PROCEEDINGS OF SCIENCE

Search for the decay $B \to D^* \eta\pi$ in Belle II

Vismaya V S,[a] **Saurabh Sandilya**[a,*] **and Karim Trabelsi**[b]

[a] *Indian Institute of Technology Hyderabad,*
Hyderabad, India
[b] *IJCLab,*
Université Paris-Saclay,
Orsay, France
E-mail: ph20resch11010@iith.ac.in, saurabh@phy.iith.ac.in,
karim.trabelsi@in2p3.fr

We present a search for the yet-unobserved $B \to D^* \eta\pi$ decay at Belle II. This search can provide information for the understanding of the so-called semileptonic gap, which is the deficit in the sum of the branching fractions (BF) of known exclusive decays with respect to the measured inclusive $b \to c\ell\nu$ branching fraction. Widely used models to fill this deficit assume the existence of $B \to D^* \eta\ell\nu$ decays with BF of 4 $\times 10^{-3}$, which could imply a BF of $B \to D^* \eta\pi$ of about 2 $\times 10^{-4}$. Using the full sample collected by the Belle II experiment in 2019-2022, the expected upper limit on the BF of $B \to D^* \eta\pi$ is 1 $\times 10^{-4}$. This search would also improve knowledge of the B hadronic sector significantly.

16th International Conference on Heavy Quarks and Leptons (HQL2023)
28 November-2 December 2023
TIFR, Mumbai, Maharashtra, India

[*] Speaker

PoS(HQL2023)088

1. Introduction

The $B \to$ hadronic sector is still largely unexplored, with only approximately 50% of it being known. At Belle II [1], PYTHIA [2] is widely used to generate the unmeasured B decay modes in our simulated data. PYTHIA predicts a substantial branching fraction (BF) for the decay $B \to D^*\eta\pi$, yet this decay has not been observed. As a result, we are initiating a preliminary search to investigate and potentially observe this decay for the first time. This search can provide information for the understanding of the so-called semileptonic (SL) gap [3], which is the deficit in the sum of the branching fractions of known exclusive decays with respect to the measured inclusive $b \to c\ell\nu$ BF. To address the SL gap problem, ongoing experimental analyses utilize models that incorporate $B \to D^*\eta\ell\nu$ transitions. These transitions include both non-resonant processes and those involving $(D^*\eta)$ particles originating from D^{**} or $D^{(*)}(2S)$ states [3]. The proposed BF for $B \to D^*\eta\ell\nu$ to fill the gap is approximately 4×10^{-3}, which corresponds to BF of $B \to D^*\eta\pi \sim 2 \times 10^{-4}$, based on a naive prediction derived from the ratio of branching fractions of $B \to D^*\pi$ and $B \to D^*\ell\nu$.

This report describes the search for $B^0 \to D^{*-}\eta\pi^+$ decay using the 400 fb^{-1} of simulated data from the Belle II experiment located at the asymmetric-energy $e^+ - e^-$ SuperKEKB [1] accelerator. The Belle II experiment has collected 362 fb^{-1} of data at the Υ(4S) resonance during the years 2019-2021 and aims to collect 50 ab^{-1} during it's span.

2. Event selection and strategy

The process of selecting events entails the identification of particles and the application of track impact parameter criteria to the reconstructed final state particles, followed by the criteria on the invariant masses of the intermediate particles, with the primary objective of optimizing the statistical sensitivity. A kaon and a pion track are selected to assemble a D^0 meson, and subsequently, a D^* candidate is reconstructed by combining the D^0 candidate with a selected slow pion. The η meson candidate is chosen in a two-photon final state, known for its cleanliness. Ultimately, a B^0 meson candidate is reconstructed by combining D^*, η, and a pion.

The properties of signal events are extensively studied using a dedicated Monte Carlo simulations (MC) sample comprising only signal decays. Another MC sample (generic MC), encompassing all possible events originating from $e^+ - e^-$ collisions, is also examined to understand the background. This investigation aids in identifying the sources of dominant backgrounds and determining relevant observables crucial for background suppression.

We employ a variety of techniques and approaches to identify and reduce backgrounds originating from different sources. The normalized second order Fox–Wolfram moment, R_2 [4], is utilized for continuum suppression, targeting events where $e^+ - e^-$ directly decay into lighter hadrons without forming a $\Upsilon(4S)$ resonance. Additionally, a π^0 veto plays a crucial role in significantly reducing major background contributions. This is accomplished by rejecting the candidate if the photon, used for eta reconstruction in combination with any other photon in an event, produces an invariant mass close to the π^0 mass. Furthermore, the D_s veto effectively addresses the peaking background associated with the $B^0 \to D^{*-}D_s^+(\to \eta\pi^+)$ decay, which shares the exact same final state as our decay of interest. These vetoed events will be utilized as a control sample later to validate our study. To enhance statistical robustness, another control sample, $B^0 \to D^{*-}\rho^+(\to \pi^+\pi^0)$, with high statistics is also employed in our analysis. In each of these scenarios, we exclusively choose the most promising candidates by relying on the χ^2 fit probability of the B vertex. The extraction of signal events is achieved through the utilization of the ΔE variable, which represents the energy difference between the B meson and the beam.

