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Matthew John Kirk

Charming New Physics in Beautiful Processes?

Doctoral Thesis accepted by
the Durham University, Durham, UK

Springer

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Supervisor's Foreword

The Standard Model (SM) of Particle Physics comprises all our knowledge about the subatomic world. It has been confirmed by thousands of experimental measurements with a high precision. The latest big success of the SM was the discovery of the Higgs Particle at the Large Hadron Collider (LHC) at CERN in 2012.

Despite these achievements the SM leaves many questions unanswered, like what is the nature of dark matter or what is the origin of the matter–antimatter asymmetry in the Universe. Identifying a breakdown of the SM, as well as finding the correct extension of the SM that will answer the abovementioned questions, is a major motivation for current research in particle physics.

There are two principal strategies for finding physics beyond the Standard Model (BSM): direct BSM searches try to directly create new unknown elementary particles by building more powerful accelerators—a strategy that was very successful in the past (e.g. the discovery of the Higgs particle in 2012 at LHC, CERN or the discovery of the top quark in 1995 at Tevatron, Fermilab). Indirect searches for BSM effects use comparisons of high-precision SM calculations with extremely precise measurements. Any discrepancy here can give first glimpses of new effects, that cannot be accommodated by the SM. This strategy was also very successful in the past: electroweak precision measurements before 2012 have shown that there should be a Higgs particle with a mass of the order of 100. The existence and the value of mass of the top quark could be deduced from the measurement of *B* mixing in 1986 (UA1, CERN) and 1987 (ARGUS, DESY).

The thesis of Dr. Matthew Kirk studies very different aspects of indirect new physics searches within the subfield of Flavour Physics—this field studies the decays of hadrons containing heavy charm or heavy bottom quarks. These systems are very promising for understanding CP violation, which seems to be the key to answer the origin of the matter–antimatter asymmetry. The main difficulty in doing indirect BSM searches within Flavour Physics is a control over hadronic effects, that dominate the decays of the heavy mesons. Any misjudgement of these QCD effects might else be interpreted as unambiguous BSM signals. Dr. Kirk will present a phenomenological study of the possible maximum size of unknown hadronic effects (denoted by duality violation) in *B* mixing and *D* mixing, as well as in the lifetimes of the B and D mesons. Moreover, he will present a determination of non-perturbative objects that govern neutral B and D meson mixing as well as B and D meson lifetime ratios. The corresponding Heavy Quark Effective Theory (HQET) sum rules require a perturbative 3-loop calculation. For meson mixing, the results are competitive with the most recent lattice evaluations and for the lifetimes they are the only available results based on QCD.

Besides these high-precision SM calculations, Dr. Kirk investigated also how hypothetical dark matter particles might couple to heavy charm quarks. He will present in his thesis a comprehensive investigation of bounds on this possibility stemming from relic densities of particles in the Universe, flavour bounds measured at particle physics colliders, direct dark matter detection bounds from underground experiments, indirect dark matter detection bounds from satellite experiments and dark matter bounds from the LHC.

Finally, Dr. Matthew Kirk worked also on BSM models that might describe the anomalies that are currently observed in the decays of b quarks by the LHCb collaboration. A confirmation and understanding of these flavour anomalies would revolutionise our understanding of the subatomic world. It also would give direct hints for where exactly to look for the new particles in accelerators. He performed a model-independent study using effective theory methods and he could show within this approach that an observation of a momentum dependence of the anomalies would not be an unambiguous signal for a hadronic origin of the discrepancy, as typically claimed in the literature, but could also be due to new BSM effects. In another study, he has shown several of the discussed BSM possibilities to explain the flavour anomalies are ruled out by a precise study of B mixing.

In summary, this thesis contains an extraordinarily broad range of topics related to indirect flavour searches for BSM effects and it is an essential read for newcomers in this field.

Durham, UK
March 2019

Prof. Alexander Lenz

Abstract

In this thesis, we study quark flavour physics and in particular observables relating to B meson mixing and lifetimes. Meson mixing arises due to the nature of the weak interaction, and leads to several related observables that are highly suppressed in the Standard Model (SM). Alongside meson mixing, lifetimes provide an insight into rare B processes which can shed light on possible new physics.

Both the calculations are based on an Effective Field Theory (EFT) framework, in particular the Weak Effective Theory. This framework allows us to separate the high-scale effects which are calculable in perturbation theory from the low-energy matrix element, which are determined through other means. Within this framework, the observables are expanded using the Heavy Quark Expansion (HQE) technique, which utilises the relatively large masses of b and c quarks to reveal a further hierarchy of corrections. The basics of EFTs and the HQE are explored in detail as an entry point to the majority of the work in this thesis.

In the rest of the thesis, we take aim at pushing the accuracy of our SM predictions further: by testing the underlying assumption of Quark-Hadron duality in the HQE; by studying possible new physics models that can explain the long-standing problem of dark matter as well as recently seen anomalies; and by using alternative approaches to determining the low-energy constants associated with mixing and lifetimes in order to provide independent and state-of-the-art results.

Publications Related to This Thesis

- T. Jubb, M. Kirk, A. Lenz and G. Tetlalmatzi-Xolocotzi, *On the ultimate precision of meson mixing observables, Nucl. Phys.* **B915** (2017) 431–453, [1603.07770].
- T. Jubb, M. Kirk and A. Lenz, *Charming Dark Matter, JHEP* **12** (2017) 010, [1709.01930].
- S. Jäger, K. Leslie, M. Kirk and A. Lenz, *Charming new physics in rare B-decays and mixing?, Phys. Rev.* **D97** (2018) 015021, [1701.09183].
- M. Kirk, A. Lenz and T. Rauh, *Dimension-six matrix elements for meson mixing and lifetimes from sum rules, JHEP* **12** (2017) 068, [1711.02100].
- L. Di Luzio, M. Kirk and A. Lenz, *Updated B_s-mixing constraints on new physics models for $b \to s\ell^+\ell^-$ anomalies, Phys. Rev.* **D97** (2018) 095035, [1712.06572].

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Beyond work, I cannot begin to describe in this short space how much I have enjoyed my time as part of Grey MCR. It has shaped me, and made these past few years some of the best of my life. It has been a pleasure and a privilege to be a part of the amazing community at Grey, both on the MCR Exec and otherwise—I hope I have, in one way or another, conveyed this to everybody I have met here. I cannot name you all, but I feel I must pick out and thank a few individually. Bear: for everything from your passing suggestion of dinner to our many hours of gaming. Darren: for the sheer joy physics inspires in you 24 hours a day, your mad banter and the many helpful conversations. Sarah: for being such an amazing friend. And Rachael: for these past 10 months.

Finally of course, my parents, for supporting me my entire life.

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