Semileptonic B_s decays

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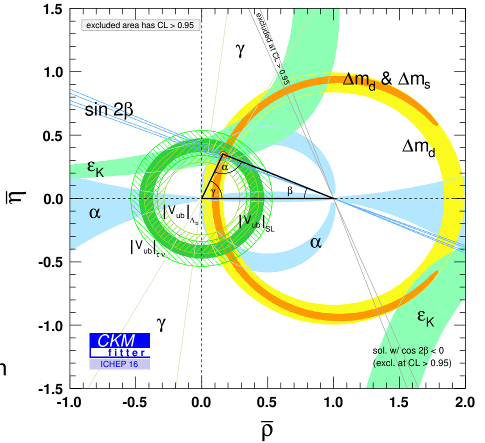
introduction

Why B_s meson decays?

- Alternative, tree-level determination of $|V_{cb}|$ and $|V_{ub}|$ from $B_s \to D_s\ell\nu$ and $B_s \to K\ell\nu$
  - → Commonly used $B \to \pi\ell\nu$ and $B \to D^{(*)}\ell\nu$
  - → Long standing $2-3\sigma$ discrepancy between exclusive $(B \to \pi\ell\nu)$ and inclusive $(B \to X_u\ell\nu)$
  - → $B \to \tau\nu$ has larger error
  - → Alternative, exclusive $(\Lambda_b \to p\ell\nu)$ determination [Detmold, Lehner, Meinel, PRD92 (2015) 034503]



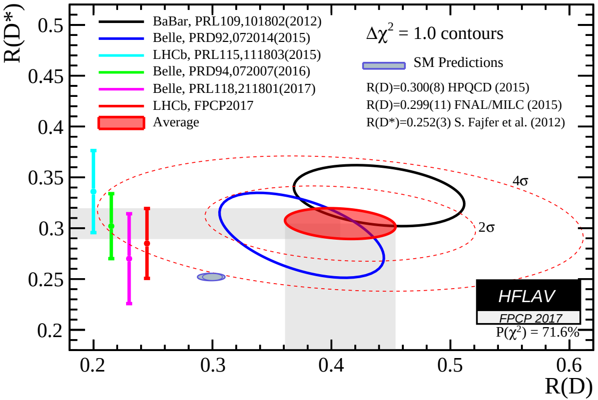
[http://ckmfitter.in2p3.fr]

Why B_s meson decays?

[HFLAV]

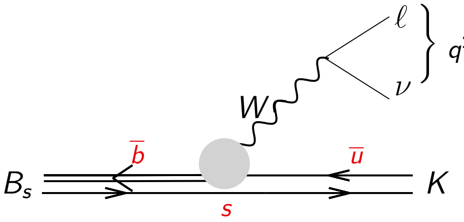
- Alternative tests of lepton flavor violations
  $\rightarrow$ Determine e.g. $R_{D_s^{(*)}}$ from B_s decays to compare with $R_{D^{(*)}}$ from B decays

$$\mathcal{R}^{\tau/\mu}_{D^{(*)}} \equiv \frac{d\Gamma(B \to D^{(*)}\tau\nu_\tau)/d_q^2}{d\Gamma(B \to D^{(*)}\mu\nu_\mu)/d_q^2}$$



- While SM prediction shown has small error, value for $R_{D^{(*)}}$ is a pheno. estimate
- Nonperturbative lattice calculation favor B_s over B decays (higher precision)
- Only the spectator quark differs: $R_{D_s^{(*)}}$ may be a good proxy for $R_{D^{(*)}}$

$|V_{ub}|$ from exclusive semileptonic $B_s \to K\ell\nu$ decay



$$q^2 = M_{B_s}^2 + M_K^2 - 2M_{B_s}E_K$$

- Conventionally parametrized by (neglecting term $\propto m_\ell^2 f_0^2$)

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

experiment known nonperturbative input CKM

Nonperturbative input

- Parametrizes interactions due to the (nonperturbative) strong force
- Use operator product expansion (OPE) to identify short distance contributions
- Calculate the flavor changing currents as point-like operators using lattice QCD

