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Editorial

b-Quark physics as a precision laboratory: a collection of articles on the present status and future prospects

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The quest for a few fundamental 'building blocks' of matter is one of the oldest and far-reaching queries of mankind. But it took two thousand years to turn a largely philosophical concept into a real scientific question. Combined developments in chemistry, mathematics and physics paved the road to a qualitative understanding of the innermost structures of the world around us. They culminated in the discovery of quantum physics which opened the door to atomic scales, into the innermost structures of matter.

With ever evolving experimental and theoretical possibilities, the quest for the smallest constituents of matter revealed that, besides the three known 'particles' proton, neutron and electron, there are many more. Further on, it was realized that proton and neutron as well as the other particles are themselves composed of two or three quarks, and there are three different quarks, up, down and strange. Some of these are unstable, and therefore not necessary as building blocks, but are required to explain many experimental and theoretical findings, including the fundamental fact that the universe and our world as we see them exist.

It turned out that these new particles are grouped into 'generations', repeating the structure of the stable constituents of matter, the up and down quarks, the electron and the neutrino. Thus, these were discovered the strange quark, the muon and its neutrino, and, in 1974, the charm quark. In that year, the second generation was completed, confirming theoretical expectations and the basic structure of the quarks and leptons. In the subsequent years, the third generation, consisting of the tau and its neutrino, the b-quark, (bottom quark, 1976) and the top quark were discovered; but no further layer has been found until today, making the study of the third (and possibly last?) generation particles especially interesting. As pointed out, the existence of more than one and two generations is intimately related to several fundamental facts. Therefore, the study of these particles and their processes, often called flavor physics, is essential for our understanding of the laws underlying our world, formulated in a theoretical framework known as the Standard Model of particle physics (SM). In these efforts, the b-quark plays a central role and many important insights have resulted from these studies.

The B-hadron system, that is all particles containing a b-quark is attractive and interesting for a variety of reasons. For one, its mass of $\sim 5\,\mathrm{GeV}$ is larger than the energy scales $\sim 1\,\mathrm{GeV}$ below which Quantum Chromodynamics (QCD), the theory of strong interactions, is non-perturbative. It is thus sufficiently heavy to give rise to a new effective theory of the SM, associated with heavy quark expansion, and to allow a perturbative treatment of QCD, using renormalization group techniques and diagrammatic calculations. This makes it a reliable laboratory for comparing experiment and theory, including lattice calculations.

On the other hand, it is light enough to be produced in copious quantities at present experimental facilities. The b-quark lives sufficiently long to hadronise and to produce a large number of long lived exclusive final states when it decays. This allows to probe its properties in many complementing ways, giving a full picture of its properties. Since it decays also and predominantly into charm quarks, it is also a rich source of charm quarks.

B-physics has developed considerably over the last thirty years, and there has been a lot of progress, also on issues that looked forbidding 20 or 30 years ago. We can say today that the accuracy and consistency of results reached today are a solid basis for further dedicated work. Thus, it is a good moment to take stock of these

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achievements and offer an overview of existing and coming work. The various contributions by leading experts treat those topics where we believe progress can be made and insights gained.

The open concept of EJPST has allowed the authors to formulate their thoughts freely and with an open view of further developments. We are therefore pleased to offer this collection of articles in the European Physical Journal—Special Topics which would serve the needs of the community of elementary particle physics in both theory and experiment, from beginning graduate students to experienced researchers who are looking for a handbook and an update on the state of the art. Furthermore, the rich bibliographies will guide the reader to the literature.

We therefore believe that the articles presented are motivating for life-long experts to continue and for starting researches to enter this field of research. We are confident that this volume will assume a central place in all particle physicists library.

In the first contribution [1], Thomas Mannel gives an overview of B-physics. The role of B-physics in the overall picture is illuminated, then the experimental facilities are presented. We then learn about the special tools that have been developed by theorists to handle the strong interactions (QCD). Perturbative and non-perturbative methods are presented. In the final part, an overview of the present status and the 'to do's' are presented.

