Nonperturbative determination of form factors for semileptonic B_s meson decays

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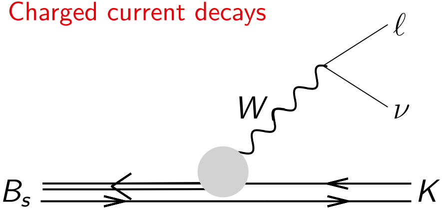
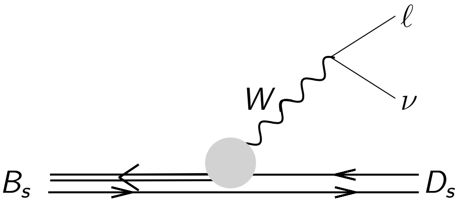
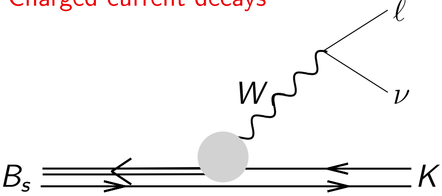
introduction

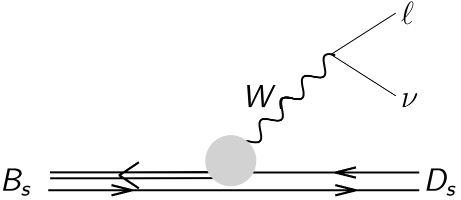
Charged current decays



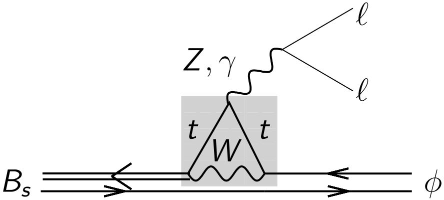


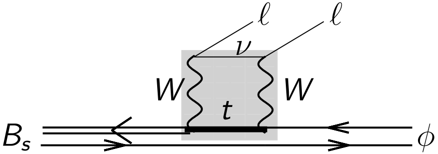
Charged current decays





Flavor changing neutral current decays

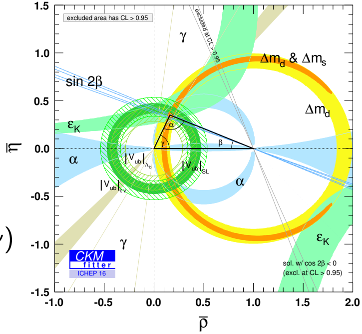




Why B_s meson decays?

- 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]

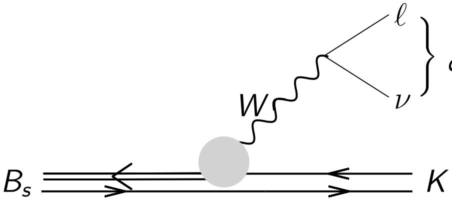
Why B_s meson decays?

- 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

flavor changing charged currents

(tree-level in the Standard Model)

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



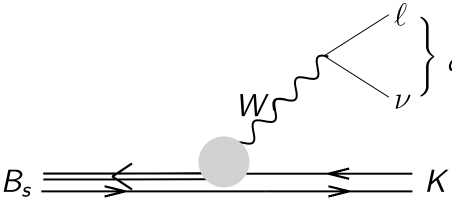
$$q^2 = M_{B_s}^2 + M_K^2 - 2M_{B_s}E_K$$

- 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

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



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experiment known nonperturbative input CKM

For $|V_{cb}|$ from $B_s \to D_s\ell\nu$ replace K with D_s

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	2.774	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

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

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

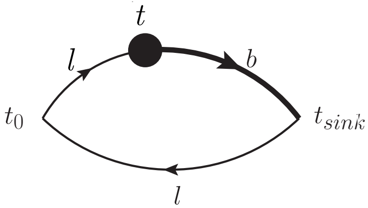
Bottom quarks

- 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 ($m_0 a$, 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 $(m_b a)^n$
- Expand in powers of the spatial momentum through $O(\vec{p}a)$
  - Resulting errors will be of $O(\vec{p}^2 a^2)$
  - 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}

$B_s \to K\ell\nu$ 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
- Updating calculation of [PRD 91 (2015) 074510] with new a^{-1} and RHQ parameters

