

Topical Groups:

- (RF1) Weak decays of b and c quarks
- (TF02) Effective field theory techniques
- (TF05) Lattice gauge theory
- (TF06) Theory techniques for precision physics
- (TF07) Collider phenomenology
- (CompF2) Theoretical calculations and simulation

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High precision determinations of $|V_{xb}|$ from a close theory-experiment collaboration

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I. INTRODUCTION

Flavor physics, and in particular the CKM matrix elements and the unitarity triangle, have become one of the most relevant high precision tests of the Standard Model (SM) in our search for New Physics (NP). The long-standing discrepancies between inclusive and exclusive determinations of $|V_{ub}|$ and $|V_{cb}|$ (together denoted as $|V_{xb}|$) have puzzled theorists and experimentalists alike, and is currently driving large efforts both at the Belle II and LHCb B -factories and on the theory side [1, 2]. The overall status of the tensions is depicted in Fig. 1.

For exclusive decays, the role of the underlying form-factors (FF) that describe the hadronization of the b quark, following the $b \rightarrow \{c, u\}$ weak decay, has made it imperative that a combined theory-experiment effort resolves these puzzles. For present Λ_b^0 [3, 4] and B_s^0 [5, 6] analyses, LHCb has already measured the FF shapes [4, 5] and major efforts are underway to extend upon these measurements in Run 3. For $B^{0,\pm}$ decays, thanks to efforts from the previous generation B -factories at BABAR/Belle [7–10], the situation is further developed. However, even for the $B^{0,\pm}$ decays, at the crucial “zero-recoil” region, $q^2 \rightarrow q_{\text{max}}^2$, although the FFs

are finite, the phase-space vanishes and the experimental decay-rate vanish. The extrapolation of the FFs from experimentally measurable data points to the zero-recoil limit has been the subject of much controversy in the recent past [1, 11], and its elimination will represent a qualitative leap for determination of $|V_{xb}|$. Further, the scalar FFs, that contribute only to the semi-tauonic decays also can not be measured experimentally, but must derive from theory. On the other hand, away from the phase-space edges, at $q^2 \rightarrow \{0, q_{\text{max}}^2\}$, the rich experimental data play the dominant role in constraining the FFs.

Very recently, lattice calculations for the decay amplitude of these processes covering the full q^2 range either have become or are becoming available. These calculations are inducing a shift in the methodology to calculate the CKM matrix elements, with no extrapolation of the experimental data to $q^2 = q_{\text{max}}^2$ required. The availability of these calculations has stressed the necessity of a close collaboration between theorists and experimentalists, in order to effectively share data within a common framework. The goal of this Letter is to convey need for a close theory-experiment collaboration, including joint fits to theory and data, to maximise sensitivities.

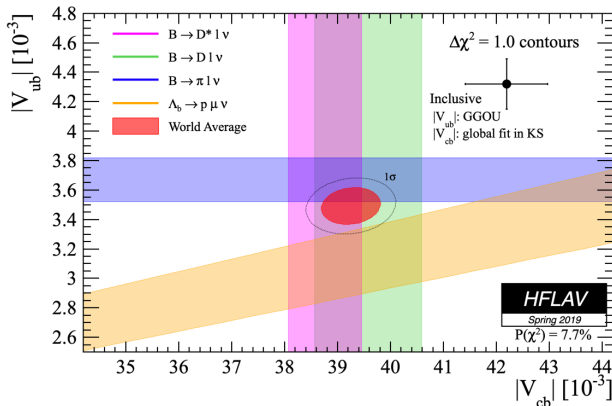


FIG. 1: The overall status of $|V_{ub}|$ - $|V_{cb}|$ from last year.

II. THEORY: LATTICE QCD AND HQET

Historically, the first lattice calculations of the $B_{(s)}^0 \rightarrow D_{(s)}^{(*)} \ell^- \bar{\nu}_\ell$ and $B_{(s)}^0 \rightarrow \{\pi, \rho, \phi, K\} \ell^- \bar{\nu}_\ell$ form factors were carried out at zero recoil for reasons of simplicity. However, lattice is now delivering many results in the nonzero recoil region where HQET makes no predictions. Precision is typically limited by discretization errors: heavy quarks require either very fine lattice spacings ($a \sim O(1/m_b)$) or complicated actions, sometimes both, and this translates into large computational requirements. Also, some actions introduce renormalization matching errors. Many collaborations have developed roadmaps to address these points (Fermilab Lattice & MILC, HPQCD, JLQCD, RBC/UKQCD, ...), using advanced actions, small lattice spacings and nonperturbative techniques to calculate the renormalization factors. Improved results are expected in the coming years.

Effective field theories and HQET play a role by providing ansätze for lattice fits, in particular the continuum extrapolation for the lattice data, and the z -expansion

* This LOI is not an official collaboration submission, for either LHCb or BABAR. The official LHCb LOI submission is available at this [link](#).

for the combined fits. Improvements in the definition of the z -expansion that could lead to both a resolution of the current controversy of parameterization and reduced errors in the fits are strongly desirable.

