Semi-leptonic B and B_s-decays with charming hadronic final state

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Motivation

- Form factors for $B \to D^{(*)}\ell\nu$
  - → Allow to determine the CKM matrix-element $|V_{cb}|$
  - → $|V_{cb}|$ enters as normalization in the unitary triangle fit
  - → $2-3\ \sigma$ discrepancy between $|V_{cb}|^{\text{incl}}$ and $|V_{cb}|^{\text{excl}}$
  - → Atlas, CMS, LHCb and Belle II will improve experimental results

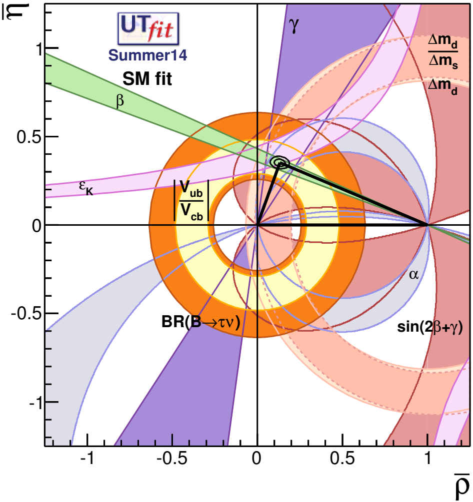
- $2-3\ \sigma$ tension in $R_{D^{(*)}}$ ratio — independent of $|V_{cb}|$

[Fajfer et al. PRD 85 (2012) 094025],[J. Bailey et al. PRL 109 (2012) 071802],[BaBar PRL 109 (2012) 101802]

$$R_{D^{(*)}} = \mathcal{B}(B \to D^{(*)}\tau\nu_\tau)/\mathcal{B}(B \to D^{(*)}\ell\nu_\ell), \text{ with } \ell = e, \mu$$

- → Due to its mass τ is sensitive to both form factors $f_+(q^2)$ and $f_0(q^2)$, $\ell = e, \mu$ are dominated by $f_+(q^2)$
- → Anomaly in R_{D^*} is seen by BaBar, LHCb, and Belle
- → New physics?

Motivation: CKM unitarity triangle fit

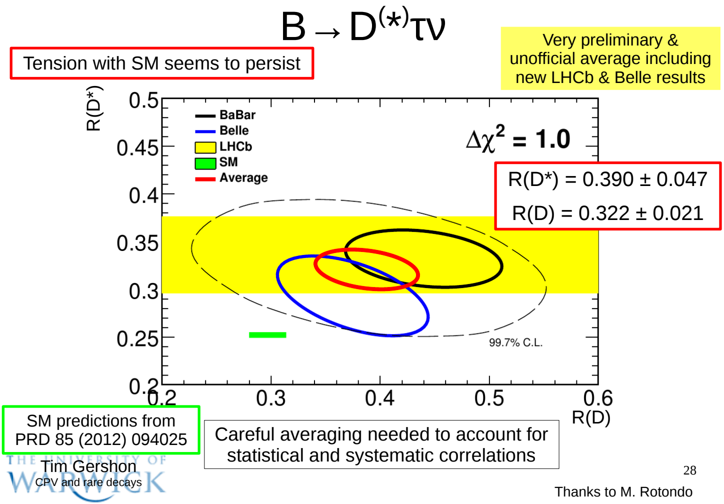


$|V_{cb}|$ enters crucially as normalization of the unitarity triangle

$\varepsilon_K \propto |V_{cb}|^4$

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

Motivation: $R_{D^{(*)}}$



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

Tension with SM seems to persist

Very preliminary & unofficial average including new LHCb & Belle results

R(D*) = 0.390 ± 0.047

R(D) = 0.322 ± 0.021

SM predictions from PRD 85 (2012) 094025

Careful averaging needed to account for statistical and systematic correlations

Tim Gershon
CPV and rare decays

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Thanks to M. Rotondo

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

- Not using latest lattice results:

  $\overline{B} \to D^*\ell\nu$: Fermilab/MILC

  [PRD 79 (2014) 014506]

  [PRD 89 (2014) 114504]

  $B \to D\ell\nu$: Fermilab/MILC

  [PRD 92 (2015) 034506]

  HPQCD

  [PRD 92 (2015) 054510]

  Atoui et al.