Relating form factors f_+ and f_0 to $f_\parallel$ and $f_\perp$

- 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

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

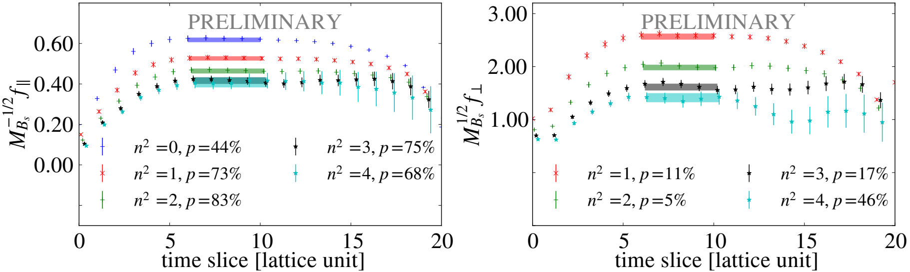
$$f_+(q^2) = \frac{1}{\sqrt{2M_{B_s}}}\left[f_\parallel(E_K) + (M_{B_s} - E_K)f_\perp(E_K)\right]$$

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

$$f_\parallel = \lim_{t, t_{\text{sink}} \to \infty} R_0^{B_s \to K}(t, t_{\text{sink}})$$

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

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

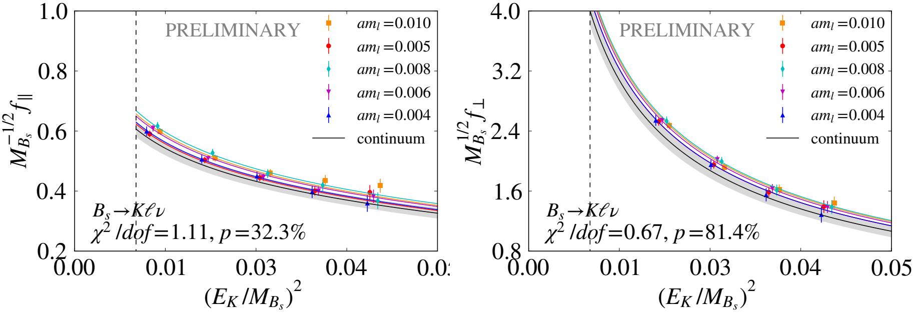


Chiral-continuum extrapolation using SU(2) hard-pion χPT

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

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

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

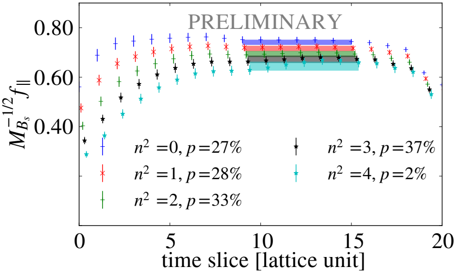


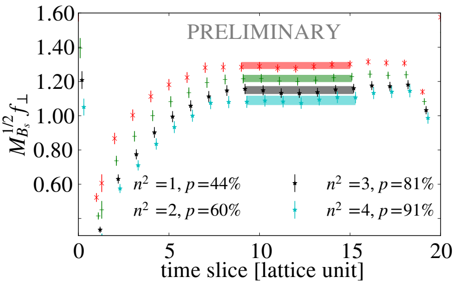
Lattice results for form factors $f_{\parallel}$ and $f_{\perp}$ for $B_s \to D_s \ell \nu$

$$f_{\parallel} = \lim_{t, t_{\text{sink}} \to \infty} R_0^{B_s \to D_s}(t, t_{\text{sink}})$$

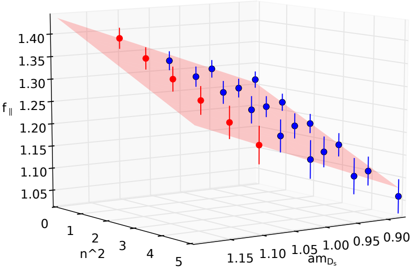
$$f_{\perp} = \lim_{t, t_{sink} \to \infty} \frac{1}{p_\pi^i} R_i^{B_s \to D_s}(t, t_{\text{sink}})$$

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

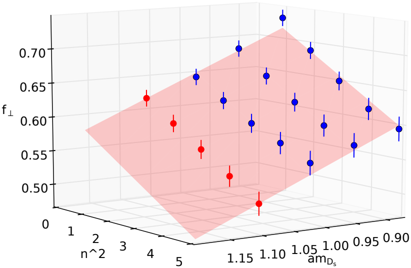




Charm extra-/interpolation for $B_s \to D_s \ell \nu$



PRELIMINARY



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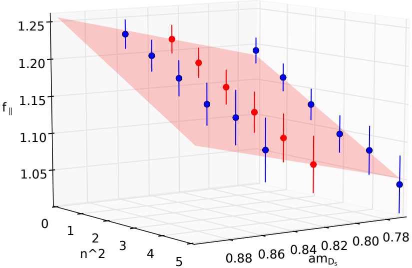
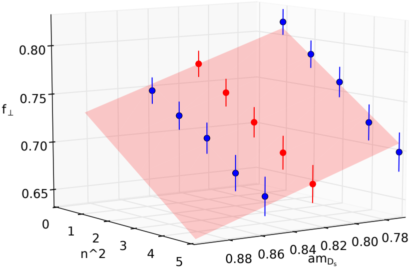


