Study of NP effects in $\bar{B}_s \to D_s^{(*)}\tau^-\bar{\nu}_\tau$ decays using SM-LQCD form factors and HQET.

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Based on: arXiv:2304.00250 [hep-ph]

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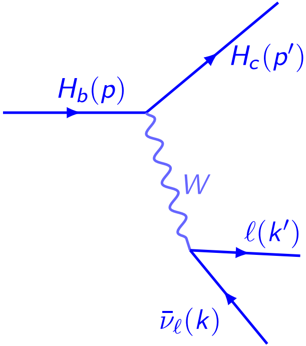
Latest results from LHCb[1–3] for $\mathcal{R}_{\Lambda_c}$ and $\mathcal{R}_{D^{(*)}}$ + other observables measured[4]:

$$\mathcal{R}_{H_c} = \frac{\Gamma(H_b \to H_c \tau \bar{\nu}_\tau)}{\Gamma(H_b \to H_c \ell \bar{\nu}_\ell)}, \quad P_\tau(D^*), \quad F_L^{D^*}.$$



$\sim 3\sigma$ away from the SM expectation.

NP should affect all $b \to c$ transitions.

What about $\bar{B}_s \to D_s^{(*)}$?

LHCb collab. [1]Phys.Rev.Lett. 128, 191803;
[2]arXiv:2302.02886 [hep-ex] and [3]arXiv:2305.01463 [hep-ex]
[4]HFLAV group. Eur.Phys.J.C 81(2021) 3, 226

Effective Hamiltonian

[5] Mandal et al. JHEP 08 (2020) 022

NP effects are introduced using an effective Hamiltonian[5]:

$$H_{\rm eff} = \frac{4 G_F V_{cb}}{\sqrt{2}} \Big[\underbrace{(1 + C^V_{LL}) \mathcal{O}^V_{LL} + C^V_{RL} \mathcal{O}^V_{RL}}_{\rm (axial-)vector} + \underbrace{C^S_{LL} \mathcal{O}^S_{LL} + C^S_{RL} \mathcal{O}^S_{RL}}_{\rm (pseudo-)scalar} + \underbrace{C^T_{LL} \mathcal{O}^T_{LL}}_{\rm tensor}$$
$$+ \underbrace{C^V_{LR} \mathcal{O}^V_{LR} + C^V_{RR} \mathcal{O}^V_{RR} + C^S_{LR} \mathcal{O}^S_{LR} + C^S_{RR} \mathcal{O}^S_{RR} + C^T_{RR} \mathcal{O}^T_{RR}}_{\rm right-handed\ \ neutrinos} \Big] + h.c.,$$

where $C^{\Gamma}_{\chi_q \chi_\nu}$ are Wilson coefficients and

$$\mathcal{O}^{\Gamma}_{\chi_q \chi_\nu} = \Big(\bar{c}(0) \Gamma \chi_q b(0) \Big) \Big(\bar{\ell}(0) \Gamma \chi_\nu \nu(0) \Big);$$
$$\Gamma = 1, \gamma^\mu, \sigma^{\mu\nu}; \quad \chi_q = \frac{1 \pm \gamma_5}{2}; \quad \chi_\nu = \frac{1 \pm \gamma_5}{2}$$

Hadronic matrix element and form factors

To describe the hadronic matrix elements:

$$\left\langle D_s^{(*)}; \vec{p}\,', r' \middle| \bar{c}(0)\Gamma\chi_q b(0) \middle| \bar{B}_s; \vec{p} \right\rangle; \qquad \chi_q = \frac{1 \pm \gamma_5}{2}$$

we will need the corresponding form factors.

