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
Jiqun Tu

U Edinburgh
Peter Boyle
Guido Cossu
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

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Julien Frison

Peking U
Xu Feng

U Plymouth
Nicolas Garron

York U (Toronto)
Renwick Hudspith

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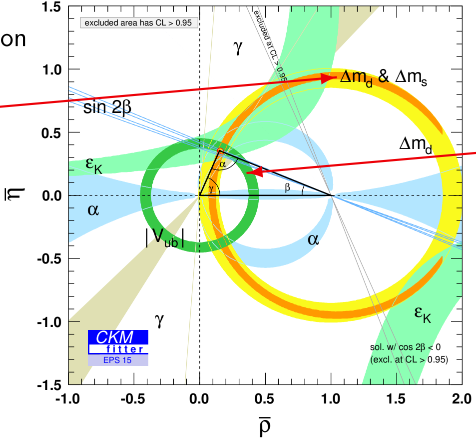
Where can lattice QCD contribute?

CKM unitarity triangle fit

- Neutral B-meson mixing
  B_B, ξ



- Exclusive semi-leptonic decays e.g.

$B \to \pi\ell\nu_\ell \Rightarrow |V_{ub}|$

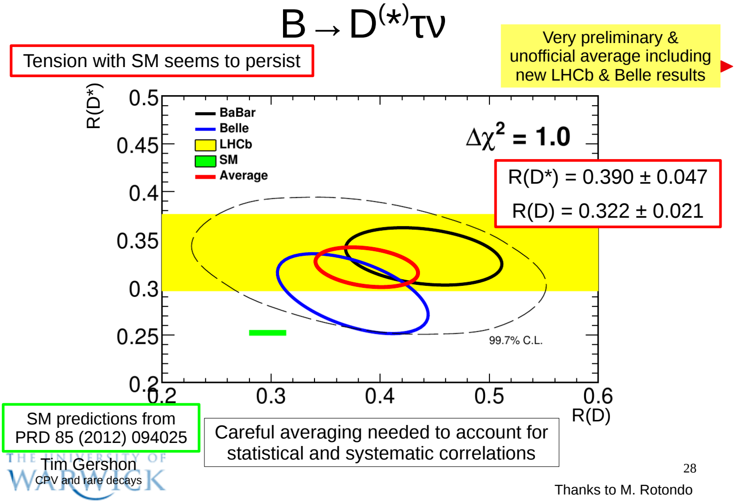
$B \to D\ell\nu_\ell \Rightarrow |V_{cb}|$

with $\ell = e, \mu, \tau$

- Tension between incl. and excl. determinations

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

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



- $R_{D^{(*)}} = \dfrac{\mathcal{B}(B \to D^{(*)}\tau\nu_\tau)}{\mathcal{B}(B \to D^{(*)}\ell\nu_\ell)}$ with $\ell = e, \mu$
- 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]
  - $B \to \pi\ell\nu$ and $B_s \to K\ell\nu$ 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

L	a^{-1}(GeV)	am_l	am_s	M_π(MeV)	# configs.	#sources	
24	1.784	0.005	0.040	338	1636	1	[PRD 78 (2008) 114509]
24	1.784	0.010	0.040	434	1419	1	[PRD 78 (2008) 114509]
32	2.383	0.004	0.030	301	628	2	[PRD 83 (2011) 074508]
32	2.383	0.006	0.030	362	889	2	[PRD 83 (2011) 074508]
32	2.383	0.008	0.030	411	544	2	[PRD 83 (2011) 074508]
48	1.730	0.00078	0.0362	139	40	81/1*	[PRD 93 (2016) 074505]
64	2.359	0.000678	0.02661	139	—	—	[PRD 93 (2016) 074505]
48	∼2.7	0.002144	0.02144	∼250	> 50	24	[in progress]

* 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: ∼ 0.11 fm, ∼ 0.08 fm, ∼ 0.07 fm

Up, down, and strange quarks

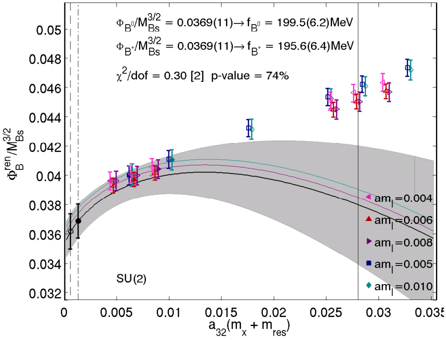
- Domain-wall fermions with same parameters as in the sea-sector (domain-wall height M_5, extension of 5^{th} dimension L_s)
- Unitary and partially quenched quark masses
- Strange quarks at/near physical the physical value

