$B_c \to J/\psi$ and $B_s \to D_s^*$ Decays with Lattice QCD

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HPQCD

Background

- Exclusive determinations of V_{cb} have historically focused on $B \to D^* \ell \bar{\nu}$ decay,
  - first, measure the differential decay rate:

$$\frac{d\Gamma}{dw} = \mathcal{N} \times \chi(w) \times \eta_{\mathrm{EW}}^2 \mathcal{F}^2(w) |V_{cb}|^2$$

  - Then fit this using some parameterisation scheme, typically either BGL or CLN, to extract $\eta_{\mathrm{EW}} \mathcal{F}(1) |V_{cb}|$
  - Use lattice calculations of the zero-recoil form factor, $\mathcal{F}(1)$, together with the perturbatively known factor η_{EW}, to determine $|V_{cb}|$
- This method has had several issues:
  - parameterisation scheme dependence of the result
  - Tension between exclusive and inclusive determinations (3.3σ using CLN)
  - More general parameterisation schemes go some way in resolving this tension, but increase the uncertainty in V_{cb}
- On the lattice side, the form factors are difficult to compute precisely, especially away from zero recoil:
  - The D^* is very close to the $D\pi$ threshold, requiring careful treatment of light mass dependence in lattice calculations of the form factor
  - The presence of the light quark makes lattice calculations much more numerically expensive.

$\rightarrow$ A comparison across the physical kinematic range is needed, but difficult.

$R(D^*)$ and Lepton Flavor Universality Violation

- Some tension is also seen in the ratio of total tauonic and muonic decay rates, $R(D^*)$. Explicitly

$$R(D^*) = \frac{\Gamma(B \to D^* \tau \bar{\nu}_\tau)}{\Gamma(B \to D^* \mu \bar{\nu}_\mu)}$$

- The standard model value for $R(D^*)$ is determined by extracting the form factors from the well measured $B \to D^* \ell \bar{\nu}_\ell$ decay distributions, together with HQET inputs related to the pseudoscalar form factor.

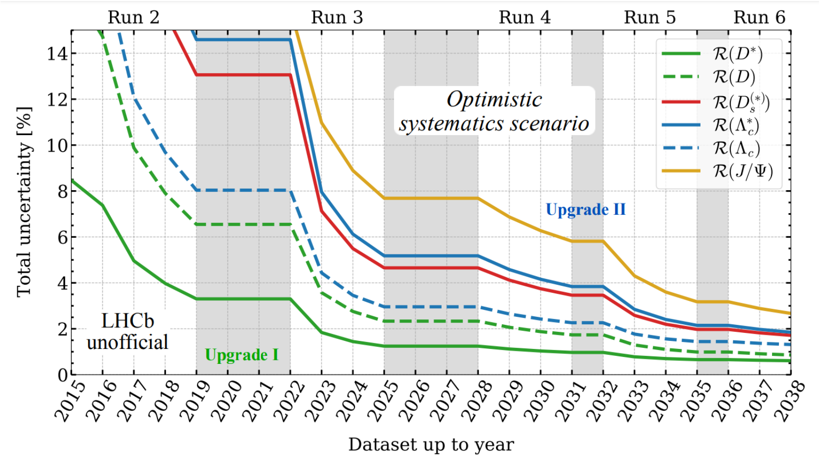
$$R(D^*)^{\mathrm{EXP}} = 0.295 \pm 0.014, \quad R(D^*)^{\mathrm{SM}} = 0.258 \pm 0.005$$

$$\text{tension of} \quad \approx 2.5\sigma$$

- $R(D^*)$ is sensitive to lepton flavor universality violation, important for detecting new physics

→ Ideally, compute form factors directly from lattice QCD without reliance upon parameterisation scheme or HQET

Other Decays



$B_s \to D_s^{(*)}$

- Recently, $B_s \to D_s^{(*)}\ell\nu$ decay has been used to determine V_{cb}:

$$B_s \to D_s^{(*)} :^{1} \quad V_{cb} = 41.4 \pm 1.6 \times 10^{-3}$$
$$B \to D^{(*)} :^{2} \quad V_{cb} = 40.3 \pm 0.8 \times 10^{-3}$$

- Again, the $B_s \to D_s^*$ determination relies upon a parameterisation and extrapolation to zero recoil
  - a comparison across the full q^2 range is needed here as well

- $B_s \to D_s^*$ offers more Advantages for a lattice calculation, compared to $B \to D^*$:

  - No up or down quarks in final or inital states - strange specator quark is much easier to deal with computationally and simple light mass dependence