	SM form factors ($\Gamma = \gamma^\mu$)	NP form factors ($\Gamma = 1, \sigma^{\mu\nu}$)
$\bar{B}_s \to D_s$	f_+, f_0	h_s, h_t
$\bar{B}_s \to D_s^*$	V, A_0, A_1, A_2	h_p, T_1, T_2, T_3

SM-LQCD Form factors

- In the lattice, there are only results for the SM FF
- They are described as power series of $z(q^2; t_{th}, t_0) = \frac{\sqrt{t_{th} - q^2} - \sqrt{t_{th} - t_0}}{\sqrt{t_{th} - q^2} + \sqrt{t_{th} - t_0}}$

$\bar{B}_s \to D_s^*$

V, A_0, A_1 and A_2

Harrison and Davies (HPQCD)
Phys. Rev. D 105, 094506 (2022)

$\mathcal{O}(\tilde{z}^*)^3 \to 16$ coeff.

$t_{th} = (M_B + M_{D*})^2; \;\; t_0 = (M_{B_s} - M_{D_s^*})$

$\bar{B}_s \to D_s$

f_+ and f_0

McLean, Davies, Koponen, and Lytle (HPQCD)
Phys. Rev. D 101, 074513 (2020)

$\mathcal{O}(\tilde{z})^2 \to 6$ coeff.

$t_{th} = (M_{B_s} + M_{D_s})^2; \;\; t_0 = 0$

And the New Physics form factors? $\longrightarrow$ Heavy Quark Effective Theory (HQET)

HQET Form factors

In HQET, one uses a different form-factor definition

[6] Bernlochner et al. Phys.Rev.D 95(2017)11, 115008
[7] Jung and Straub JHEP 01(2019) 009

$$\{V, A_0, A_1, A_2, f_+, f_0\} \leftrightarrow \{h_V, h_{A_1}, h_{A_2}, h_{A_3}, h_+, h_-\}$$

$$h_i(\omega) = \boxed{\xi(\omega)} \times \boxed{\hat{h}_i(\omega)}$$

Isgur-Wise function (3par.)

- $\xi(\omega) = 1 + \rho^2(\omega - 1) + c(\omega - 1)^2 + d(\omega - 1)^3 + \cdots$
- $m_Q \to \infty$:
  - $h_V = h_{A_1} = h_{A_3} = h_+ = h_S = h_P = h_T = h_{T_1} = \xi$
  - $h_{A_2} = h_- = h_{T_2} = h_{T_3} = 0$

Corrections:

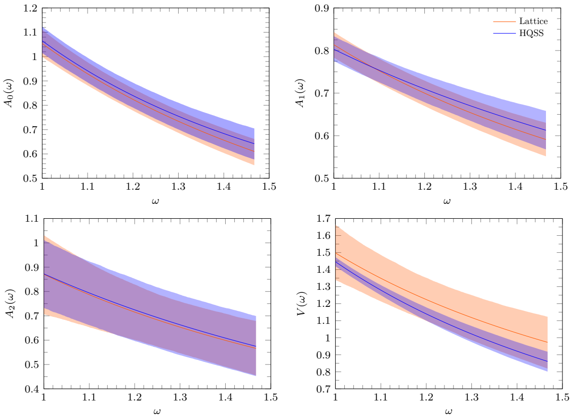
- perturbative corrections matching QCD and HQET[6]
- $\mathcal{O}[\Lambda_{QCD}/m_Q]$ corrections: 3 sub-leading Isgur-Wise functions (+5 par.)[6]
- $\mathcal{O}[(\Lambda_{QCD}/m_c)^2]$ constant corrections to $\hat{h}_+$ and $\hat{h}_{A_1}$ (+2 par.)[7]

Fit of the SM-LQCD form factors to their HQET expressions.