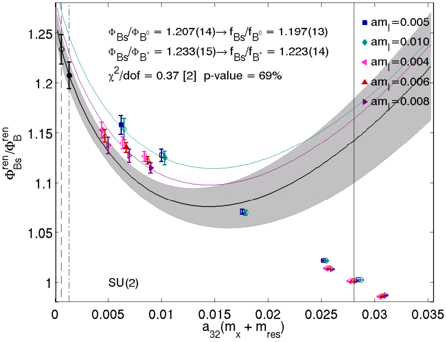
Bottom quarks

- Relativistic Heavy Quark (RHQ) action developed by Christ, Li, and Lin [Christ et al. PRD 76 (2007) 074505], [Lin and Christ PRD 76 (2007) 074506]
- Builds upon Fermilab approach [El-Khadra et al. PRD 55 (1997) 3933]
- Allows to tune the three parameters ($m_0 a$, c_P, ζ) nonperturbatively [PRD 86 (2012) 116003], recently re-tuned to update a^{-1} values
- Heavy quark mass is treated to all orders in $(m_b a)^n$
- Has a smooth continuum limit

Decay constants

[PRD 91 (2015) 054502]

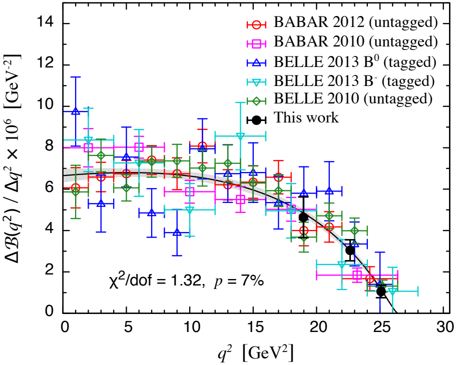


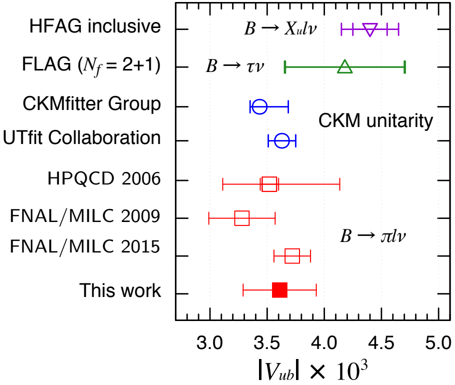


- $f_{B^0} = 199.5(12.6)$ MeV
- $f_{B^+} = 195.6(14.9)$ MeV
- $f_{B_s} = 235.4(12.2)$ MeV
- $f_{B_s}/f_{B^0} = 1.197(50)$
- $f_{B_s}/f_{B^+} = 1.223(71)$

Semi-leptonic form factors: $B \to \pi \ell \nu$ and $|V_{ub}|$

[PRD 91 (2015) 074510]



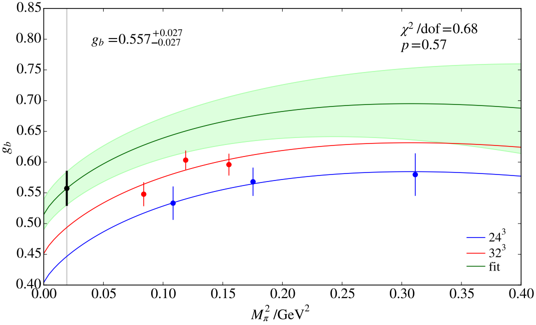


- In good agreement with existing and new FNAL/MILC result
- Result agrees with value obtained from CKM unitarity

$B^*B\pi$ coupling constant

[PRD 93 (2016) 014510]

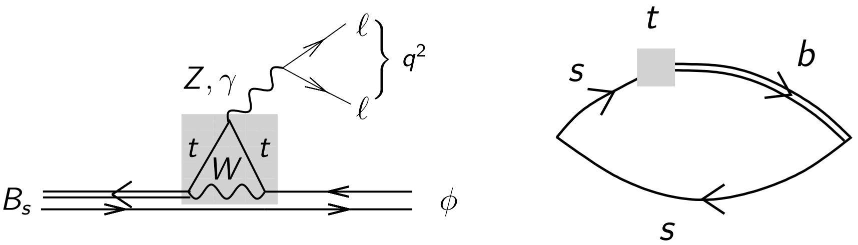
- Strong coupling $g_{B^*B\pi}$ parametrizes $\langle B\pi | B^* \rangle$
- Related to LEC g_b of HMχPT $g_b = g_{B^*B\pi} \cdot f_\pi / (2M_B)$
- Not accessible experimentally but needed to determine e.g. $f_+^{B\pi}$
- First determination at physical $b-$quark mass



Outlook

- Update/improve determinations for decay constants f_B, f_{B_s} as well as semi-leptonic-form factors for $B \to \pi\ell\nu$ ($\Rightarrow |V_{ub}|$) and $B_s \to K\ell\nu$
  $\to$ 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 $B_{(s)} \to D^*_{(s)}\ell\nu$ form factors

