ decays. While computations with pseudoscalar final states are well under control, vector final states present additional challenges. Overcoming the narrow width approximation (treating the vector final state as QCD-stable) is one of the outstanding challenges for the future. Improved theoretical knowledge of loop-level decays is also needed to better understand deviations between theory and experiment for certain q^2 bins. Here, addressing the impact of long-distance contributions related to the charmonium resonances is a key challenge. Reliably treating long-distance effects and QCD resonances also helps build methodology for calculating heavy meson decays into multihadron states. Processes such as $D \rightarrow \pi\pi$ are of great phenomenological interest and represent significant challenges on the lattice, requiring both further formal developments and pre-exascale computing resources.

Finally, semileptonic decays of baryons can provide further tests of the SM and are part of the research programs of LHCb and other experiments.

Inclusive decays and distribution amplitudes

There are promising new ideas [24–26] to calculate inclusive decays using lattice QCD. This may be the best approach for new insight into the long-established deviations between inclusive and exclusive determinations of $|V_{ub}|$ and $|V_{cb}|$. Furthermore, these ideas may enable new nonperturbative determinations of $B_{(s)}$ and $D_{(s)}$ meson distribution amplitudes.

Radiative decays

Adding a hard photon in the final state for leptonic decay of a pseudoscalar meson lifts helicity suppression [27], providing sensitivity to a larger set of operators in the weak effective Hamiltonian. For large photon energy the process $B \rightarrow \ell\nu_\ell\gamma$ is the cleanest probe of the first inverse moment, $1/\lambda_B$, of the B -meson lightcone distribution amplitude, an important input for QCD factorization predictions for nonleptonic B decays [28, 29]. Using the upper limit for $\mathcal{B}(B^- \rightarrow \ell^- \bar{\nu}_\ell \gamma, E_\gamma > 1 \text{ GeV})$ from Belle [30], a lattice form factor calculation can constrain λ_B [31]. A similar calculation in the charm sector can take advantage of BESIII results for $D_{(s)}^+ \rightarrow e^+ \nu_e \gamma$ [32, 33]. The general procedure for the lattice calculations has been demonstrated [34, 35] and first-principles computations are in progress for the structure-dependent form factors for $B_{(s)} \rightarrow \ell\nu_\ell\gamma$, $D_{(s)} \rightarrow \ell\nu_\ell\gamma$ and $B_{(s)} \rightarrow \ell^+\ell^-\gamma$ and $D_{(s)} \rightarrow \ell^+\ell^-\gamma$, with a broad photon energy spectrum. With next-generation gauge field ensembles we can reach significantly improved precision in determining the corresponding CKM matrix elements.

Affiliations

- ^a Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA
- ^b Higgs Centre for Theoretical Physics, The University of Edinburgh, EH9 3FD, UK
- ^c Theoretical Physics Department, CERN, 1211 Geneva 23, Switzerland
- ^d Physics and Astronomy, University of Southampton, Southampton SO17 1BJ, UK
- ^e Universität Regensburg, Fakultät für Physik, 93040 Regensburg, Germany
- ^f DISCnet Centre for Doctoral Training, University of Southampton, Southampton SO17 1BJ, UK
- ^g RIKEN/BNL Research Center, Brookhaven National Laboratory, Upton, NY 11973, USA
- ^h STAG Research Center and Mathematical Sciences, University of Southampton, Southampton SO17 1BJ, UK
- ⁱ Physics Department, University of Connecticut, Storrs, CT 06269, USA
- ^j CP3-Origins and IMADA, University of Southern Denmark, Campusvej 55, 5230 Odense M, Denmark
- ^k Department of Physics, University of Colorado Boulder, Boulder, CO 80303, USA

