Form factors from lattice QCD

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Implications of LHCb measurements and future prospects
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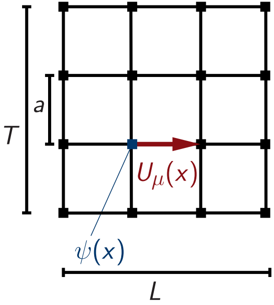
Lattice QCD

Lattice calculation

- Wick-rotate to Euclidean time $t \to i\tau$
- Discretize space-time and set up a hypercube of finite extent $L^3 \times T$ and spacing a
- Use path integral formalism

$$\langle \mathcal{O} \rangle_E = \frac{1}{Z} \int \mathcal{D}[\psi, \overline{\psi}]\, \mathcal{D}[U]\, \mathcal{O}[\psi, \overline{\psi}, U]\, e^{-S_E[\psi,\overline{\psi},U]}$$

$\Rightarrow$ Large but finite dimensional path integral



- Finite volume of length L $\to$ IR regulator
  - $\to$ Study physics in a finite box of volume $(aL)^3$
  - $\to$ Strongly prefer decays with 1 (QCD-stable) hadronic final state (narrow width approximation)

- Finite lattice spacing a $\to$ UV regulator
  - $\to$ Quark masses need to obey $am < 1$

Simulating charm and bottom (schematic)

$a^{-1} > 1.5$ GeV

charm: RHQ; extrapolations of fully relativistic actions (?)

bottom: HQET, NRQCD, RHQ

$a^{-1} > 2.2$ GeV

charm: fully relativistic action

bottom: (guided) extrapolation of fully relativistic action

$a^{-1} > 4.6$ GeV

bottom: fully relativistic action

HQET: static limit, relatively noisy

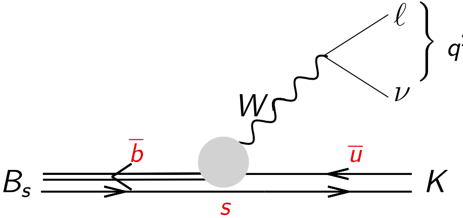
NRQCD: non-relativistic QCD, no continuum limit

RHQ or Fermilab: relativistic heavy quark action, complicated discretization errors

(heavy) HISQ or (heavy) MDWF: fully relativistic, clean nonperturbative renormalization

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

$|V_{ub}|$ 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 (B_s meson at rest)

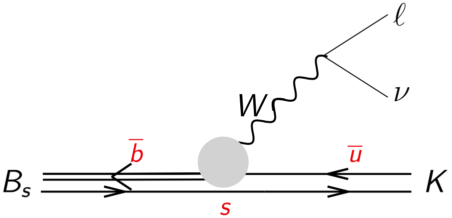
$$\frac{d\Gamma(B_s \to K\ell\nu)}{dq^2} = \frac{G_F^2|V_{ub}|^2}{24\pi^3} \frac{(q^2 - m_\ell^2)^2\sqrt{E_K^2 - M_K^2}}{q^4 M_{B_s}^2}$$

experiment CKM known

$$\times \left[\left(1 + \frac{m_\ell^2}{2q^2}\right) M_{B_s}^2(E_K^2 - M_K^2)|f_+(q^2)|^2 + \frac{3m_\ell^2}{8q^2}(M_{B_s}^2 - M_K^2)^2|f_0(q^2)|^2 \right]$$

nonperturbative input

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



- $f_+(q^2)$ and $f_0(q^2)$
  - → 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

- Conventionally parametrized by (B_s meson at rest)

$$\frac{d\Gamma(B_s \to K\ell\nu)}{dq^2} = \frac{G_F^2|V_{ub}|^2}{24\pi^3} \frac{(q^2 - m_\ell^2)^2\sqrt{E_K^2 - M_K^2}}{q^4 M_{B_s}^2}$$

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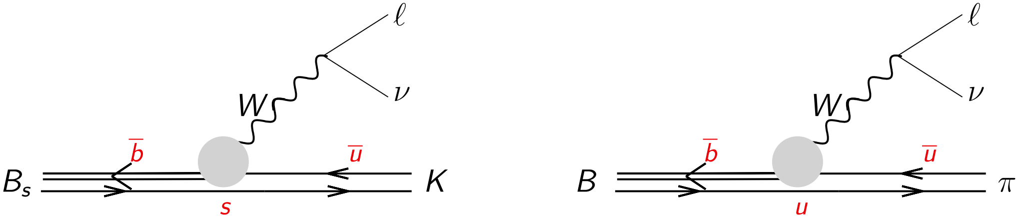
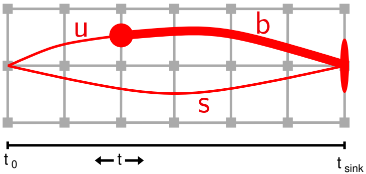


- Compared to $B \to \pi\ell\nu$ only spectator quark differs
  - → Lattice QCD prefers s quark over u quark: statistically more precise, computationally cheaper
  - → B factories run mostly at $\Upsilon(4s)$ threshold ⇒ B mesons
  - → LHC collisions create many B and B_s mesons which decay ⇒ LHCb