$\Rightarrow$ Nonperturbative calculation: lattice QCD

$\to$ Additional challenge $m_b = 4.18\text{GeV} \sim 1000 \times m_d$

$m_c = 1.28\text{GeV} \sim 270 \times m_d$

Set-up

- RBC-UKQCD's 2+1 flavor domain-wall fermion and Iwasaki gauge action ensembles
  - → Three lattice spacings $a \sim 0.11$ fm, 0.08 fm, 0.07 fm; one ensemble with physical pions
    [PRD 78 (2008) 114509][PRD 83 (2011) 074508][PRD 93 (2016) 074505][JHEP 1712 (2017) 008]

- Unitary and partially quenched domain-wall up/down quarks
  [Kaplan PLB 288 (1992) 342], [Shamir NPB 406 (1993) 90]
- Domain-wall strange quarks at/near the physical value
- Charm: Möbius domain-wall fermions optimized for heavy quarks [Boyle et al. JHEP 1604 (2016) 037]
  - → Simulate 3 or 2 charm-like masses then extrapolate/interpolate

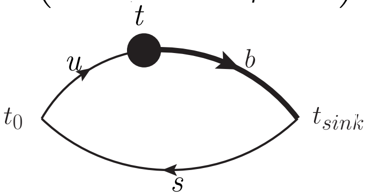
- Effective relativistic heavy quark (RHQ) action for bottom quarks
  [Christ et al. PRD 76 (2007) 074505], [Lin and Christ PRD 76 (2007) 074506]
  - → Builds upon Fermilab approach [El-Khadra et al. PRD 55 (1997) 3933]
  - → Allows to tune the three parameters (m_0a, c_P, ζ) nonperturbatively [PRD 86 (2012) 116003]
  - → Smooth continuum limit; heavy quark treated to all orders in $(m_ba)^n$

$$B_s \to K\ell\nu$$

$B_s \to K\ell\nu$ form factors

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

$$\langle K|V^\mu|B_s\rangle = f_+(q^2)\left(p^\mu_{B_s} + p^\mu_K - \frac{M^2_{B_s} - M^2_K}{q^2}q^\mu\right) + f_0(q^2)\frac{M^2_{B_s} - M^2_K}{q^2}q^\mu$$



- Calculate 3-point function by
  - → Inserting a quark source for a "light" propagator at t_0
  - → Allow it to propagate to t_{sink}, turn it into a sequential source for a b quark
  - → Use another "light" quark propagating from t_0 and contract both at t

Determining $B_s \to K\ell\nu$ form factors f_+ and f_0 on the lattice

- Updating calculation [PRD 91 (2015) 074510] with new values for a^{-1} and RHQ parameters
- New analysis directly fitting form factors and accounting for excited state contributions
- On the lattice we prefer using the B_s-meson rest frame and compute

$$f_{\|}(E_K) = \langle K|V^0|B_s\rangle/\sqrt{2M_{B_s}} \quad \text{and} \quad f_{\perp}(E_K)p_K^i = \langle K|V^i|B_s\rangle/\sqrt{2M_{B_s}}$$

- Both are related by

$$f_0(q^2) = \frac{\sqrt{2M_{B_s}}}{M_{B_s}^2 - M_K^2}\left[(M_{B_s} - E_K)f_{\|}(E_K) + (E_K^2 - M_K^2)f_{\perp}(E_K)\right]$$

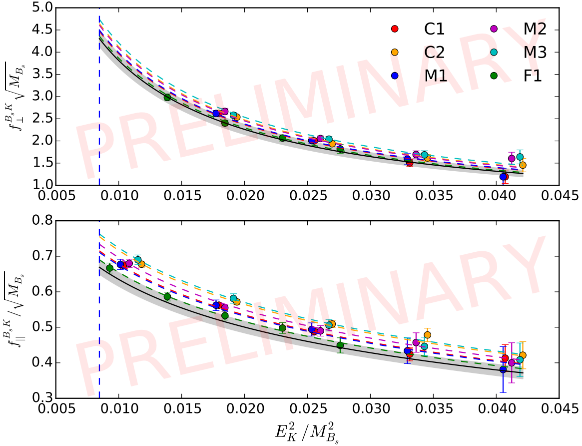
$$f_+(q^2) = \frac{1}{\sqrt{2M_{B_s}}}\left[f_{\|}(E_K) + (M_{B_s} - E_K)f_{\perp}(E_K)\right]$$

