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Summary of the working group for V_{ub}, V_{cb} and semileptonic/leptonic B decays including τ at CKM 2021

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A summary of the activities of WG2 at the 2021 CKM conference is presented. This includes discussion of the latest developments regarding the determination of the CKM elements $|V_{cb}|$, $|V_{ub}|$ and measurements of lepton universality with decays involving τ leptons. Consideration is given to both the theoretical and experimental aspects of the subject.

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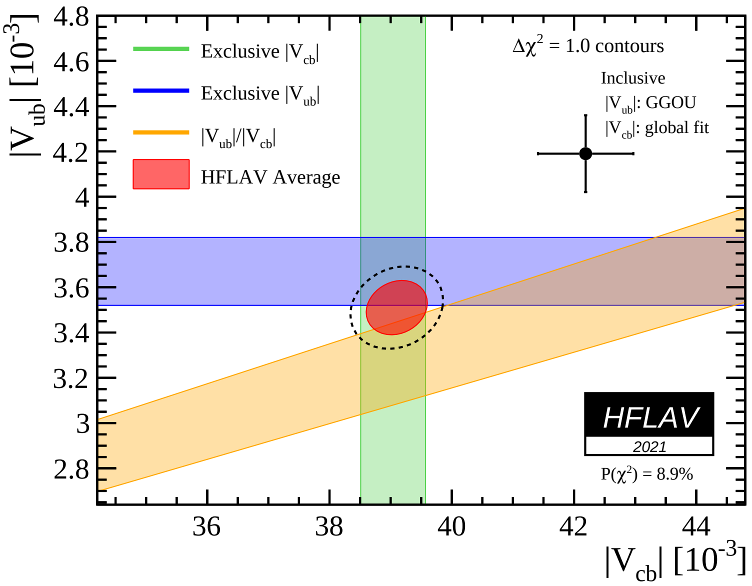

Figure 1: Status of inclusive and exclusive V_{ub} and V_{cb} measurements [1]

1. Introduction

Semileptonic decays, involving a final state with one neutrino, occur at tree-level in the Standard Model (SM) and therefore tend to have large branching fractions. The possibility of factorising the hadron and lepton currents allows for precise theoretical calculations of the decay rates. As a consequence such decays are an ideal laboratory for precisely measuring SM parameters as well as searching for new physics, particularly involving the heavy $\tau^{\pm}$ lepton. However, the presence of at least one undetected neutrino in the final state presents a significant experimental challenge.

The material covered by WG2 may be roughly split into two parts: the determination of the CKM elements $|V_{ub}|$ and $|V_{cb}|$ either exclusively or inclusively; measurements of lepton (non-)universality with semi-tauonic B decays and the implications for physics beyond the Standard Model. These cover the principle areas of interest of the community at this time and the discussions in WG2 elucidated the significant progressions being made.

2. CKM elements

Measurements of the CKM elements $|V_{ub}|$ and $|V_{cb}|$ using inclusive B decays show tension with complementary determinations using exclusive decays. The current status of the discrepancy is shown in Fig. 1 [1].

There has been a noticeable progress in the determination of $|V_{xb}|$ in both, theoretical and experimental fronts, since the last CKM conference. This progress has increased the tension between the inclusive and the exclusive determinations of these CKM matrix elements, but an explanation of why this tension exists is still missing.

2.1 Inclusive determinations

Ongoing lattice-Quantum Chromodynamics (LQCD) efforts for determining the inclusive decay rates are introduced. The group of S. Hashimoto presented a framework to perform inclusive calculations using LQCD, and showed some very preliminary tests that agree with the more standard approach using the Operator Product Expansion or OPE [2]. Although more work is needed, these steps are pointing in the right direction, and future improvements might lead to high precision calculations of inclusive decay rates.
Outside LQCD, theory progress with regards to $|V_{cb}|$ has been shown, where new calculations to third order of the Heavy Quark Expansion of the relation between the shell and kinematic quark mass and the $b \to c$ decay rate are presented [3–6]. Such calculations lead to a new determination of inclusive $|V_{cb}|$ that is consistent with previous ones but with a slightly reduced uncertainty [7].