$B_s \to K\ell\nu$ 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 strange quark propagator at t_0
  - → Allow it to propagate to t_{sink}, turn it into a sequential source for a b quark
  - → Use a "light" quark propagating from t_0 and contract both at t with $t_0 \leq t \leq t_{sink}$

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

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- On the lattice we prefer to compute

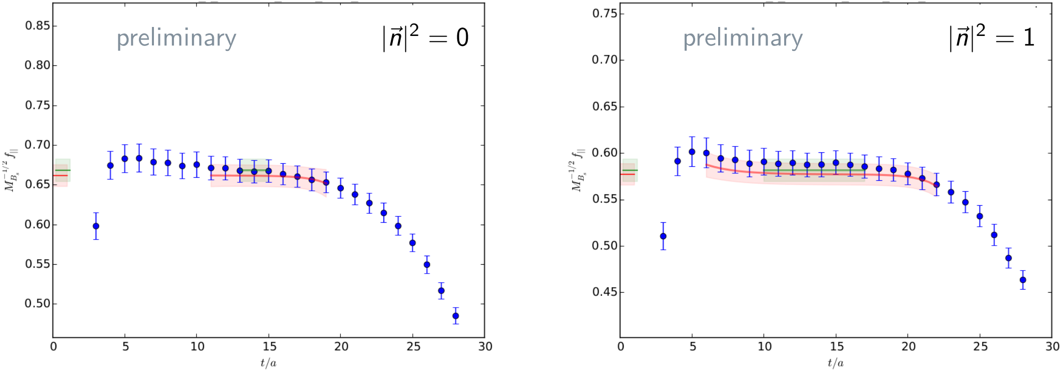
$$f_\parallel(E_K) = \langle K|V^0|B_s\rangle/\sqrt{2M_{B_s}} \quad \text{and} \quad f_\perp(E_K)p^i_K = \langle K|V^i|B_s\rangle/\sqrt{2M_{B_s}}$$

- Both are related by

$$f_0(q^2) = \frac{\sqrt{2M_{B_s}}}{M^2_{B_s} - M^2_K}\left[(M_{B_s} - E_K)f_\parallel(E_K) + (E^2_K - M^2_K)f_\perp(E_K)\right]$$

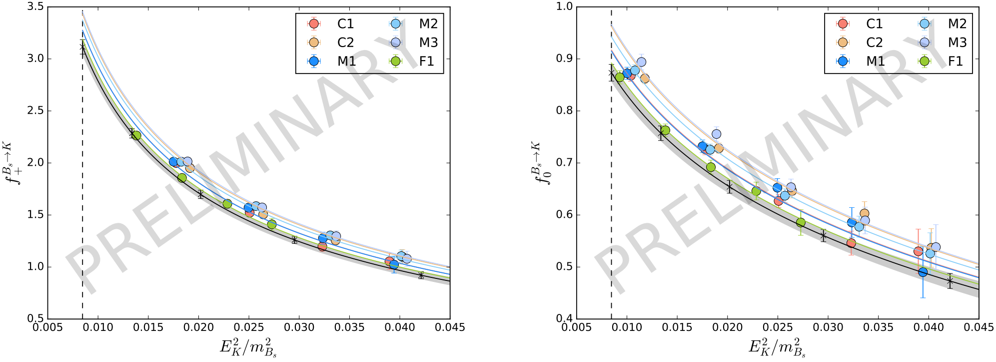
$$f_+(q^2) = \frac{1}{\sqrt{2M_{B_s}}}\left[f_\parallel(E_K) + (M_{B_s} - E_K)f_\perp(E_K)\right]$$

$B_s \to K\ell\nu$ form factors: F1 ensemble



- Comparison of fit to the ground state only with fit including one excited state term for K and B_s

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



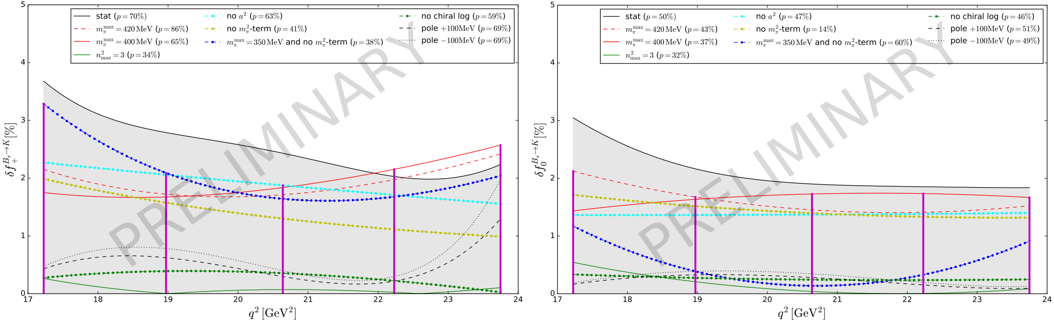
- Updating calculation [Flynn et al. PRD 91 (2015) 074510] with improved values for a^{-1} and RHQ parameters
- $f_{pole}(M_K, E_K, a^2) = \frac{1}{E_K+\Delta} c^{(1)} \times \left[1 + \frac{\delta f}{(4\pi f)^2} + c^{(2)} \frac{M_\pi^2}{\Lambda^2} + c^{(3)} \frac{E_K}{\Lambda} + c^{(4)} \frac{E_K^2}{\Lambda^2} + c^{(5)} \frac{a^2}{\Lambda^2 a_{32}^4}\right]$
- 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, vary pole mass, etc.
  - → Impose different cuts on the data
- Discretization errors of light and heavy quarks
  - → Estimate via power-counting
- Uncertainty of the renormalization factors
  - → Estimate effect of higher loop corrections
- Finite volume, iso-spin breaking, ...
- Uncertainty due to RHQ parameters and lattice spacing (a^{-1})
  - → Carry out additional simulations to test effects on form factors
- Uncertainty of strange quark mass
  - → Repeat simulation with different valence quark mass