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

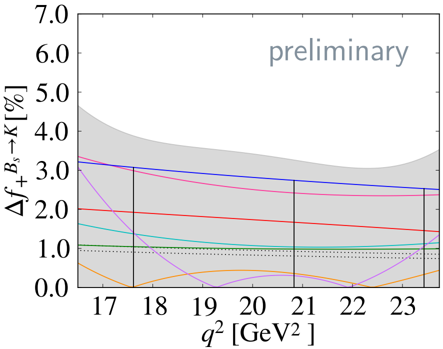
$$f_\perp(M_K, E_K, a^2) = \frac{1}{E_K+\Delta} c_\perp^{(1)}$$
$$\times \left[1 + \frac{\delta f_\perp}{(4\pi f)^2} + c_\perp^{(2)} \frac{M_K^2}{\Lambda^2} + c_\perp^{(3)} \frac{E_K}{\Lambda} + c_\perp^{(4)} \frac{E_K^2}{\Lambda^2} + c_\perp^{(5)} \frac{a^2}{\Lambda^2 a_{32}^4}\right]$$

$$f_\parallel(M_K, E_K, a^2) = \frac{1}{E_K+\Delta} c_\parallel^{(1)}$$
$$\times \left[1 + \frac{\delta f_\parallel}{(4\pi f)^2} + c_\parallel^{(2)} \frac{M_K^2}{\Lambda^2} + c_\parallel^{(3)} \frac{E_K}{\Lambda} + c_\parallel^{(4)} \frac{E_K^2}{\Lambda^2} + c_\parallel^{(5)} \frac{a^2}{\Lambda^2 a_{32}^4}\right]$$

with δf non-analytic logs of the kaon mass
and hard-kaon limit is taken by $M_K/E_K \to 0$



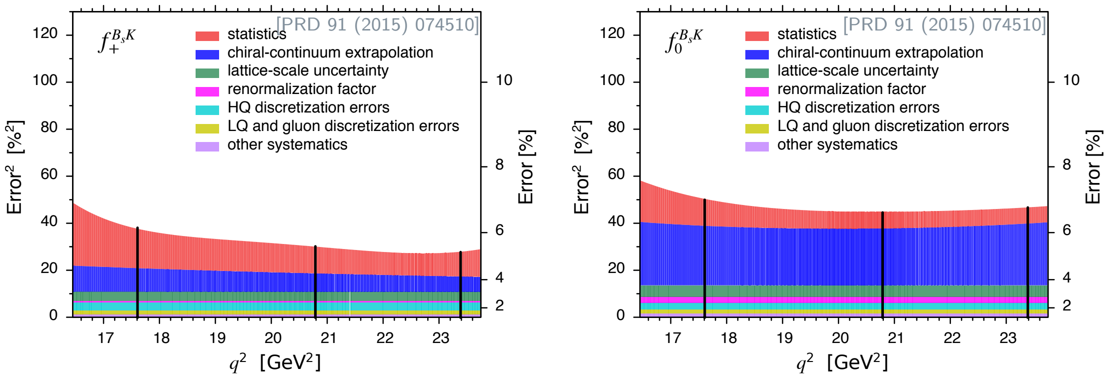
Estimate systematic errors due to



- Chiral-continuum extrapolation
  - → Use alternative fit functions
  - → Impose different cuts on the data
- Uncertainties of the lattice spacing (a^{-1})
  - → Repeat the fit varying a^{-1} by its uncertainty
- Uncertainty of the renormalization factors
  - → Estimate effect of higher loop corrections
- Discretization errors and uncertainties of light and heavy quarks
  - → Vary by uncertainty
  - → Carry out additional simulations to test effects on form factors
- Finite volume, iso-spin breaking, ...