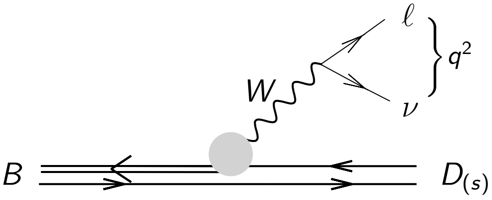
  [EPJ. C74 (2014) 2861]

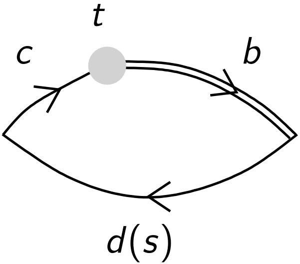
Our RHQ Project

- 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] Talk by E. Lizarazo, Friday, July 29, 17:10

- 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

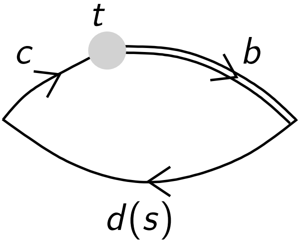
$B \to D\ell\nu$ and $B_s \to D_s\ell\nu$ charged current decays





- $\langle D(p_D)|\mathcal{V}^\mu|B(p_B)\rangle = f_+(q^2)\left[(p_B+p_D)^\mu - \frac{M_B^2-M_D^2}{q^2}q^\mu\right] + f_0(q^2)\frac{M_B^2-M_D^2}{q^2}q^\mu$

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



- Re-use DWF point-source light and strange quark propagators
- Generate Gaussian smeared MDWF charm quark propagators (on the fly)
- Create Gaussian smeared-source sequential heavy quark propagators

- Compute all possible contractions for pseudoscalar or vector final states
- General building blocks code incl. terms for 1-loop $O(\alpha_S a)$ improvement
- Coefficients to be computed in lattice perturbation theory

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 hight M_5, extension of 5th dimension L_s)
- Unitary and partially quenched quark masses
- Strange quarks at/near physical the physical value

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 $am_c < 0.45$
  - → 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 Talk by T. Tsang, Friday, July 29, 13:00

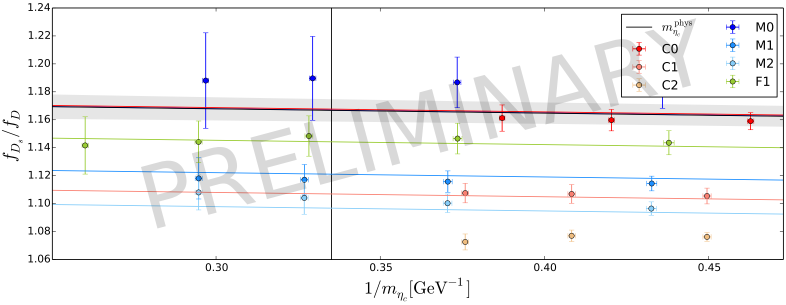


Figure by T. Tsang

- Small extrapolation for $a^{-1} = 1.784$ GeV ensembles
- Interpolation for $a^{-1} \geq 2.383$ GeV ensembles

MDWF charm quarks

Advantages

- Very similar setup for computing $B_s \to D_s$ as for $B_s \to K$
  - → Only minor modifications for the perturbative calculations
- No nonperturbative tuning of the RHQ action for charm quarks
- Allows to explore new concept of heavy DWF for semileptonic decays
  - → Fully nonperturbative renormalization of f_D in progress
    Talk by A. Khamseh, Wednesday, July 27, 10:20

Disadvantages

- Larger numerical costs than RHQ charm
- On coarse ensembles small extrapolation needed

Bottom quarks

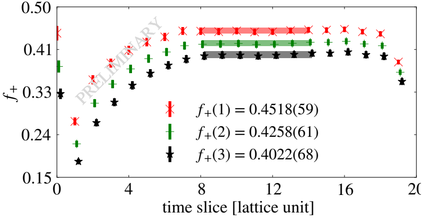
- Relativistic Heavy Quark action developed by Christ, Li, and Lin [Christ et al. PRD 76 (2007) 074505], [Lin and Christ PRD 76 (2007) 074506]
- Allows to tune the three parameters (m_0a, c_P, ζ) nonperturbatively [PRD 86 (2012) 116003]
- Builds upon Fermilab approach [El-Khadra et al. PRD 55 (1997) 3933] by tuning all parameters of the clover action non-perturbatively; close relation to the Tsukuba formulation [S. Aoki et al. PTP 109 (2003) 383]
- Heavy quark mass is treated to all orders in $(m_ba)^n$
- Expand in powers of the spatial momentum through $O(\vec{p}a)$
  - Resulting errors will be of $O(\vec{p}^2a^2)$
  - Allows computation of heavy-light quantities with discretization errors of the same size as in light-light quantities
- Applies for all values of the quark mass
- Has a smooth continuum limit
- Recently re-tuned to account for updated values of a^{-1}

