Search for $B^+ \rightarrow e^+\nu$ and $B^+ \rightarrow \mu^+\nu$ decays using hadronic tagging

Abstract

We present a search for the rare leptonic decays $B^+ \rightarrow e^+\nu$ and $B^+ \rightarrow \mu^+\nu$, using the full $\Upsilon(4S)$ data sample of $772 \times 10^6$ $B\bar{B}$ pairs collected with the Belle detector at the KEKB asymmetric-energy $e^+e^-$ collider. One of the $B$ mesons from the $\Upsilon(4S) \rightarrow B\bar{B}$ decay is fully reconstructed in a hadronic mode while the recoiling side is analyzed for the signal decay. We find no evidence of a signal in any of the decay modes. Upper limits of the corresponding branching fractions are determined as $\mathcal{B}(B^+ \rightarrow e^+\nu) < 3.4 \times 10^{-6}$ and $\mathcal{B}(B^+ \rightarrow \mu^+\nu) < 2.7 \times 10^{-6}$ at 90% confidence level.

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The purely leptonic decays $B^+ \to e^+\nu$, $B^+ \to \mu^+\nu$, and $B^+ \to \tau^+\nu$ proceed via annihilation of the $B^+$ meson’s constituent quarks into a lepton and a neutrino of the same generation. In the Standard Model (SM), this annihilation is mediated by a $W^+$ boson leading to a branching fraction

$$\mathcal{B}(B^+ \to \ell^+\nu_\ell) = \frac{G_F^2 m_B m_\ell^2}{8\pi} \left(1 - \frac{m_\ell^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B,$$  \label{eq:1}

where $G_F$ is the Fermi coupling constant, $m_\ell$ is the mass of the charged lepton, $m_B$ is the mass of the $B^+$ meson, $\tau_B$ is the $B^+$ meson lifetime, $V_{ub}$ is an element of the Cabibbo-Kobayashi-Maskawa (CKM) matrix governing the weak transition from the $b$ to the $u$ quark and $f_B$ is the $B$ decay constant. Therefore, this decay can either test the SM, if one has external information on all the parameters, or measure the product of the least well-known parameters, $|V_{ub}|f_B$. The expectations for the branching fractions using $|V_{ub}| = (3.51^{+0.15}_{-0.14}) \times 10^{-3}$ \cite{4} from a fit to the full CKM unitarity triangle and $f_B = 186 \pm 4$ MeV \cite{5} from lattice QCD calculations and the world average for all other parameters \cite{4} are $\mathcal{B}(B^+ \to e^+\nu) = (7.9^{+0.8}_{-0.7}) \times 10^{-12}$, $\mathcal{B}(B^+ \to \mu^+\nu) = (3.4 \pm 0.3) \times 10^{-7}$, and $\mathcal{B}(B^+ \to \tau^+\nu) = (7.5 \pm 0.7) \times 10^{-5}$.

The $B^+ \to \tau^+\nu$ mode has been measured previously by the Belle \cite{6} and BABAR \cite{7} experiments, resulting in a combined branching fraction of $(1.05 \pm 0.25) \times 10^{-4}$ \cite{4}. Due to the relatively small expected branching fractions, owing to helicity suppression in the SM, the search for the $B^+ \to e^+\nu$ and $B^+ \to \mu^+\nu$ decay modes remains a challenge.

The $B^+ \to \ell^+\nu$ decays are expected to provide an excellent probe for new physics (NP), thanks to the small theoretical uncertainty in the SM branching fractions. For instance, in NP scenarios containing hypothetical particles such as the charged Higgs in 2-Higgs Doublet models (type-II) \cite{8} or the minimal super symmetric model (MSSM) \cite{9} or leptoquarks \cite{10}, the branching fractions of the $B^+ \to \ell^+\nu$ decays can be greatly enhanced.

