



[arXiv:210X.?]

Updated Predictions for $\mathcal{R}(D^{(*)})$ with constrained $1/m_c^2$ corrections

Florian Bernlochner — florian.bernlochner@uni-bonn.de

In Collaboration with: Z. Ligeti, D. Robinson, M. Papucci C. Xiong, M. Prim

EPS-HEP 2021 - Hamburg / Virtual

BERKELEY LAB Lawrence Berkeley National Laboratory

/ERSITAT <mark>BONN</mark>

The $\mathscr{R}(D^{(*)})$ anomaly





Obs.	Current World Av./Data	Current SM Prediction	Significance
$\mathcal{R}(D)$	0.340 ± 0.030	0.299 ± 0.003	1.2σ
$\mathcal{R}(D^*)$	0.295 ± 0.014	0.258 ± 0.005	2.5σ \int 5.10
$P_{\tau}(D^*)$	$-0.38\pm0.51^{+0.21}_{-0.16}$	-0.501 ± 0.011	0.2σ
$F_{L,\tau}(D^*)$	$0.60 \pm 0.08 \pm 0.04$	0.455 ± 0.006	1.6σ
$\mathcal{R}(J\!/\psi)$	$0.71 \pm 0.17 \pm 0.18$	0.2582 ± 0.0038	1.8σ
$\mathcal{R}(\pi)$	1.05 ± 0.51	0.641 ± 0.016	0.8σ
$\mathcal{R}(D)$	0.337 ± 0.030	0.299 ± 0.003	1.3σ
$\mathcal{R}(D^*)$	0.298 ± 0.014	0.258 ± 0.005	2.5σ \int 5.00

Crucial to obtain **reliable** and **precise SM predictions** for such **ratios**

Central for this: Knowledge of Form Factors (FFs)



R(D)

FFs proportional to m_{ℓ}

New experimental Input & Updated BLPR

"BLPR" $\mathcal{O}(1/m_{c,b}, \alpha_s)$

Phys. Rev. D 95, 115008 (2017) arXiv:1703.05330

<u>Key Idea:</u> Exploit expansion of $B \to D^{(*)}$ form factors into **leading** and **sub-leading** $\mathcal{O}(1/m_{c,b})$ Isgur-Wise functions

 $\hat{h}(w) = h(w) / \xi(w) \,.$

$$D \qquad \hat{h}_{+} = 1 + \hat{\alpha}_{s} \Big[C_{V_{1}} + \frac{w+1}{2} (C_{V_{2}} + C_{V_{3}}) \Big] + (\varepsilon_{c} + \varepsilon_{b}) \hat{L}_{1}, \\ \hat{h}_{-} = \hat{\alpha}_{s} \frac{w+1}{2} (C_{V_{2}} - C_{V_{3}}) + (\varepsilon_{c} - \varepsilon_{b}) \hat{L}_{4}, \\ \hat{h}_{V} = 1 + \hat{\alpha}_{s} C_{V_{1}} + \varepsilon_{c} (\hat{L}_{2} - \hat{L}_{5}) + \varepsilon_{b} (\hat{L}_{1} - \hat{L}_{4}), \\ \hat{h}_{A_{1}} = 1 + \hat{\alpha}_{s} C_{A_{1}} + \varepsilon_{c} (\hat{L}_{2} - \hat{L}_{5} \frac{w-1}{w+1}) + \varepsilon_{b} (\hat{L}_{1} - \hat{L}_{4} \frac{w-1}{w+1}), \\ \hat{h}_{A_{2}} = \hat{\alpha}_{s} C_{A_{2}} + \varepsilon_{c} (\hat{L}_{3} + \hat{L}_{6}), \\ \hat{h}_{A_{3}} = 1 + \hat{\alpha}_{s} (C_{A_{1}} + C_{A_{3}}) + \varepsilon_{c} (\hat{L}_{2} - \hat{L}_{3} + \hat{L}_{6} - \hat{L}_{5}) + \varepsilon_{b} (\hat{L}_{1} - \hat{L}_{4}), \end{cases}$$

Falk, Neubert, Phys.Rev. D47 (1993) 2965-2981

Constrains full set of New Physics FFs & FFs proportional to m_{ℓ}

New very precise measurement from Belle of $w \sim q^2$ spectrum of $B \to D^* \ell \bar{\nu}_{\ell}$



4

Events

BLPR with new untagged D^*

	Fit	QCDSR	Lattice QCD			Dalla Data
	L' 10		$\mathcal{F}(1)$	$f_{+,0}(1)$	$f_{+,0}(w > 1)$	Belle Data
	$L_{w=1}$		\checkmark	\checkmark		\checkmark
┥	$L_{w=1}+SR$	\checkmark	\checkmark	\checkmark		\checkmark
	NoL					\checkmark
	NoL+SR	\checkmark				\checkmark
	$L_{w \ge 1}$		\checkmark	\checkmark	\checkmark	\checkmark
	$L_{w \ge 1} + SR$	\checkmark	\checkmark	\checkmark	\checkmark	\checkmark
	th: $L_{w \ge 1} + SR$	\checkmark	\checkmark	\checkmark	\checkmark	