III. EXPERIMENTAL OVERVIEW

On the inclusive side, *BABAR* released an analysis on its full dataset for $b \rightarrow u$ [12] where the dependence of $|V_{ub}|$ on the QCD calculations of the underlying shape function, persisted. For $|V_{cb}|$, the last inclusive measurements from *BABAR* / *Belle* date more than a decade back [13], and needs to be revisited. The exclusive data is dominated by pseudo-scalar final states, $B \rightarrow \pi$ [9, 14] and $B \rightarrow D$ [8, 15]. LHCb, as a relatively new player, has brought in Λ_b and B_s^0 decays in the fold. In particular the $|V_{ub}|$ measurement from $\Lambda_b \rightarrow p\mu^-\bar{\nu}_\mu$ [3] was possible thanks to timely availability of high- q^2 baryonic FFs from lattice [16].

In the process $b \rightarrow X\ell^-\bar{\nu}_\ell$, the angular distributions of the daughter tracks provide information on nature of the leptonic system, whether it is a pure SM W_L^{*-} , or has NP elements such as a scalar H^- or a right-handed W_R^{*-} . For example, in $\bar{B} \rightarrow D\ell^-\bar{\nu}_\ell$, a pure spin-1 W^{*-} boson would result in a $\sin^2\theta_\ell$ distribution, while an admixture of a scalar component gives an additional $\cos\theta_\ell$ term. These terms can be searched for experimentally without requiring detailed knowledge of the hadronic FF.

For $\ell^- \in \{e^-, \mu^-\}$, the hadronic tagging procedure at e^+e^- B -factories allows for full reconstruction of the single missing neutrino 4-momentum, well facilitating these angular studies. For the semi-tauonic case, since there are at least two missing neutrinos, the situation is more difficult. A special case occurs for single-prong hadronic τ^- decays, as has been utilized at *Belle* already [17].

When the hadronic system, X , is a vector particle like $D_{(s)}^*$, the spin information on the leptonic side is fully preserved by the hadronic side as well. Analyzing the subsequent $D_{(s)}^* \rightarrow D_{(s)}^*\{\gamma, \pi\}$ decays, in addition to the leptonic side, results in a rich haul of angular observables that disentangles the NP contributions in the leptonic side. The angular distributions have been well studied in the literature [18], including the semitauonic case that needs special attention [19].

For the $\ell^- \in \{e^-, \mu^-\}$ cases, the first full 4d angular analysis has recently been published by *BABAR* [10]. The analysis works within the SM paradigm, retains all cross-terms among the angular variables and employs an unbinned fitting technique to the raw *BABAR* data. The cross-terms in the 4d fit crucially allows resolving ambiguous solutions to previous fits performed on the product of four 1d distributions [20]. While the *BABAR* [10] data confirmed on the $|V_{cb}|$ tension, some new tensions with the HFLAV averages on the FFs were found, as sum-

marized in Fig. 2. In particular, the ratio $R_2(w)$ shows large deviations from the HFLAV average. The implications on higher order Λ_{QCD}/m_c terms to the HQET FFs from these data have to be studied further. New $B \rightarrow D^*$ lattice data in the $w \rightarrow 1$ region will shed new light on this.

BABAR also intends to perform a 2d analysis in $q^2\text{-cos}\theta_\ell$ for the $\bar{B} \rightarrow D\ell^-\bar{\nu}_\ell$ case. The HPQCD collaboration has recently published $B_s \rightarrow D_s$ [21] over the full q^2 range. Assuming minimal flavor-SU(3) breaking, the FFs are expected to be very similar in $B_{(s)} \rightarrow D_{(s)}$. The *BABAR* analysis aims to revisit this assumption.

IV. COMBINED EXPERIMENT+THEORY FITS

New lattice results at nonzero recoil [22, 23] on $B \rightarrow D^*$ are expected soon. They should shed light on the extrapolation of the FFs to zero recoil. But to extract the maximal physics information requires a combined data plus lattice fit. In Refs. [24, 25] one such joint fit was done. In that example, the experimental data are binned. However, fits to unbinned data are preferred for best sensitivity. Since experimental data are obtained in a 4D phase space, such a joint fit requires careful coordination between the experimental and theoretical teams. Such coordination can help decide the most effective format for releasing the experimental data. For example, Ref. [18] proposes using q^2 -binned angular moments. *BABAR* intends to release its $B \rightarrow D^*$ data in this format, which might be adopted by other experiments.

In conclusion, in order to maximize opportunities for discovery in semi-leptonic decays, we see an increasing need over the next decade for close coordination in the analysis stage between theoretical and experimental teams. While this LOI focused on combining lattice QCD and experimental results for $|V_{xb}|$ determinations, similar issues arise in rare neutral-current decays, such as $B \rightarrow K\ell^+\ell^-$ and $B \rightarrow \pi\ell^+\ell^-$.

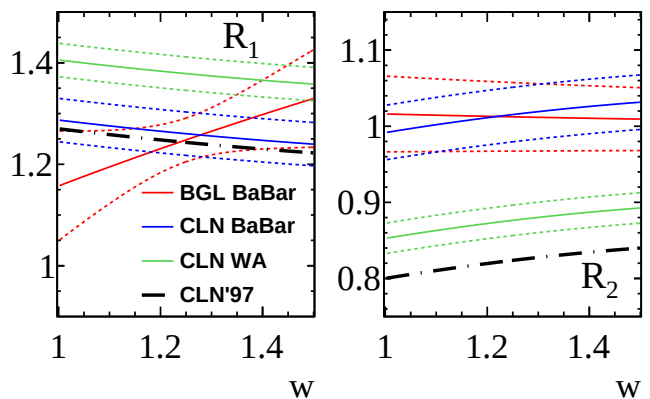


FIG. 2: $R_{1,2}(w)$ from the *BABAR* analysis [10].

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