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Challenges in Semileptonic B Decays

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The magnitudes of two of the elements of the CKM quark mixing matrix, V_{ub} and V_{cb}, are extracted from semi-leptonic B-meson decays. The results of the B factories, analyzed in the light of the most recent theoretical calculations, remain puzzling, because – for both $|V_{ub}|$ and $|V_{cb}|$– the exclusive and exclusive determinations are in tension by about 3σ. Recent experimental and theoretical results reduce the tension but the situation remains unclear. Meanwhile, measurements in the tau channels at Belle, Babar, and LHCb show discrepancies with the Standard Model predictions, pointing to a possible violation of lepton flavor universality. LHCb and the upcoming experiment Belle II have the potential to resolve these issues in the next few years.

Thirty-five participants met in Mainz to develop a medium-term strategy of analyses and calculations aimed at the resolution of these issues. Lattice and continuum theorists discussed with experimentalists how to reshape the semi-leptonic analyses in view of the much larger luminosity expected at Belle II and how to best exploit the new possibilities at LHCb, searching for ways to systematically validate the theoretical predictions, to confirm new physics indications in semi-tauonic decays, and to identify the kind of new physics responsible for the deviations.

The topical workshop took place during a period of five days, allowing for ample discussion time among the participants. Each of the five workshop days was devoted to specific topics: the inclusive and exclusive determinations of $|V_{cb}|$ and $|V_{ub}|$, semi-tauonic B decays and how they can be affected by new physics as well as related subjects such as purely leptonic B decays and heavy quark masses. In the mornings, there were overview talks from the experimental and theoretical sides, reviewing the main aspects and summarizing the state of the art. In the late afternoon, a discussion sessions led by experts of the various topics, addressing questions that were brought up before or during the morning talks.

Exclusive heavy-to-heavy decays: The $B \to D^{(*)}$ l ν decays have received significant attention in the last few years. New Belle results for the q^2 and angular distributions have allowed studies of the role played by the parametrization of the form factors in the extraction of $|V_{cb}|$. It turns out that the extrapolation to zero-recoil is very sensitive to the parametrization employed, a problem that can only be solved by precise calculations of

the form factors at non-zero recoil. Until these are completed, the situation remains unclear - with repercussions on the calculation of R(D^*) and with diverging views on the theoretical uncertainty of present estimates based on HQET expressions.

In addition to a critical reexamination of these recent developments, several incremental and qualitative improvements in lattice QCD were discussed - also in baryonic decays. Though unlikely to contribute to the V_{cb} determination, the latter decays offer great opportunities to test lepton-flavor universality violation (LFUV) and lattice QCD. The discussions also addressed the fact that the QCD errors are now almost as small as the effects from QED. Thus, further improvement must be theoretically made by properly studying the effect of QED radiation, especially the treatment of soft photons and photons that are neither soft nor hard. Their sensitivity to the meson wave functions has to be considered, too. Concerning studies of LFUV, we discussed the role played by higher excited charmed states in establishing new physics and the challenges which the present R($D^{(*)}$) measurements pose for model building.

Exclusive heavy-to-light decays: This determination relies on non-perturbative calculations of the form factor of $B\to\pi l\nu$ which, up to now, is the most precise channel. We discussed the status of the LCSR calculations and several recent improvements in lattice QCD. In particular the most recent lattice calculations by the Fermilab/MILC and the RBC/UKQCD collaborations and the future prospects. The Fermilab/MILC calculation alone leads to a remarkably small total error on$|V_{ub}|$, of about 4%. While at present the most precise extraction of $|V_{ub}|$ comes from $B\to\pi l\nu$, it has been stated that in the future the golden channel could be $B_s\to K\ l\ \nu$ because here the lattice-QCD calculations are affected by smaller uncertainties. $B_s\to Kl\nu$ can be accessible at Belle II in the run at the $\Upsilon(5S)$ and a precision of about 5-10% could be achieved with $1fb^{-1}$.

The great opportunities for charmless semi-leptonic decays at LHCb have been demonstrated by the precise measurement of the ratio $B(\Lambda_b\to p\mu\nu)/(\Lambda_b\to\Lambda_c\mu\nu)$ in the high q^2 region. This measurement, combined with a precise lattice calculation of the form factors ratio, allowed the extraction of ratio $|V_{ub}/V_{cb}|$ with an uncertainty of 7%. The ongoing analysis of the $B(B_s\to Kl\nu)/B(B_s\to D_s l\nu)$ ratio, is going to give a new determination of $|V_{ub}/V_{cb}|$ ratio. We also discussed other channels, in particular how to study $B\to\pi\pi l\nu$ including the resonant structures. Careful studies of other heavy to light channels will also be crucial to improve the signal model for the inclusive $|V_{ub}|$ measurements.

