PROCEEDINGS OF SCIENCE

Review of semileptonic b-hadron decays excluding the $|V_{\mathrm{xb}}|$ and $R(D^{(*)})$ measurements

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A review of other semileptonic b-hadron decays that are not related to $R(D^{(*)})$ and $|V_{\mathrm{xb}}|$ anomalies are presented. A couple of long-standing puzzles in $B \to D^{**}\ell\nu$ decays are revisited and potential issues and advantages of studying B^0_s and Λ^0_b semileptonic decays are discussed.

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1. Introduction

Although the majority of attention in semileptonic b-hadron decays is currently devoted to understanding the $R(D^{(*)})$ and $|V_{\rm xb}|$ anomalies, there are several reasons to study semileptonic decays beyond the traditional channels. For example, decays such as $B \to D^{**}\ell\nu$ have their own long-standing puzzles, which challenge our understanding of non-perturbative QCD. These decays also form important backgrounds for the $R(D^*)$ analysis, and so it is desirable to improve our knowledge if we are to be absolutely confident of any possible signal from beyond the Standard Model.

Another important avenue to pursue is other b-hadron species. Relatively little is known about B_s^0 and Λ_b^0 semileptonic decays. Studying these decays is interesting as they are sensitive to different hadronic form factors compared to the traditional $B \to D^{(*)}$ measurements. It is also an important pre-cursory step for testing lepton universality and CKM element determination, where agreement in several b-hadron species will bring the ultimate confidence in these controversial measurements.

2. Measurements of $B \to D^{**}\ell\nu$ decays

Around 70% of the inclusive $B \to X_c\ell\nu$ branching fraction, where X_c represents any charmed hadron, is comprised of the ground and first excited states. The remaining 30% is denoted $B \to D^{**}\ell\nu$. Knowledge of $B \to D^{**}\ell\nu$ decays is mostly limited to the four p-wave states, depicted in Fig. 1 from Ref. [3]. The analyses from Belle [1] and BaBar [2], which combined one additional pion to the ground and first excited states revealed a couple of interesting anomalies. The first is the fact the $B \to D^{**} \to D^{(*)}\pi\ell\nu$ branching fraction is composed of approximately equal contributions from the $j_q = 1/2$ and $j_q = 3/2$ states, where j_q is the spin of light quark of the D^{**} meson. This is unexpected as theoretically one would expect the $j_q = 1/2$ states to be suppressed. This anomaly merits more precise measurement of the

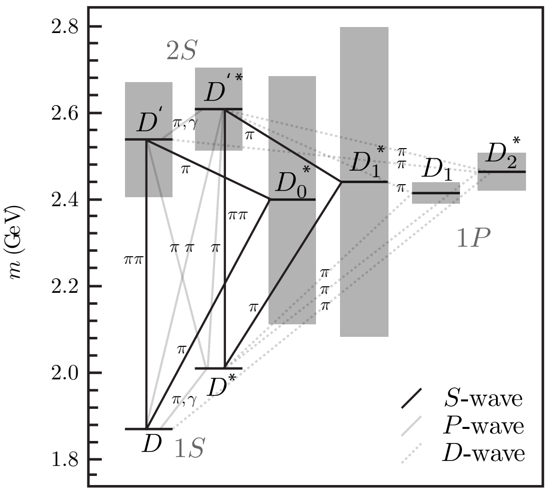

Figure 1: Spectra of charmed mesons, showing the decays into the ground and excited states with additional pions. From Ref. [].

The second puzzle is that the $B \to D^{**} \to D^{(*)}\pi\ell\nu$ branching fraction measurements did not saturate the inclusive $B \to X_c\ell\nu$ rate. This has been alleviated somewhat by a recent BaBar measurement [6] of $B \to (D^{**} \to D^{(*)}\pi\pi)\ell\nu$ rate, but still remains at the 2-3σ level as seen in Fig. 2. This is in contrast to the situation with the tauonic channels, also shown in Fig 2, where the branching fractions of $B \to D^{(*)}\tau\nu$ saturate the inclusive $B \to X_c\tau\nu$ rate measured at LEP. This should be resolved if one is to be completely free of doubt regarding the enhancement seen in $B \to D^{(*)}\tau\nu$. Prospects for improving the understanding in this area include searching for the decay $B \to (D^{**} \to D^{(*)}\eta)\ell\nu$, which is difficult due to the neutral final state. The $B \to (D^{**} \to D^{(*)}\pi)\ell\nu$ $B \to (D^{**} \to D^{(*)}\pi\pi)\ell\nu$ decay channels can also be studied further, with prospects of measuring $R(D^{**})$ for the narrow states [9].