	$\bar{B}_s \to D_s^{(*)}$	$\bar{B} \to D^{(*)}$[8]
ρ^2	1.26 ± 0.07	1.32 ± 0.06
c	1.20 ± 0.11	1.20 ± 0.12
d	-0.91 ± 0.10	-0.84 ± 0.17
$\hat{\chi}_2(1)$	0.30 ± 0.23	-0.058 ± 0.020
$\hat{\chi}_2'(1)$	0.14 ± 0.08	0.001 ± 0.020
$\hat{\chi}_3'(1)$	0.08 ± 0.09	0.036 ± 0.020
$\eta(1)$	0.07 ± 0.21	0.355 ± 0.040
$\eta'(1)$	-0.51 ± 0.25	-0.03 ± 0.11
$l_1(1)$	0.28 ± 0.50	0.14 ± 0.23
$l_2(1)$	-2.24 ± 0.94	-2.00 ± 0.30

$$\chi^2/dof = 0.81$$

[8] Murgui et al. JHEP 09 (2019) 103
[9] HPQCD collab. PRD105, 094506 (2022)
[10] HPQCD collab. PRD101, 074513 (2020)



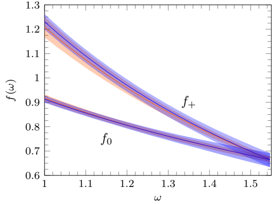


Figure: HQET predictions vs. LQCD Form Factors[9–10]

Fit results: SM Decay

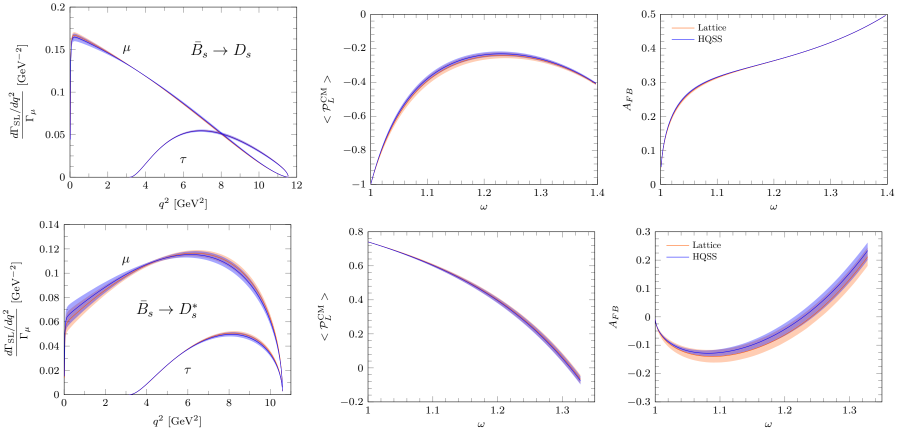


Figure: $d\Gamma/d\omega$, $< \mathcal{P}_L^{CM} >$ and A_{FB} for $\bar{B}_s \to D_s$ and $\bar{B}_s \to D_s^*$ in the SM.

Observables I

The information of the interaction is encoded in 10 functions of $\omega(q^2)$ (τ angular, spin and angular-spin asymmetries)[9]

unpolarized τ^-	$\frac{d\Gamma_{SL}}{d\omega} \propto n_0$, $A_{\rm FB}$, A_Q
polarized τ^-	$\langle P_L^{\rm CM}\rangle$, $\langle P_T^{\rm CM}\rangle$, Z_L, Z_Q, $Z_\perp$
complex WC's	$\langle P_{TT}\rangle$, Z_T

The τ^- particle decays very fast and we have to look into the full decay $H_b \to H_c\tau^-(\to d^-\nu_\tau)\bar\nu_\tau$

8 of them obtained from →

$$\frac{d^3\Gamma_d}{d\omega d\xi_d d\cos\theta_d}$$

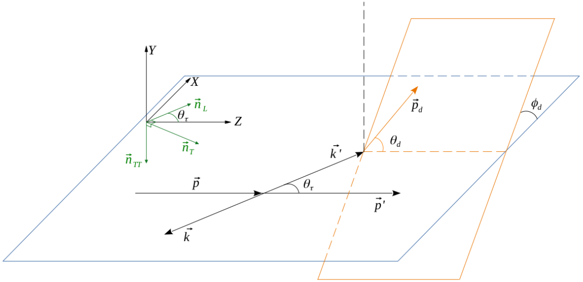


Figure: Kinematics in the $\tau\bar\nu_\tau$ CM reference system.

