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

RBC and UKQCD collaborations

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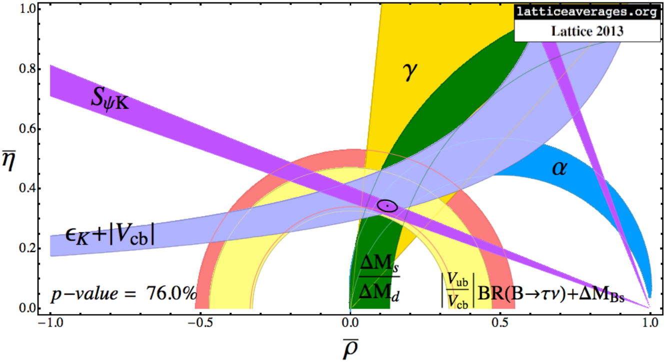
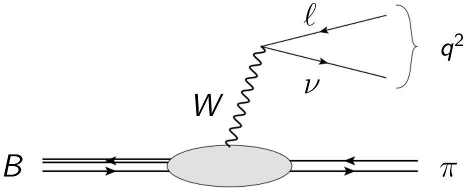
Motivation: Constraining the Standard Model

- Determination of CKM matrix elements V_{ub} and V_{cb}
- B-physics provides constraints on the apex of the CKM unitarity triangle
  - B^0–$\overline{B^0}$ mixing
  - V_{ub} and V_{cb} e.g. from $B \to \pi\ell\nu$ and $\overline{B} \to D^*\ell\nu$ form factors
- Experimental results and nonperturbative inputs are needed



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

Example: V_{ub} from exclusive semileptonic decay $B \to \pi \ell \nu$



$$q^2 = M_B^2 + M_\pi^2 - 2 M_B E_\pi$$

- Conventionally parameterized by

$$\frac{d\Gamma(B\to\pi\ell\nu)}{dq^2} = \frac{G_F^2}{192\pi^3 M_B^3}\left[\left(M_B^2 + M_\pi^2 - q^2\right)^2 - 4M_B^2 M_\pi^2\right]^{3/2} \times |f_+(q^2)|^2 \times |V_{ub}|^2$$

experiment known nonperturbative input CKM

Motivation: New Physics in 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!

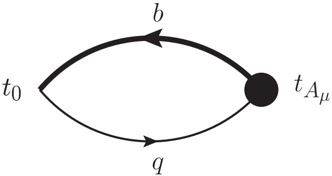
Challenges for B-physics on the lattice

- The mass of the b-quark introduces another scale
  - Light quark masses: $m_u = 2.3$ MeV, $m_d = 4.8$ MeV, $m_s = 95$ MeV
  - Mass of the b-quark: $m_b = 4.18$ GeV
- Today's lattices have an inverse lattice spacing of $a^{-1} \approx 1.7 \ldots 3$ GeV
  - $am_b > 1$
  - Forced to simulate b-quarks with an effective action
    e.g. HQET (static), NRQCD, Fermilab or RHQ action
- Relativistic Heavy Quark (RHQ) action
  - Anisotropic action to simulate dynamical b-quarks
  - Similar size discretization errors in heavy-light quantities as in light-light
  - Requires (perturbative) mixed-action renormalization factors

Our project

- Based on RBC-UKQCD's 2+1 flavor domain-wall Iwasaki gauge field configurations
- 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 [Taichi Kawanai]
  - $g_{B^*B\pi}$ coupling constant [Ben Samways]
- Provides important cross-check of other $N_f = 2 + 1$ determinations using the MILC staggered ensembles

B-meson decay constant [arXiv:1404.4670 [hep-lat]]



- Use point-source light quark and generate Gaussian smeared-source heavy quark
- On the lattice we compute Φ_{B_q}

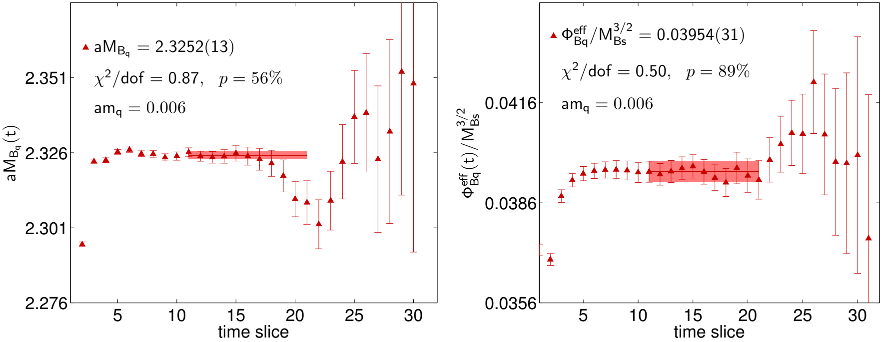
$$f_B = \Phi^{\text{ren}}_{B_q} \cdot a_{32}^{-3/2} / \sqrt{M_{B_q}}$$

- Improve axial current at 1-loop ($O(\alpha_S a)$, perturbatively computed coefficient)
- Use mostly-nonperturbative renormalization [El-Khadra et al. Phys.Rev. D64 (2001) 014502]