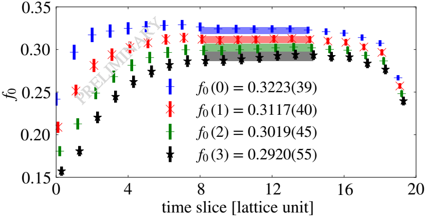
First results

- Define (single) ratios for $B_s \to D_s \ell \nu$, with B_s meson at rest

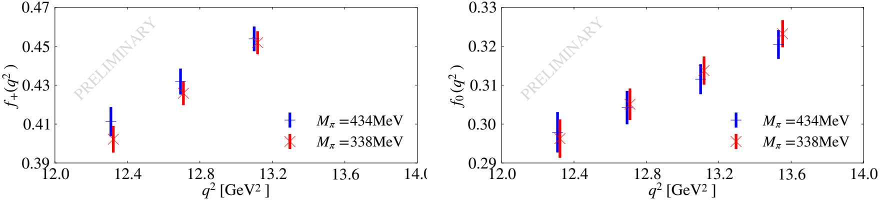
$$R_{3,\mu}(t, t_{\mathrm{snk}}, \vec{p}_{D_s}) = \frac{C_{3,\mu}(t, t_{\mathrm{snk}}, \vec{p}_{D_s})}{\sqrt{C_2^{D_s}(t, \vec{p}_{D_s})\, \tilde{C}_2^{B_s}(t_{\mathrm{snk}} - t)}} \frac{\sqrt{2E_{D_s}}}{\exp(-E_{D_s} t)\exp(-M_{B_s}(t_{\mathrm{snk}} - t))}$$

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





q^2 dependence



- Data on further ensembles exists
- Have to obtain renormalization factors for meaningful combination

Alternative determination via double ratios

- Introduced by Hashimoto et al. for $B \to D\ell\nu$ at zero recoil [PRD 66 (2002) 014503]
- Extended to nonzero recoil by Fermilab/MILC [PRD92 (2015) 034506]
- Get form factors from double ratio at zero and single ratios at nonzero recoil

$$R_+ = \frac{\langle D(\vec{0})|V^4_{cb}|B(\vec{0})\rangle\langle B(\vec{0})|V^4_{cb}|D(\vec{0})\rangle}{\langle D(\vec{0})|V^4_{cc}|D(\vec{0})\rangle\langle B(\vec{0})|V^4_{bb}|B(\vec{0})\rangle}$$

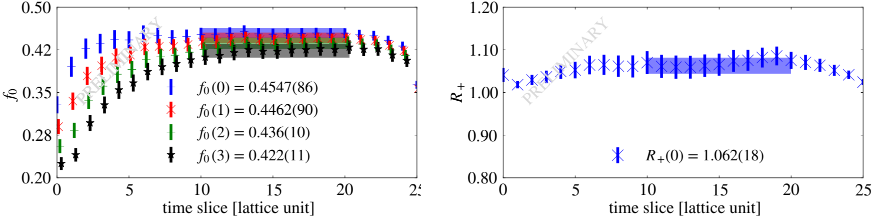
$$Q_+(\vec{p}) \equiv \frac{\langle D(\vec{p})|V^4|B(\vec{0})\rangle}{\langle D(\vec{0})|V^4|B(\vec{0})\rangle} \quad R_-(\vec{p}) \equiv \frac{\langle D(\vec{p})|\vec{V}|B(\vec{0})\rangle}{\langle D(\vec{p})|V^4|B(\vec{0})\rangle} \quad x_f(\vec{p}) \equiv \frac{\langle D(\vec{p})|\vec{V}|D(\vec{0})\rangle}{\langle D(\vec{p})|V^4|D(\vec{0})\rangle}$$

- Need renormalization factors (ϱ) for obtaining form factors at $q^2 > 0$

Exploratory comparison of single vs. double ratios

- $32^3 \times 64$ ensemble with $a^{-1} = 2.383$ GeV and $am_\ell = 0.006$ ($M_\pi \approx 362$ MeV)
- Subset of data (1 source), only pseudoscalar final states (D and D_s)
- Analyzed data for $B_s \to D_s \ell \nu$

single ratio double ratio



- Relative error: 1.9% 1.7%
- Will it be worth 5 × larger costs?

— Have to look at $B \to D$, nonzero momenta, fitting ranges, etc.

Resources and Acknowledgements

- 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

SEVENTH FRAMEWORK PROGRAMME

MARIE CURIE ACTIONS

Cost for charm 3-point functions

- Single ratios
  - $B \to D\ell\nu$, $B \to D^*\ell\nu$ (1 charm inversion)
  - $B_s \to D_s\ell\nu$, $B_s \to D_s^*\ell\nu$ (0 additional charm inversions)
- Double ratios
  - $B \to D\ell\nu$ and $B \to D^*\ell\nu$ (3 charm inversions)

    $B \to D$, $B \to B$, $D \to B$, $D \to D$

    $B \to D^*$, $B \to B$,$D^* \to B$, $D^* \to D^*$
  - $B_s \to D_s\ell\nu$ and $B_s \to D_s^*\ell\nu$ (2 additional charm inversions)

    $B_s \to D_s$, $B_s \to B_s$, $D_s \to B_s$, $D_s \to D_s$

    $B_s \to D_s^*$, $B_s \to B_s$, $D_s^* \to B_s$, $D_s^* \to D_s^*$
- Since we are extrapolating (interpolating) to the physical charm quark pass, we encounter the factor 5 for 3 (2) used charm quark masses
- Total: $N_{configurations} \times N_{sources} \times 2 \times N_{charm} \times (5 \text{ or } 1)$