B-physics with domain-wall light quarks and nonperturbatively tuned relativistic b-quarks

RBC and UKQCD collaborations

Oliver Witzel
Center for Computational Science
BOSTON UNIVERSITY

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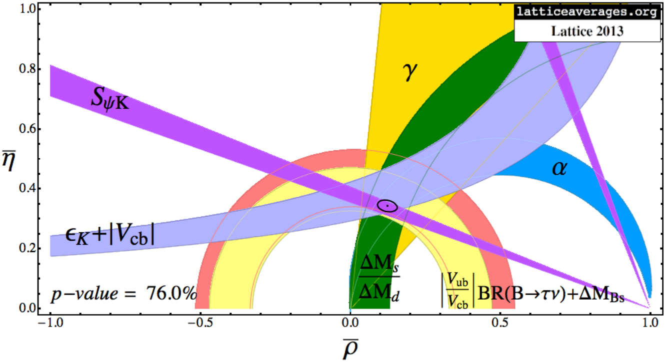
Motivation: CKM unitarity triangle fit

- B^0–$\overline{B^0}$ mixing enables precise constraint on apex of the CKM unitarity triangle
- Requires nonperturbative determination of the ratio of B-meson mixing matrix elements $\xi^2 = f^2_{B_s} B_{B_s} / f^2_{B_d} B_{B_d}$
- Lattice still the dominant source of error



[http://ckmfitter.in2p3.fr, http://utfit.roma1.infn.it, http://www.latticeaverages.org]

Motivation: rare B-decays

$B \to \tau\nu$ [UTfit Phys.Lett. B687 (2010) 61]

- f_B is needed for the Standard-Model prediction of $BR(B \to \tau\nu)$
- Potentially sensitive to charged-Higgs exchange due to large τ mass

$B_s \to \mu_+\mu_-$ [Buras et al. Eur.Phys.J. C72 (2012) 2172, Buras et al. arXiv:1303.3820 [hep-ph]]

- f_{B_s} is needed for Standard-Model prediction of $BR(B_s \to \mu_+\mu_-)$
- Strong sensitivity to NP because FCNC processes are suppressed by the Glashow-Iliopoulos-Maiani (GIM)-mechanism in the SM
- Measured by LHCb with 3.5σ significance [LHCb Phys.Rev.Lett. 110 (2013) 02180], at EPS2013: combination of LHCb and CMS results gives $> 5\sigma$ significance — in agreement with SM

Both are sensitive to new physics!

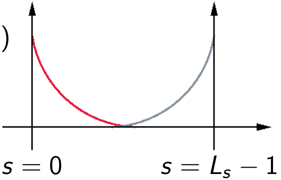
Our project

- Use domain-wall light quarks and nonperturbatively tuned relativistic b-quarks to compute at few-percent precision
  - B^0–$\overline{B^0}$ mixing
  - Decay constants f_B and f_{B_s}
  - $B \to \pi\ell\nu$ and $B_s \to K\ell\nu$ form factors [T. Kawanai, Fri. 16:50]
  - $g_{B^*B\pi}$ coupling constant [PoS(Lattice 2013)408]

- Provides important cross-check of other $N_f = 2+1$ determinations using the MILC staggered ensembles

2+1 flavor domain-wall gauge field configurations

- Domain-wall fermions for the light quarks (u, d, s) [Kaplan Phys.Lett. B288 (1992) 342] [Shamir Nucl.Phys. B406 (1993) 90]
- Iwasaki gauge action [Iwasaki UTHEP-118(1983)]
- Configurations generated by RBC and UKQCD collaborations [C. Allton et al. Phys.Rev. D78 (2008) 114509, Y. Aoki et al. Phys.Rev. D83 (2011) 074508]

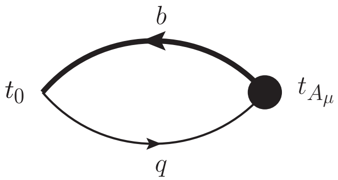


L	a(fm)	m_l	m_s	M_π(MeV)	approx. # configs.	# time sources
24	≈ 0.11	0.005	0.040	329	1636	1
24	≈ 0.11	0.010	0.040	422	1419	1
32	≈ 0.08	0.004	0.030	289	628	2
32	≈ 0.08	0.006	0.030	345	889	2
32	≈ 0.08	0.008	0.030	394	544	2