GIM suppressed semi-leptonic decays e.g. $B_s \to \phi \ell^+ \ell^-$

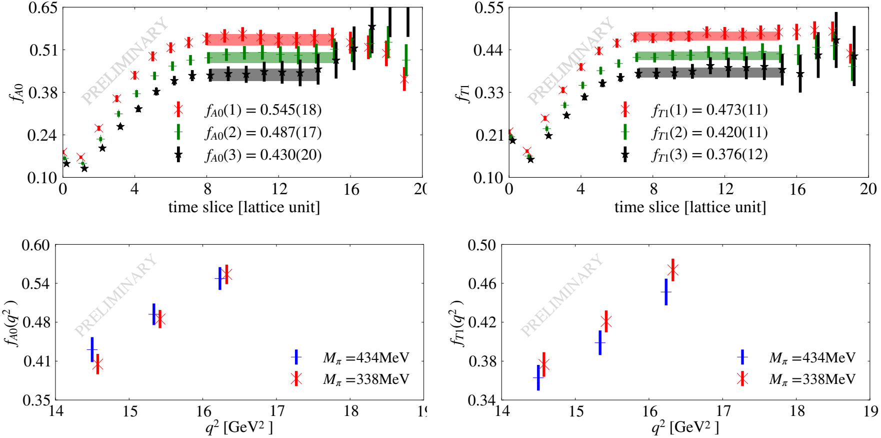


- Full basis contains 20 operators but at short distance only $O_7^{(\prime)}$, $O_9^{(\prime)}$, and $O_{10}^{(\prime)}$ contribute
- Short distance contributions only!

  (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 $B_s \to \Phi\ell^+\ell^-$: f_{A0} and f_{T1}

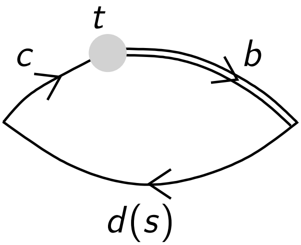
- $24^3 \times 64$ ensemble with $a^{-1} = 1.784$ GeV and $am_l = 0.005$ ($M_\pi \approx 338$ MeV)



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

$B_{(s)} \to D_{(s)}^{(*)}$ form factors

- Same setup as for $B \to \pi \ell \nu$ or $B_s \to K \ell \nu$
- 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^{phys}
  - → Simulate 3 or 2 charm-like masses and then extrapolate/interpolate
  - → Linear extrapolation is small and benign; interpolation is safe

Charm extrapolation

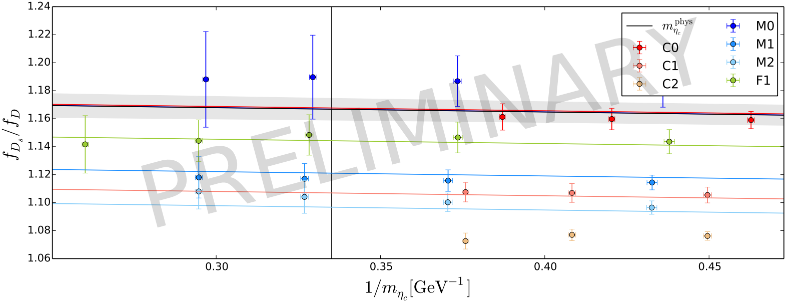
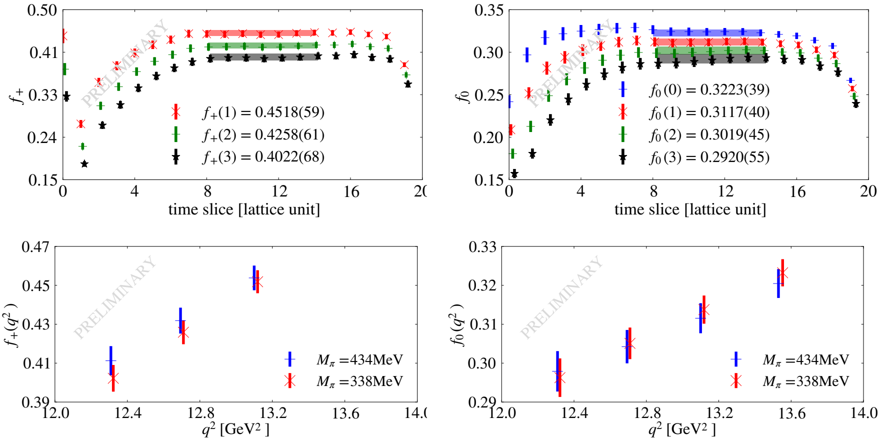


Figure by T. Tsang

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

First results for $B_s \to D_s \ell \nu$

- $24^3 \times 64$ 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

MARIE CURIE ACTIONS

SEVENTH FRAMEWORK PROGRAMME