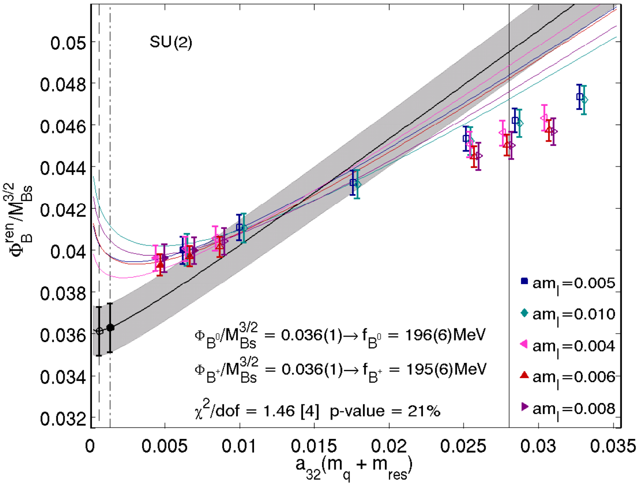
$$Z_V^{bl} = \varrho^{bl} \cdot \sqrt{Z_V^{bb} Z_V^{ll}}$$

B-meson decay constant [arXiv:1404.4670 [hep-lat]]

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

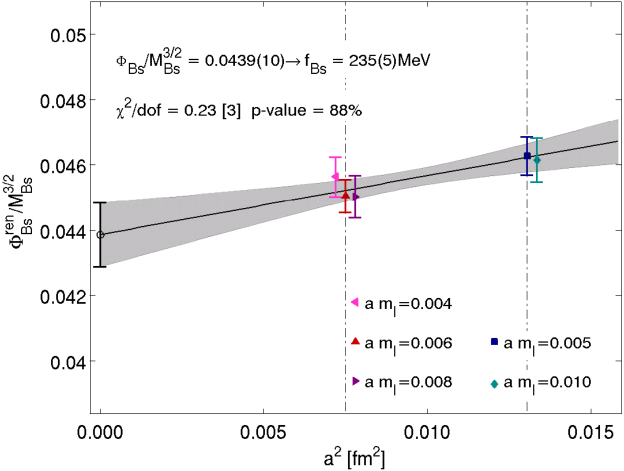


Chiral-continuum extrapolation of f_B [arXiv:1404.4670 [hep-lat]]



- NLO SU(2) HMχPT
- Only data points with filled symbols included in the fit ($M_\pi < 420$ MeV)
- Statistical errors only
- $g_{B^*B\pi} = 0.57(8)$ [PoS(Lattice 2013)408]
- $f_\pi = 130.4$ MeV [PDG]
- $\Lambda_\chi = 1$ GeV

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

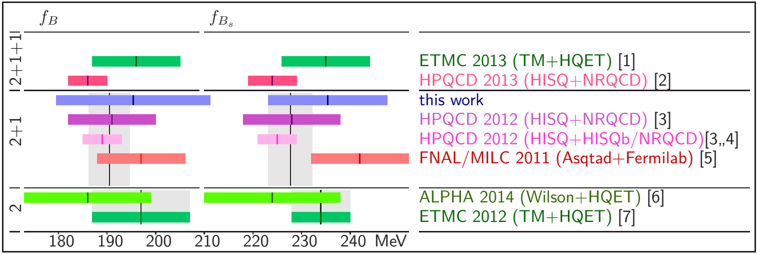


- Data for Φ_{B_s} show no sea-quark mass dependence
- Average data at same lattice spacing
- Assume a^2 scaling to remove LQ and gluon discretization errors
- Statistical errors only

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

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

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

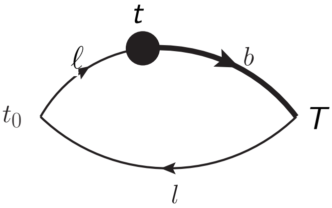


- Good agreement with other results

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] Bernardoni et al. arXiv:1404.3590 [hep-lat]
[7] Carrasco et al. PoS LATTICE2012 (2012) 104

$B \to \pi \ell \nu$: computation of lattice form factors $f_\parallel$ and $f_\perp$

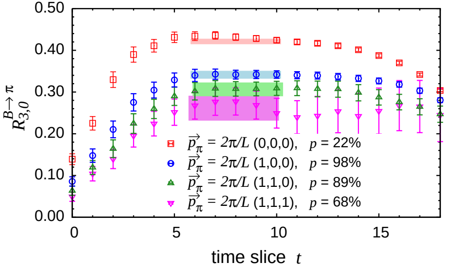
(which are linearly related to f_+ and f_0)

