Mainz Institute for Theoretical Physics

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MITP Program Suggestion

Proposed title	**Challenges in semileptonic B decays 2018**
Proposal submitted by (corresponding organizer)	**Paolo Gambino (Univ. Turin)**
Name of organizer #2	**Andreas Kronfeld (Fermilab)**
Name of organizer #3	**Marcello Rotondo (INFN-LNF Frascati)** **Christoph Schwanda (OEWA Wien)**
Type of program	**Scientific Program** X **Topical Workshop** ☐
Duration	**2 weeks**
Preferred dates	**April 2018**

Executive summary including expected impact

Two of the elements of the Cabibbo-Kobayasha-Maskawa quark mixing matrix, Vub and Vcb, are extracted from semileptonic B decays. The results of the B factories, analysed in the light of the most recent theoretical calculations, remain puzzling, because—for both |Vcb| and |Vub|—the exclusive and exclusive determinations are in tension by about 3σ. This discrepancy has survived several independent checks and could be an indication for New Physics. Further, measurements in the tau channels at Belle, Babar, and LHCb show discrepancies with the Standard Model predictions, pointing to a possible violation of lepton flavour universality. LHCb and the upcoming experiment Belle-II have the potential to resolve the issue in the next few years.

The proposed workshop follows a first successful MITP workshop held in 2015, sharing with it the goal to develop a medium-term strategy of analyses and calculations aimed at solving the puzzles. We plan to have lattice and continuum theorists working together with experimentalists to discuss how to reshape the semileptonic analyses in view of the much higher luminosity expected at Belle-II, searching for ways to systematically validate the theoretical predictions in both exclusive and inclusive B decays, and to exploit the unexpectedly rich possibilities at LCHb.

In this second workshop, scheduled for the spring of 2018, we will focus on the expanding prospects of semileptonic decays at LHCb, on the implications of the first Belle-II data, on the possible violation of lepton universality, as well as on progress in lattice QCD, where first simulations treating b quarks like light quarks may become available. As the theoretical methods used to predict rare semileptonic transitions b → sl+l-, which could provide evidence for new physics, are the same as those used for semileptonic decays, we plan to cover some of their QCD aspects as well.

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Description of the scientific program / scientific motivation

The semileptonic decays of B mesons have been employed at the B factories to measure precisely the magnitude of the CKM matrix elements V_{cb} and V_{ub}, which play an important role in the analysis of CP violation in the Standard Model and in the detailed verification of its flavour structure. Two complementary methods have been used, based on the study of either exclusive transitions to specific hadronic final states, or inclusive decay rates and distributions. These two approaches rely on different theoretical frameworks: the exclusive method is mostly based on lattice calculations of the relevant form factors, while the inclusive method is rooted in an operator-product expansion and attempts to extract the relevant non-perturbative quantities from experimental data.

The same QCD techniques (lattice, OPE) are used for semileptonic decays mediated by flavour-changing neutral currents (FCNC), such as $B \to K^{(*)}l^+l^-$ ($l = e,\mu$). The combination of theory and experiment has revealed some hints of new physics. While phenomenologists have devised observables with a reduced sensitivity to QCD effects, it may be impossible to be confident of a new-physics signal without a full understanding of other observables that rely on QCD as do the CKM determinations.

In addition, the results of the B factories, analysed with the most recent lattice and continuum calculations, are puzzling. For both $|V_{cb}|$ and $|V_{ub}|$ the most precise exclusive determinations are 2-3σ *below* the inclusive ones. This discrepancy has been around for a while, and has survived several independent checks. While this could be an indication for new physics, a recent measurement of Λ_b decays by LHCb appears to disfavour the simplest explanation in terms of a new right-handed component in the weak current. Recent data from Babar, Belle, and LHCb also suggest a violation of lepton-flavour universality (LFU) in semitauonic B decays. As lepton-flavour non-universality is linked to lepton-flavour violation In many new-physics scenarios, precise measurements of the various leptonic channels would open very interesting possibilities.

Both LHCb and the upcoming experiment Belle-II have the potential to contribute in a significant way to these issues, if adequately supported by the theoretical community. The purpose of the proposed workshop is therefore to bring together lattice and continuum theorists as well as experimentalists and phenomenologists, in order to devise a medium-term strategy that will include a new set of experimental analyses (made possible by the higher luminosity at Belle-II and by the unexpected possibilities at LHCb), and a detailed scrutiny of all theoretical systematics in the exclusive and inclusive calculations.