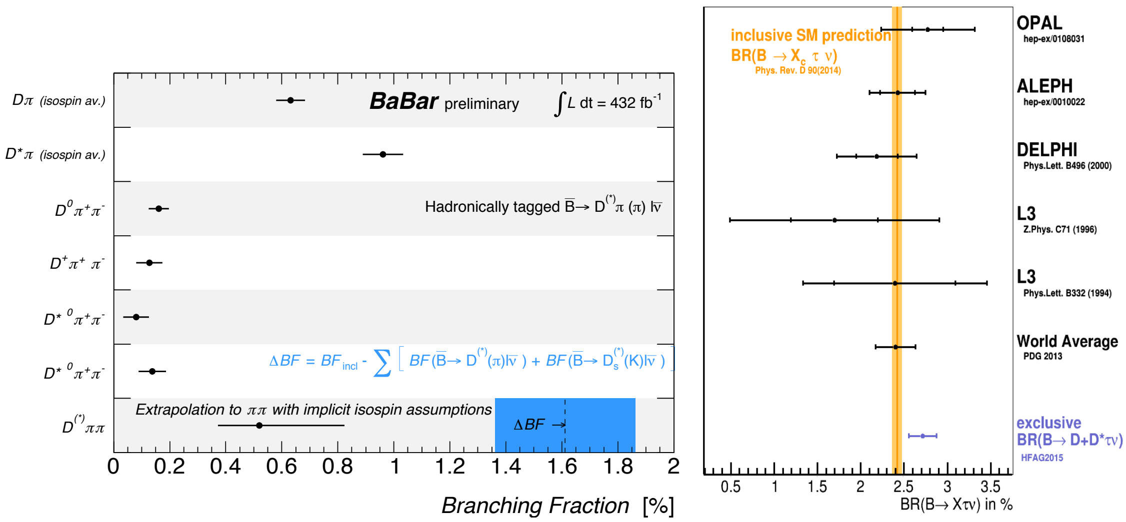

Figure 2: Comparison of the sum of exclusive branching fractions with the inclusive measurements for $B \to X_c\ell\nu$ decays (left) from Ref. [7] and $B \to X_c\tau\nu$ from Ref. [8].

3. Possibilities with other b-hadron species

In addition to refining measurements of $B \to D^{(*)}$ transitions, studies of semileptonic B_s^0, Λ_b^0 and B_c^+ decays are vital to confirm and understanding the existing anomalies. The B_s^0 system is interesting for a few of reasons. Firstly, due to the fact that the D_s^{*+} meson decays only into $D_s^+\gamma$, only two helicity states are available. This makes the form factor measurement somewhat different to the $B \to D^{(*)}$ case. Another interesting feature of B_s^0 sector is that the $j_q = 1/2\ D^{**+}$ states are narrow, which is the opposite of the situation in the $B \to D^{**}$ case. Perhaps studies $B_s^0 \to D_s^{**+}$ transitions could help shed light on the $1/2$ vs $2/3$ puzzle. Finally, lattice calculations are generally more precise than in B^0 and B^+ decays due to the larger mass of the s-quark, see for example Ref. [10] for a comparison between the $B \to \pi$ and $B_s^0 \to K$ form factors.

Experimental knowledge of B_s^0 is rather limited, with the most precise measurement from the Belle experiment [11]. With its large B_s^0 sample, the LHCb experiment could be expected to contribute here. The decay signature of $D_s^+\gamma$ might be an interesting signature theoretically but it is quite tricky to deal with experimentally. The photon from the D_s^{*+} will be very soft as the decay is

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close to kinematic threshold which means that the corrected mass technique used in LHCb [12] is difficult to employ as there will be little discrimination between the ground and first excited states. There are possible solutions however, such as the technique described in Ref. [13], which could help for form-factor measurements. The measurement will clearly be a challenge but owing huge LHC cross-section, LHCb has the potential to make some precise measurements in this area.

Another possible avenue is measurements of semileptonic Λ_b^0 decays. As its a fermion transition, the form factors are different to the mesonic channels and measurements are highly anticipated. Theoretically, baryonic form factors are more difficult to calculate compared to mesonic case. However, precise results for the ground state have been reported in [14], which pave the way for future lattice calculations and measurements. In addition to this, a couple of interesting differences to the mesonic case can help with possible lepton universality tests. The first is that the ground state channel $\Lambda_b^0 \to \Lambda_c^0 \mu \nu$ accounts for about 60% of the inclusive semileptonic rate [8], which is over twice as much as $B \to D\mu\nu$ decays for example. This means that feed-down background from excited states such as Λ_c^{*+} are smaller which is useful for a potential measurement of $R(\Lambda_c^+)$. Another difference is that the Λ_c^{*+} decays into two pions rather than a single pion due to isospin conservation. This helps improve the kinematic reconstruction of the excited states, which increases discrimination with the ground state and allows a more precise measurement of the τ lifetime. Baryon number conservation also reduces the possible combinations to form backgrounds. The Λ_b^0 baryons are therefore expected to play an important role in future semileptonic observables due to the differences in the theoretical and experimental situation compared to the mesonic channels.

4. Conclusion

In summary, measurements outside the traditional $B \to D^{(*)}\ell\nu$ channels will become increasingly more important to complete the picture of semileptonic field. Improvements to $B \to D^{**}\ell\nu$ measurements will be important to solve some puzzles which (rightly or wrongly) cast doubt over the observed enhancement in $B \to D^{(*)}\tau\nu$. Measurements of other b-hadrons have the potential to provide lepton universality and CKM element measurements with complementary theoretical and experimental uncertainties. This would provide confidence that the theoretical and experimental systematic uncertainties are under control for these challenging and controversial measurements.

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