Moreover, it has been suggested that the relative ratios of the branching fractions $R^{\ell\ell} = \mathcal{B}(B^+ \to \ell^+\nu)/\mathcal{B}(B^+ \to \ell^+\nu)$ can be used to test the minimal flavor violation (MFV) hypothesis. In NP models with MFV \cite{11}, the ratios $R^{\ell\ell}$ are expected to be nearly unmodified from SM expectations. However, in the framework of a Grand Unified Theory (GUT) model, the ratios $R^{e\mu}$ and $R^{e\tau}$ may increase to more than one order of magnitude above SM expectations due to the enhancement of the electron mode \cite{12}. It has been also suggested that, in a general MSSM model at large $\tan \beta$ \cite{13} with heavy squarks \cite{14}, the ratios $R^{e\tau}$ and $R^{\mu\tau}$ can deviate from SM expectations. Therefore measurements of $B^+ \to e^+\nu$ and $B^+ \to \mu^+\nu$ combined with the existing $B^+ \to \tau^+\nu$ determination can provide significant constraints on NP.

In this paper, we present a search for the previously unobserved $B^+ \to \ell^+\nu$ decays, using the hadronic tagging method, where $\ell$ stands for $e$ or $\mu$. In the hadronic tagging method, we fully reconstruct one of the $B$ mesons from the $\Upsilon(4S) \to BB$ decay in a hadronic mode and then select the $B^+ \to \ell^+\nu$ signal from the rest of the event. The existing upper limits on the branching fraction determined using the hadronic tagging method are $\mathcal{B}(B^+ \to e^+\nu) < 5.2 \times 10^{-6}$ and $\mathcal{B}(B^+ \to \mu^+\nu) < 5.6 \times 10^{-6}$ \cite{15} at 90% C.L.

Currently, the most stringent upper limits of these decays are obtained by the untagged method: $\mathcal{B}(B^+ \to e^+\nu) < 9.8 \times 10^{-7}$ \cite{16} and $\mathcal{B}(B^+ \to \mu^+\nu) < 1.0 \times 10^{-6}$ \cite{17} at 90% C.L. By not explicitly reconstructing a $B$ meson, the untagged method does not fully utilize
the information from the accompanying $B$ meson decay. While it leads to higher signal selection efficiencies, it suffers from a substantially higher background level. This could lead to ambiguities with other processes having similar decay signatures in case a signal is observed far in excess of the SM expectation. For instance, if an unknown heavy neutrino $\nu_h$ appears in the $B^+ \to e^+ \nu_h$ decay, it will be nearly impossible to distinguish it from the known process, $B^+ \to e^+ \nu_e$, because of the limited kinematic precision of the untagged method.

In the hadronic tagging method used in this analysis, by fully reconstructing one $B$ meson ($B_{\text{tag}}$), we have the best possible knowledge on the kinematics of the signal $B$ meson ($B_{\text{sig}}$) in the event. This enables a precise measurement of the missing four-momentum of the neutrino in the $B^+ \to \ell^+ \nu$ decays. As a result, the momentum of the charged lepton in the $B^+ \to \ell^+ \nu$ signal can be determined with an order-of-magnitude higher resolution compared to the untagged method [10]. This results in a very strong background suppression and provides an extra constraint for identifying the nature of the undetected particle.

The data sample used in this analysis was collected with the Belle detector [19] at the KEKB asymmetric-energy $e^+ e^-$ collider [20]. The sample corresponds to an integrated luminosity of $711 \text{ fb}^{-1}$ or $772 \times 10^6 B \bar{B}$ pairs, collected on the $\Upsilon(4S)$ resonance at a center-of-mass (CM) energy ($\sqrt{s}$) of 10.58 GeV.

The Belle detector is a large-solid-angle spectrometer that consists of a silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), aerogel threshold Cherenkov counters (ACC), an array of a barrel-like arrangement of time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter comprised of 8736 CsI(Tl) crystals (ECL) located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux return located outside of the coil is instrumented to detect $K_L$ mesons and to identify muons (KLM).

Electron identification is based on the ratio between the cluster energy in the ECL and the track momentum from the CDC ($E/p$), the specific ionization $dE/dx$ in the CDC, the position and shower shape of the cluster in the ECL and the response from the ACC. Muon identification is based on the hit position and the penetration depth in the KLM. In the momentum range of interest in this analysis, the electron (muon) identification efficiency is above 90% and the hadron fake rate is under 0.5% (5%). A more detailed description can be found elsewhere [21].