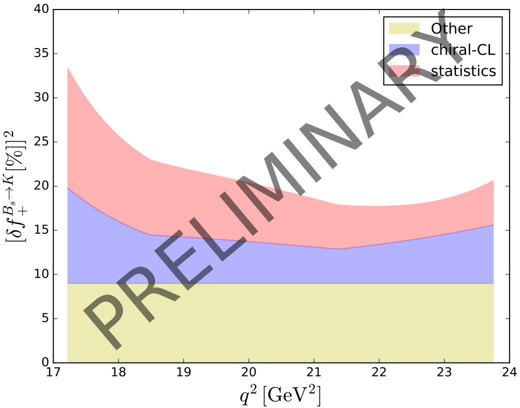
$\Longrightarrow$ full error budget

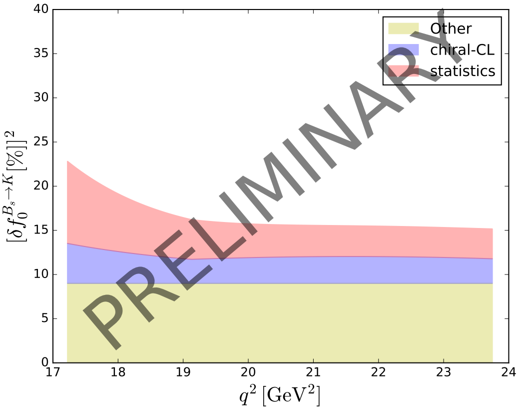
PRELIMINARY error budget $B_s \to K\ell\nu$



- $\delta f = \left| f^{\text{variation}} - f^{\text{central}} \right| / f^{\text{central}}$

PRELIMINARY error budget $B_s \to K\ell\nu$





- "Other": 3% placeholder to cover higher order corrections, lattice spacing, finite volume, ...

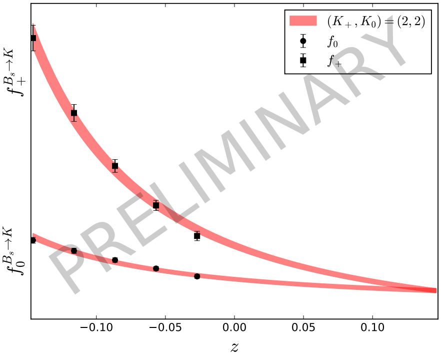
Kinematical extrapolation (z-expansion)

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

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

[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
- BCL with poles $M_+ = B^* = 5.33$ GeV and $M_0 = 5.63$ GeV
- Exploit kinematic constraint $f_+ = f_0\big|_{q^2=0}$

→ Include HQ power counting to constrain size of f_+ coefficients

- Systematic errors subject to changes!

Kinematical extrapolation (z-expansion)

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

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

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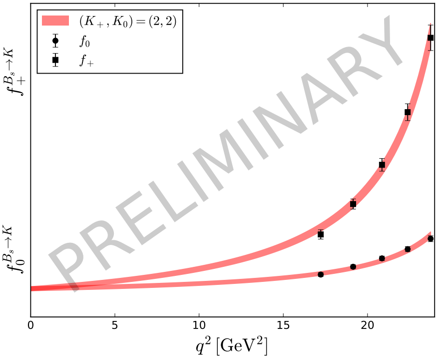


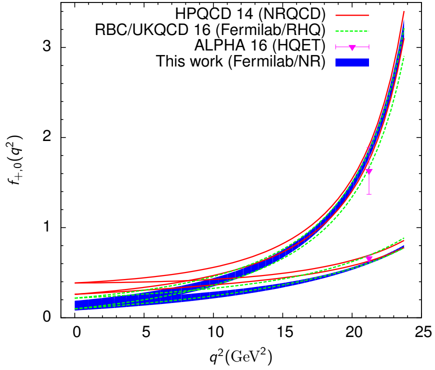
- Allows to compare shape of form factors
  - → Obtained by other lattice calculations
    [Bouchard et al. PRD 90 (2014) 054506]
    [Bazavov et al. arXiv:1901.02561]
  - → Predicted by QCD sum rules and alike

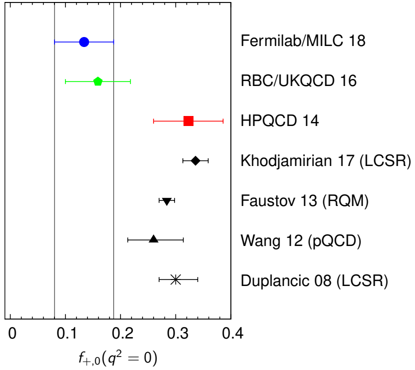
- Combination with experiment leads to the overall normalization: $|V_{ub}|$

- Systematic errors subject to changes!

