Study of $B \to D^{**}\ell\nu_\ell$ decays with semi-leptonic tagging at Belle II

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Semileptonic decays of B mesons provide a crucial testing ground for the interplay between weak and strong interactions, offering valuable input for determining fundamental parameters such as CKM matrix elements. In particular, decays of the type $B \to D^{**}\ell\nu$, where D^{**} denotes an orbitally excited charm meson, are essential for understanding the dynamics of heavy-quark transitions and the structure of the hadronic final state.

A key challenge in studying these transitions is modelling the hadronic matrix elements that govern the decay amplitudes. The BLR (Bernlochner, Ligeti and Robinson) model [1] has been developed to describe the form factors associated with semileptonic $B \to D^{**}\ell\nu$ decays. These form factors are usually based on the assumption of narrow-width D^{**} states, which simplifies the theoretical treatment but does not reflect the complex nature of the broad excited states.

In simulation tools such as EvtGen [2], the D^{**} states are commonly treated as Breit-Wigner resonances, with their nominal masses and widths taken from the Particle Data Group (PDG) [3]. While this approach is relatively robust for narrow states, it becomes increasingly problematic for broad resonances such as the $D_0^*(2300)$ and $D_1'(2430)$. Using a Breit-Wigner form to describe these broad states can lead to biased signal yields when fitting invariant mass distributions, potentially misidentifying or misquantifying the contributions from individual resonances.

Recent theoretical efforts have highlighted the limitations of the narrow-width approximations and Breit-Wigner parameterisation. For example, extensions of Heavy Quark Effective Theory (HQET) aim to generalize the form factor description beyond the narrow-width limit [4], and alternative approaches such as the extended Boyd-Grinstein-Lebed (BGL) parameterisation offer more flexibility in modeling the dynamics of broad states [5]. Moreover, studies of the $D\pi$ phase motion suggest that the broad D^{**} states are not well modeled by simple resonances. The structure identified as the $D_0^*(2300)$, for example, appears to be dynamically generated by two poles far from the real axis, as shown in unitarized chiral perturbation theory (UChPT) [6, 7]. These findings challenge the conventional picture of such states as pure $q\bar{q}$ mesons.

In light of these challenges, a more model-independent strategy is desirable from the experimental perspective. The most robust approach involves extracting background-subtracted invariant mass spectra of the $D^{(*)}\pi$ system without imposing strong assumptions about the signal composition. This allows for flexible post-hoc modeling of the underlying amplitudes, enabling fits to the $M(D^{(*)}\pi)$ distributions using arbitrary models. From such fits, it is then possible to derive event by event weights and systematically disentangle the individual contributions from different D^{**} states. This data-driven strategy provides a path to more accurate determinations of signal yields, branching fractions, and a deeper understanding of the nature of excited charm mesons.

My work performs a first feasibility study of the semileptonic decays $B \to D^{**}\ell\nu$ at Belle II using two different reconstruction strategies: an untagged approach and a semileptonic (SL) tagged approach. The Belle II experiment operates at the center-of-mass energy corresponding to the $\Upsilon(4S)$ resonance ($\sqrt{s} \approx 10.58$ GeV). The decay of a $\Upsilon(4S)$ resonance produces a pair of B-mesons. While one B-meson decays into the mode of interest (denoted as B_{sig}), the second B-meson, referred to as B_{tag}, can be treated using different tagging strategies. In exclusive tagging, the B_{tag} is first fully reconstructed in hadronic or semileptonic decay modes. Using the known initial state and the reconstructed tag-side kinematics, one can then infer essential properties of the signal-side B meson, such as its charge, flavour, and momentum, thereby enabling a more constrained and precise analysis of the signal decay.

- **Untagged:** The B_{tag} is not explicitly reconstructed. Instead, the signal-side B (B_{sig}) is reconstructed first, and the rest of the event (ROE) is interpreted as the B_{tag}. This approach retains the highest efficiency, as it implicitly includes all possible decay modes of the tag-side B without applying stringent constraints on its reconstruction.
- **Semileptonic tag (SL tag):** The B_{tag} is reconstructed in a semileptonic decay mode. While this provides partial information about the event, the presence of neutrinos leads to missing energy and incomplete reconstruction.
- **Hadronic tag:** The B_{tag} is reconstructed in fully hadronic decay modes. Although this approach has lower efficiency due to the small branching fractions of hadronic decays, it allows for complete reconstruction of the tag-side B meson. This is particularly useful when the signal B decays to final states with invisible particles, such as neutrinos, as it enables indirect access to the full event information.

The goal is to evaluate the sensitivity and practical challenges associated with these methods, as well as to establish whether a full measurement effort based on these channels is promising. This study is performed using Monte Carlo (MC) simulations only.

The untagged analysis reconstructs only the signal side and suffers from a high background contribution with significant cross-feed from the tag side, making this approach not feasible in the scope of a master thesis.
Subsequently, we focus on the SL tagged approach. This method benefits from better kinematic constraints and background suppression. Following the event selection, the signal extraction is performed using the sPlot technique. Since this method requires a discriminating variable that is statistically independent of the observables of interest, we train a second BDT

with variables uncorrelated to $M(D^{(*)}\pi)$, q^2, and $\cos\theta_V$. The output BDT score is then used as the discriminating variable in the fit. As a final step, we explore corrections for detector and reconstruction effects. Migration matrices are constructed to unfold detector smearing effects, including inter-mode migrations between $D\pi$ and $D^*\pi$ final states. This study, demonstrates the potential of SL tagged analyses at Belle II and identifies the main areas where further work is needed. The results provide a foundation for continued development of a full measurement strategy for $B \to D^{**}\ell\nu$ decays.

References

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