Non-perturbative determinations of B-meson decay constants and semi-leptonic form factors

Oliver Witzel
Higgs Centre for Theoretical Physics

THE UNIVERSITY
of EDINBURGH

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## RBC- and UKQCD collaborations

### BNL/RBRC
- Mattia Bruno
- Tomomi Ishikawa
- Taku Izubuchi
- Chulwoo Jung
- Christoph Lehner
- Meifeng Lin
- Hiroshi Ohki
- Shigemi Ohta (KEK)
- Amarjit Soni
- Sergey Syritsyn

### Columbia U
- Ziyuan Bai
- Norman Christ
- Luchang Jin
- Christopher Kelly
- Bob Mawhinney
- Greg McGlynn
- David Murphy
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### U Edinburgh
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- Luigi Del Debbio
- Richard Kenway
- Julia Kettle
- Ava Khamseh
- Antonin Portelli
- Brian Pendleton
- Oliver Witzel
- Azusa Yamaguchi

### U Southampton
- Jonathan Flynn
- Vera Gülpers
- James Harrison
- Andreas Jüttner
- Andrew Lawson
- Edwin Lizarazo
- Chris Sachrajda
- Francesco Sanfilippo
- Matthew Spraggs
- Tobias Tsang

### CERN
- Marina Marinkovic

### U Connecticut
- Tom Blum

### FZ Jülich
- Taichi Kawanai

### KEK
- Julien Frison

### Peking U
- Xu Feng

### U Plymouth
- Nicolas Garron

### York U (Toronto)
- Renwick Hudspith
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Where can lattice QCD contribute?

CKM unitarity triangle fit

- Neutral $B$-meson mixing $B_B, \xi$

- Exclusive semi-leptonic decays e.g.
  
  $B \rightarrow \pi \ell \nu_\ell \Rightarrow |V_{ub}|$
  $B \rightarrow D \ell \nu_\ell \Rightarrow |V_{cb}|$
  
  with $\ell = e, \mu, \tau$

- Tension between incl. and excl. determinations

Help to explore tensions: $R_{D(*)}$

$\mathcal{B}(B \to D^{(*)}\tau\nu)$

Tension with SM seems to persist

Very preliminary & unofficial average including new LHCb & Belle results

$R(D^*) = 0.390 \pm 0.047$

$R(D) = 0.322 \pm 0.021$

SM predictions from PRD 85 (2012) 094025

Careful averaging needed to account for statistical and systematic correlations

Consistent with latest lattice results

Figure: [Talk by T. Gershon at MIAPP June 2015]
Our RHQ Project

- Use domain-wall light quarks and nonperturbatively tuned relativistic $b$-quarks to compute at few-percent precision
  - Nonperturbative tuning of RHQ parameters [PRD 86 (2012) 116003]
  - Decay constants $f_B$ and $f_{B_s}$ [PRD 91 (2015) 054502]
  - $B \rightarrow \pi \ell \nu$ and $B_s \rightarrow K \ell \nu$ form factors [PRD 91 (2015) 074510]
  - $g_{B^*B\pi}$ coupling constant [PRD 93 (2016) 014510]
  - $B^0-\overline{B^0}$ mixing
  - Rare $B$ decays [arXiv:1511.06622]

- $f_B$, $f_{B_s}$, and semi-leptonic form factors
  - $O(a)$ improvement at 1-loop and mostly nonperturbative renormalization
  - Correction factors and coefficients computed at 1-loop

- $B$ mixing
  - Tree-level $O(a)$ improvement
  - Perturbative or mostly nonperturbative renormalization
2+1 Flavor Domain-Wall Iwasaki ensembles

<table>
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<th>$a^{-1}$ (GeV)</th>
<th>$a m_l$</th>
<th>$a m_s$</th>
<th>$M_\pi$ (MeV)</th>
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<td>$\sim 250$</td>
<td>$&gt; 50$</td>
<td>24</td>
<td>[in progress]</td>
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</table>

* All mode averaging: 81 “sloppy” and 1 “exact” solve [Blum et al. PRD 88 (2012) 094503]

▲ Lattice spacing determined from combined analysis [Blum et al. PRD 93 (2016) 074505]

▲ $a$: $\sim 0.11$ fm, $\sim 0.08$ fm, $\sim 0.07$ fm
Up, down, and strange quarks

- Domain-wall fermions with same parameters as in the sea-sector (domain-wall height $M_5$, extension of 5th dimension $L_s$)
- Unitary and partially quenched quark masses
- Strange quarks at/near physical the physical value

Bottom quarks

- Builds upon Fermilab approach [El-Khadra et al. PRD 55 (1997) 3933]
- Allows to tune the three parameters ($m_0a$, $c_P$, $\zeta$) nonperturbatively [PRD 86 (2012) 116003], recently re-tuned to update $a^{-1}$ values
- Heavy quark mass is treated to all orders in $(m_ba)^n$
- Has a smooth continuum limit
Decay constants

[PRD 91 (2015) 054502]

$\Phi^\text{en}_{B_0} / M_{B_0}^{3/2} = 0.0369(11) \rightarrow f_{B^0} = 199.5(6.2)\text{MeV}$