- ξ_d = ratio of the energy d^- and the τ^- in the $\tau\nu_\tau$ center of mass
- θ_d = angle made by the final-hadron and the τ-decay massive product

[9] N.P. et al. JHEP 10 (2021) 122

New Physics

With that result, now we can predict the rest of the form factors and add NP effects to the observables.

$$H_{\rm eff} = \frac{4 G_F V_{cb}}{\sqrt{2}} \left[\mathcal{O}^V_{LL} + \sum_i C_i \mathcal{O}_i \right]$$

Wilson coeff. are fitted to experimental data. → Different models give the same results for $\mathcal{R}_{H_c}$.

- Fit 7 from Murgui, Peñuelas, Jung and Pich, JHEP 09 (2019) 103 (LH neutrinos, real WCs)
- S7a from Mandal, Murgui, Peñuelas and Pich, JHEP 08 (2020) 022 (RH neutrinos, real WCs)
- R2 from Shi, Geng, Grinstein, Jäger and Martin Camalich, JHEP 12 (2019) 065 (LH neutrinos, complex WCs)

NP results: Decay

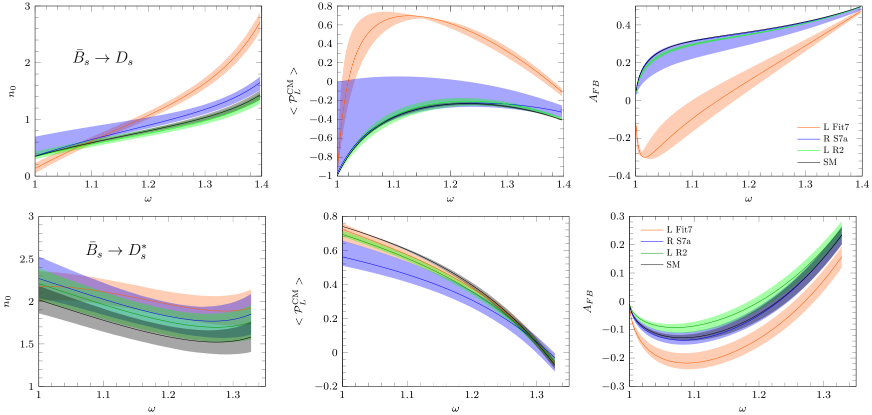


Figure: n_0, $< \mathcal{P}_L^{CM} >$ and A_{FB} for $\bar{B}_s \to D_s$ and $\bar{B}_s \to D_s^*$ with New Physics.

$\langle P_{TT}^{\mathrm{CM}} \rangle(\omega)$

- Different from zero only if some of the WCs are complex
- Cannot be accessed from the triple differential decay width
- Small CP violating effects

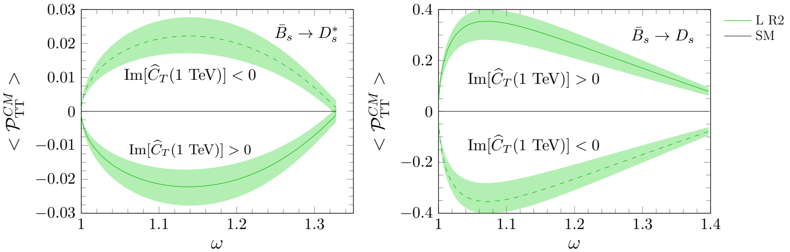


Figure: $\langle P_{TT}^{\mathrm{CM}} \rangle(\omega)$ for the $\bar{B}_s \to D_s^*$ (left) and $\bar{B}_s \to D_s$ (right) decays.