$\Longrightarrow$ full error budget

Graphical error budget (plots from previous analysis!)



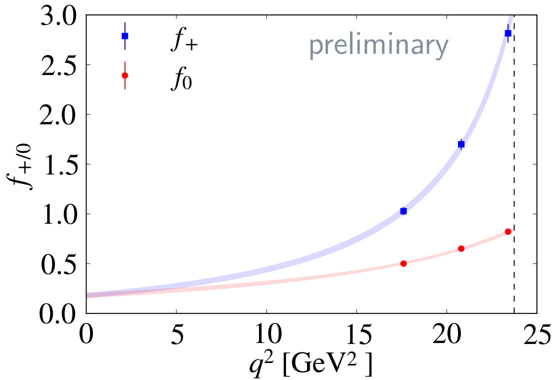
- Read off values for "synthetic" data points
  - → Use values in the chiral-continuum limit with uncertainties representing the full error budget
  - → Chiral-continuum extrapolation performed over range of our data
  - → Avoids parametrizing lattice artifacts in kinematic expansion

Kinematical extrapolation (z-expansion)

- Map q^2 to z with minimized magnitude in the semileptonic region: $|z| \leq 0.146$

$$z(q^2, t_0) = \frac{\sqrt{1-q^2/t_+} - \sqrt{1-t_0/t_+}}{\sqrt{1-q^2/t_+} + \sqrt{1-t_0/t_+}} \quad \text{with} \quad \begin{aligned} t_\pm &= (M_B \pm M_\pi)^2 \\ t_0 \equiv t_{\text{opt}} &= (M_B + M_\pi)(\sqrt{M_B} - \sqrt{M_\pi})^2 \end{aligned}$$

[Boyd, Grinstein, Lebed, PRL 74 (1995) 4603]
[Bourrely, Caprini, Lellouch, PRD 79 (2009) 013008]



- Express f_+ as convergent power series
- f_0 is analytic, except for B^* pole
- Exploit kinematic constraint $f_+ = f_0$ at $q^2 = 0$
- Use HQ power counting to constrain size of f_+ coefficients

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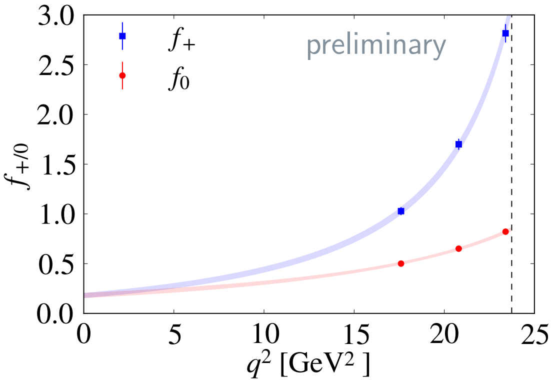
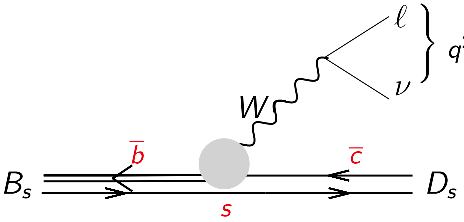


- Allows to compare shape of form factors
  - → Obtained by other lattice calculations [HPQCD PRD90 (2014) 054506]
  - → Predicted by QCD sum rules and alike

- Combination with experiment leads to the overall normalization: $|V_{ub}|$

$$B_s \to D_s \ell \nu$$

$|V_{cb}|$ from exclusive semileptonic $B_s \to D_s\ell\nu$ decay



$q^2 = M_{B_s}^2 + M_{D_s}^2 - 2M_{B_s}E_{D_s}$

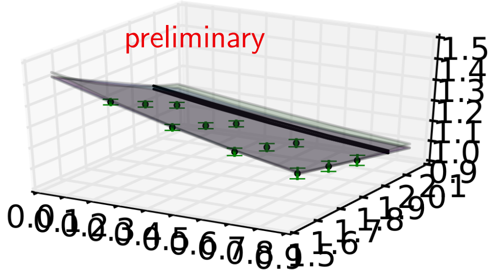
- Conventionally parametrized by (neglecting term $\propto m_\ell^2 f_0^2$)

