Nonperturbative determination of form factors for semileptonic B_s meson decays

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RBC- and UKQCD collaborations

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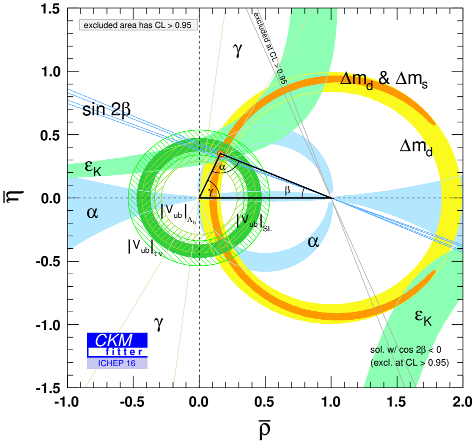
introduction

Why B_s meson decays?

- Alternative, tree-level determination of $|V_{cb}|$ and $|V_{ub}|$ from $B_s \to D\ell\nu$ and $B_s \to K\ell\nu$
- Commonly used $B \to \pi\ell\nu$ and $B \to D^{(*)}\ell\nu$
- Longstanding $2-3\sigma$ 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]

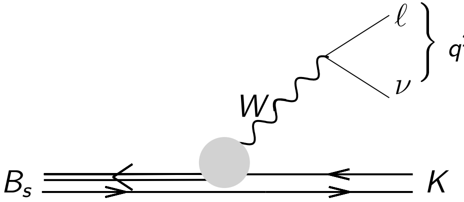


[http://ckmfitter.in2p3.fr]

Why B_s meson decays?

- Not (yet) experimentally measured with sufficient precision
- B-factories typically run at the $\Upsilon(4s)$ threshold
  $\rightarrow$ B but no B_s mesons are produced
- At the LHC energies are large enough to produce sufficient B_s mesons
- LHCb is working on the analysis
  $\rightarrow$ Absolute normalization is challenging; ratios are preferred
  $\rightarrow$ Determine $|V_{cb}|/|V_{ub}|$
- strange-quarks are easier on the lattice

$|V_{ub}|$ 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

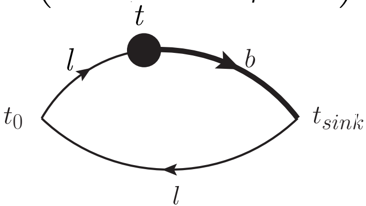
$$\frac{d\Gamma(B_s\to K\ell\nu)}{dq^2} = \frac{G_F^2}{192\pi^3 M_{B_s}^3}\left[\left(M_{B_s}^2 + M_K^2 - q^2\right)^2 - 4M_{B_s}^2 M_K^2\right]^{3/2} \times |f_+(q^2)|^2 \times |V_{ub}|^2$$

experiment known nonperturbative input CKM

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

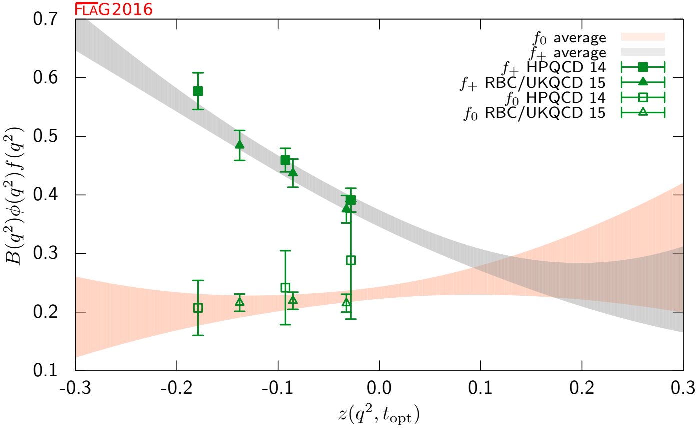
- Parametrize the hadronic matrix element for the flavor changing vector current V^μ in terms of the form factors $f_+(q^2)$ and $f_0(q^2)$