Relativistic heavy quark action for the b-quarks

- Relativistic Heavy Quark action developed by Christ, Li, and Lin
  [Christ et al. Phys.Rev. D76 (2007) 074505; Lin and Christ Phys.Rev. D76 (2007) 074506]
- Builds upon Fermilab approach [El-Khadra et al. Phys.Rev. D55 (1997) 3933]
  by tuning all parameters of the clover action non-perturbatively;
  close relation to the Tsukuba formulation
  [S. Aoki et al. Prog.Theor.Phys. 109 (2003) 383]
- Heavy quark mass is treated to all orders in $(m_b a)^n$
  - Applies for all values of the quark mass
- Expand in powers of the spatial momentum through $O(\vec{p}a)$
  - Resulting errors will be of $O(\vec{p}^2 a^2)$
  - Allows computation of heavy-light quantities with discretization errors of the same size as in light-light quantities
- Tune parameters to physical b-quarks i.e. require:
  - Spin-averaged mass and hyperfine splitting of the B_s-meson agree with experiment
  - B_s-meson rest and kinetic masses are equal
- Validated by computing $b\bar{b}$ masses and splittings [Phys.Rev. D86 (2012) 116003]

B-meson decay constant



- Use point-source light quark and generate Gaussian smeared-source heavy quark
- On the lattice we compute Φ_{B_q} $f_B = \Phi^{\text{ren}}_{B_q} \cdot a_{32}^{-3/2} / \sqrt{M_{B_q}}$

$O(a)$ improvement and operator renormalization

[arXiv:1404.4670 [hep-lat]]

- Axial current is 1-loop $O(\alpha_S a)$ improved
  - Coefficient computed at one-loop in mean-field improved LPT

- Use mostly-nonperturbative renormalization scheme for f_B, f_{B_s} and $B \to \pi \ell \nu$
  [El-Khadra et al. Phys.Rev. D64 (2001) 014502]

$$Z_V^{bl} = \varrho^{bl} \cdot \sqrt{Z_V^{bb} Z_V^{ll}}$$

  - Nonperturbative computation for Z_V^{ll} [Y. Aoki et al. Phys.Rev. D83 (2011) 074508] and Z_v^{bb} [arXiv:1404.4670 [hep-lat]]
  - Flavor-diagonal factors Z_V^{bb} and Z_V^{ll} account for the bulk of the renormalization factor
  - Use one-loop mean-field improved LPT for small correction ϱ^{bl}
    [C. Lehner http://physyhcal.lhnr.de]

Strategy for combined chiral-continuum extrapolation

[arXiv:1404.4670 [hep-lat]]

- Perform analysis in terms of dimensionless ratios over M_{B_s}

- Preferred fit: NLO SU(2) heavy meson chiral perturbation theory
- Alternative fit to estimate systematic error: linear fit

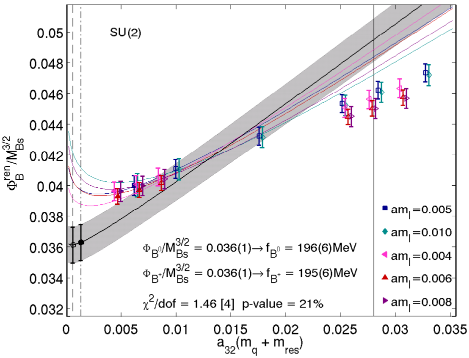
- Restrict to data points with $M_\pi^{\mathrm{val}} < 420$ MeV

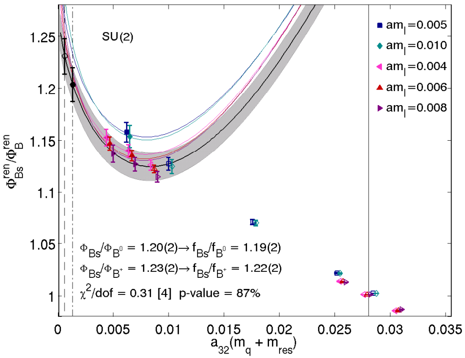
- $g_{B^*B\pi} = 0.57(8)$ [PoS(Lattice 2013)408]
- $f_\pi = 130.4$ MeV [PDG]
- $\Lambda_\chi = 1$ GeV