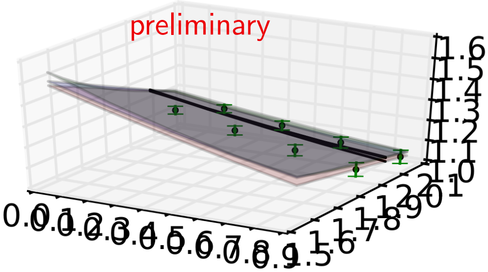
$$\frac{d\Gamma(B_s\to D_s\ell\nu)}{dq^2} = \frac{G_F^2}{192\pi^3 M_{B_s}^3}\left[\left(M_{B_s}^2 + M_{D_s}^2 - q^2\right)^2 - 4M_{B_s}^2 M_{D_s}^2\right]^{3/2} \times |f_+(q^2)|^2 \times |V_{cb}|^2$$

experiment known nonperturbative input CKM

Charm extra-/interpolation for $B_s \to D_s\ell\nu$

- Simulate charm quarks using DWF
  - → Similar action as for u, d, s quarks
  - → "Fully" relativistic setup simplifies renormalization
  - → Established by calculating $f_{D_{(s)}}$
    [Boyle et al. JHEP 1712 (2017) 008]
- Coarse ensembles
  - → Linearly extrapolate three charm-like masses
- Medium and fine ensembles
  - → Interpolate between two charm-like masses
- Analysis of data at third, finer lattice spacing will help to better estimate uncertainty

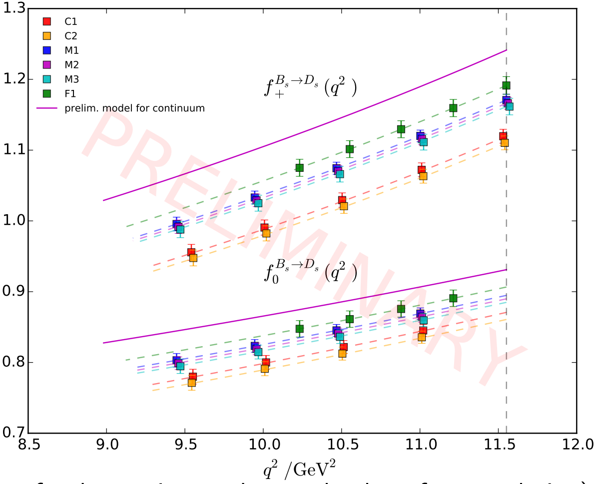




Chiral-continuum extrapolation

- No light valence quarks, no need for χPT
- Account for dependence on
  - $\to$ charm quark mass
  - $\to$ lattice spacing
  - $\to$ light sea-quark mass

$$f(q,a) = \frac{\alpha_0 + \alpha_1 M_{D_s} + \alpha_2 a^2 + \alpha_3 M_\pi^2}{1 + \alpha_4 q^2 / M_{B_s}^2}$$



(Only stat. errors for data points and central value of extrapolation)

conclusion

Conclusion

- In the final stages to complete $B_s \to K\ell\nu$ and $B_s \to D_s\ell\nu$ form factor calculation
  - $\to$ As usual, carefully estimating all systematic uncertainties is tedious
  - $\to$ Can even require additional simulations

- Our lattice calculation also includes
  - $\to B \to \pi\ell\nu$, $B \to \pi\ell^+\ell^-$
  - $\to B \to K^*\ell^+\ell^-$
  - $\to B \to D^{(*)}\ell\nu$
  - $\to B_s \to K^*\ell^+\ell^-$
  - $\to B_s \to D_s^*\ell\nu$
  - $\to B_s \to \phi\ell^+\ell^-$
  - $\to \ldots$