Inclusive heavy-to-heavy decays: The theoretical predictions in this case are based on an operator product expansion. We learned that better control of all higher-order corrections is needed to reduce theoretical uncertainties which are already dominant. In this respect, it would be important to have the QCD perturbative corrections to the coefficient of the Darwin operator and to check the treatment of QED radiation in the

experimental analyses. A full $O(\alpha_s^3)$calculation of the total width may be within reach with recently developed techniques. From the experimental point of view, new and more accurate measurements will be most welcome, in particular to understand the correlations. An improved determination of the higher hadronic mass moments and a first measurement of the forward-backward asymmetry would be advantageous for the global fit, as would a better understanding of higher power corrections. The importance of having global fits to the moments in different schemes and by different groups has also been stressed. This calls for an update of the 1S scheme fit and could lead to a cross-check of the present theoretical uncertainties. Lattice QCD already provides inputs to the fit with the calculation of the heavy quark masses which were reviewed. New developments discussed at the workshop may soon be able to provide additional information that can be fed into the fits such as constraints on the heavy-quark parameters μ_π^2 and μ_G^2. The two main approaches are (i) computing inclusive rates directly on the lattice and (ii)using the heavy quark expansion for meson masses, precisely computed at different quark mass values. The state of theoretical calculations for inclusive semi-tauonic decays was also discussed, as they represent an important cross-check of the LFUV signals.

Inclusive heavy-to-light decays: This determination is based on various well-founded theoretical methods which generally agree nicely. The 2017 endpoint analysis by BaBar seems to challenge this consolidated picture suggesting discrepancies between some of the methods and a lower $|V_{ub}|$. For future scientific projects, the complete NNLO corrections in the full phase space should be implemented and the various methods should be upgraded in order to make the best use of the Belle II differential data based on much higher statistics. These data will make it possible to test the various methods and to calibrate them, as they will contain information on the shape functions. The SIMBA and NNV_{ub} methods seem to have the potential to fully exploit the $B\to X_u l\nu$ (and possibly radiative) measurements through combined fits to the shape function(s) and $|V_{ub}|$. The separation of $B^\pm$ and B^0 in the experimental analyses will certainly help to constrain weak annihilation, but the real added value of Belle II could be precise measurements of kinematic distributions in M_X, q^2, E_l, etc.. A detailed measurement of the high-q^2 tail might be very useful, also in view of attempts to check quark-hadron duality. Experimentally, better hybrid (incl.+excl.) Monte Carlos are urgently needed. S-bar s popping should be investigated to develop a deeper understanding of kaon vetos. The b→c background will be measured more precisely which will be advantageous for these analyses.

Leptonic decays: The measurement of $B\to\tau\nu$ is not yet competitive with semi-leptonic decays for measuring$|V_{ub}|$, because of a 20% error on the rate. Belle II will improve this. The corresponding lattice-QCD calculation is very precise, with an error below 1%, according to the forthcoming report from FLAG and mainly based on a result from Fermilab/MILC presented at the topical workshop. That said, the mode is useful today to model builders trying to understand new physics explanations of the tension between inclusive and exclusive determinations of $|V_{ub}|$. Belle-II will also access $B\to\mu\nu(\gamma)$ with the

possibility to reach an uncertainty on the branching fraction of about 5% with 50ab−1, allowing for a new determination of $|V_{ub}|$ in the long run. The LHCb contribution to leptonic decays with the process $B \to \mu\mu\nu_\mu$ was also discussed, where a couple of muons comes from virtual γ or light vector boson decays. The study of this channel has recently been shown at CKM2018. The very stringent upper limit obtained, which is inconsistent with the existing branching fraction predictions, calls for new reliable theoretical calculations.

Conclusion: The topical workshop was very successful and was appreciated by all participants. It brought together scientists from different disciplines working on the same subject. Various new ideas have been put forward in order to scrutinize the current understanding of the current discrepancies and anomalies and eventually to resolve or confirm them. New calculations are still necessary and new analyses will be possible at Belle II and LHCb. The discussion sessions turned out to be very useful to develop these ideas.