References

- [1] RBC/UKQCD collaboration, T. Blum, P. Boyle, N. Christ, F. Erben, J. Flynn, V. Gülpers et al., *Snowmass 2021 Letter of Interest: Chiral Lattice Fermions and the Computational Frontier*, 2020.
- [2] C. W. Bernard, T. Blum and A. Soni, *SU(3) flavor breaking in hadronic matrix elements for $B - \bar{B}$ oscillations*, *Phys.Rev.* **D58** (1998) 014501, [[hep-lat/9801039](#)].
- [3] CKMFITTER GROUP collaboration, J. Charles et al., *CP violation and the CKM matrix: Assessing the impact of the asymmetric B factories*, *Eur.Phys.J.* **C41** (2005) 1–131, [[hep-ph/0406184](#)].
- [4] UTFIT collaboration, M. Bona et al., *The Unitarity Triangle Fit in the Standard Model and Hadronic Parameters from Lattice QCD: A Reappraisal after the Measurements of Δm_s and $BR(B \rightarrow \tau \nu_\tau)$* , *JHEP* **10** (2006) 081, [[hep-ph/0606167](#)].
- [5] HFLAV collaboration, Y. S. Amhis et al., *Averages of b-hadron, c-hadron, and τ -lepton properties as of 2018*, [1909.12524](#).
- [6] LHCb collaboration, R. Aaij et al., *Observation of B_s^0 - $\bar{B}_s^0$ mixing and measurement of mixing frequencies using semileptonic B decays*, *Eur. Phys. J. C* **73** (2013) 2655, [[1308.1302](#)].
- [7] LHCb collaboration, R. Aaij et al., *A precise measurement of the B^0 meson oscillation frequency*, *Eur. Phys. J. C* **76** (2016) 412, [[1604.03475](#)].
- [8] RBC/UKQCD collaboration, P. A. Boyle, L. Del Debbio, N. Garron, A. Jüttner, A. Soni, J. T. Tsang et al., *SU(3)-breaking ratios for $D_{(s)}$ and $B_{(s)}$ mesons*, [1812.08791](#).
- [9] D. King, A. Lenz and T. Rauh, *B_s mixing observables and $-v_{td}/v_{ts}$ — from sum rules*, *JHEP* **05** (2019) 034, [[1904.00940](#)].
- [10] G. Bell, O. Cata, T. Feldmann, T. Huber, A. Khodjamirian, W. Kilian et al., *Snowmass Letter of Interest: High Precision SM Predictions for Quark Flavor Observables*, 2020.
- [11] BELLE collaboration, A. Abdesselam et al., *Measurement of $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$ with a semileptonic tagging method*, [1904.08794](#).
- [12] LHCb collaboration, R. Aaij et al., *Measurement of the ratio of branching fractions $\mathcal{B}(\bar{B}^0 \rightarrow D^{*+} \tau^- \bar{\nu}_\tau) / \mathcal{B}(\bar{B}^0 \rightarrow D^{*+} \mu^- \bar{\nu}_\mu)$* , *Phys. Rev. Lett.* **115** (2015) 111803, [[1506.08614](#)].
- [13] LHCb collaboration, R. Aaij et al., *Test of lepton flavor universality by the measurement of the $B^0 \rightarrow D^{*-} \tau^+ \nu_\tau$ branching fraction using three-prong τ decays*, *Phys. Rev.* **D97** (2018) 072013, [[1711.02505](#)].
- [14] BABAR collaboration, J. P. Lees et al., *Measurement of an Excess of $\bar{B} \rightarrow D^{(*)} \tau^- \bar{\nu}_\tau$ Decays and Implications for Charged Higgs Bosons*, *Phys. Rev.* **D88** (2013) 072012, [[1303.0571](#)].
- [15] LHCb collaboration, R. Aaij et al., *Measurement of the ratio of branching fractions $\mathcal{B}(B_c^+ \rightarrow J/\psi \tau^+ \nu_\tau) / \mathcal{B}(B_c^+ \rightarrow J/\psi \mu^+ \nu_\mu)$* , [1711.05623](#).
- [16] LHCb collaboration, R. Aaij et al., *Differential branching fractions and isospin asymmetries of $B \rightarrow K^{(*)} \mu^+ \mu^-$ decays*, *JHEP* **06** (2014) 133, [[1403.8044](#)].
- [17] LHCb collaboration, R. Aaij et al., *Measurements of the S-wave fraction in $B^0 \rightarrow K^+ \pi^- \mu^+ \mu^-$ decays and the $B^0 \rightarrow K^{*}(892)^0 \mu^+ \mu^-$ differential branching fraction*, *JHEP* **11** (2016) 047, [[1606.04731](#)].
- [18] LHCb collaboration, R. Aaij et al., *Angular analysis of the $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ decay using 3 fb^{-1} of integrated luminosity*, *JHEP* **02** (2016) 104, [[1512.04442](#)].