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



- 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

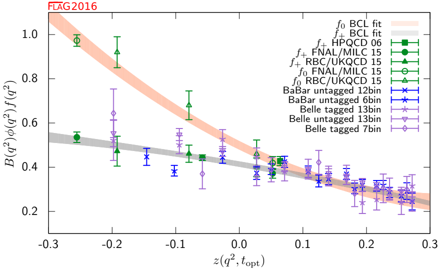
Lattice determinations of $B_s \to K\ell\nu$ form factors

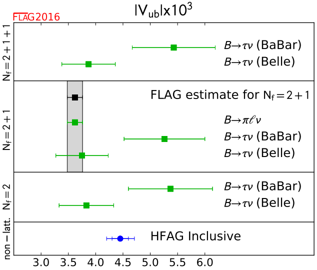


[FLAG2016]

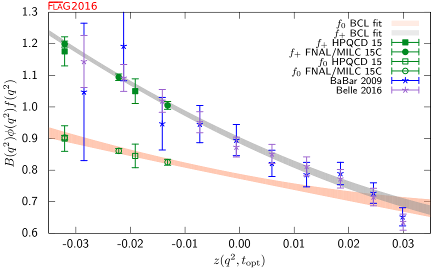
Lattice determinations of $|V_{ub}|$ and $|V_{cb}|$

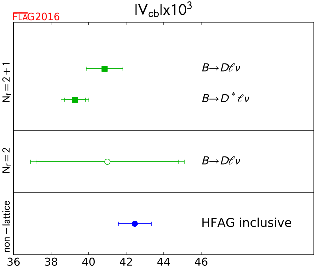
$B \to \pi \ell \nu$





$B \to D \ell \nu$





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RBC-UKQCD's project

Target quantities

- Decay constants f_B and f_{B_s}
- $B^0 - \overline{B}^0$ mixing matrix elements
- Semileptonic form factors with charged and neutral flavor changing currents

  $B \to \pi\ell\nu$, $B_s \to K\ell\nu$, $B \to D^{(*)}\ell\nu$, $B_s \to D_s^{(*)}\ell\nu$, ...

  $B \to K^{(*)}\ell^+\ell^-$, $B_s \to \phi\ell^+\ell^-$, ...

→ Ratios $R(D^{(*)})$, $R(K^{(*)})$, ...

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][arXiv:1701.02644]
- 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 $(m_0a,\ c_P,\ \zeta)$ nonperturbatively [PRD 86 (2012) 116003]
  - → Smooth continuum limit; heavy quark treated to all orders in $(m_b a)^n$

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
- On the lattice we prefer using the B_s-meson rest frame and compute

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

- Both are related by

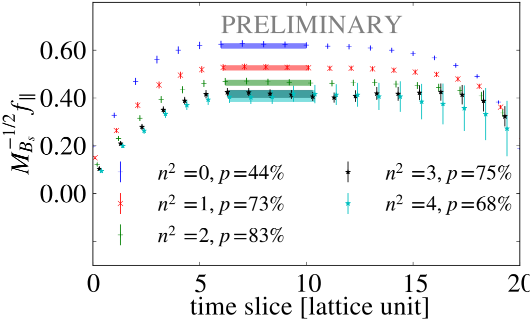
$$f_0(q^2) = \frac{\sqrt{2M_{B_s}}}{M_{B_s}^2 - M_K^2}\left[(M_{B_s} - E_K)f_\parallel(E_K) + (E_K^2 - M_K^2)f_\perp(E_K)\right]$$

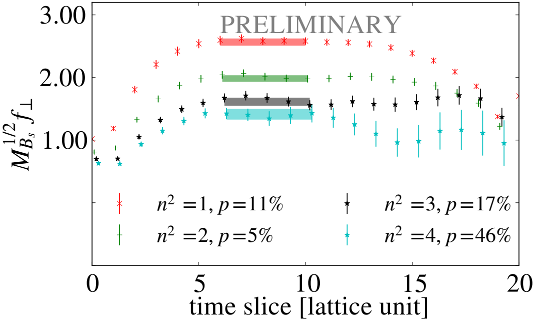
$$f_+(q^2) = \frac{1}{\sqrt{2M_{B_s}}}\left[f_\parallel(E_K) + (M_{B_s} - E_K)f_\perp(E_K)\right]$$