Indeed, the close interaction between experimental collaborations, phenomenologists, and QCD experts is at the heart of this workshop concept. We plan to build on the positive experience of the first workshop, which proved very useful, and change its format to a two-week formula that should favour informal discussions and collaborations over public presentations. The first week will focus on theoretical uncertainties, on ways to validate the theoretical predictions, and dialogue on QCD aspects of FCNCs, while the second week will confront these issues with the experimental reality.

The Belle-II collaboration is presently reshaping the semileptonic program and studying ways to validate the theoretical calculations. Belle-II will accumulate about 50 times the Belle dataset. This will allow them to employ hadronic tagging in all analyses of semileptonic B decays, leading to a significant

reduction of backgrounds and to a better control of the final state kinematics. In this way, a precise understanding of $B \to D^{**}lv$ decays can be obtained and various inclusive charmless distributions can be measured. Other important questions brought forward by experimentalists, and which need attention by theorists, are signal simulations and QED corrections. We also plan to explore the prospects for testing LFU in the light lepton channels at Belle-II. In spring 2018 the first Belle-II data will be available: we will discuss them at the workshop, as they will be crucial for a better understanding of the machine backgrounds and to evaluate the prospects of the semileptonic measurements.

The LHCb collaboration has recently demonstrated an unexpected potential in measuring exclusive semileptonic b decays. In particular, LHCb has the unique opportunity to study the B_c and Λ_b decays, that will not be accessible to Belle II. It is now clear that these new experimental opportunities can contribute to the precise determination of V_{ub} and V_{cb}, and possibly shed light on the FCNCs. In order to make this possible, however, precise theoretical predictions are needed, for example, in the case of decays to tau, only few calculations are available for the various accessible Λ_b and B_c decays. LHCb has also very big samples of B and B_s already available, and it might be possible to study $B_s \to K^{(*)}lv$ decays before Belle-II dominates the field. Again, it is important to start assessing the potential of these new channels together with QCD theorists and phenomenologists. The large statistics available will also allow to extend the exploration of the LFU violation to light leptons, comparing semileptonic decays in electron and muons, hopefully with systematic uncertainties below the percent level.

Lattice QCD calculations have made important steps forward in the last decade. As far as the semileptonic form factors are concerned, the main directions of development are to extend the calculations beyond zero recoil, with sea quarks realistically incorporated (2+1 or 2+1+1 flavours). In addition, increasing computing power is pushing the lattice spacing down far enough that it is now becoming feasible to use light-quark methods with absolutely normalized currents. Last, several ensembles of gauge fields now include up and down quarks of physical mass; by the time of the workshop calculations on these ensembles should become available. These developments are interesting in their own right. At the same time, the broader scope and stronger fundamentals may reconcile or clarify disagreements on form factors between heavy-quark sum rules and lattice QCD.

For what concerns the Heavy Quark Expansion (HQE) in inclusive charmed decays, the calculation of higher order corrections remains a high priority despite recent progress. Indeed, the theoretical errors are already dominant in the inclusive determination of V_{cb}. We plan to review status and prospects of such calculations and to study new observables that may be accessible at Belle-II, such as the forward-backward asymmetry, which was proposed at our first workshop. We will look for ways to constrain the higher dimensional matrix elements that appear at $O(1/m^n)$, n = 4,5. We also intend to explore ways in which lattice gauge theory can enhance the predictive power of the HQE, and consequently improve the V_{cb} and V_{ub} determinations, by measuring directly or indirectly HQE matrix elements, as well as the heavy quark masses.

In the case of inclusive charmless decays the differential distributions will become available at Belle-II, and will help constraining the relevant shape functions. We need to test and compare the model-independent methods (SIMBA and NNVub) which can incorporate this new information in the inclusive analyses and reduce the uncertainty of the theoretical predictions. In parallel, the existing NNLO corrections have to be implemented in the full phase space in all the methods employed for the V_{ub} extraction, also in view of an ongoing debate on their actual relevance. We plan to discuss estimates of the actual precision that can be reached at Belle-II, which will be very valuable in order to establish

goals and priorities. A detailed measurement of the high q^2 tail might be very useful, also in view of attempts to check quark-hadron duality. Problems closer to experiment which will be discussed include s-sbar popping and the need for better hybrid (inclusive+exclusive) Monte Carlos.