Observables II: Partially integrated decay distributions

We can also increase the statistics by integrating the decay width in some of the variables. The distributions will depend on the τ^- decay mode considered:[10]

- $\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$
- $\tau^- \to \pi^- \nu_\tau$
- $\tau^- \to \rho^- \nu_\tau$

$$\frac{d^3\Gamma_d}{d\omega\, d\xi_d\, d\cos\theta_d}$$

$$\frac{d^2\Gamma_d}{d\omega\, d\cos\theta_d} \qquad \frac{d^2\Gamma_d}{d\omega\, d\xi_d}$$

$$\frac{d\Gamma_d}{d\cos\theta_d} \qquad \frac{d\Gamma_d}{d\omega} = \mathcal{B}_d \frac{d\Gamma_{SL}}{d\omega} \qquad \frac{d\Gamma_d}{dE_d}$$

unpolarized τ^-	$n_0,\ A_{\rm FB},\ A_Q$
polarized τ^-	$\langle P_L^{\rm CM}\rangle,\ \langle P_T^{\rm CM}\rangle,\ Z_L,\ Z_Q,\ Z_\perp$
complex WC's	$\langle P_{TT}\rangle,\ Z_T$

[10] N.P. et al. JHEP 04 (2022) 026

NP results: Angular distribution

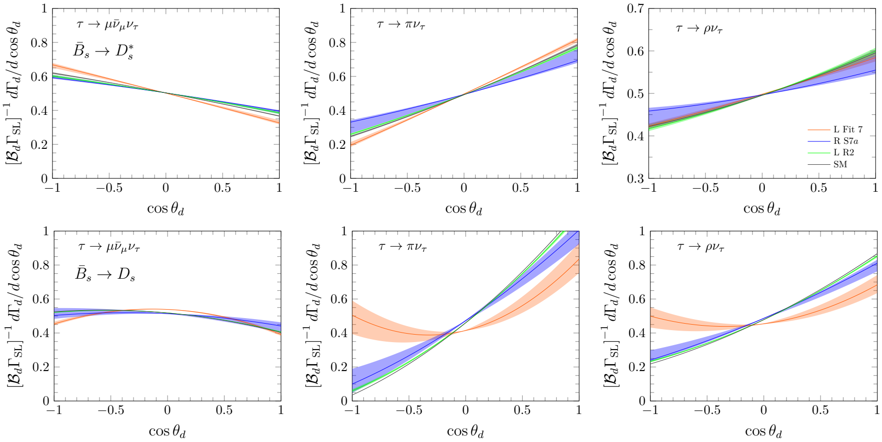


Figure: The ω-integrated $d\Gamma_d/d\cos\theta_d$ distributions for the $\bar{B}_s \to D_s^{(*)} \tau^- (\pi^- \nu_\tau, \rho^- \nu_\tau, \mu^- \bar{\nu}_\mu \nu_\tau) \bar{\nu}_\tau$ sequential decays.

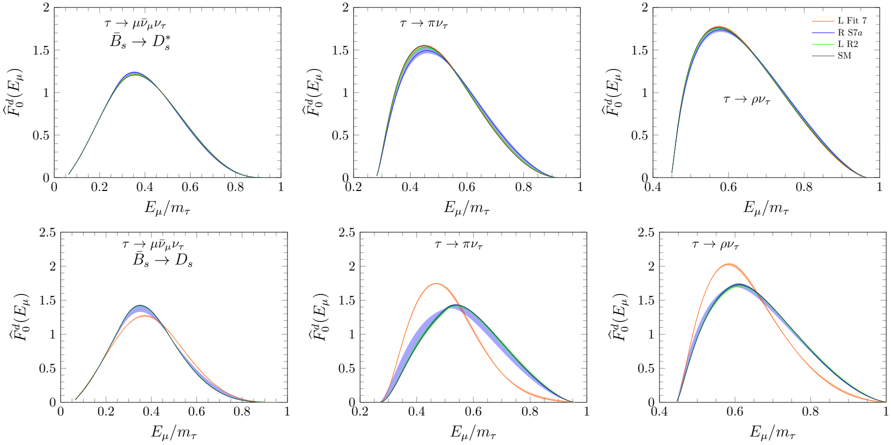


Figure: The ω-integrated $d\Gamma_d/dE_d$ distributions for the $\bar{B}_s \to D_s^{(*)}\tau^-(d^-\nu_\tau)\bar{\nu}_\tau$ sequential decays.