$B_s \to K\ell\nu$

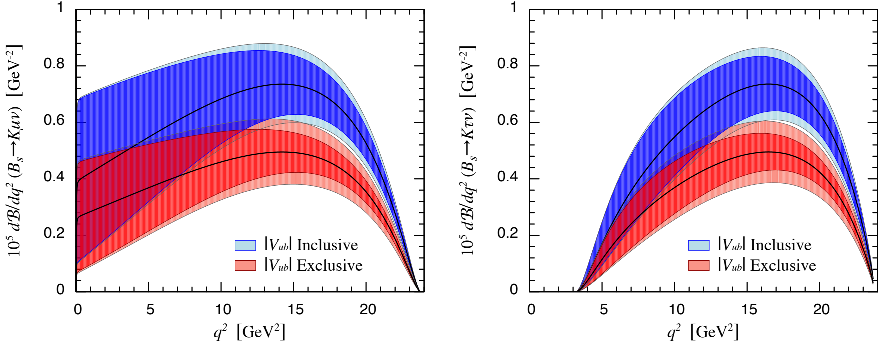
- HPQCD, RBC-UKQCD, ALPHA
  [Bouchard et al. PRD90(2014)054506] [Flynn et al. PRD91(2015)074510] [Bahr et al. PLB757(2016)473]
- New 2019: Fermilab/MILC [Bazavov et al. PRD100(2019)034501]





Phenomenological predictions

- Predict SM differential branching fractions using $|V_{ub}|$ as input for lepton $= \mu$ or τ

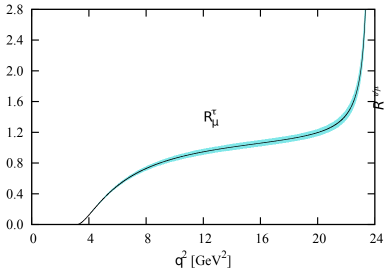


[Flynn et al. PRD 91 (2015) 074510]

Phenomenological predictions

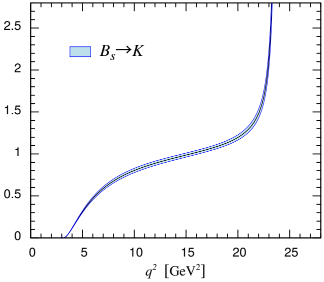
- Predict SM differential branching fractions using $|V_{ub}|$ as input for lepton $= \mu$ or τ
- Predict ratio of branching fractions $\rightsquigarrow$ LFUV

$R_K^{\tau/\mu} = 0.695(50)$

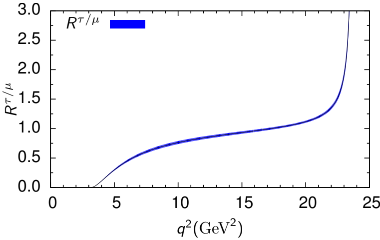


[Bouchard et al. PRD90(2014)054506]

$R_K^{\tau/\mu} = 0.77(12)$



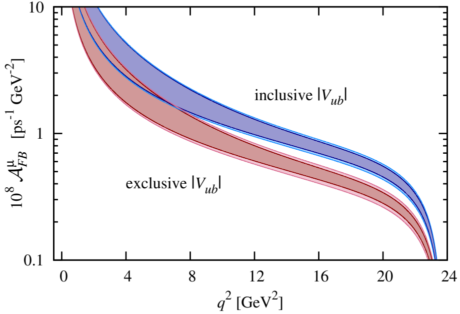
[Flynn et al. PRD 91 (2015) 074510]

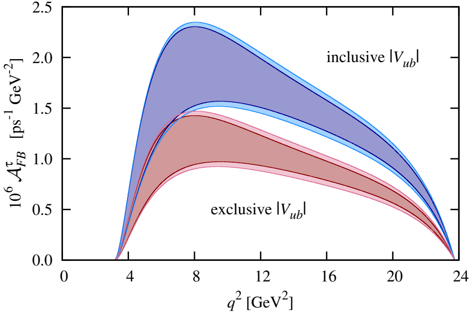


[Bazavov et al. PRD100(2019)034501]

Phenomenological predictions

- Predict SM differential branching fractions using $|V_{ub}|$ as input for lepton $= \mu$ or τ
- Predict ratio of branching fractions $\rightsquigarrow$ LFUV
- Predict forward-backward asymmetries using $|V_{ub}|$ as input for lepton $= \mu$ or τ

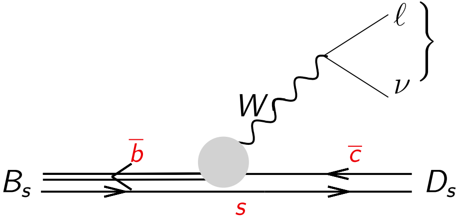




[Bouchard et al. PRD90(2014)054506]

