

Precision theory inputs for $|V_{cb}|$ and LFUV observables

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The study of flavor is a central theme of high energy physics, one which has fruitfully led to many dramatic advances in the understanding of fundamental particles. One of the current outstanding questions in the field is a resolution of the long-standing discrepancy between inclusive and exclusive determinations of $|V_{cb}|$. There are additionally several anomalies, which have attracted intense theoretical interest in recent years, in the $b \rightarrow c$ decays which have yet to be resolved and which could point to new physics. The next several years we can expect will be characterized by an increase in experimental precision, and qualitative change due to increasing number of channels under experimental scrutiny. Lattice efforts from the US and international community will be a vital component of the program to resolve these long-standing questions.

Increasing the experimental precision of $|V_{cb}|$ is a major objective of the Belle II experiment at KEK, which began collecting data in 2019 and is expected to run through 2025. The SuperKEKB facility will achieve an instantaneous luminosity up to $40\times$ that of its predecessor and produce around 50 billion $B\bar{B}$ pairs during its lifetime. While the current experimental uncertainty in $|V_{cb}|$ is around 2%, this will be reduced to 1.4% once Belle II achieves its expected 50 ab^{-1} integrated luminosity around 2025. In order to profit from this increasing experimental precision, determination of $|V_{cb}|$ requires theoretical calculations with a commensurate level of precision, and the ab-initio methods of lattice QCD are required to meet this challenge.

Meanwhile, the experimental reach of the LHC continues to expand, allowing study of other $b \rightarrow c$ channels never before possible. LHCb has measured $B_c \rightarrow J/\psi$ semileptonic decays, exploiting the subsequent decay of the J/ψ to two muons, and also completed an entirely new measurement of $|V_{cb}|$ from $B_s \rightarrow D_s^{(*)}$ decays – analogous to $B \rightarrow D^{(*)}$ but with the light spectator quark replaced with a strange quark. This is the first determination of $|V_{cb}|$ from exclusive decays at a hadron collider, and the first using B_s decays [1]. The current precision of this result can be compared with e.g. the 2018 Belle result from $B \rightarrow D^*$ [2]:

$$|V_{cb}| = 42.3(8)_{\text{stat}}(9)_{\text{syst}}(12)_{\text{ext}} \times 10^{-3} \quad \text{LHCb } B_s \rightarrow D_s^{(*)}, \quad (1)$$

$$|V_{cb}| = 38.3(3)_{\text{stat}}(7)_{\text{syst}}(6)_{\text{lqcd}} \times 10^{-3} \quad \text{Belle total } B \rightarrow D^*. \quad (2)$$

Although not yet comparable with the precision of determinations from $B \rightarrow D^*$, these innovative new measurements will continue to improve, providing a completely new window into the $b \rightarrow c$ sector.

The LHCb collaboration also for the first time measured the ‘ R -ratio’ in $R(B_c \rightarrow J/\psi l \nu_l)$, which measures the overall ratio of branching fractions for the outgoing lepton to be a τ vs. a μ , finding a $\sim 2\sigma$ deviation from the predictions of the Standard Model [3], thus adding to the long-standing discrepancies in $R(D^{(*)})$. This cluster of anomalies has led to intense theoretical interest. If these anomalies remain, it would force a vast rethink of particle physics. In the next few years, the experimental uncertainties on these observables will decrease dramatically. If new physics is verified in these decays, much more detailed studies will be required, and the precise theoretical knowledge of QCD form factors will be crucial to tease apart the nature of new physics across observables specifically engineered for this purpose [4]. These reasons strongly motivate the need for theoretical determination of the complete form factors for all relevant decays, so that precision comparisons for any battery of observables will be possible.

Given the preceding discussion, it is clear that a robust theory effort is required from the lattice community to best leverage the results from our experimental colleagues. The lattice community is well positioned in this regard, having several ongoing efforts both with US and international collaborators in tackling these challenging and resource-intensive precision calculations [5]. The most precise exclusive $|V_{cb}|$ determinations are currently based on the value of the $B \rightarrow D^* A_1$ form factor at zero recoil [6, 7], and activity is being focussed on extending the calculation to all form factors over the full kinematic range [8]. Having full knowledge of the form factors will be critical to fully utilize the new results from Belle II, making model independent bin-by-bin determinations of $|V_{cb}|$ a possibility and generally reducing the reliance on model approximations for the form factors. The recent and anticipated experimental progress also motivates an increased focus on other $b \rightarrow c$ processes, including $B_{(c,s)}$ semileptonic and baryon decays. Towards this goal lattice theorists have completed the first calculations of $B_c \rightarrow J/\psi$ [9], $B_s \rightarrow D_s$ [10], and $\Lambda_b \rightarrow \Lambda_c$ [11], including all form factors. This work should be extended to all relevant processes, and given their challenging technical nature, it is vital that competing collaborations, using methodologies subject to differing systematic errors, can contribute.

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