Lattice results for form factors $f_\parallel$ and $f_\perp$ for $B_s \to K\ell\nu$

$$R_\mu^{B_s\to K}(t, t_{\text{sink}}) = \frac{C_{3,\mu}^{B_s\to K}(t, t_{\text{sink}})}{C_2^K(t) C_2^{B_s}(t_{\text{sink}} - t)} \sqrt{\frac{4 M_{B_s} E_K}{e^{-E_k t} e^{-M_{B_s}(t_{\text{sink}} - t)}}}$$

$$f_\parallel = \lim_{t, t_{\text{sink}} \to \infty} R_0^{B_s\to K}(t, t_{\text{sink}}) \qquad f_\perp = \lim_{t, t_{sink} \to \infty} \frac{1}{p_\pi^i} R_i^{B_s\to K}(t, t_{\text{sink}})$$



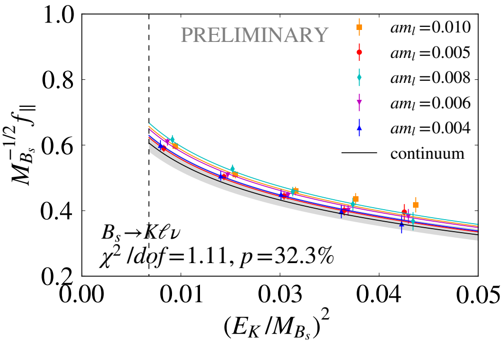


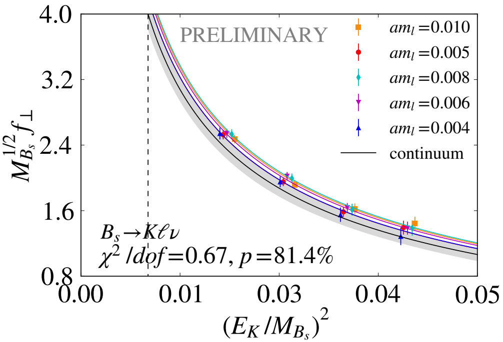
Chiral-continuum extrapolation using SU(2) hard-kaon χPT

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

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

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

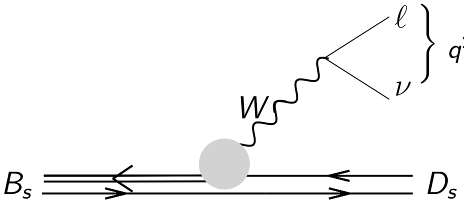




Next steps

- Estimate full systematic errors for three "synthetic" data points
- Perform z-expansion and polynomial fits
- Comparison with other result(s) [HPQCD PRD90 (2014) 054506]

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



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

- Conventionally parametrized by

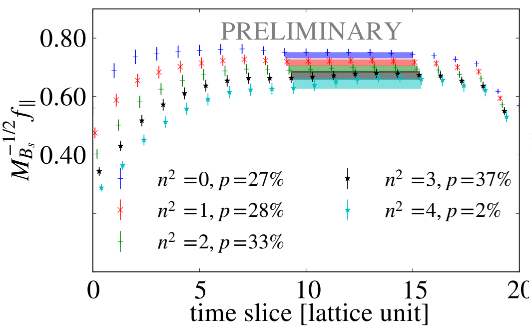
$$\frac{d\Gamma(B_s \to D_s \ell \nu)}{dq^2} = \frac{G_F^2}{192\pi^3 M_{B_s}^3} \left[\left(M_{B_s}^2 + M_{D_s}^2 - q^2 \right)^2 - 4 M_{B_s}^2 M_{D_s}^2 \right]^{3/2} \times |f_+(q^2)|^2 \times |V_{cb}|^2$$

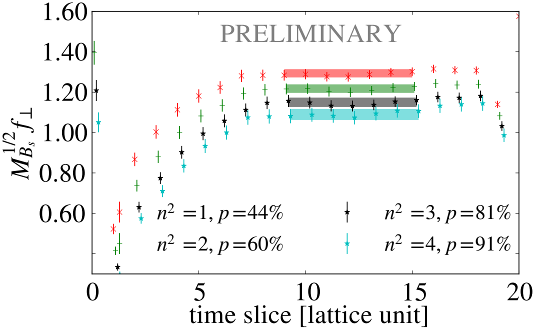
experiment known nonperturbative input CKM