Further improvements will come with new experimental results. In particular it has been proposed to incorporate measurements of the moments of the q^2 distribution of $\bar{B} \to X_c \ell \bar{\nu}_\ell$ [8]. This is a new avenue for $|V_{cb}|$ determination, exploiting reparametrization invariance (RPI) to reduce the number of parameters in the Heavy Quark Expansion. To determine these parameters, one must measure the moments of RPI variables such as the q^2. Belle has measured these moments [9] using its full data set and a hadronic tagged approach. Here, hadronic tagging refers to the analysis approach where one B in the decay $\Upsilon(4S) \to B\bar{B}$ is exclusively reconstructed using hadronic modes. The remaining information in the event is used to measure the $B \to X\ell\nu$ decays and determine the $< (q^2)^n >$ where $n = 1..4$. The experimental approach involves correcting for reconstruction and residual biases introduced due to differences between simulated samples and real data. The results for the measured $< (q^2)^n >$ are currently in progress and their incorporation into the determination of the CKM element is an ongoing exercise.
In addition, Belle has also produced new results for inclusive $B \to X_u \ell \nu$ [10] and $|V_{ub}|$. In this measurement, a boosted decision tree was used to suppress the challenging $B \to X_c \ell \nu$ background. The corresponding signal yield was then extracted in three phase space regions and the determined partial branching fractions were then used to extract $|V_{ub}|$. The result is compatible with exclusive expectations within $1.3\,\sigma$. Another measurement of the differential branching fraction of $B \to X_u \ell \nu$ is also performed at Belle II [11] where 6 kinematic results are measured. The extracted signal yields are corrected for detector reconstruction and acceptance effects and then used to determine the partial branching fraction. These measurements will serve as input for future model independent measurements of $|V_{ub}|$ by the Belle II experiment.

2.2 Exclusive determinations

On the experimental front, there has been a series of exclusive semileptonic measurements. For the $B \to D^* \ell \nu$ decay, the Belle collaboration published a new result using an untagged data set [12]. Their result for $|V_{cb}|$ is consistent regardless of the parametrisation employed (CLN[13] or BGL[14]) for the form factors that enter the $B \to D^* \ell \nu$ decay rate to describe the hadronic current in the $b \to c$ transition. The collaboration also made their unfolded data public, which allowed a wide variety of phenomenological calculations (see, for instance, Refs. [15–21] for a non-comprehensive list). The BaBar collaboration also published a new result for $|V_{cb}|$, based on a 4-dimensional analysis of their data set [22], but only the fit results were published, limiting the

PoS(CKM2021)011

number of calculations based on BaBar data.
Recent results from LHCb have shown for the first time exclusive determinations of the CKM elements using B_s^0 decays. The value of $|V_{cb}|$ from $B_s^0 \to D_s^{(*)-}\mu^+\nu_\mu$ has been measured using two different form-factor parametrisations [23]. The two results are consistent with each other and with the current exclusive average from HFLAV [1]. For $|V_{ub}|$ a measurement has been carried out with $B_s^0 \to K^-\mu^+\nu_\mu$ decays [24] in two bins of q^2 allowing for separate theory input from LQCD [25] and Light Cone Sum Rules (LCSR)[26] calculations in the lower and higher bins, respectively. The results of the two bins are not consistent, suggesting that further theoretical work would be beneficial. In that vein the first fit of the differential $B_s^0 \to K^-\mu^+\nu_\mu$ rate has been carried out, along with the $B \to \pi\ell^+\nu_\ell$ decays using a novel parametrisation of the form-factor q^2 dependence [27].
Looking ahead, Belle II is already laying the foundation for a wide set of measurements in the semileptonic sector. The analysis approach for these measurements is either with or without B tagging. As mentioned earlier, B tagging refers to the full reconstruction of the companion B in the event using hadronic or semileptonic modes. Belle II has measured the branching fraction for $B \to D^*\ell\nu$ using both a tagged and untagged approach with 34.6 fb^{-1} collected in 2020. These measurements are used to validate the Belle II data and software analysis chain. A measurement of $|V_{cb}|$ will follow this year. Furthermore, measurements of hadronic tagged $B \to \pi\ell\nu$ and $B \to \rho\ell\nu$ have also been performed and have laid the ground work for an upcoming extraction of $|V_{ub}|$. As the size of the Belle II data set increases, the expected precision for $|V_{cb}|$ and $|V_{ub}|$ is expected to be within 1-2% and will shed the light on the current disagreement between exclusive and inclusive determinations.
Regarding the theoretical advances, there has been a lot of activity in the lattice community, especially regarding mesonic semileptonic decays. In general, lattice calculations are reaching fine enough lattice spacings to treat the b quark as a light quark, with no special action required, thus reducing the amount of lattice artefacts and allowing for easier and more accurate, non-perturbative renormalization schemes. This shift should yield more accurate calculations, as the statistics of the finest ensembles increase in the following years. Also, the same channel is being calculated by several groups using different data and methods, enabling the possibility of an accurate crosscheck of the lattice calculations. A recent lattice calculation by the Fermilab lattice and MILC collaborations provides the form factors for the $B \to D^*\ell\nu$ in the whole recoil range [28], although they still use a special action for the b quark. In combination with Belle [12] and BaBar [22] data, they quote a $|V_{cb}|$ value very close to the HFLAV average [1]. An ongoing calculation by JLQCD that uses the same action for heavy and light quarks will be able to crosscheck the Fermilab - MILC results for the form factors in the forthcoming months [29]. They perform simulations at several values for the mass of the b quark, and then they extrapolate to the physical mass to extract physical results. So far they find reasonable agreement between their preliminary form factors and the already published ones of Fermilab Lattice and MILC collaborations. The JLQCD collaboration is also working on a $B \to D\ell\nu$ calculation, for which there already exists a variety of lattice results in the whole recoil range (see, for instance, Ref. [30]). The HPQCD collaboration presented results at zero and non-zero recoil for the $B_{(s)} \to D_{(s)}^{(*)}\ell\nu$ decays, without using any special action for the b quark [31, 32]. Their results for $B \to D^*\ell\nu$ are limited to zero recoil, and they are in agreement with previous calculations. They are currently working on extending their form factors to the whole recoil range. Their results on the $B_s \to D_s^{(*)}\ell\nu$ allow, in combination with the latest LHCb experimental results

