Search for the decay $B \to D^{(*)}\eta\pi$ in Belle and Belle II

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Abstract. We present a search for the yet-unobserved $B \to D^{(*)}\eta\pi$ decay at Belle and Belle II. This search aims to provide insights into the semileptonic gap, which refers to the deficit in the sum of the branching fractions of known exclusive decays compared to the measured inclusive $b \to c\ell\nu$ branching fraction. Common models addressing this deficit suggest the existence of $B \to D^{(*)}\eta\ell\nu$ decays with a branching fraction of 4×10^{-3}, which could imply a branching fraction of $B \to D^{(*)}\eta\pi$ around 2×10^{-4} based on a naive prediction derived from the ratio of branching fractions of $B \to D^{(*)}\pi$ and $B \to D^{(*)}\ell\nu$. Utilizing the ~1.1 ab^{-1} of data collected at Belle and Belle II combined, we are initiating a preliminary search to investigate and potentially observe this decay for the first time. This search is also expected to significantly enhance our understanding of the B hadronic sector.

Keywords: Experimental high energy physics, B physics, Belle II experiment, Semi-leptonic Gap

1 Introduction

Hadronic B decays account for approximately 25% of the total B meson branching fraction, yet much of this sector remains unexplored, with only about 50% of the decays currently known. At Belle and Belle II [1], we rely heavily on PYTHIA [2] simulations to model decays that have not yet been observed. For instance, PYTHIA simulations predict a significant branching fraction for the decay $B \to D^{(*)}\eta\pi$, of the order of 10^{-3}. This search holds potential for shedding light on the "semi-leptonic gap" [3] which is the deficit between the inclusive and exclusive branching fractions in the $b \to c\ell\nu$ transition and also observing the decay for the first time. Common models addressing this deficit suggest the existence of $B \to D^{(*)}\eta\ell\nu$ decays with a branching fraction of 4×10^{-3}, which could imply a branching fraction of $B \to D^{(*)}\eta\pi$ around 2×10^{-4} based on a naive prediction derived from the ratio of branching fractions of $B \to D^{(*)}\pi$ and $B \to D^{(*)}\ell\nu$. If this decay is found to have a large branching fraction as observed in MC, it could be incorporated into B-tagging algorithms to enhance tagging efficiency. We perform this search using approximately 1.1 ab^{-1} of data collected by Belle and Belle II at the SuperKEKB [1] e^+e^- energy asymmetry collider.

2 Analysis - selection and strategy

Event selection involves particle identification, track impact parameter cuts, and invariant mass criteria for intermediate particles, aiming to optimize statistical sensitivity. A D^0 meson candidate is formed from a kaon and pion and also through a kaon and three charged pions, which is then combined with a slow pion to construct a D^* candidate. An η meson candidate, selected in the clean two-photon decay mode, is combined with D^* and a pion to reconstruct a B meson candidate.

Signal properties are studied using dedicated Monte Carlo (MC) samples of signal decays and generic MC samples from $e^+ - e^-$ collisions, which help identify dominant backgrounds and critical observables for suppression. A D_s veto addresses peaking backgrounds from $B \to D^{(*)} D_s^+ (\to \eta\pi^+)$, and these vetoed events used as one of the control sample. An additional high-statistics control sample from $B \to D^{(*)} \rho^+ (\to \pi^+\pi^0)$ strengthens our analysis.

We evaluate different resonant modes where the $D^{(*)}$ and η originate from D^{**} or $D^{(*)}(2S)$ states, and where η and π come from an a_0 state, in addition to the non-resonant mode. Signal efficiency is calculated separately for each mode. To distinguish these resonant modes, we use the angular variables $\cos\theta_{\eta\pi}$ and $\cos\theta_{D^{(*)}\eta}$ where $\cos\theta_{\eta\pi}$ is the cosine of the helicity angle of η in $\eta\pi$ rest frame and $\cos\theta_{D^{(*)}\eta}$ is the cosine of the helicity angle of η in $D^{(*)}\eta$ rest frame. Figure 1 displays these angular variables across modes, along with their data-MC agreement, using the $B \to D^{(*)} D_s$ control sample. We perform a combined simultaneous fit of four categories : $D \to K3\pi$ and $D \to K\pi$ in Belle and Belle II samples. We proceed to calculate the branching fraction (BF), or the corresponding upper limit (UL) on the BF at 90% confidence level (CL) for the case where an actual signal is not observed. The simultaneous fit for four categories of $B \to D^* \eta\pi^+$ in MC and the same for $B \to D^* D_s^+$ in data are shown in Figure 2. The BF is measured as,