Lattice results for form factors $f_\parallel$ and $f_\perp$ for $B_s \to D_s \ell\nu$

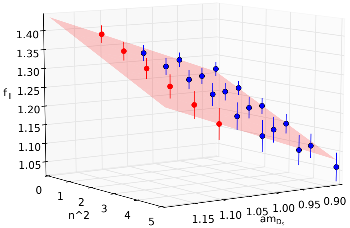
$$R_\mu^{B_s\to D_s}(t, t_{\rm sink}) = \frac{C_{3,\mu}^{B_s\to D_s}(t, t_{\rm sink})}{C_2^{D_s}(t)\,C_2^{B_s}(t_{\rm sink}-t)}\sqrt{\frac{4M_{B_s}E_{D_s}}{e^{-E_{D_s}t}e^{-M_{B_s}(t_{\rm sink}-t)}}}$$

$$f_\parallel = \lim_{t,t_{\rm sink}\to\infty} R_0^{B_s\to D_s}(t, t_{\rm sink}) \qquad f_\perp = \lim_{t,t_{sink}\to\infty} \frac{1}{p_\pi^i} R_i^{B_s\to D_s}(t, t_{\rm sink})$$

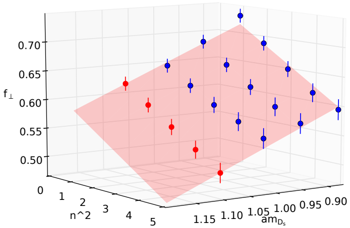




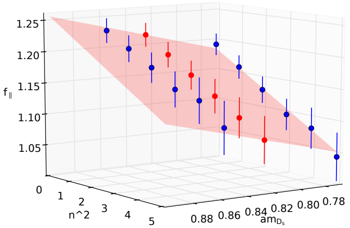
Charm extra-/interpolation for $B_s \to D_s \ell \nu$



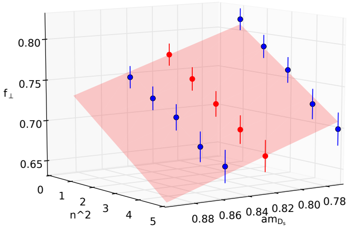
PRELIMINARY



PRELIMINARY



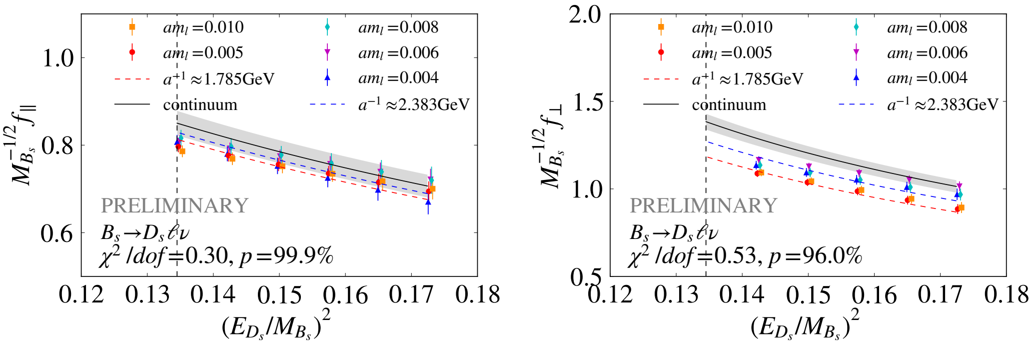
PRELIMINARY



PRELIMINARY

Chiral-continuum extrapolation for $B_s \to D_s \ell\nu$

$$f(q,a) = \frac{c_0 + c_1(\Lambda_{\rm QCD}\, a)^2}{1 + c_2(q/M_{B_c})^2}$$



Next steps

- Estimate full systematic errors for three "synthetic" data points
- Perform z-expansion and polynomial fits
- Comparison with other result(s) [HPQCD 2017]
- Explore advantageous ratios

conclusion

Conclusion

- About to complete calculation for $B_s \to K\ell\nu$ and $B_s \to D_s\ell\nu$

$\to$ Finalizing systematic error estimates and kinematic extrapolations

- Not enough time to cover $B_s \to \phi\ell^+\ell^-$ ($\to$ see appendix)