Chiral-continuum extrapolation of f_B and f_{B_s}/f_B

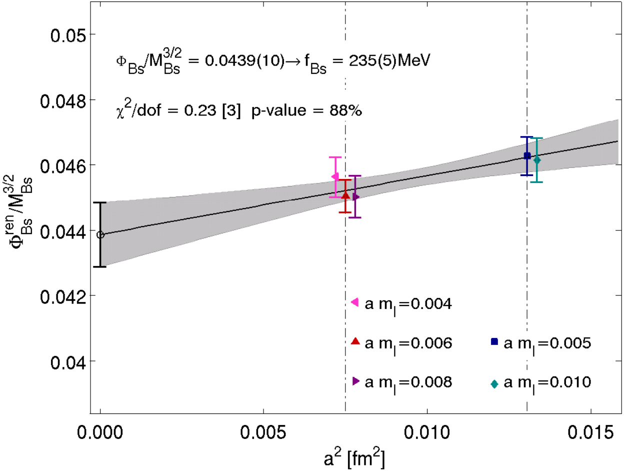
[arXiv:1404.4670 [hep-lat]]

- Only data points with filled symbols included in the fit ($M_\pi < 420$ MeV)
- Statistical errors only





Continuum extrapolation of f_{B_s} [arXiv:1404.4670 [hep-lat]]

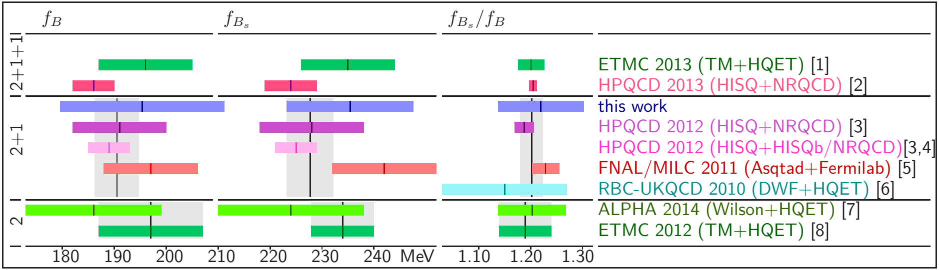


- Data for Φ_{B_s} show no sea-quark mass dependence
- Average data at same lattice spacing
- Assume a^2 scaling to remove LQ and gluon discretization errors
- Statistical errors only

Error budget [arXiv:1404.4670 [hep-lat]]

	f_{B^0}(%)	f_{B^+}(%)	f_{B_s}(%)	f_{B_s}/f_{B^0}(%)	f_{B_s}/f_{B^+}(%)
statistics	3.2	3.2	2.2	1.3	1.4
chiral-continuum extrapolation	6.5	6.6	3.1	4.5	6.3
lattice-scale uncertainty	1.5	1.5	1.5	0.1	0.1
light- and strange-quark mass uncertainty	0.1	0.2	0.9	1.0	1.1
RHQ parameter tuning	1.2	1.2	1.2	0.1	0.1
HQ discretization errors	1.7	1.7	1.7	0.3	0.3
LQ and gluon disc. errors	1.1	1.1	1.2	0.6	0.6
renormalization factor	1.7	1.7	1.7	0.0	0.0
finite volume	0.4	0.4	0.0	0.7	0.7
isospin-breaking and EM	0.7	0.7	0.7	0.1	0.7
total	8.0	8.1	5.2	4.9	6.7

Comparison with other results [arXiv:1404.4670 [hep-lat]]