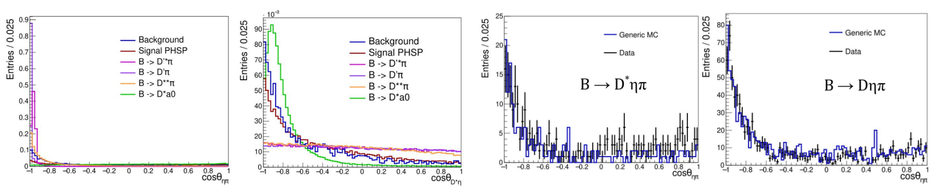

Fig. 1. $\cos\theta_{\eta\pi}$ and $\cos\theta_{D^{(*)}\eta}$ distribution in MC and data-MC distribution of $\cos\theta_{\eta\pi}$ in $B \to D^{(*)} D_s$.

$$BF = \frac{N_{sig}}{\epsilon \times N_{B\bar{B}} \times BF(inter) \times 2 f_{00}}$$

where $N_{B\bar{B}}$ is the number of $B\bar{B}$ pairs in the data sample, f_{00} is the fraction of neutral B mesons, ϵ is the signal efficiency, BF(inter) is the product of the

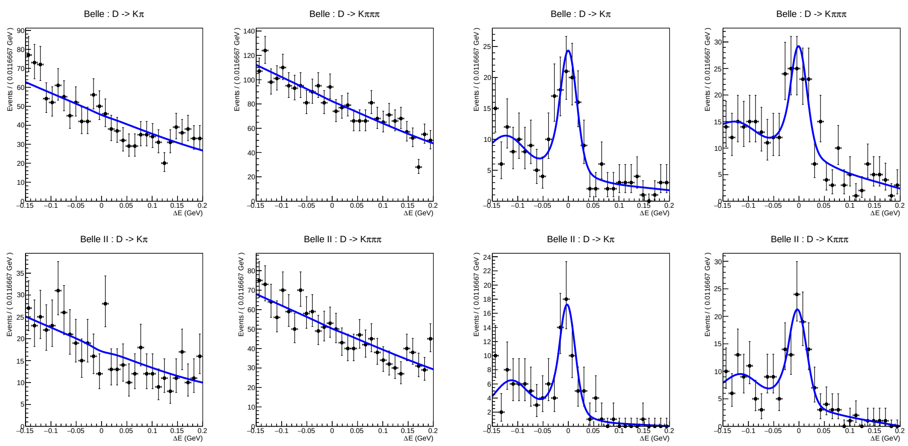

Fig. 2. Simultaneous fit distribution of ΔE assuming no signal in MC for $B \to D^{*}\eta\pi$ (left) and $B \to D^{*}D_{s}$ control sample in data (right).

BFs of the intermediate decays of the reconstruction chain. The same formula with N_{sig} replaced with N_{sig} at 90% CL is used for the UL calculation with no signal assumption. Our limit with phase space (non-resonant) efficiency is $6(2.7) \times 10^{-5}$ for $B \to D\eta\pi$ ($B \to D^{*}\eta\pi$) which is lower by an order of magnitude than expected. We obtain the BF for $B \to DD_{s}$ and $B \to D^{*}D_{s}$ in data as $(1.55 \pm 0.12) \times 10^{-4}$ and $(1.66 \pm 0.14) \times 10^{-4}$ respectively, which is compatible with PDG BF [4].

3 Conclusion

In our research, we have successfully reconstructed and examined the decay $B \to D^{(*)}\eta\pi^{+}$. A control sample study was performed using $B \to D^{(*)}D_{s}^{+}$ and $B \to D^{(*)}\rho^{+}$ decays, obtaining the BFs consistent with the values present in the particle data group. Our next step involves analyzing the actual data for the targeted decay, with the anticipation of observing the signal for the first time.

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