- We have more data for
  - $\to B \to \pi\ell\nu$, $B \to \pi\ell^+\ell^-$
  - $\to B \to K^*\ell^+\ell^-$
  - $\to B \to D^{(*)}\ell\nu$
  - $\to B_s \to D_s^*\ell\nu$
  - $\to \ldots$

Resources and Acknowledgments

USQCD: Ds, Bc, and pi0 cluster (Fermilab), qcd12s cluster (Jlab)

RBC qcdcl (RIKEN) and cuth (Columbia U)

UK: ARCHER (EPCC) and DiRAC (UKQCD)

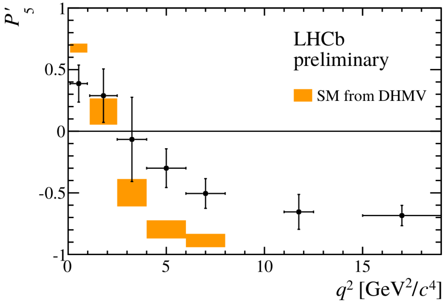
appendix

flavor changing neutral currents

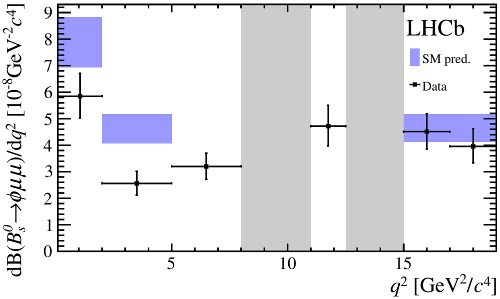
(loop-level in the Standard Model)

Rare B decays (FCNC)

- GIM suppressed in the Standard Model $\Rightarrow$ sensitive to new physics
- Angular observable P_5' in $B \to K^* \mu^+ \mu^-$ received a lot of attention



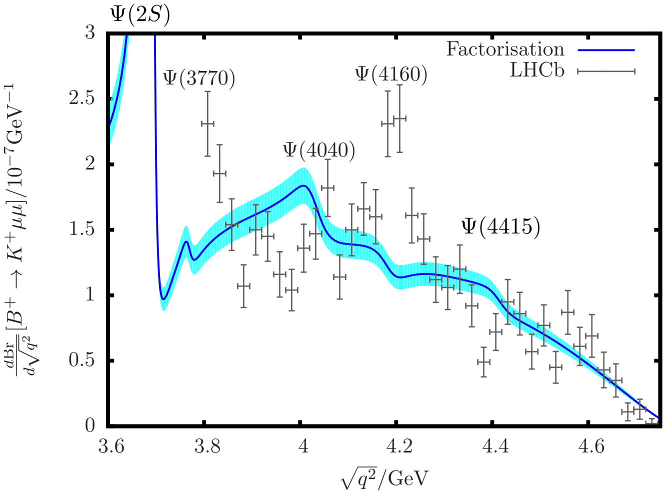
[LHCb-CONF-2015-002]



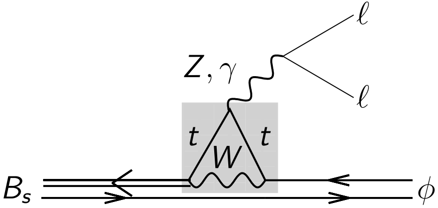
[LHCb JHEP 1509 (2015) 179]

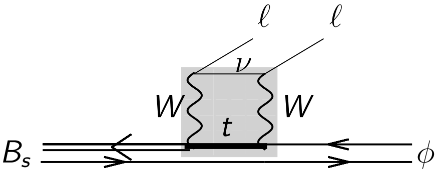
- Lattice QCD: [Horgan et al. PRD 89 (2013) 094501]

▶ Charm resonances under control? [Lyon and Zwicky, arXiv:1406.0566]