$$\hat{F}_0^d = \frac{m_\tau}{2\mathcal{B}_d\Gamma_{SL}}\frac{d\Gamma}{dE_d}$$

Conclusions

- We have succesfully fitted the SM-LQCD form factors to their HQET expansions
- The scalar, pseudoscalar and tensor (new physics) form factors are obtained using the previous fit and their expressions in HQET.
- The NP results are similar to the $SU(3)$-analogue $\bar{B} \to D^{(*)}$. (see N.P. et al. JHEP 04 (2022) 026)
- The analysis of this transition, as well of other CC $b \to c$ decays, could then help in establishing or ruling out LFUV.

Conclusions

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Thank you!

BACK-UP

$\mathcal{R}(D_s^{(*)})$

		SM	L Fit 7	R S7a	L R_2
$\bar{B}_s \to D_s$	$\Gamma_{e(\mu)}$	0.92 ± 0.06			
	Γ_τ	0.27 ± 0.01	0.36 ± 0.02	$0.305^{+0.061}_{-0.017}$	$0.259^{+0.029}_{-0.017}$
	$\mathcal{R}_{D_s}$	$0.298^{+0.009}_{-0.007}$	$0.391^{+0.021}_{-0.017}$	$0.333^{+0.066}_{-0.016}$	$0.283^{+0.031}_{-0.017}$
$\bar{B}_s \to D_s^*$	$\Gamma_{e(\mu)}$	$2.11^{+0.17}_{-0.22}$			
	Γ_τ	$0.52^{+0.04}_{-0.05}$	0.62 ± 0.05	0.59 ± 0.06	0.57 ± 0.05
	$\mathcal{R}_{D_s^*}$	$0.245^{+0.007}_{-0.006}$	$0.293^{+0.011}_{-0.007}$	$0.280^{+0.016}_{-0.015}$	0.27 ± 0.01

Table: Semileptonic decay widths $\Gamma_\ell = \Gamma(\bar{B}_s \to D_s^{(*)} \ell \bar{\nu}_\ell)$ and ratios $\mathcal{R}_{D_s^{(*)}}$

SM-LQCD Form factors

Form factors as a power series: $F \propto \frac{1}{P(q^2)} \sum_{i=0}^{n} a_i z^i(q^2)$

where $z(q^2; t_{th}, t_0) = \frac{\sqrt{t_{th} - q^2} - \sqrt{t_{th} - t_0}}{\sqrt{t_{th} - q^2} + \sqrt{t_{th} - t_0}}$

$\bar{B}_s \to D_s^*$

V, A_0, A_1 and A_2

Harrison and Davies (HPQCD)
Phys. Rev. D 105, 094506 (2022)

$\mathcal{O}(\tilde{z}^*)^3 \to 16$ coeff.

$t_{th} = (M_B + M_{D^*})^2$

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f_+ and f_0

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$\mathcal{O}(\tilde{z})^2 \to 6$ coeff.

$t_{th} = (M_{B_s} + M_{D_s})^2$

$t_0 = 0$

LQCD Form factors: change of variables

We change the parametrizations to symmetrize the range of z corresponding to $0 \leqslant q^2 \leqslant t_-^{(*)} = (M_{B_s} - M_{D_s^{(*)}})^2$ for the two decays.

$\bar{B}_s \to D_s^*$	$\bar{B}_s \to D_s$
$t_{th} = (M_B + M_{D*})^2$	$t_{th} = (M_B + M_D)^2$
$t_0 = t_{th} - \sqrt{t_{th}(t_{th} - t_-^*)}$	$t_0 = t_{th} - \sqrt{t_{th}(t_{th} - t_-)}$

- $\{\tilde{a}_i\} \to \{a_i\}$
- $a_3^{A_2}$ and a_2^+ fixed by $q^2 = 0$ constraints. $\to$ 20 independent coefficients a_i