Resources and Acknowledgments

USQCD: Ds, Bc, and pi0 cluster (Fermilab), qcd12s cluster (Jlab)
RBC qcdcl (RIKEN) and cuth (Columbia U)
UK: ARCHER, Cirrus (EPCC) and DiRAC (UKQCD)

appendix

2+1 Flavor Domain-Wall Iwasaki ensembles

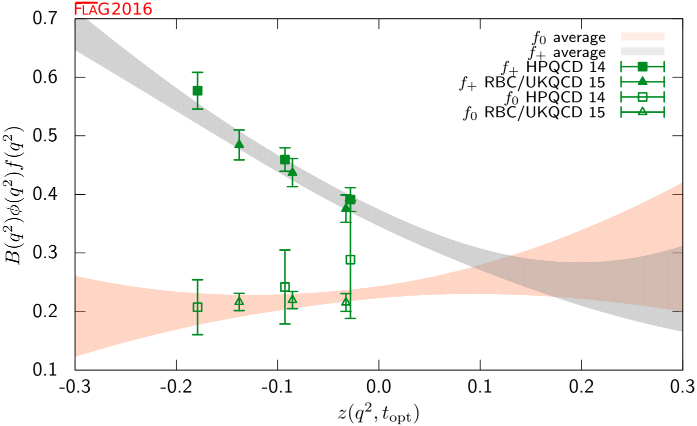
L	a^{-1}(GeV)	am_l	am_s	M_π(MeV)	# configs.	#sources	
24	1.784	0.005	0.040	338	1636	1	[PRD 78 (2008) 114509]
24	1.784	0.010	0.040	434	1419	1	[PRD 78 (2008) 114509]
32	2.383	0.004	0.030	301	628	2	[PRD 83 (2011) 074508]
32	2.383	0.006	0.030	362	889	2	[PRD 83 (2011) 074508]
32	2.383	0.008	0.030	411	544	2	[PRD 83 (2011) 074508]
48	1.730	0.00078	0.0362	139	40	$81/1^\star$	[PRD 93 (2016) 074505]
64	2.359	0.000678	0.02661	139	—	—	[PRD 93 (2016) 074505]
48	2.774	0.002144	0.02144	234	70	24	[arXiv:1701.02644]

* 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

Flavor Lattice Averaging Group

Lattice determinations of $B_s \to K\ell\nu$ form factors

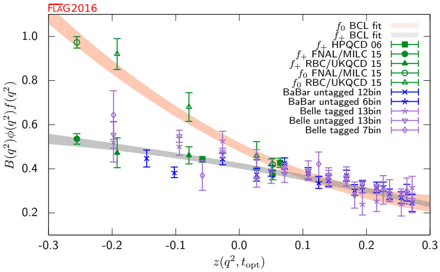


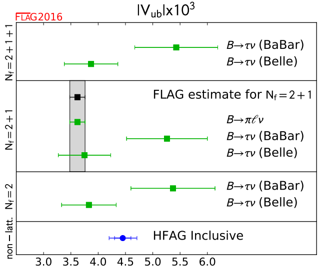
- Two independent calculations
  - $\to$ Different actions
  - $\to$ Different gauge field ensembles
  - $\Rightarrow$ Entirely uncorrelated
- Combined analysis by FLAG

[FLAG2016]

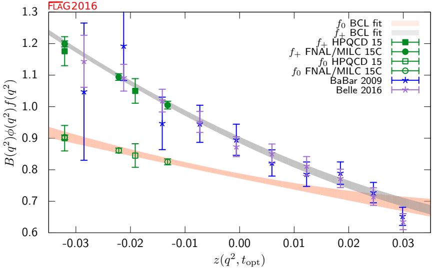
Lattice determinations of $|V_{ub}|$ and $|V_{cb}|$

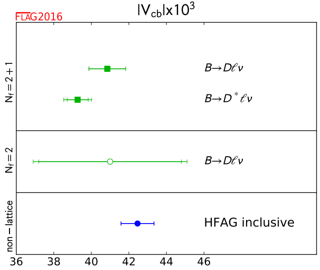
$B \to \pi\ell\nu$





$B \to D\ell\nu$





[FLAG2016]