Rare B decays: $B_s \to \phi \ell^+ \ell^-$





- Pseudoscalar or vector final state (narrow width approximation)
- Effective Hamiltonian

$$\mathcal{H}_{\text{eff}}^{b \to s} = -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \sum_i^{10} C_i O_i^{(\prime)}$$

- Leading contributions at short distance

$$O_7^{(\prime)} = \frac{m_b e}{16\pi^2} \bar{s} \sigma^{\mu\nu} P_{R(L)} b F_{\mu\nu}$$
$$O_9^{(\prime)} = \frac{e^2}{16\pi^2} \bar{s} \gamma^\mu P_{L(R)} b \bar{\ell} \gamma_\mu \ell$$
$$O_{10}^{(\prime)} = \frac{e^2}{16\pi^2} \bar{s} \gamma^\mu P_{L(R)} b \bar{\ell} \gamma_\mu \gamma^5 \ell$$

Seven form factors

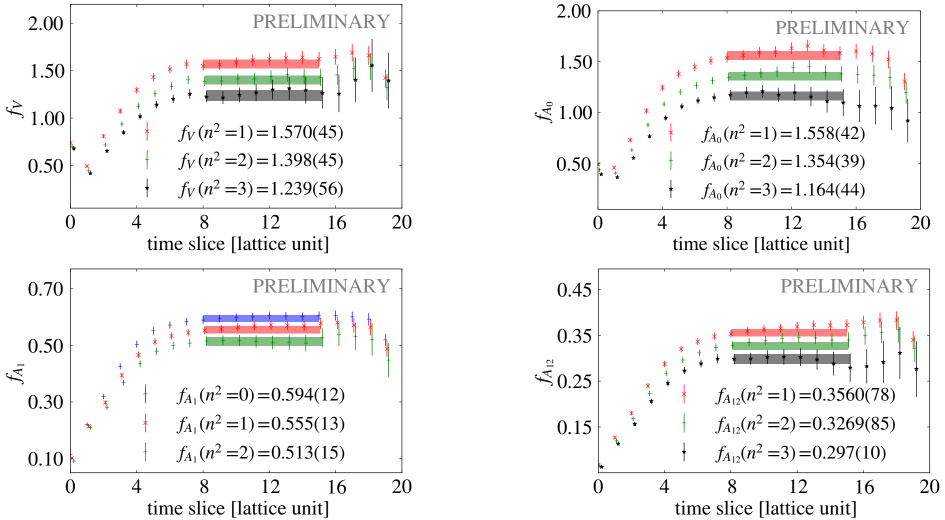
$$\langle\phi(k,\lambda)|\bar{s}\gamma^{\mu}b|B_s(p)\rangle = f_V(q^2)\frac{2i\epsilon^{\mu\nu\rho\sigma}\varepsilon^*_{\nu}k_{\rho}p_{\sigma}}{M_{B_s}+M_{\phi}}$$

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

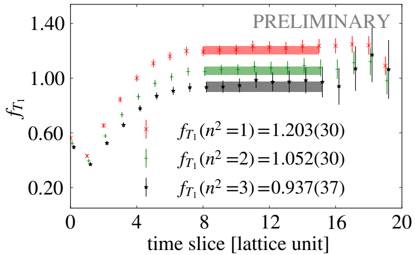
$$q_{\nu}\langle\phi(k,\lambda)|\bar{s}\sigma^{\nu\mu}b|B_s(p)\rangle = 2f_{T_1}(q^2)\epsilon^{\mu\rho\tau\sigma}\varepsilon^*_{\rho}k_{\tau}p_{\sigma}\ ,$$

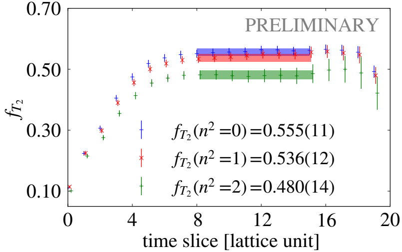
$$q_{\nu}\langle\phi(k,\lambda)|\bar{s}\sigma^{\nu\mu}\gamma^5 b|B_s(p)\rangle = if_{T_2}(q^2)\left[\varepsilon^{*\mu}(M_{B_s}^2-M_{\phi}^2)-(\varepsilon^*\cdot q)(p+k)^{\mu}\right]$$
$$+ if_{T_3}(q^2)(\varepsilon^*\cdot q)\left[q^{\mu}-\frac{q^2}{M_{B_s}^2-M_{\phi}^2}(p+k)^{\mu}\right]$$