  - The D_s^* is gold plated,

[1] LHCb 2001.03225

[2] Bordone et al. 1908.09398

$B_c \to J/\psi$

- $B_c \to J/\psi$ is an excellent starting point for lattice calculations of form factors across the full kinematic range:
  - J/ψ is gold plated
  - no light quarks in inital or final states; less noise than $B \to D^*$ or $B_s \to D_s^*$ and simple dependence on u/d mass
  - charm propagators less numerically expensive than strange

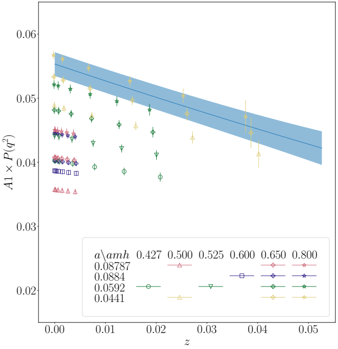
Lattice Methodology[3]

In the standard model $\mathcal{F}(w)$ is a simple function of the form factors, $A_1(w)$, $A_0(w)$, $A_2(w)$ and $V(w)$, with

- Use HISQ action for all quarks - fully relativistic, small discretisation effects, nonperturbatively normalised currents
- Compute form factors at multiple w, using multiple heavy masses ranging up to close to the physical mass
- Fit the form factor data including am_h discretisation effects, physical heavy mass dependence, and lattice spacing dependence
  - Here we first convert to z space

$$F(w) = \frac{1}{P(q^2)} \sum_{n=0}^{3} a_n z^n \mathcal{N}_n$$

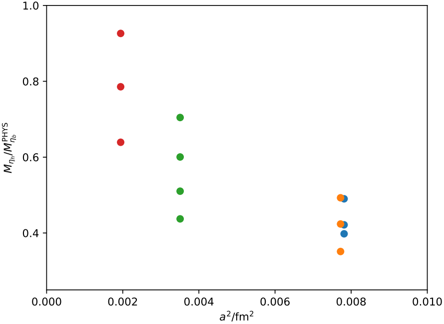
$$a_n = \sum_{j,k,l=0}^{3} b_n^{jkl} \Delta_h^{(j)} \left(\frac{am_c^{\rm val}}{\pi}\right)^{2k} \left(\frac{am_h^{\rm val}}{\pi}\right)^{2l}$$



Form factor A_1 for $B_c \to J/\psi$, with the pole factor $P(q^2)$ removed, plotted in z space, showing the physical continuuum form factor as a blue band

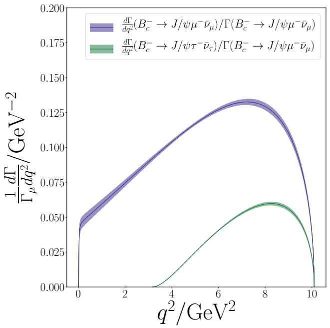
[3]Full details may be found in 2007.06957

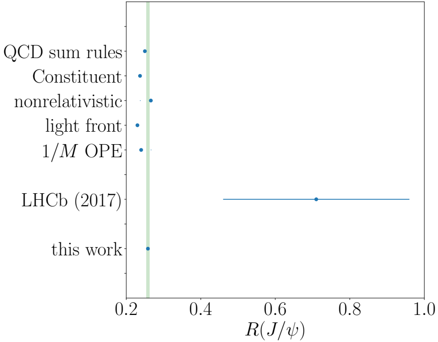
- We use the second generation MILC HISQ gauge configurations with u/d, s and c quarks in the sea.



- The subset of configurations we use include physical u/d quark masses, and have small lattice spacings allowing us to come very close to the physical b mass.

$B_c \to J/\psi$ Results - 2007.06956, 2007.06957



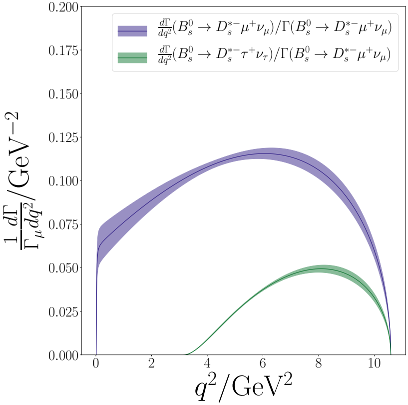


$$R(J/\psi) = 0.2582(38)$$

$$\Gamma(B_c^- \to J/\psi\mu^-\bar{\nu}_\mu)/\eta_{\mathrm{EW}}^2|V_{cb}|^2 = 1.73(12) \times 10^{13}s^{-1}$$

- Experimental results for $B_c \to J/\psi$ are currently much less precise than our lattice results, but expect this to improve in future.
- In addition to $R(J/\psi)$, other observables and ratios may be constructed with high precision from our form factor results
  - Can study the effect of NP couplings - full details in 2007.06956

$B_s \to D_s^*$ Results - 2105.11433



$$R(D_s^*) = 0.2442(79)$$

$$\Gamma(B_s^0 \to D_s^{*-}\mu^+\nu_\mu)/\eta_{\mathrm{EW}}^2|V_{cb}|^2 = 2.06(21) \times 10^{13} s^{-1}$$

$R(D_s^*)$, V_{cb}...