LQCD form factors parameterization

	$B_s \to D_s^*$	$B_s \to D_s$
HPQCD parametrization[†‡]	$F(q^2) = \frac{1}{P_F(q^2)} \sum_{n=0}^{3} \tilde{a}_n^F (\tilde{z}^*)^n$	$f_0(q^2) = \frac{1}{1 - q^2/M_{B_{c0}}^2} \sum_{n=0}^{2} \tilde{a}_n^0 \tilde{z}^n$ $f_+(q^2) = \frac{1}{1 - q^2/M_{B_c^*}^2} \sum_{n=0}^{2} \tilde{a}_n^+ \left[\tilde{z}^n - \frac{(-1)^{n-3} n}{3} \tilde{z}^3 \right]$
New parametrization*	$F(q^2) = \frac{1}{P_F(q^2)} \sum_{n=0}^{3} a_n^F (z^*)^n$	$f_0(q^2) = \frac{1}{1 - q^2/M_{B_{c0}}^2} \sum_{n=0}^{2} a_n^0 z^n$ $f_+(q^2) = \frac{1}{1 - q^2/M_{B_c^*}^2} \sum_{n=0}^{2} a_n^+ z^n$

*N.P., Flynn, Nieves, Hernández arXiv:2304.00250 [hep-ph]

†Harrison and Davies (HPQCD) Phys. Rev. D 105, 094506 (2022)

‡McLean, Davies, Koponen, and Lytle (HPQCD) Phys. Rev. D 101, 074513 (2020)

LQCD Form factors

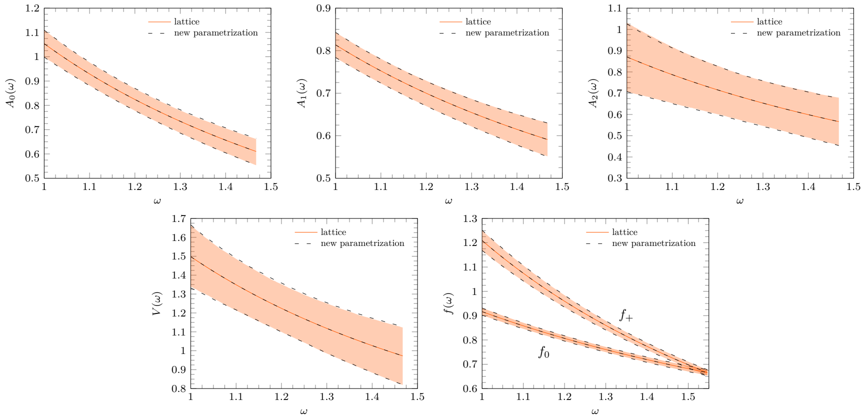

Figure: LQCD form factors from HPQCD vs the new parametrization.

Isgur-Wise functions

Isgur-Wise function parametrization Murgui et al. JHEP 09 (2019) 103

$$\xi(\omega) = 1 - 8\rho^2\hat{z} + (64c - 16\rho^2)\hat{z}^2 + (256c - 24\rho^2 + 512d)\hat{z}^3$$

where

$$\hat{z}(\omega) = \frac{\sqrt{\omega+1} - \sqrt{2}}{\sqrt{\omega+1} + \sqrt{2}}.$$

Sub-leading Isgur-Wise functions Bernlochner et al. Phys.Rev.D 95(2017)11, 115008

$$\hat{\chi}_2(\omega) = \hat{\chi}_2(1) + \hat{\chi}_2'(1)(\omega - 1), \quad \hat{\chi}_3(\omega) = \hat{\chi}_3'(1)(\omega - 1), \quad \eta(\omega) = \eta(1) + \eta'(1)(\omega - 1)$$