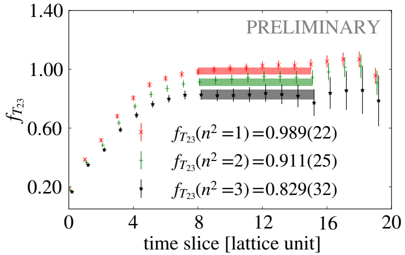
Seven form factors



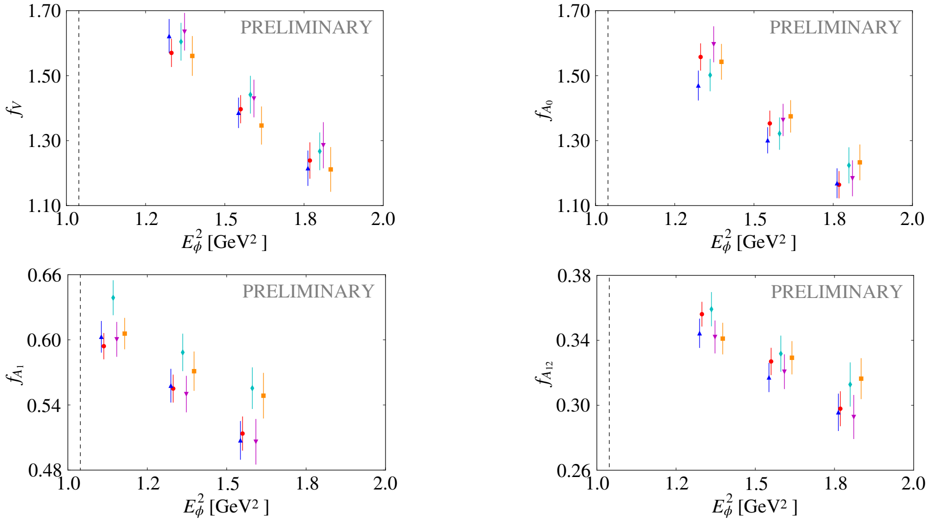
Seven form factors



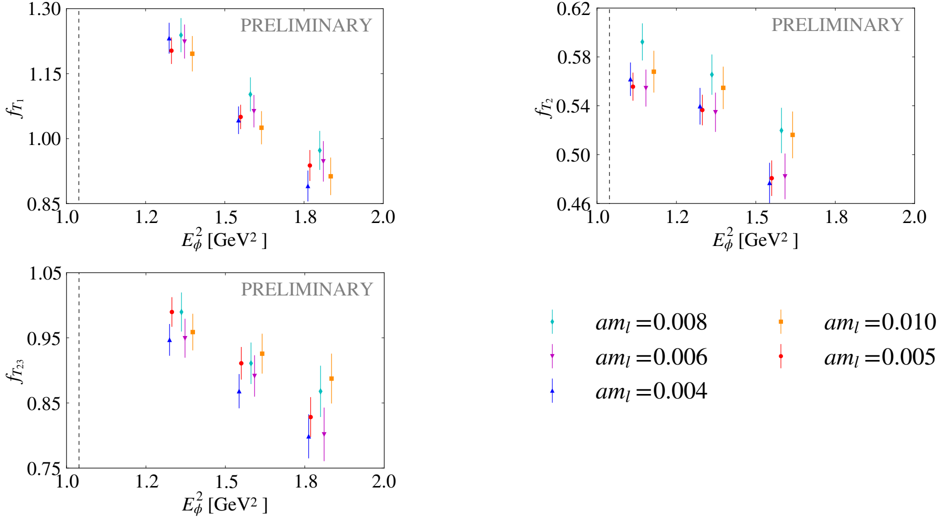




Seven form factors vs. q^2



Seven form factors vs. q^2



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