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Heavy-quark physics

Recent developments and old problems

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Abstract. Recent advances as well as some problems in physics of bottom and top quarks are discussed.

PACS. 12.39.-x Phenomenological quark models – 13.20.-v Leptonic, semileptonic, and radiative decays of mesons – 13.30.-a Decays of baryons – 13.60.Rj Baryon production

1 Introduction

There are multiple reasons for studying physics of heavy quarks: to probe our theoretical understanding of QCD, extract fundamental quantities like quark masses and CKM mixing matrix; search for New Physics. During last few years a tremendous progress in both experimental and theoretical studies of heavy-flavor dynamics has been achieved. B-meson physics is now the most intensively studied part of the high-energy particle physics. In particular the CKM paradigm has been successfully tested and nearly established; see, *e.g.*, [1]. This development is accompanied by an impressive progress in theoretical methods including applications of effective theories in heavy-flavor physics. In this short review some recent advances are briefly reviewed as well as some problems which still remain unsolved.

2 Old and new problems in B physics

B physics is an ideal place to check our understanding of QCD. Both exclusive and inclusive B decays have been studied. Recently CP violation and rare decays attract particular attention because theoretical predictions can soon be tested by experiments at B factories. Combining experimental input from different decay channels experimentalist can perform multidimensional fits and extract not only fundamental parameters like b-quark mass and the strong-coupling constant α_s but also phenomenological parameters of the Heavy Quark Effective Theory or Heavy Quark Expansion which describe non-perturbative aspects of QCD for inclusive and exclusive decays, respectively. An example of this strategy is presented in ref. [2] where by combining the information from $b \to s\gamma$ and inclusive semileptonic B decays a fairly precise determination of V_{ub} has been obtained. With higher statistics a further significant reduction of experimental errors is expected. At this point accuracy will be limited by perturbative QCD calculations which for differential distributions in semileptonic B decays have been done only at the lowest non-trivial order [3]. Moreover, there are also some data which cannot be explained by present-day theory in a convincing way: semileptonic branching ratios for B-mesons are smaller than expected, the ratio of the lifetimes for the Λ_{B}-baryon and B-meson is much smaller than predicted, and the bottom production cross-section measured at Tevatron, HERA and LEP is about a factor of three larger than QCD calculations predict. It is possible that these problems reflect contributions of some New Physics. A light gluino and a $\tilde{b}$-squark may explain the high value of the bottom production cross-section [4]. However, much less spectacular options are also possible [5] implying that our present understanding of QCD is not as good as believed.

3 Top quark pair production

Studies of top quark pair production will be an important part of the physics program at future linear e^+e^- colliders [6,7]. A Linear Collider (LC) operating at energies close to the $t\bar{t}$ threshold is an ideal machine to study the properties of the top quark. Prospects that the LC will be built during this decade stimulate growing interest in the precise theoretical description of this reaction. The large top quark width $\Gamma_t \sim 1.5$ GeV [8] makes the threshold cross-section look quite different from those for charmonium and bottomium production. As first observed by Fadin and Khoze [9] the excitation curve for top pairs is smooth due to smearing of overlapping topponium resonances. They showed also that thanks to the large top

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width this curve is not sensitive to large distance effects in QCD and allows for a precise determination of important short-distance parameters like the strong-coupling constant α_s, and top quark mass m_t and width Γ_t. This leading order (LO) results were extended to the next-to-leading order (NLO) in [10]. Furthermore in [11] and [12] some differential distributions, including the momentum distribution of top quarks, were calculated with NLO accuracy in momentum and position space, respectively. It should be mentioned that, although these numerical calculations are in perfect agreement, in QCD the transition between the momentum and the position space is highly non-trivial and in fact in higher orders it introduces renormalon ambiguities related to asymptotic characters of the corresponding series [13]. In the threshold region ($\sqrt{s} \approx 2m_t$) both t and $\bar{t}$ move with non-relativistic velocities $\beta \sim \alpha_s$. In this region an approach based on pure α_s expansion is not useful at all. Instead one considers the following expansion for the cross-section:

$$\sigma_{t\bar{t}} \sim \sum_k c_k \left(\frac{\alpha_s}{\beta}\right)^k \left[1 + \{\alpha_s, \beta\} \left\{\alpha_s^2, \alpha_s\beta, \beta^2\right\} + \dots\right]. \tag{1}$$

In the above expression the terms in the square bracket correspond to the LO and NLO approximations, respectively. At the end of the nineties even the next–to–next-to-leading order (NLLO) results were computed independently by a few groups, see [14] and the original papers cited therein. It was very disappointing when rather large uncertainties were observed at NNLO in the normalization of $\sigma_{t\bar{t}}$. However, recently an even more ambitious calculation has been accomplished by Hoang, Manohar, Stewart and Teubner, see [15,16] for recent reviews. Using renormalization group equations they have also performed additional resummation of terms proportional to $(\alpha_s \log \beta)^j$. In this way theoretical uncertainties in the normalization of the total cross-section $\sigma_{t\bar{t}}$ have been reduced to the level of few percent. This paves the way to precision studies of top quark pair production near threshold at a future linear collider [17]. It has been also shown that e^+e^- annihilation near the top quark production threshold is an ideal place for studies of top quark polarization and spin-dependent interactions [18]. Unfortunately, even at the NNLO level neither calculations of top quark polarization nor of its momentum distribution have been performed.

Top quark production and decay will be also studied at hadron colliders. High-statistic data samples from Run II of the Tevatron collider and the LHC will make possible detailed investigations of the electroweak and strong interactions of top quarks. On the theory side NLO QCD calculations for hadronic production and decay have been recently completed by Bernreuther *et al.*, see [19] and references therein.

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