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

$|V_{cb}|$ 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 (B_s meson at rest)
- Accommodate charm quarks

$$\underbrace{\frac{d\Gamma(B_s \to D_s\ell\nu)}{dq^2}}_{\text{experiment}} = \underbrace{\frac{G_F^2|V_{ub}|^2}{24\pi^3}}_{\text{CKM}} \underbrace{\frac{(q^2 - m_\ell^2)^2\sqrt{E_{D_s}^2 - M_{D_s}^2}}{q^4 M_{B_s}^2}}_{\text{known}}$$

$$\times \left[\left(1 + \frac{m_\ell^2}{2q^2}\right) M_{B_s}^2(E_{D_s}^2 - M_{D_s}^2)|f_+(q^2)|^2 + \frac{3m_\ell^2}{8q^2}(M_{B_s}^2 - M_{D_s}^2)^2|f_0(q^2)|^2\right]$$

nonperturbative input

$B_s \to D_s\ell\nu$

- z-expansion enforcing kinematical constraint $f_0^{B_s\to D_s}(0) = f_+^{B_s\to D_s}(0)$

- Fermilab/MILC 2019

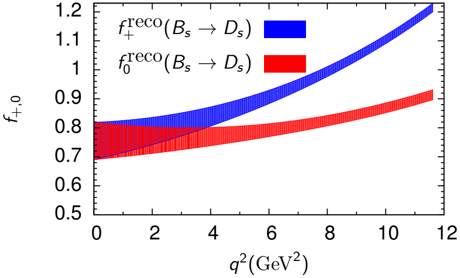
  [Bazavov et al. PRD100(2019)034501 (reco)]

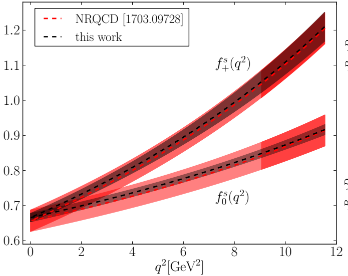
- HPQCD 2017 and 2019

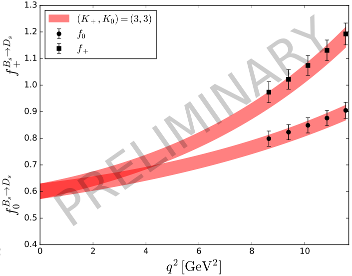
  [Monahan et al. PRD95(2017)114506]
  [McLean et al. arXiv:1906.00701]

- RBC-UKQCD (preliminary)

  [OW Lattice X IF 2019]







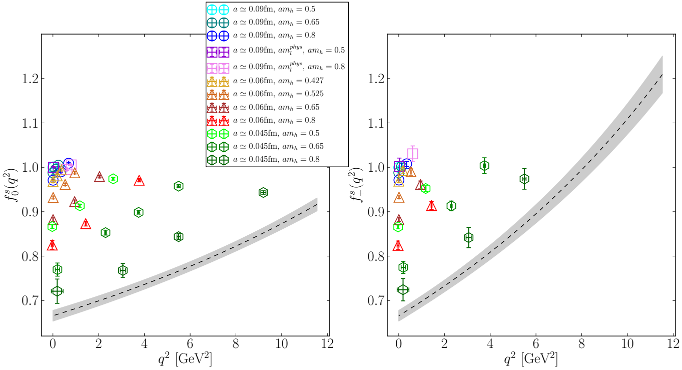
- Reconstructed from $[f_{+,0}(B \to D)]^{2015}$ and $[f_{+,0}(B_s \to D_s)/f_{+,0}(B \to D)]^{2012}$

- $R(D_s) = [0.301(6)]^{2017}$, $[0.299(5)]^{2019}$
- Modified BCL $M_+ = B_c^* = 6.33$ GeV and $M_0 = 6.42$ GeV [2017]

- Incomplete error budget!
- BCL: poles $M_+ = B_c^* = 6.33$ GeV and $M_0 = 6.42$ GeV

$B_s \to D_s\ell\nu$: HPQCD 2019 [McLean et al. arXiv:1906.00701]

- Gauge fields: 2+1+1 flavor HISQ ensembles generated by MILC
- u, d, s, c valence HISQ; bottom: "heavy" HISQ ⇝ fully nonperturbative renormalization
  - → Simulate array of "lighter" b-quarks and extrapolate
  - → Cover full q^2 range using twisted BC



- Modified BCL z-expansion
  - → Physical final state (D_s); lighter than physical initial state H_s
  - → Requires to reconsider poles for unphysical H_{c0} and H_c^*
- $R(D_s) = 0.2987(46)$

$B_s \to D_s\ell\nu$: HPQCD 2019 [McLean et al. arXiv:1906.00701]