3. Branching fraction and upper limit estimation

The signal MC sample is used to determine the reconstruction efficiency and to model the distribution of signal events in the ΔE. The efficiency is defined as the ratio of the number of reconstructed events to the generated ones. The signal shape obtained from the signal MC is kept fixed, and included the sum of signal and background probability density functions to fit the ΔE distribution in the generic MC. We proceed to calculate the 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 BF is measured as,

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

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 branching fractions 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. We consider two cases of simulated data,

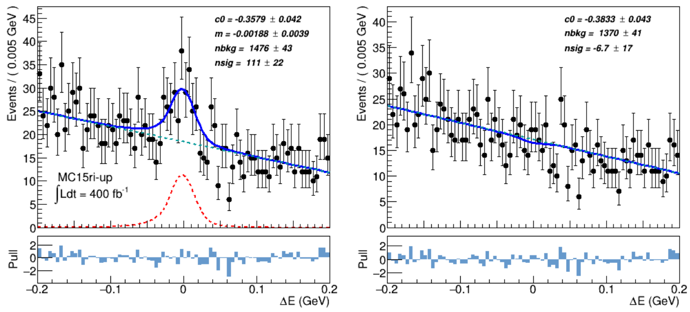

Figure 1: ΔE fit distribution in MC (left) and assuming no signal (right).

one with the BF of 2.56×10^{-4} and one with zero BF and the results for both the cases are shown in the Figure 1. Achieving an efficiency of 9.5%, we determined the BF to be $(2.71 \pm 0.54) \times 10^{-4}$, a result consistent within one standard deviation from the simulated value. Similarly, we put an an UL on BF at 90% CL as 0.7×10^{-4}. Additionally, we computed the UL as a function of $D^*\eta$ mass in order to accommodate the decay involving the intermediate states such as D^{**} and $D^{(*)}(2S)$.

4. Validation using control samples

To validate our methodology, we have undertaken a control sample study, where by applying only slight modifications to our measurement method we measure well-established decays exhibiting similar kinematics. Specifically, our control samples, $B^0 \to D^{*-}D_s^+(\to \eta\pi)$ and $B \to D^*\rho(\to \pi\pi^0)$, where the former one shares an identical final state with our target decay and the latter one involves a π^0 decays into two photons, similar to the decay of η, are documented with a BF of $(1.34 \pm 0.14) \times 10^{-4}$ [5] and $(6.8 \pm 0.9) \times 10^{-3}$ [6] respectively in the Particle Data Group [5]

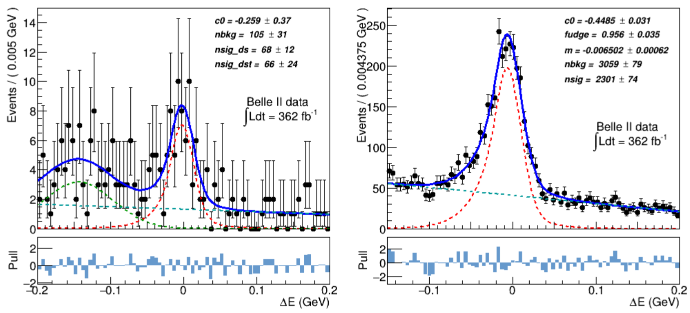

Figure 2: ΔE fit distribution in data for $B^0 \to D^{*-}D_s^+(\to \eta\pi^+)$ (left) and $B^0 \to D^{*-}\rho^+(\to \pi^+\pi^0)$ (right).

database. The analysis selections and strategies are similar as for our target decay. We follow the same procedures for extracting the signal and calculating the BFs associated with it. The obtained BFs in the 362 fb^{-1} of Belle II data for $B^0 \to D^{*-}D_s^+(\to \eta\pi^+)$ and $B^0 \to D^{*-}\rho^+(\to \pi^+\pi^0)$ are $(1.63 \pm 0.29) \times 10^{-4}$ and $(7.6 \pm 0.2) \times 10^{-3}$ respectively, which are within one standard deviation from the BF present in the particle data group.

5. Conclusion

In our research, we have successfully reconstructed and examined the decay $B^0 \to D^{*-}\eta\pi^+$. In the simulated data corresponding to the integrated luminosity of 400 fb^{-1} and with the generated BF of 2.56×10^{-4}, we obtain the BF $(2.71 \pm 0.54) \times 10^{-4}$. Additionally, we calculated the expected UL on the BF at 90 % CL $< 0.7 \times 10^{-4}$ in the scenario where no signal is present. To account for decays involving intermediate states like D^{**} and $D^{(*)}(2S)$, we determined the UL as a function of the $D^*\eta$ mass. A control sample study was performed using $B^0 \to D^{*-}D_s^+$ and $B^0 \to D^{*-}\rho^+$ decays, obtaining the BFs consistent with the values present in the particle data group. Our next step involves analysing the actual data for the targeted decay, with the anticipation of observing the signal for the first time.

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