on the same decays, the determination of $|V_{cb}|$ using these new channels. The current value found using these decays is *not* in disagreement with the inclusive determinations, but the errors on these new channels are still too high to be competitive. HPQCD is also exploring B_c decay modes, and they have made available data for the form factors of the $B_c \to J/\psi$ decay [33, 34].

Regarding $|V_{ub}|$, there are a variety of ongoing calculations by several groups. JLQCD is working on a new calculation of the $B \to \pi\ell\nu$ form factors using a similar setup to the one they employ in $B \to D^{(*)}\ell\nu$ [35]. The RBC/UKQCD collaboration is extending their existing calculation [36, 37] to incorporate a finer lattice spacing, which should reduce their discretization errors. This collaboration is also working on an improved calculation of the $B_s \to K\ell\nu$ form factors. The Fermilab lattice and MILC collaborations are working on two different calculations of the $B \to \pi\ell\nu$, $B_s \to K\ell\nu$ and $B \to K\ell\ell$ decays at the same time that mainly differ on the treatment of the b quark: one calculation uses the Fermilab action [38], whether the other employs the same action as in the light sector [39]. Although the best determinations of $|V_{ub}|$ come from the $B \to \pi\ell\nu$ channel, the $B_s \to K\ell\nu$ offers an interesting alternative for the lattice, especially now that LHCb is producing data for this decay: it allows for a more controlled chiral extrapolation, with smaller errors, due to the heavier mass of the kaon, and in combination with the $B_s \to D_s\ell\nu$ form factors, it also allow for a direct lattice calculation of the $|V_{ub}|/|V_{cb}|$ ratio without experimental input. Calculations on the $B \to K\ell\ell$ mode from the lattice can also potentially be very interesting, as this is a rare process driven by FCNC that might be very sensitive to new physics.
G. Rendon presented a variety of lattice calculations addressing the $\Lambda_b \to \Lambda_c^*\ell\nu$ semileptonic decay and the $\Lambda_b \to \Lambda\ell\ell$ rare process [40–42], and improving previous existing results [43]. These calculations still use an effective action for the heavy quarks. In general, the main efforts of the lattice community are focused on meson decays, where higher precisions are attainable, but the inclusion of these channels might allow for non-trivial crosschecks in the future. The ETMC collaboration presented a non-perturbative method to calculate the susceptibilities $\chi^{L,T}$ that can have a large impact in the accuracy of the implementation of the unitarity constraints [44, 45]. They also presented results that combine their own calculation of the susceptibilities with a dispersive approach to bound the form factor data [46–48], instead of using any of the well-established parametrisations. Their results for $|V_{xb}|$ are closer to the inclusive value, nonetheless further investigation is required.