- [19] BELLE collaboration, S. Wehle et al., *Lepton-Flavor-Dependent Angular Analysis of $B \rightarrow K^* \ell^+ \ell^-$* , *Phys. Rev. Lett.* **118** (2017) 111801, [[1612.05014](#)].
- [20] The ATLAS collaboration, *Angular analysis of $B_d^0 \rightarrow K^* \mu^+ \mu^-$ decays in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector*, 2017.
- [21] CMS Collaboration, *Measurement of the P_1 and P_5' angular parameters of the decay $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ in proton-proton collisions at $\sqrt{s} = 8$ TeV*, 2017.
- [22] LHCb collaboration, R. Aaij et al., *Angular analysis and differential branching fraction of the decay $B_s^0 \rightarrow \phi \mu^+ \mu^-$* , *JHEP* **09** (2015) 179, [[1506.08777](#)].
- [23] RBC/UKQCD collaboration, J. M. Flynn, T. Izubuchi, T. Kawanai, C. Lehner, A. Soni, R. S. Van de Water et al., *$B \rightarrow \pi \ell \nu$ and $B_s \rightarrow K \ell \nu$ form factors and $|V_{ub}|$ from 2 + 1-flavor lattice QCD with domain-wall light quarks and relativistic heavy quarks*, *Phys. Rev.* **D91** (2015) 074510, [[1501.05373](#)].
- [24] P. Gambino and S. Hashimoto, *Inclusive semi-leptonic decays from lattice QCD*, *Phys. Rev. Lett.* **125** (2020) 032001, [[2005.13730](#)].
- [25] S. Hashimoto, *Inclusive semi-leptonic b meson decay structure functions from lattice qcd*, *PTEP* **2017** (2017) 053B03, [[1703.01881](#)].
- [26] M. T. Hansen, H. B. Meyer and D. Robaina, *From deep inelastic scattering to heavy-flavor semileptonic decays: Total rates into multihadron final states from lattice qcd*, *Phys.Rev.D* **96** (2017) 094513, [[1704.08993](#)].
- [27] D. Atwood, G. Eilam and A. Soni, *Pure leptonic radiative decays $B^\pm, D(s) \rightarrow \ell^\pm \nu_\ell \gamma$ and the annihilation graph*, *Mod. Phys. Lett. A* **11** (1996) 1061–1968, [[hep-ph/9411367](#)].
- [28] S. Descotes-Genon and C. Sachrajda, *Factorization, the light cone distribution amplitude of the B meson and the radiative decay $B \rightarrow \gamma \ell \nu_\ell$* , *Nucl. Phys. B* **650** (2003) 356–390, [[hep-ph/0209216](#)].
- [29] M. Beneke, V. Braun, Y. Ji and Y.-B. Wei, *Radiative leptonic decay $B \rightarrow \gamma \ell \nu_\ell$ with subleading power corrections*, *JHEP* **07** (2018) 154, [[1804.04962](#)].
- [30] BELLE collaboration, M. Gelb et al., *Search for the rare decay of $B^+ \rightarrow \ell^+ \nu_\ell \gamma$ with improved hadronic tagging*, *Phys. Rev. D* **98** (2018) 112016, [[1810.12976](#)].
- [31] M. Beneke and J. Rohrwild, *B meson distribution amplitude from $B \rightarrow \gamma \ell \nu$* , *Eur. Phys. J. C* **71** (2011) 1818, [[1110.3228](#)].
- [32] BESIII collaboration, M. Ablikim et al., *Search for the radiative leptonic decay $D^+ \rightarrow \gamma e^+ \nu_e$* , *Phys. Rev. D* **95** (2017) 071102, [[1702.05837](#)].
- [33] BESIII collaboration, M. Ablikim et al., *Search for the decay $D_s^+ \rightarrow \gamma e^+ \nu_e$* , *Phys. Rev. D* **99** (2019) 072002, [[1902.03351](#)].
- [34] C. Kane, C. Lehner, S. Meinel and A. Soni, *Radiative leptonic decays on the lattice*, [[1907.00279](#)].
- [35] A. Desiderio et al., *First lattice calculation of radiative leptonic decay rates of pseudoscalar mesons*, [[2006.05358](#)].