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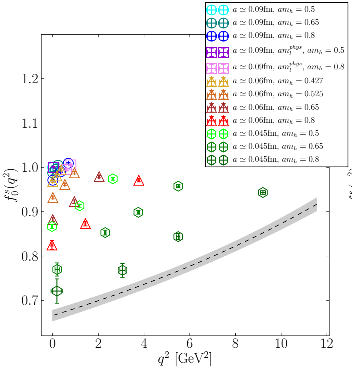
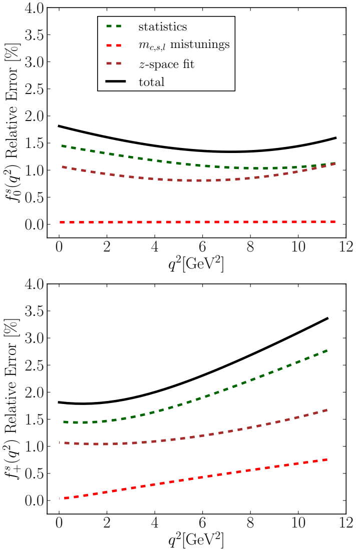




$$B \to D^* \ell \nu$$

$B \to D^*\ell\nu$ form factors

- Vector final state with narrow width approximation

$$\langle D^*(k,\lambda)|\bar{c}\gamma^\mu b|B(p)\rangle = f_V \frac{2i\epsilon^{\mu\nu\rho\sigma}\varepsilon^*_\nu k_\rho p_\sigma}{M_B + M_D^*}$$

$$\langle D^*(k,\lambda)|\bar{c}\gamma^\mu\gamma_5 b|B(p)\rangle = f_{A_0}(q^2)\frac{2M_{D^*}\varepsilon^*\cdot q}{q^2}q^\mu + f_{A_1}(q^2)(M_B + M_{D^*})\left[\varepsilon^{*\mu} - \frac{\varepsilon^*\cdot q}{q^2}q^\mu\right] - f_{A_2}(q^2)\frac{\varepsilon^*\cdot q}{M_B + M_{D^*}}\left[k^\mu + p^\mu - \frac{M_B^2 - M_{D^*}^2}{q^2}q^\mu\right]$$

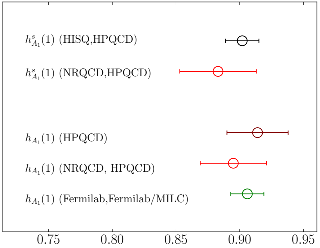
- Commonly the HQET variable $w = v\cdot v' > 1$ is used with $v = p/M_B$ and $v' = k/M_{D^*}$

$B \to D^{(*)}_{(s)}\ell\nu$

- Still only results at zero recoil [FLAG 2019]

Collaboration	Ref.	N_f	publication status	continuum extrapolation	chiral extrapolation	finite volume	renormalization	heavy-quark treatment	$w=1$ form factor / ratio	
HPQCD 15, HPQCD 17	[614, 616]	2+1	A	○	○	○	○	✓	$\mathcal{G}^{B\to D}(1)$	1.035(40)
FNAL/MILC 15C	[613]	2+1	A	★	○	★	○	✓	$\mathcal{G}^{B\to D}(1)$	1.054(4)(8)
Atoui 13	[610]	2	A	★	○	★	—	✓	$\mathcal{G}^{B\to D}(1)$	1.033(95)
HPQCD 15, HPQCD 17	[614, 616]	2+1	A	○	○	○	○	✓	$\mathcal{G}^{B_s\to D_s}(1)$	1.068(40)
Atoui 13	[610]	2	A	★	○	★	—	✓	$\mathcal{G}^{B_s\to D_s}(1)$	1.052(46)
HPQCD 17B	[618]	2+1+1	A	○	★	★	○	✓	$\mathcal{F}^{B\to D^*}(1)$	0.895(10)(24)
FNAL/MILC 14	[612]	2+1	A	★	○	★	○	✓	$\mathcal{F}^{B\to D^*}(1)$	0.906(4)(12)
HPQCD 17B	[618]	2+1+1	A	○	★	★	○	✓	$\mathcal{F}^{B_s\to D_s^*}(1)$	0.883(12)(28)
HPQCD 15, HPQCD 17	[614, 616]	2+1	A	○	○	○	○	✓	$R(D)$	0.300(8)
FNAL/MILC 15C	[613]	2+1	A	★	○	★	○	✓	$R(D)$	0.299(11)

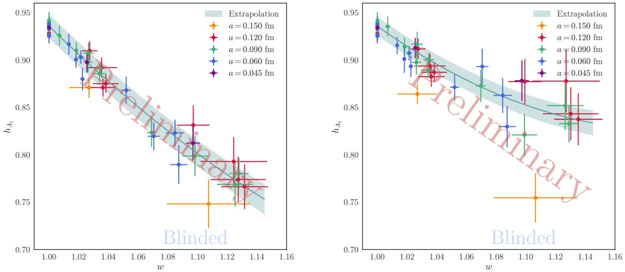
- New 2019: HPQCD $B_s \to D_s^*\ell\nu$ at zero recoil [McLean et al. PRD99(2019)114512]



[Atoui et al. EPJC74(2014)2861] [Bailey et al. PRD89(2014)114504] [Bailey et al. PRD92(2015)034506] [Na et al PRD92(2015)054510] [Monahan et al. PRD95(2017)114506] [Harrison et al. PRD97(2018)054502]