 $L_{w>1}$ + SR: All of the above + QCD Sum rule (SR) constraints



Including $1/m_c^2$

BLPRXP

M. Bordone, M. Jung, D. Van Dyk

EPJC vol 80, 74 (2020) arXiv:1908.09398

order fu	unction f	f(1)	f'(1)
$1/m_{Q}^{2}$	$\hat{\ell}_{1} \ \hat{\ell}_{2} \ \hat{\ell}_{3} \ \hat{\ell}_{4} \ \hat{\ell}_{5} \ \hat{\ell}_{6}$	$\begin{array}{rrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrr$	$\begin{array}{rrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrr$

Use **LCSR**, QCD SR, Data to constrain full set of $1/m_c^2$



Including $1/m_c^2$

BLPR^{XP}

to *appear* [arXiv:210X]

Exploring **modified** power-counting to reduce # of $1/m_c^2$ contribution to a much smaller number



M. Bordone, M. Jung, D. Van Dyk

EPJC vol 80, 74 (2020) arXiv:1908.09398

order	function f	f(1)	f'(1)
$1/m_Q^2$	$\hat{\ell}_1 \ \hat{\ell}_2 \ \hat{\ell}_3 \ \hat{\ell}_4$	$\begin{array}{l} +0.12 \ [-0.10, +0.36] \\ -1.89 \ [-2.26, -1.54] \\ +0.86 \ [-8.29, +5.17] \\ -2.02 \ [-3.53, -0.75] \end{array}$	$\begin{array}{rrrr} -5.78 & [-12.5, -0.16] \\ -3.14 & [-9.53, +1.31] \\ +0.06 & [-2.96, +9.55] \\ -0.05 & [-1.88, +1.71] \end{array}$
	$\hat{\ell}_5 \ \hat{\ell}_6$		

Use **LCSR**, QCD SR, Data to constrain full set of $1/m_c^2$



Full $\mathcal{O}(1/m_{c,b}^2)$ matching of QCD to HQET:

$$\frac{\langle H_c \,|\,\bar{c}\,\Gamma b\,|\,H_b\rangle}{\sqrt{m_{H_c}m_{H_b}}} \sim 1 + \frac{1}{2m_c} + \frac{1}{2m_b} + \frac{1}{4m_c^2} + \frac{1}{4m_b^2} + \frac{1}{4m_bm_c}$$

6 combinations of Isgur-Wise functions at $\mathcal{O}(\frac{1}{m^2})$ in SM





Additional power counting parameter parametrizes expansion in $|\mathbf{k}_{muck}|/\Lambda_{QCD}$

At second order only 2 extra Isgur-Wise functions seem to enter all other parameters being constrained by mass-splittings

Need to **test** if this expansion is fully applicable

In what follows: no rescaling to $\mathcal{G}(1), \mathcal{F}(1)$ from lattice

		$\mathcal{L}_{w\geq 1} + 1/m_c^2$	$\mathbf{L}_{w\geq 1} + \mathbf{SR} + 1/m_c^2$
	χ^2	32.6	40.4
	dof	29	33
	$ V_{cb} \times 10^3$	38.5 ± 0.6	39.0 ± 0.6
	$ar{ ho}_*^2$	1.49 ± 0.56	0.84 ± 0.23
	$\hat{\chi}_2(1)$	1.00 ± 0.37	-0.06 ± 0.02
1/ <i>m_{b,c}</i>	$\hat{\chi}_2'(1)$	-0.90 ± 0.28	-0.01 ± 0.02
	$\hat{\chi}_3'(1)$	0.36 ± 0.13	0.03 ± 0.01
	$\eta(1)$	0.29 ± 0.03	0.29 ± 0.03
	$\eta'(1)$	(0)	-0.06 ± 0.09
	$\hat{\chi}_1'(1)$ *	-0.10 ± 0.97	-0.52 ± 0.32
$1/m_{c}^{2}$	$\hat{\phi}_1'(1)$ *	-0.34 ± 0.34	-0.54 ± 0.25

* = additional IW parameters that enter in the expansion







<u>Preliminary</u> BLPR^{XP} $\mathscr{R}(D^{(*)})$ SM Predictions



	Scenario	R(D)	$R(D^*)$	Correlation
	$L_{w \ge 1}$	0.294 ± 0.003	0.253 ± 0.002	-18%
	$L_{w \ge 1} + SR$	0.298 ± 0.003	0.251 ± 0.001	22%
Updated predictions	$\mathcal{L}_{w\geq 1} + 1/m_c^2$	0.293 ± 0.003	0.256 ± 0.003	8%
with $1/m_c^2$ terms	$\mathcal{L}_{w\geq 1} + \mathcal{SR} + 1/m_c^2$	0.299 ± 0.004	0.252 ± 0.002	43%
	Data (HFLAV)	0.340 ± 0.030	0.295 ± 0.014	-38%

New! FNAL *D** Lattice Results

See also BGL fit to BaBar Data Phys. Rev. Lett. 123, 091801 (2019) and studies of Belle untagged D* spectrum Phys. Rev. D 103, 073005 (2021)

New results from **FNAL/MILC** on $B \rightarrow D^*$ form factors [FNAL/MILC: arXiv:2105.14019]



 h_{A1} captures HQET dependence well; can try to include it into fit and compare $R_{1/2}(w)$ predictions

Preliminary BLPR^{XP} with new FNAL h_{A1}



Summary & Outlook