3. Lepton universality

Lepton Flavour universality (LFU) in semileptonic decays is measured in the ratios $R(H_c)$, defined as

$$R(H_c) = \frac{\mathcal{B}(H_b \to H_c\tau^+\nu_\tau)}{\mathcal{B}(H_b \to H_c\ell^+\nu_\ell)},$$

where H_b and H_c denote some b or c hadron and $\ell = e$ or μ depending on the experimental measurement. These ratios have been precisely calculated in the SM and experimentally can be measured to high precision since multiple systematic uncertainties can be cancelled. At this point in time the quantities $R(D^{(*)})$ have been measured, with the experimental average[1] showing an approximately $3\,\sigma$ deviation from the SM expectation.

PoS(CKM2021)011

The Belle II experiment is preparing for a set of measurements in the semitauonic sector to confirm or annul the current B anomaly. The anticipated integrated luminosity in the next year (2022-2023) is around 800 fb^{-1}. The planned measurements include $R(D^{(*)})$ with hadronic and semileptonic B tagging and with hadronic or leptonic τ decays. Belle II has developed a new B-tagging algorithm based on a multi-variate approach, which leads to 30% improvement in overall performance and will positively impact the precision of $R(D^{(*)})$. In addition, another multivariate approach has been used to increase signal to background separation of a key variable in called E_{ECL}. E_{ECL} is the sum energy of all energy deposits in a collision event after fully reconstructing the B mesons. With these tools, Belle II plans to measure $R(D^{(*)})$ using hadronic and semileptonic tagging, with leptonic and hadronic tau decays. The first results are expected for summer 2022. Furthermore, $R(X)$, defined as the ratio of the inclusive rate $B \to X\tau\nu$ to its lighter lepton counterparts $B \to X\ell\nu$ will also be measured at Belle II and a first result is expected with 500 fb^{-1} of data before the upcoming detector upgrade in 2023. This measurement has not been updated for more than 20 years and is expected to shed light on the nature of the semitauonic B anomaly. $R(X)$ is sensitive to the modelling of semileptonic background processes and current Belle II tools are being developed to overcome this. Finally, another important measurement that is unique to Belle II is the measurement of $\mathcal{B}(B \to \tau\nu)$. The reconstruction of this leptonic decay is theoretically clean and experimental measurements can provide orthogonal measurements of the CKM matrix element $|V_{ub}|$. The first results are also expected with 500 of data. The precision of all 3 semitauonic Belle II measurements: $R(D^{(*)})$, $R(X)$ and $\mathcal{B}(B \to \tau\nu)$ will considerably improve as the size of the Belle II data set increases to 1, 5 and 50 ab^{-1}.

There have been many developments on the theoretical side as well. M. Jung presented an improved Heavy Quark Expansion (HQE) analysis of existing data on $B \to D^{(*)}\ell\nu$, including systematic $O(1/m_c^2)$ corrections that are necessary to find agreement with LQCD data [15]. Most improvements, nonetheless, came from lattice calculations. The recent Fermilab Lattice/MILC calculation of the $B \to D^*\ell\nu$ form factors [28] allows for a first principles determination of $R(D^*)$, which agrees with previous SM theoretical estimates. This result will be crosschecked when the ongoing JLQCD calculation [29] of the $B \to D^{(*)}\ell\nu$ form factors is complete. The HPQCD collaboration is exploring different universality ratios, providing results for $R(D_s^{(*)})$ [31, 32] and $R(J/\psi)$ [33, 34] with relatively high precision. These ratios will increase in importance as experimental data on the relevant processes becomes more and more accurate.

Beyond ratios of branching fractions, the angular distributions of the decay products will give insight into the structure of new physics operators, should they exist [49–51]. Although such analyses are experimentally challenging, it has been shown that LHCb can make a contribution [52]. Such work would be complementary to indirect limits on new physics interpretations from the B_c^+ lifetime of [53]. In addition, physics reweighting tools such as HAMMER [54] will allow the experiments to directly extract form-factors or new physics parameters directly from experimentally measured distributions.

4. Conclusions

The anomalous results from measurements of semileptonic B decays continue to persist. Attention is currently being given to the theoretical aspects leading to considerable innovation.

Similarly the experiments continue to work hard to produce and exploit large data sets to continue to study these decays with higher precision. In the near future one may expect a wide array of new measurements from both Belle II and LHCb, as well as a large number of high-precision lattice calculations that can cast some light on the current issues. New theoretical avenues to probe new physics beyond the Standard Model are being developed and will thus expand the current tool set available to track anomalies.

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PoS(CKM2021)011

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