Update Fermilab/MILC: $B \to D^*\ell\nu$ [A. Vaquero Lattice X IF 2019]

Results: Chiral-continuum fits



- **Left** Old fit, **Right** New fit. Preliminary blinded results.
- Both plots differ on the accounting of discretization effects, which seem to be large at large recoil

- Old double ratio

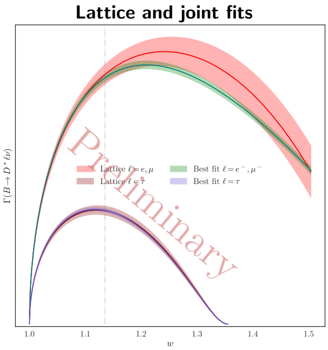
$$\frac{C^{3pt,A_j}_{B\to D^*}(p_\perp,t,T)\,C^{3pt,A_j}_{D^*\to B}(p_\perp,t,T)}{C^{3pt,V^4}_{D^*\to D^*}(0,t,T)\,C^{3pt,V^4}_{B\to B}(0,t,T)} = \frac{M_{D^*}}{E_{D^*}(p_\perp)}\frac{Z^2_{D^*}(p_\perp)}{Z^2_{D^*}(0)}e^{-(E_{D^*}(p_\perp)-M_{D^*})T}\left(\frac{1+w}{2}h_{A_1}(w)\right)^2$$

- New ratio

$$\frac{C^{3pt,A_1}_{B\to D^*}(p_\perp,t,T)}{C^{3pt,A_1}_{B\to D^*}(0,t,T)} \to \frac{C^{3pt,A_1}_{B\to D^*}(p_\perp,t,T)}{C^{3pt,A_1}_{B\to D^*}(0,t,T)} \times \sqrt{\frac{C^{2pt}_{D^*}(0,t)}{C^{2pt}_{D^*}(p_\perp,t)}}$$

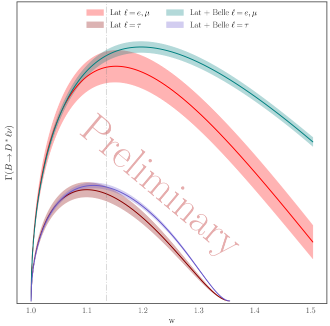
Update Fermilab/MILC: $B \to D^*\ell\nu$ [A. Vaquero Lattice X IF 2019]

Results: $R(D^*)$



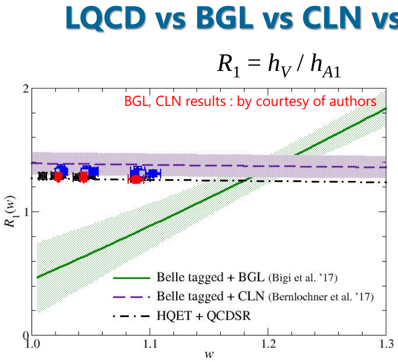
- Old analysis

[Vaquero et al. arXiv:1906.01019]



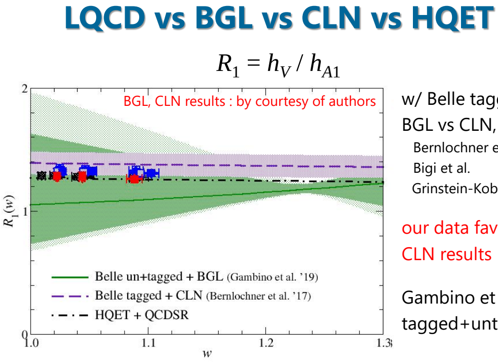
Update JLQCD: $B \to D^*\ell\nu$ [T. Kaneko Lattice X IF 2019]

- Ratio method: $\dfrac{\langle D^*|V_\mu^{\rm lat}|B\rangle}{\langle D^*|A_\mu^{\rm lat}|B\rangle} \to \dfrac{h_V(w)}{h_{A_1}(w)}$ $\Rightarrow$ renormalization factors Z_A, Z_V cancel
  [Hashimoto et al. PRD61(1999)014502]



w/ Belle tagged '17
BGL vs CLN, HQET
Bernlochner et al.
Bigi et al.
Grinstein-Kobach

our data favor the CLN results



w/ Belle tagged '17
BGL vs CLN, HQET
Bernlochner et al.
Bigi et al.
Grinstein-Kobach

our data favor the CLN results

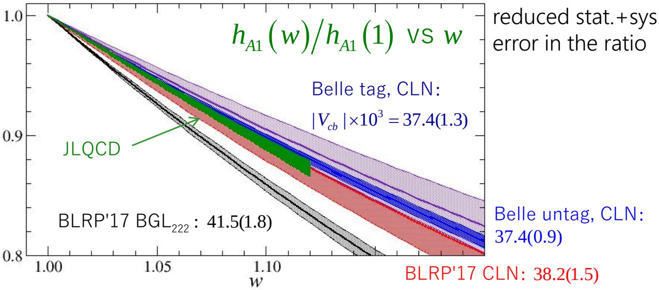
Gambino et al '19 tagged+untagged

consistency among LQCD, BGL, CLN, HQET

Update JLQCD: $B \to D^*\ell\nu$ [T. Kaneko Lattice X IF 2019]