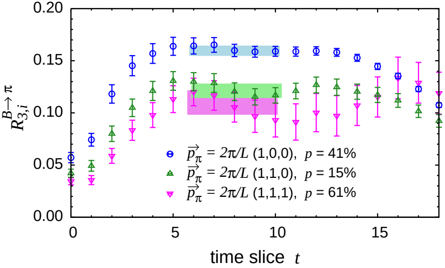


$$f_\parallel = \lim_{t,T\to\infty} R_0^{B\to\pi}(t,T)$$

$$f_\perp = \lim_{t,T\to\infty} \frac{1}{p_\pi^i} R_i^{B\to\pi}(t,T)$$

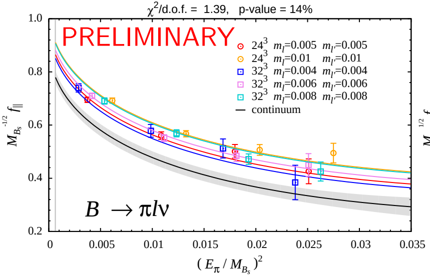
$$R_\mu^{B\to\pi}(t,T) = \frac{C_{3,\mu}^{B\to\pi}(t,T)}{C_2^\pi(t)\,C_2^B(T-t)} \sqrt{\frac{2E_\pi}{e^{-E_\pi t} e^{-M_B(T-t)}}}$$

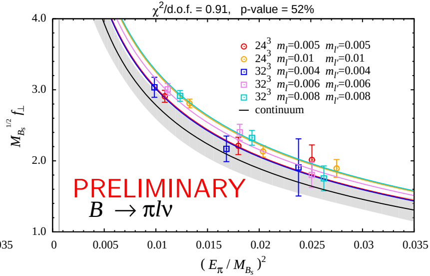




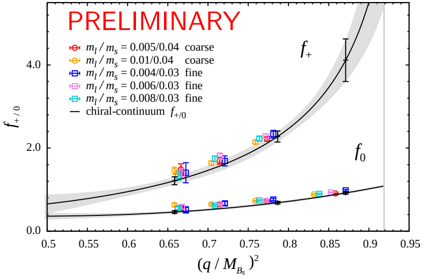
[plots by Taichi Kawanai]

Chiral-continuum extrapolation using SU(2) hard-pion χPT



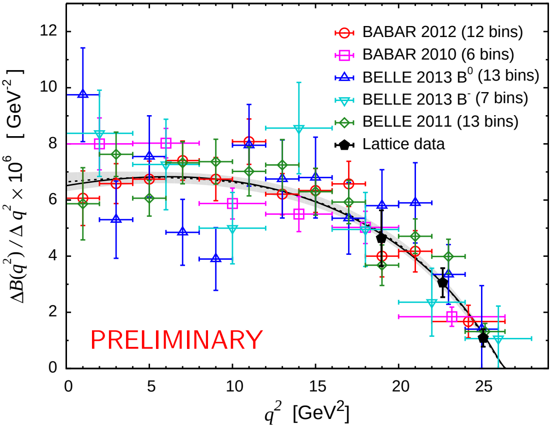


- Extract $f_{||}$ and $f_\perp$ for three different q^2 values
- Estimate all systematic errors and add in quadrature
- Convert results to f_+ and f_0



[plots by Taichi Kawanai]

Combine with experimental data to determine $|V_{ub}|$



- $|V_{ub}| \approx 3.6(3) \cdot 10^{-3}$ (preliminary)
- in good agreement with existing results

[plot by Taichi Kawanai]

Conclusion

- Results for decay constants f_B and f_{B_s} 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

- Finalizing analyses for $B \to \pi\ell\nu$ and $B_s \to K\ell\nu$ form factors
  - Promising looking results

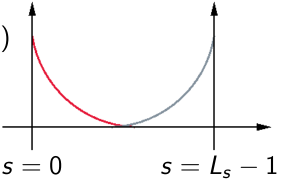
- First determination of the $g_{B^*B\pi}$ coupling with relativistic b-quarks (publication in preparation)

- Measurements for $B^0 - \overline{B^0}$ mixing are in progress

Appendix

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]

$B \to \pi\ell\nu$: relating form factors f_+ and f_0 to $f_\parallel$ and $f_\perp$

- Parametrize the hadronic matrix element for the flavor changing vector current V^μ in terms of the form factors $f_+(q^2)$ and $f_0(q^2)$

$$\langle\pi|V^\mu|B\rangle = f_+(q^2)\left(p_B^\mu + p_\pi^\mu - \frac{M_B^2-M_\pi^2}{q^2}q^\mu\right) + f_0\frac{M_B^2-M_\pi^2}{q^2}q^\mu$$

- Using the B-meson rest frame we compute on the lattice

$$f_\parallel(E_\pi) = \langle\pi|V^0|B\rangle/\sqrt{2M_B} \quad \text{and} \quad f_\perp(E_\pi)p_\pi^i = \langle\pi|V^i|B\rangle/\sqrt{2M_B}$$

- Both are related by

$$f_0(q^2) = \frac{\sqrt{2M_B}}{M_B^2-M_\pi^2}\left[(M_B-E_\pi)f_\parallel(E_\pi) + (E_\pi^2-M_\pi^2)f_\perp(E_\pi)\right]$$

$$f_+(q^2) = \frac{1}{\sqrt{2M_B}}\left[f_\parallel(E_\pi) + (M_B-E_\pi)f_\perp(E_\pi)\right]$$