It is worth noting that in addition to CMS and ATLAS, which serve as the general-purpose LHC experiments, LHCb stands out as a significant experiment devoted to exploring the properties of the b-physics system. Its detector capabilities are specifically tailored to meet these requirements, and LHCb has already delivered numerous critical measurements, with more to come. Patrick Owens and Nicola Serra provide an insightful review [2] of the current status and future prospects of the LHCb experiment in this collection. James Libby offers a comprehensive review [3] of Physics at BELLE II, the other flagship experiment dedicated to B-physics. The clean environment of this B-factory enables results with higher precision, and this review delves into the complementary decay channels and observables as compared to LHCb.

The description of hadron decays necessitates handling the non-perturbative aspect effectively. Two complementary methods addressing this challenge are Lattice QCD and QCD sum rule techniques. J. Tobias Tsang and Michelle Dela Morte provide an overview [4] of studies on heavy quarks using lattice simulations. They summarize computations of B-meson decay constants and relevant form factors for semi-leptonic decays, along with the parametrization of bag parameters crucial for understanding mixing.

In a separate review [5], Alexander Khodjamirian, Blaženka Melić, and Yu-Ming Wang discuss QCD light-cone sum rule techniques for B-hadron decays. They explore the complementarity of approaches for calculating B- to light-meson form factors using either light-meson or B-meson distribution amplitudes. Additionally, they outline methods for addressing non-local contributions in these hadronic transitions within the light-cone sum rule framework.

The theoretical developments and challenges in exclusive decays are expertly showcased by Pilipp Böer and Thorsten Feldmann in a detailed, yet very legible overview [6]. The authors give insights into principal effects of QCD, describe the progress made in the corresponding effective theory (known as SCET) and the expected improvements.

A major aspect of B-physics is the precise determination of the CKM matrix elements. The challenges are to calculate QCD effects and to experimentally measure decay rates into a large number of final states. Two kinds of final states with their own difficulties are usually distinguished, inclusive and exclusive final states. In an authoritative review [7], Matteo Fael, Markus Prim and Keri Vos give a detailed overview of the methods used to extract the matrix elements V_{ub} and V_{cb} from inclusive semileptonic decays. The underlying heavy quark expansion as well a the various experimental issues are well described and the prospects for further refinements presented. On the other hand, the extraction from exclusive decays is described by Florian Bernlochner, Markus Prim and Keri Vos in equally comprehensive manner [8]. Various exclusive decays are considered and the results compared, giving much insight into the various hurdles that had to be overcome.

The lifetimes and mixing parameters of the various B-mesons are basic quantities for precision studies of b-quark. Johannes Albrecht, Florian Bernlochner, Alexander Lenz and Aleksey Rusov give an authoritative overview [9] on the very many issues to be considered. It is impressive to follow the tremendous progress made and to appreciate the challenges ahead.

The topic of CP violation is discussed by Robert Fleischer [10]. He shows that the B-system offers an ideal environment for the study of CP violation, and indeed the most significant tests have been performed there. The Experimental and theoretical methods and their interplay are explained in great detail and further refinements are discussed, and a wealth of future tests are presented.

Joaquium Matias, Andreas Crivellin, and Bernat Capdevila provide a comprehensive review [11] of semileptonic B-anomalies. These anomalies have been a focal point for discussions regarding potential deviations from the SM predictions in specific final states, and for investigating the possibility of violations of fundamental principles such as lepton universality. The experimental landscape was uncertain until recently, but new analyses from LHCb and BELLE have brought clarity to the situation. While it is disappointing that many anomalies have vanished, this review presents a cohesive overview from combined effective theory fits to all conceivable low-energy operators, illustrating the potential for beyond the SM physics.

The fourth major experiment at LHC is the ALICE experiment, primarily focused on heavy-ion collisions. Its main objective is to investigate the properties of matter under extremely high densities and temperatures, aiming to replicate conditions akin to those during the Big Bang. The review [12] by Vinod Chandra and Santosh K. Das delves into B-meson systems within the context of hot QCD environments, which serve as invaluable probes for understanding the intricacies of this complex system.

The Charm quark offers a complementary approach to fundamental physics and, with its mass of around 1.2 GeV, an interesting, although difficult system to study QCD. In his contribution, Alexey Petrov gives a fascinating overview [13] of the studies possible with charm quarks.

The authors have taken pains to explain in an accessible manner all aspects of their subject and we express our gratitude to every one of them, as well as to the publishers and the production teams and members of the editorial teams, especially to Sandrine Karpe at EDP Sciences and Sabine Lehr at Springer Verlag.

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