$\Phi^\text{en}_{B_s} / M_{B_s}^{3/2} = 0.0369(11) \rightarrow f_{B^-} = 195.6(6.4)\text{MeV}$

$\chi^2/\text{dof} = 0.30\ [2] \ p\text{-value} = 74\%$

$\Phi^\text{en}_{B_{s}} / f_{B_{s}} = 1.207(14) \rightarrow f_{B_{s}} / f_{B^+} = 1.197(13)$

$\Phi^\text{en}_{B_{s}} / f_{B_{s}} = 1.233(15) \rightarrow f_{B_{s}} / f_{B^+} = 1.223(14)$

$\chi^2/\text{dof} = 0.37\ [2] \ p\text{-value} = 69\%$

$\Box \ f_{B^0} = 199.5(12.6)\text{MeV}$

$\Box \ f_{B^+} = 195.6(14.9)\text{MeV}$

$\Box \ f_{B_s} = 235.4(12.2)\text{MeV}$

$\Box \ f_{B_s} / f_{B^0} = 1.197(50)$

$\Box \ f_{B_s} / f_{B^+} = 1.223(71)$
Semi-leptonic form factors: $B \rightarrow \pi \ell \nu$ and $|V_{ub}|$

[PRD 91 (2015) 074510]

- In good agreement with existing and new FNAL/MILC result
- Result agrees with value obtained from CKM unitarity
**$B^* B\pi$ coupling constant**

[PRD 93 (2016) 014510]

- Strong coupling $g_{B^* B\pi}$
  parametrizes $\langle B\pi | B^* \rangle$

- Related to LEC $g_b$ of HM$\chi$PT
  
  $$g_b = g_{B^* B\pi} \cdot f_\pi / (2M_B)$$

- Not accessible experimentally
  but needed to determine e.g. $f^B_\pi$

- First determination at physical $b$–quark mass
Outlook

- Update/improve determinations for decay constants $f_B, f_{B_s}$ as well as semi-leptonic-form factors for $B \rightarrow \pi \ell \nu$ ($\Rightarrow |V_{ub}|$) and $B_s \rightarrow K \ell \nu$
- Two new ensembles adding physical pions and a third lattice spacing

- Include GIM suppressed decays (FCNC) in measurements (short distance contributions)

- Simulate charm quarks to determine $B(s) \rightarrow D^*_s \ell \nu$ form factors
GIM suppressed semi-leptonic decays e.g. $B_s \rightarrow \phi \ell^+ \ell^-$

- Full basis contains 20 operators but at short distance only $O_7^{(')}$, $O_9^{(')}$, and $O_{10}^{(')}$ contribute
- Short distance contributions only!
  (Issues with factorization of long distance charm resonances [arXiv:1406.0566])
- Form factors: $f_V$, $f_{A1}$, $f_{A2}$, $f_{A2}$, $f_{T1}$, $f_{T2}$, $f_{T3}$
First results for $B_s \rightarrow \Phi \ell^+ \ell^-$: $f_{A0}$ and $f_{T1}$

- $24^3 \times 64$ ensemble with $a^{-1} = 1.784$ GeV and $am_l = 0.005$ ($M_\pi \approx 338$ MeV)

- Data on further ensembles exists, but renormalization factors are missing
$B(s) \rightarrow D^{(*)}_{(s)}$ form factors

- Same setup as for $B \rightarrow \pi \ell \nu$ or $B_s \rightarrow K \ell \nu$
- Addition form factors for vector final state (stable)

Charm quarks

- Möbius DWF optimized for heavy quarks [Boyle et al. JHEP 1604 (2016) 037]
- $M_5 = 1.6, L_s = 12$
- Discretization errors well under control for $am_c \leq 0.40$
  - On coarse ($a^{-1} = 1.784$ GeV) ensembles we simulate just below $m_c^{\text{phys}}$
  - Simulate 3 or 2 charm-like masses and then extrapolate/interpolate
  - Linear extrapolation is small and benign; interpolation is safe
Charm extrapolation

- Small extrapolation for $a^{-1} = 1.784$ GeV ensembles
- Interpolation for $a^{-1} \geq 2.383$ GeV ensembles
- Analysis on $f_D$, $f_{Ds}$, and $f_{Ds}/f_D$ almost finalized
First results for $B_s \rightarrow D_s \ell \nu$

$24^3 \times 64$ ensemble with $a^{-1} = 1.784$ GeV and $am_l = 0.005$ ($M_\pi \approx 338$ MeV)

- Data on further ensembles exists, but renormalization factors are missing
Resources and Acknowledgments

- Simulations on $24^3$, $32^3$, and the $48^3$ ensemble with physical pions
  - **USQCD**: kaon, J/psi, Ds, Bc, and pi0 cluster at Fermilab
  - 12s at Jlab
  - **RBRC/BNL and Columbia U**: small local clusters
- Simulations on the $a^{-1} \sim 2.7$ GeV $48^3$ ensemble
  - **ARCHER UoE**: Cray XC30
  - **DiRAC UoE**: BG/Q