PROCEEDINGS OF SCIENCE

Studies of the CKM matrix elements and b-hadron production using semileptonic decays at LHCb

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Exclusive semileptonic b-hadron decays are under good theoretical control, which allows precise determinations of the CKM matrix elements, V_{ub} and V_{cb}. The large production of Λ_b baryons and B_s mesons at the LHC allows LHCb to provide complementary information with respect to the B-factories in this sector, as well as in the measurement of the shape of the Λ_b differential decay rates. Novel experimental techniques are used to measure the fraction of semileptonic B^+ to charm meson decays, in order to improve the understanding of the inclusive charm semileptonic rate and the background description for analyses exploiting exclusive $b \to c$ and $b \to u$ transitions. The latest LHCb results on CKM matrix element determination and related measurements and searches are presented.

The 39th International Conference on High Energy Physics (ICHEP2018)
4-11 July, 2018
Seoul, Korea

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1. Introduction

Semileptonic decays of heavy flavoured hadrons are commonly used to measure CKM parameters. Also, they are used to minimise the uncertainties arising from the interaction of the strong force, described by quantum chromodynamics (QCD), between the final state quarks. At LHCb the momentum of the b-hadrons cannot be directly measured and thus the invariant mass of the hadrons is not known. Hence, different techniques have been developed to access it. The most used ones are the corrected mass which is defined as $m_{\mathrm{corr}} = \sqrt{m_{vis}^2 + p_\perp^2} + p_\perp$ where m_{vis} is the visible mass of the reconstructed particles and $p_\perp$ is the momentum of the visible candidate transverse to the b-hadron flight direction. Besides, the momentum of the b-hadron can be approximated as $p_z(B) \simeq (m_B/m_{\mathrm{vis}})p_z(\mathrm{vis})$. In the following analyses, these techniques have been used to reconstruct the signal candidates allowing to access the invariant mass of the lepton-neutrino system, q^2, with a two-fold ambiguity.

2. Measurement of V_{ub} from $\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu$

The magnitude of V_{ub} can be measured via the semileptonic quark-level transition $b \to ul\nu_l$. The ratio $|V_{ub}|^2/|V_{cb}|^2$ can be determined according to

$$\frac{|V_{ub}|^2}{|V_{cb}|^2} = \frac{\mathscr{B}(\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu)}{\mathscr{B}(\Lambda_b^0 \to \Lambda_c^+\mu^-\overline{\nu}_\mu)} R_{\mathrm{FF}}$$

where $\mathscr{B}$ denotes the branching fraction and R_{FF} is a ratio of the relevant form factors calculated using LQCD [1]. This is then converted into a measurement of $|V_{ub}|$ using the existing measurements of $|V_{cb}|$ obtained from exclusive decays. The normalisation to the $\Lambda_b^0 \to \Lambda_c^+\mu^-\overline{\nu}_\mu$ decay cancels many experimental uncertainties, including the uncertainty on the total production rate of Λ_b^0 baryons. The LQCD form factors are most precise where q^2 is high. To avoid influence on the measurement by the large uncertainty in form factors at low q^2, both solutions are required to exceed $15\,\mathrm{GeV}^2/c^4$ for the $\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu$ decay and $7\,\mathrm{GeV}^2/c^4$ for the $\Lambda_b^0 \to \Lambda_c^+\mu^-\overline{\nu}_\mu$ decay. From the ratio of yields and their determined efficiencies, the ratio of branching fractions of $\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu$ to $\Lambda_b^0 \to \Lambda_c^+\mu^-\overline{\nu}_\mu$ in the selected q^2 regions is

$$\frac{\mathscr{B}(\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu)}{\mathscr{B}(\Lambda_b^0 \to \Lambda_c^+\mu^-\overline{\nu}_\mu)} = (1.00 \pm 0.04 \pm 0.08) \times 10^{-2},$$

where the first uncertainty is statistical and the second is systematic. Using the value $R_{\mathrm{FF}} = 0.68 \pm 0.07$ [1], the measurement $|V_{ub}|/|V_{cb}| = 0.083 \pm 0.004 \pm 0.004$ is obtained which yields $|V_{ub}| = (3.27 \pm 0.15 \pm 0.16 \pm 0.06) \times 10^{-3}$ [2] after using the exclusive value of $|V_{cb}|$ [3]. The measurement is in agreement with the exclusively measured world average [4], but disagrees with the inclusive measurement at a significance level of 3.5 standard deviations.

3. Measurement of $\Lambda_b \to \Lambda_c$ form factors

The decay $\Lambda_b^0 \to \Lambda_c^+\mu^-\overline{\nu}_\mu$ is described by six form factors corresponding to the vector and axial-vector components of the flavour-changing charged current [5]. In HQET, Λ_b^0 decays are particularly simple, as the light ud quark pair has total spin j=0, and thus the chromomagnetic corrections are not present [6]. In the static approximation of infinite heavy-quark masses, the six form factors characterizing the decay $\Lambda_b^0 \to \Lambda_c^+ \mu^- \overline{\nu}_\mu$ can be expressed in terms of the Isgur-Wise function $\xi_B(w)$ [7]. This function cannot be determined from first principles in HQET, but calculations based on a variety of approaches exist. In particular, in the kinematic limit $w = 1$ only modest corrections in the $(1/m_b,\ 1/m_c)$ expansion are expected, due to the absence of hyperfine corrections [1]. Thus, $\xi_B(w)$ can be expressed as a Taylor series expansion $\xi_B(w) = 1 - \rho^2(w-1) + \frac{1}{2}\sigma^2(w-1)^2 + \ldots$ where ρ^2 is the magnitude of the slope of $\xi_B(w)$ and σ^2 is its curvature at $w = 1$.