By early 2018 we expect significant progress in the exclusive determination of $|V_{cb}|$, both experimental (new, model-independent analyses for $B \to D^* l\nu$) and theoretical (first lattice QCD calculation of the $B \to D^*$ form factors at non-zero recoil, as already done for $B \to Dl\nu$). QED corrections to both exclusive and inclusive processes have been discussed at the first workshop, but their correct implementation in the analyses remains an open problem to be addressed.

In the case of the exclusive semileptonic determination of $|V_{ub}|$ from $B \to \pi l\nu$, light cone sum rules have been employed to estimate the relevant form factor at low q^2, while lattice calculations are possible only at large q^2. The combination of these two methods allows us to predict the complete q^2 spectrum, which will be measured precisely at Belle-II. A thorough uncertainty analysis of the theoretical calculations will be discussed and may guide to possible tests and new experimental analyses. Semileptonic decays to vector mesons, or directly to their non-resonant decay products, open up additional analysis strategies, although the theoretical calculations seem quite challenging at the moment, due to the broadness of the resonances. An improved understanding of $B \to \rho l\nu$ will also benefit the study of the FCNC decay $B \to \rho ll$. The future prospects of the golden mode $B_s \to Kl\nu$ and of $\Lambda_b \to pl\nu$ are brighter, but need to be carefully assessed.

Eventually, the purely leptonic $B \to \tau\nu$ decay is expected to be the most sensitive channel for the $|V_{ub}|$ determination at Belle-II. A precise measurement of $|V_{ub}|$ requires in this case improvements in the computation of the B decay constant for the current 2% level. In the long term, therefore, the semileptonic results will confront those of $B \to \tau\nu$, with far reaching consequences for the Unitarity Triangle analyses and for the constraints on the fermion currents, which may receive contributions from new physics operators. This development provides additional motivation to the main goal of the workshop, the better understanding of semileptonic B decays.

As discussed above, we also plan to slightly extend the workshop's scope to FCNCs. Indeed, the methodologies used to describe semileptonic B decays (lattice, OPE, shape functions, sum rules) are the same as those used in rare semileptonics transitions $b \to sl^+l^-$. We plan to cover some of the QCD aspects, reflecting the core expertise of the organizers. Although an examination of new-physics scenarios is also timely, there are many such workshops and we see a need to discuss the status of the underlying theory with phenomenologists and model-builders, to have a better idea of what is needed from QCD, as well as what is possible. We note that it can be difficult for experimentalists to spend two weeks at a workshop, so one week could focus on the QCD-FCNC interface, the other on aspects relevant to experiments.

List of potential participants and their status of commitment
a) likely to attend the program or
b) already have expressed their interest to participate

(theorists)
Zoltan Ligeti, LBNL, USA (a)
Thomas Mannel, Siegen, Germany (a)

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Gil Paz, Wayne State, USA (a)
Jernej Kamenik, Ljubjana, Slovenia (b)
Roman Zwicky, Edinburgh, UK (a)
Yu-Ming Wang, Vienna and Nankai, China (a)
Alex Khodjamirian, Siegen, Germany (a)
Aoife Bharucha, Marseille, France (a)
Enrico Lunghi, Indiana, USA (a)
David Straub, Munich, Germany (a)
Christine Davies, Glasgow, UK (a)
Shoji Hashimoto, KEK, Japan (a)
William Detmold, MIT, USA (b)
Aida El-Khadra, Urbana-Champaign, USA (a)
Jonathan Flynn, Southampton, UK (b)
Steve Gottlieb, Indiana, USA (b)
Weonjong Lee, Seoul National, Korea (a)
David Lin, National Chiao-Tung, Taiwan (b)
Vittorio Lubicz, Roma III, Italy (b)
Stefan Meinel, Arizona, USA (b)
Carlos Pena, Autónoma Madrid, Spain (a)
Matthew Wingate, Cambridge, UK (b)
Christoph Lehner, BNL, USA (b)
Andreas Jüttner, Southampton, UK (a)
Jack Laiho, Syracuse, USA (b)

(experimentalists)
Marta Calvi, Milan, Italy (a)
Ulrik Egede, Imperial College London, UK (a)
Concezio Bozzi, INFN-Ferrara (a)
Bob Kowalewski, Victoria, Canada (a)
Gregory Ciezarek, Nikhef, Netherlands (a)
Jochen Dingfelder, Bonn, Germany (a)
Phillip Urquijo, Melbourne, Australia (a)