- Good agreement with other results

FLAG: S. Aoki et al. arXiv:1310.8555 [hep-lat]
[1] Carrasco et al. arXiv:1311.2837 [hep-lat]
[2] Dowdall et al. Phys.Rev.Lett. 110 (2012) 222003
[3] Na et al. Phys.Rev.D86 (2012) 034506
[4] McNeile et al. Phys.Rev.D85 (2012) 031503
[5] Bazavov et al. Phys.Rev.D85 (2012) 114506
[6] Albertus et al. Phys.Rev.D82 (2010) 014505
[7] Bernardoni et al. arXiv:1404.3590 [hep-lat]
[8] Carrasco et al. PoS LATTICE2012 (2012) 104

Future plan: physical pions

	f_{B^0}(%)	f_{B^+}(%)	f_{B_s}(%)	f_{B_s}/f_{B^0}(%)	f_{B_s}/f_{B^+}(%)
statistics	3.2	3.2	2.2	1.3	1.4
chiral-continuum extrapolation	6.5	6.6	3.1	4.5	6.3
lattice-scale uncertainty	1.5	1.5	1.5	0.1	0.1
light- and strange-quark mass uncertainty	0.1	0.2	0.9	1.0	1.1
RHQ parameter tuning	1.2	1.2	1.2	0.1	0.1
HQ discretization errors	1.7	1.7	1.7	0.3	0.3
LQ and gluon disc. errors	1.1	1.1	1.2	0.6	0.6
renormalization factor	1.7	1.7	1.7	0.0	0.0
finite volume	0.4	0.4	0.0	0.7	0.7
isospin-breaking and EM	0.7	0.7	0.7	0.1	0.7
total	8.0	8.1	5.2	4.9	6.7

- To reduce errors we have to shorten or eliminate the chiral-extrapolation to the physical point
- This will also decrease the statistical uncertainties

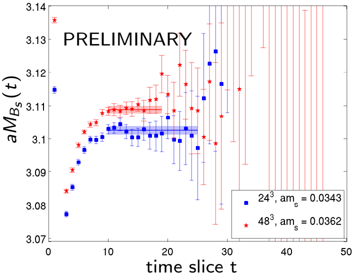
Work in progress

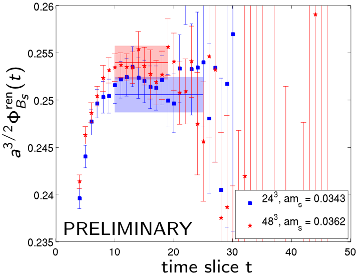
Physical pion masses with Möbius DWF

- $48^3 \times 96,\ L_s = 24$ at $a^{-1} \approx 1.73$ GeV
- MDWF light quark propagators are generated
- Improving statistics using all-mode averaging [Blum et al. Phys.Rev.D88 (2013) 094503]
- Tuning of RHQ parameters is in progress
- First result for f_{B_s} using 80% of the desired number of measurements

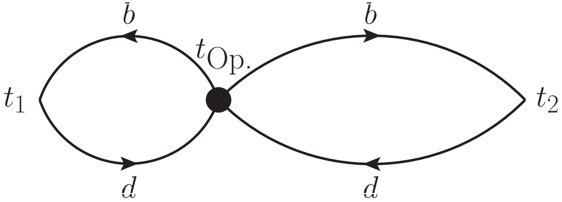
Finer lattice $a^{-1} \approx 3.1$ GeV

- $32^3 \times 64,\ L_s = 12,\ M_\pi \approx 360$ MeV





$B^0 - \overline{B^0}$ mixing matrix element calculation



- Location of four-quark operator is fixed
- Location of B-mesons is varied over all possible time slices
- Need: one point-source light quark and one point-source heavy quark originating from operator location
- Project out zero-momentum component using a Gaussian sink
- Tree-level $O(a)$-improvement of operators via HQ field rotation
- Finally we have a first set of data ready to be analyzed!

Conclusion

- Results for f_B, f_{B_s} and f_{B_s}/f_B are posted and submitted to PRD
  - Good agreement with results in the literature
  - Errors dominated by chiral-continuum extrapolation
- Already improving our errors by simulating with physical pion mass
- Another ensemble with finer lattice spacing will be added

- Measurements for $B - \overline{B}$ mixing are in progress

- Friday: $B \to \pi \ell \nu$ and $B_s \to K \ell \nu$ form factors