Many new lattice predictions for $B_s \to D_s^*$ quantities:

	This work	Exp.[4]	$B \to D^*$ [5]
$\frac{\Gamma(B_s^0 \to D_s^- \mu^+ \nu_\mu)}{\Gamma(B_s^0 \to D_s^{*-} \mu^+ \nu_\mu)}$	0.444(49)	0.464(45)	0.457(23)
$R(D_s^*)$	0.2442(79)	–	0.258(5)
F_L	0.448(22)	–	0.464(10)
$\mathcal{A}_{\lambda_\tau} = -P_\tau$	0.514(18)	–	0.496(15)

- Can also infer a total experimental rate Γ from LHCb analysis of V_{cb} in 2001.03225, we can use this with our results to give a value of V_{cb}

$$|V_{cb}| = 43.0(2.1) \times 10^{-3}$$

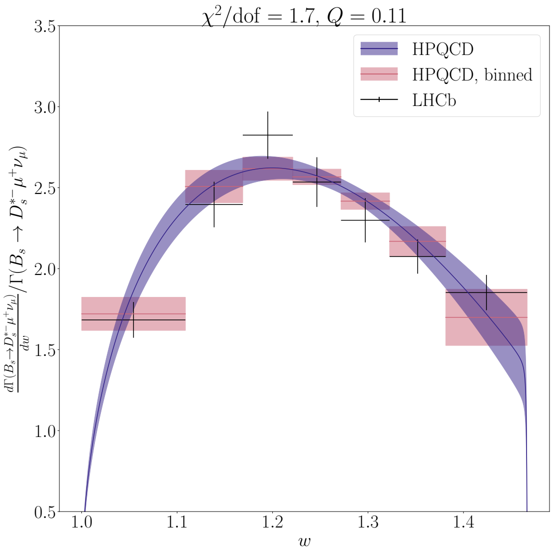
- Consistent with the result using lattice data only at zero-recoil.

[4] LHCb 2001.03225

[5] HFLAV 1909.12524,Bordone et. al 1908.09398

$B_s \to D_s^*$ Shape

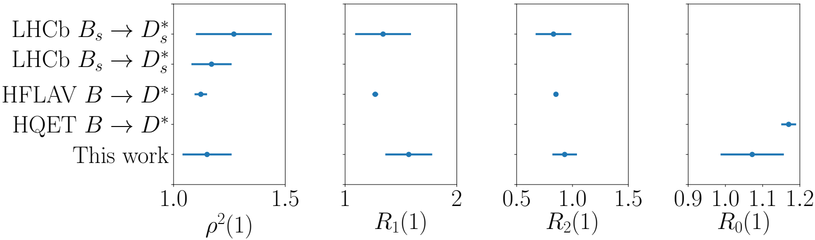
We can compare the binned experimental results[6] for the $B_s \to D_s^*$ shape to our results



[6] LHCb:2003.08453

$B_s \to D_s^*$ Shape Parameters

In the CLN parameterisation, the shape of the decay for massive leptons in the SM is fully described by the four parameters ρ^2, $R_1(1)$, $R_2(1)$ and $R_0(1)$, with ρ^2, $R_1(1)$, $R_2(1)$ determined from experiment and $R_0(1)$ known to NLO in HQET[7]



- Our results are broadly consistent with the measured values of ρ^2, $R_1(1)$ and $R_2(1)$ for $B_s \to D_s^*$, and with the NLO HQET value of $R_0(1)$.

[7] LHCb:2001.03225+2003.08453, HFLAV:1909.12524, HQET:1703.05330

Summary

- Published lattice results for $B_c \to J/\psi$ form factors, corresponding experimental measurements are currently imprecise.
  - Experimental results for $B_c \to J/\psi$ decays are expected to become more precise
- Results for the $B_s \to D_s^*$ form factors now on arXiv
  - Model independent determinations of $R(D_s^*)$ and other observables
  - Model independent determination of $|V_{cb}|$, though ideally would use experimental results directly
- Work on $B \to D^*$, including Tensor form factors, now underway