LQCD vs BGL vs CLN

shape of h_{A1}

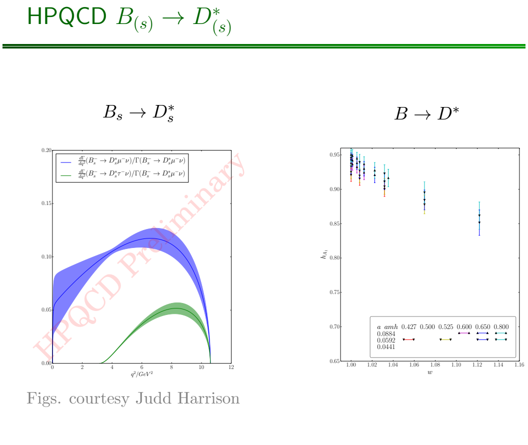


reduced stat.+sys. error in the ratio

$$h_{A1}(w)/h_{A1}(1) = 1 - 8\rho^2 z + (53\rho^2 - 15)z^2 + (231\rho^2 - 91)z^3$$

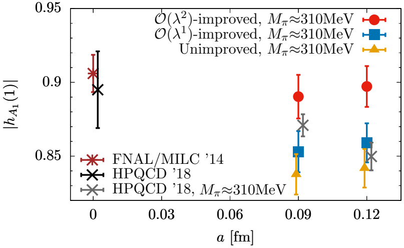
Further updates: $B \to D^*\ell\nu$

- HPQCD form factors for $B_{(s)} \to D^*_{(s)}\ell\nu$
  [Plenary talk A. Lytle Lattice 2019]



Figs. courtesy Judd Harrison

- LANL/SWME form factors at zero recoil
  [PoS Lattice2018 283]



summary

Summary

- Many calculation for exclusive decays are in progress [OW overview talk Beauty 2019]
  - → Calculations are hard, tedious, and take time
  - ⇝ Not easy to gain by considering the ratio $B_s \to K\mu\nu / B_s \to D_s\mu\nu$

- New ideas to compute inclusive decays using lattice techniques
  [Hashimoto PTEP 2017 (2017) 053B03] [Hansen, Meyer, Robaina arXiv:1704.08993] [Bailas Lattice 2019]

- Interesting new ideas for radiative decays
  [Kane et al. arXiv:1907.00279] [Martinelli Lattice 2019] [Sachrajda Lattice 2019]

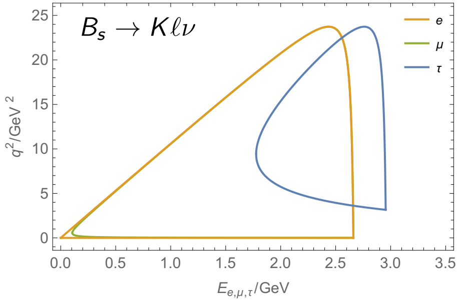
- Not covered: B_c decays, $R(J/\psi)$, etc.
  [Colquhoun et al. PoS Lattice2016 281][Harrison Poster Beauty 2019]

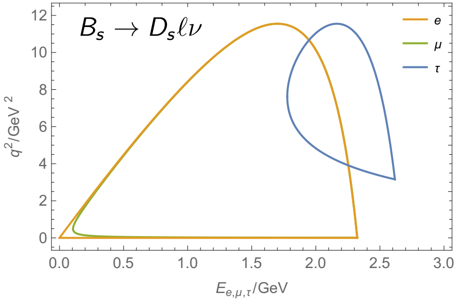
- Not covered: exclusive baryonic decays
  - → $\Lambda_b \to \Lambda_c\ell\nu$ and $\Lambda_b \to p\ell\nu \Rightarrow |V_{cb}|/|V_{ub}|$ [Detmold, Lehner, Meinel, PRD92(2015)034503]
  - → $\Lambda_b \to \Lambda_c\tau\nu$ [Datta et al. JHEP08(2017)131]
  - → $\Lambda_c \to \Lambda\ell\nu$ [Meinel PRL118(2017)082001]

Ratio $B_s \to K\mu\nu / B_s \to D_s\mu\nu$

- Phase space is quite different and our simulations are most precise near q^2_{max}

[Plots courtesy by J. Flynn]





- Order of steps in the lattice calculation does not help
  - → Chiral-continuum extrapolation and estimate of systematic uncertainties are performed before kinematical z-expansion
  - ⇝ Modified z-expansion for ratio or simultaneous correlated fit of form factors

Ratio $B_s \to K\mu\nu / B_s \to D_s\mu\nu$

- HPQCD [Monahan et al. PRD98(2018)114509]

→ 2+1 flavor asqtad sea quark; u, d, s, c HISQ valence, NRQCD b

→ Correlated and simulatenous fits

→ Perturbative NRQCD-continuum matching with significantly reduced uncertainty

- Fermilab/MILC [Bazavov et al. PRD100(2019)034501]

→ 2+1 flavor asqtad sea and u, d, s valence quark; Fermilab/RHQ c, b

→ Combination z extrapolated form factors over restricted q^2 range

→ Neglecting statistical correlations