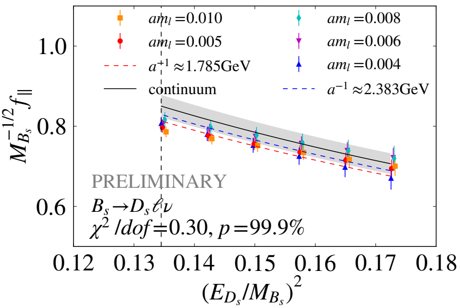
PRELIMINARY

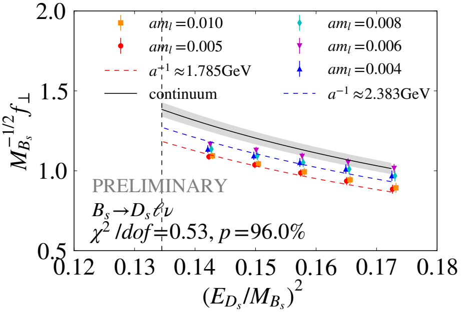


PRELIMINARY

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

- 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
  - $\to B \to \pi\ell\nu$, $B \to \ell^+\ell^-\nu$
  - $\to B \to K^*\ell^+\ell^-$
  - $\to B \to D^{(*)}\ell\nu$
  - $\to \ldots$

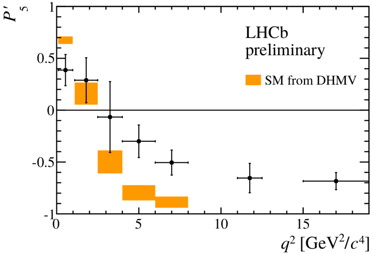
Appendix

flavor changing neutral currents

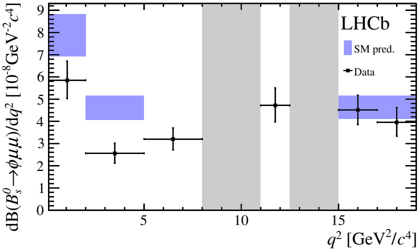
(loop-level in the Standard Model)

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



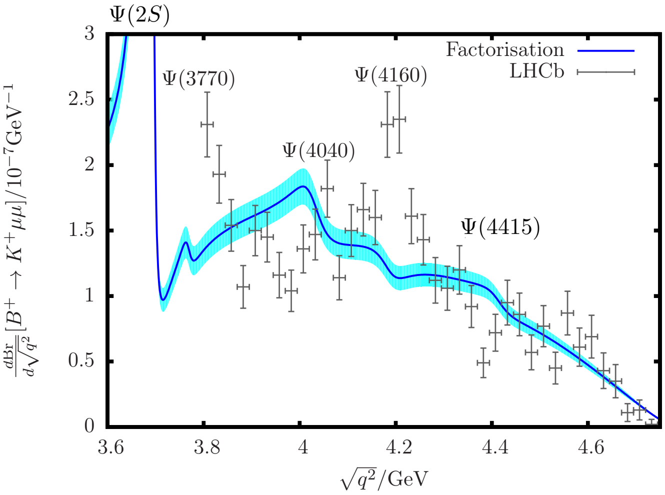
[LHCb-CONF-2015-002]



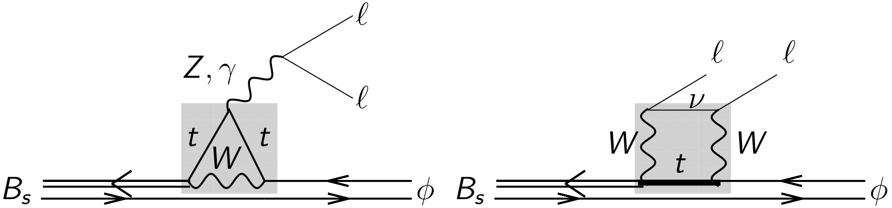
[LHCb JHEP 1509 (2015) 179]