Bernlochner et al. Phys.Rev.D 95(2017)11, 115008

$$\hat{h}_V = 1 + \hat{\alpha}_s C_{V_1} + \epsilon_c(\hat{L}_2 - \hat{L}_5) + \epsilon_b(\hat{L}_1 - \hat{L}_4),$$

$$\hat{h}_{A_1} = 1 + \hat{\alpha}_s C_{A_1} + \epsilon_c\left(\hat{L}_2 - \hat{L}_5\frac{\omega-1}{\omega+1}\right) + \epsilon_b\left(\hat{L}_1 - \hat{L}_4\frac{\omega-1}{\omega+1}\right),$$

$$\hat{h}_{A_2} = \hat{\alpha}_s C_{A_2} + \epsilon_c(\hat{L}_3 + \hat{L}_6),$$

$$\hat{h}_{A_3} = 1 + \hat{\alpha}_s(C_{A_1} + C_{A_3}) + \epsilon_c(\hat{L}_2 - \hat{L}_3 + \hat{L}_6 - \hat{L}_5) + \epsilon_b(\hat{L}_1 - \hat{L}_4),$$

$$\hat{h}_+ = 1 + \hat{\alpha}_s\left[C_{V_1} + \frac{\omega+1}{2}(C_{V_2} + C_{V_3})\right] + (\epsilon_c + \epsilon_b)\hat{L}_1,$$

$$\hat{h}_- = \hat{\alpha}_s\frac{\omega+1}{2}(C_{V_2} - C_{V_3}) + (\epsilon_c - \epsilon_b)\hat{L}_4.$$

Fit

Goal: Fit the SM-LQCD form factors to their HQSS expressions.

1. Expand the HQSS form factors in powers of $z^{(*)}$.
2. Compare them with the LQCD expansions to obtain f_i, the coefficients in terms of the 10 HQET parameters $\rho^2, c, d, \hat{\chi}_2(1), \hat{\chi}_2'(1), \hat{\chi}_3'(1), \eta(1), \eta'(1), l_1(1), l_2(1)$.
3. Minimize $\chi^2 = \sum_j \sum_k (a_j - f_j) C^{-1}_{jk} (a_k - f_k)$
   - block-diagonal covariance $C = \begin{pmatrix} C_{D*} & 0 \\ 0 & C_D \end{pmatrix}$

Covariance and error

- We expect $\bar{B}_s \to D_s^*$ and $\bar{B}_s \to D_s$ to be correlated but we don't have that information
- block-diagonal covariance $C = \begin{pmatrix} C_{D*} & 0 \\ 0 & C_D \end{pmatrix}$ vs. no-correlated fit $C = Diag(\sigma^2)$
- $\epsilon_x = \sqrt{(\underbrace{\Delta x}_{\text{fit error}})^2 + (\underbrace{\bar{x} - \bar{x}_{unc.}}_{\text{sist. error}})^2}$

	$\bar{B}_s \to D_s^{(*)}$	$\bar{B}_s \to D_s^{(*)}$ (unc)	$\epsilon[\bar{B}_s \to D_s^{(*)}]$	$\bar{B} \to D^{(*)}$
ρ^2	1.26 ± 0.07	1.33 ± 0.10	0.10	1.32 ± 0.06
c	1.20 ± 0.11	1.28 ± 0.13	0.13	1.20 ± 0.12
d	-0.91 ± 0.10	-0.97 ± 0.12	0.11	-0.84 ± 0.17
$\hat{\chi}_2(1)$	0.30 ± 0.23	0.18 ± 0.24	0.26	-0.058 ± 0.020
$\hat{\chi}'_2(1)$	0.14 ± 0.08	-0.02 ± 0.15	0.18	0.001 ± 0.020
$\hat{\chi}'_3(1)$	0.08 ± 0.09	0.07 ± 0.08	0.09	0.036 ± 0.020
$\eta(1)$	0.07 ± 0.21	0.14 ± 0.23	0.22	0.355 ± 0.040
$\eta'(1)$	-0.51 ± 0.25	0.12 ± 0.59	0.68	-0.03 ± 0.11
$l_1(1)$	0.28 ± 0.50	0.38 ± 0.52	0.51	0.14 ± 0.23
$l_2(1)$	-2.24 ± 0.94	-2.66 ± 1.1	1.03	-2.00 ± 0.30