The value of ρ^2 measured by LHCb from the Taylor series expansion is $\rho^2 = 1.63 \pm 0.07 \pm 0.08$ [8], where the first uncertainty is statistical and the second systematic. This value is consistent with previous measurements, lattice calculations, QCD sum rules, and relativistic quark model expectations. The measured slope is compatible with theoretical predictions and with the bound $\rho^2 \geq 3/4$.

4. Relative branching fractions in $B^- \to D^0/D^*/D^{**}\mu^-\overline{\nu}_\mu$ decays

The composition of the inclusive $b \to c$ semileptonic rate is not fully understood. Measurements of the exclusive branching fractions for $B \to Dl\nu$ and $B \to D^*l\nu$ and corresponding decays with up to two additional charged pions [4] do not saturate the total $b \to c$ semileptonic rate as determined from analysis of the charged lepton's kinematic moments. One way to resolve the gap is to make measurements of relative rates between different charm final states.

The contribution of excites states to the total semileptonic rate can be studied using B decays in which its momentum is known. By tagging B^- mesons produced from the decay of excited B_{s2}^{*0} mesons, the B^- energy can be determined up to a quadratic ambiguity using the B_{s2}^{*0} and B^- decay vertices and by imposing mass constraints for the B^- and B_{s2}^{*0} mesons. The relative branching fractions of B^- to D^0, D^{*0}, and D^{**0} are determined in the $B^- \to D^0 X \mu^- \overline{\nu}_\mu$ channel by fitting the distribution of the missing mass for $B_{s2}^{*0} \to B^- K^+$ candidate.

The resulting measured fractions are $f_{D^0} = \mathscr{B}(B^- \to D^0\mu^-\overline{\nu}_\mu)/\mathscr{B}(B^- \to D^0 X \mu^- \overline{\nu}_\mu) = 0.25 \pm 0.06$ and $f_{D^{**0}} = \mathscr{B}(B^- \to D^{**0}\mu^-\overline{\nu}_\mu)/\mathscr{B}(B^- \to D^0 X \mu^- \overline{\nu}_\mu) = 0.21 \pm 0.07$, where the uncertainty is the total due to statistical and systematic uncertainties [10]. The fraction of $B^- \to D^{*0}\mu^-\overline{\nu}_\mu$ is equal to $1 - f_{D^0} - f_{D^{**0}} = 0.54 \pm 0.07$, but this cannot be taken as an independent determination.

5. Lifetimes of B_s, D_s and Ω_c hadrons

Comparisons of precise measurements and predictions associated with quark-flavour dynamics probe the existence of unknown particles at energies much higher than those directly accessible at particle colliders. The precision of the predictions is often limited by the strong-interaction theory at low energies, where calculations are intractable. Predictive power is recovered by resorting to effective models such as heavy-quark expansion [11] which rely on an expansion of the QCD corrections in powers of $1/m$, where m is the mass of the heavy quark in a bound system of a heavy quark and a light quark. These predictions are validated and refined using lifetime measurements of heavy hadrons. Measurements of the "flavour-specific" B_s^0 meson lifetime, $\tau_{B_s^0}^{\mathrm{fs}}$ allow an indirect determination of the width difference that can be compared with direct determinations in tests for non-standard model physics. Using $B_s^0 \to D_s^{(*)-}\mu^+\nu_\mu X$ decays, the lifetime can be determined from the variation in the B_s^0 signal yield as a function of decay time, relative to that of B^0 decays that are reconstructed in the same final state and whose lifetime is precisely known. By doing so, a significant improved determination of the B_s^0 and D_s^- lifetimes can be obtained yielding [12],

$$\tau^{\rm fs}_{B_s^0} = 1.547 \pm 0.013({\rm stat}) \pm 0.010({\rm syst}) \pm 0.004(\tau_{\rm B})\,{\rm ps}$$
$$\tau^{\rm fs}_{D_s^-} = 0.5064 \pm 0.0030({\rm stat}) \pm 0.0017({\rm syst}) \pm 0.0017(\tau_{\rm D})\,{\rm ps}$$

which are consistent with, and significantly more precise than the current values. The last uncertainties arise from the limited knowledge of the B^0 and D^- lifetimes, respectively.

As m_c is significantly smaller than m_b, higher order corrections can be sizable for charm hadrons. Improved measurements of the charm baryon lifetimes provide complementary information to what can be gleaned from charm mesons. Using $\Omega_b^- \to \Omega_c^0\mu^-\overline{\nu}_\mu X$ decays the Ω_c^0 lifetime is measured to be $\tau_{\Omega_c^0} = 268 \pm 24 \pm 10 \pm 2\,$fs [13] which is about four times larger than, and inconsistent with the world average value of $69 \pm 12\,$fs [3].

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