- 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

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

- 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

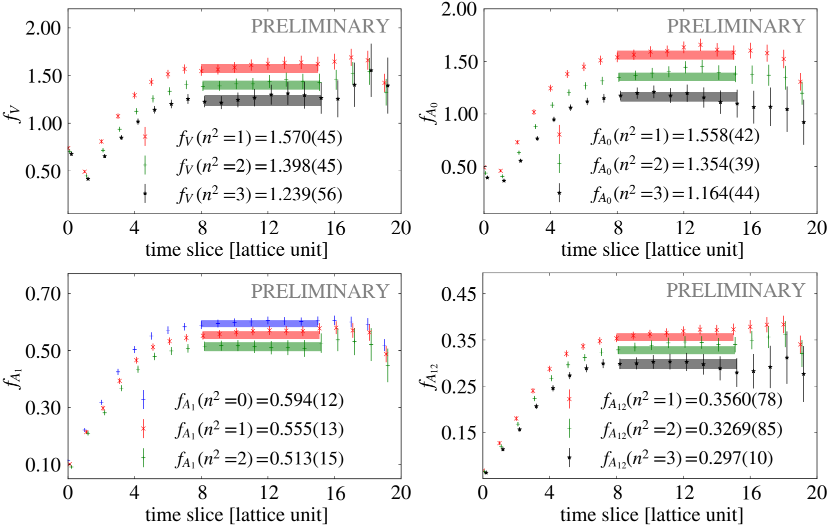
$$\langle\phi(k,\lambda)|\bar{s}\gamma^\mu b|B_s(p)\rangle = f_V(q^2)\frac{2i\epsilon^{\mu\nu\rho\sigma}\varepsilon^*_\nu k_\rho p_\sigma}{M_{B_s}+M_\phi}$$

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

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

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

Seven form factors



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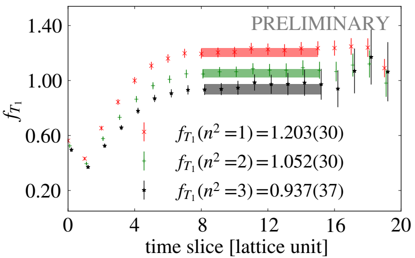
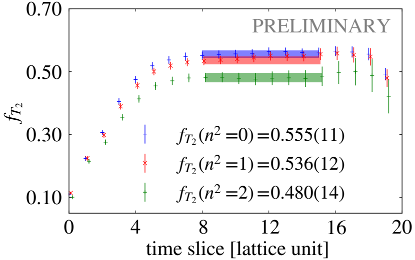
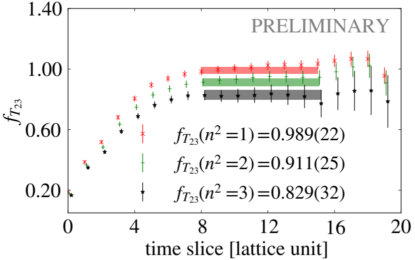
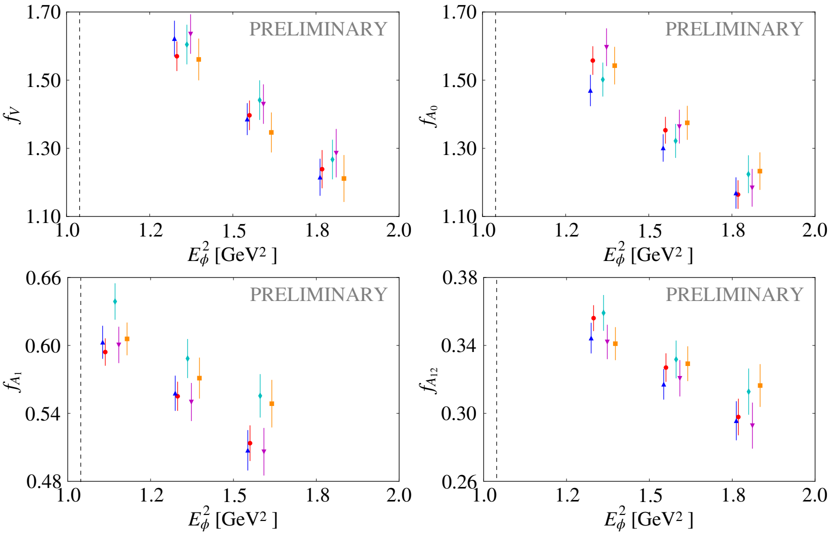






Seven form factors vs. q^2



Seven form factors vs. q^2