The $B_{\text{tag}}$ candidates are reconstructed in 615 exclusive charged $B$ meson decay channels with a reconstruction algorithm based on a hierarchical neural network [25]. To compensate for the difference between the MC and data in the $B_{\text{tag}}$ reconstruction efficiency ($\epsilon_{\text{tag}}$) due to uncertainties in branching fractions and dynamics of hadronic modes, we apply a correction obtained from a control sample study in which the signal-side $B$ meson decays via $B^+ \to \bar{D}^{(*)0} \ell^+ \nu$ [26]. The MC efficiency is corrected according to the $B_{\text{tag}}$ decay mode as well as the output of the hadronic tagging algorithm ($o_{\text{tag}}$) on an event-by-event basis. The $o_{\text{tag}}$ distribution peaks near zero for combinatorial or continuum backgrounds, and near one for well reconstructed $B_{\text{tag}}$ candidates.

The correction factors for each $B_{\text{tag}}$ decay mode is determined by the comparison of the number of events in MC and data from a fit to the distribution of the square of the missing particle’s undetected four-momentum ($M_{\text{miss}}^2$). Here $M_{\text{miss}}^2$ is expected to peak near zero for correctly reconstructed $B^+ \to \bar{D}^{(*)0} \ell^+ \nu$ events in which the only missing particle is a massless neutrino. For each $B_{\text{tag}}$ mode, the correction factor is then obtained
as a function of $\alpha_{\text{tag}}$. These corrections are done separately for each \( B^+ \to \bar{D}^{(*)0} \ell^+ \nu_\ell \) decay mode listed in Ref. \[26\] and the correction factor is determined as the average of each correction factor obtained from those decays.

In 42\% of the events for both the \( B^+ \to e^+ \nu \) and \( B^+ \to \mu^+ \nu \) samples, we find multiple \( B_{\text{tag}} \) candidates. In such cases, we select the \( B_{\text{tag}} \) candidate with the highest \( \alpha_{\text{tag}} \). To ensure a well reconstructed \( B_{\text{tag}} \) candidate, we further require \( \alpha_{\text{tag}} \), the energy difference, \( \Delta E = E_{B_{\text{tag}}}^* - \sqrt{s}/2 \), and the beam-constrained-mass \( M_{bc} = \sqrt{s/4 - |\vec{p}_{B_{\text{tag}}}^*|^2} \), to satisfy 

\[
\alpha_{\text{tag}} > 0.0025, |\Delta E| < 0.05 \text{ GeV}, \text{ and } 5.27 \text{ GeV}/c^2 < M_{bc} < 5.29 \text{ GeV}/c^2,\]

where \( E_{B_{\text{tag}}}^* \) and \( \vec{p}_{B_{\text{tag}}}^* \) are the \( B_{\text{tag}} \) energy and momentum, respectively, in the CM frame. The efficiencies of this \( B_{\text{tag}} \) reconstruction procedure on events containing signal decays are: \( \epsilon_{\text{tag}} = 0.29\% \) for the \( B^+ \to e^+ \nu \) and \( \epsilon_{\text{tag}} = 0.30\% \) for the \( B^+ \to \mu^+ \nu \). These \( \epsilon_{\text{tag}} \) values include a correction factor of 0.71, which was described above.

On the \( B_{\text{sig}} \) side, we require exactly one remaining track in the detector and that it be identified as an electron or a muon with a momentum above 1.8 GeV/c in the laboratory frame. The lepton is required to satisfy \(|dz| < 1.5 \text{ cm and } dr < 0.05 \text{ cm, where } dz \text{ and } dr \text{ are impact parameters of the track along the beam direction and in the perpendicular plane, respectively.} \)

To suppress the continuum background (\( e^+e^- \to q\bar{q} \ [q = u, d, s, c] \)), we use the event shape difference between \( B\bar{B} \) events and continuum. Since each \( \Upsilon(4S) \) decays nearly at rest, the decay products of the resulting \( B\bar{B} \) pair have a spherical event shape. On the other hand, continuum event shapes tend to be two-jet-like. We define \( \theta_T \) as the angle between the momentum of the signal lepton and the unit vector \( \hat{n} \) that maximizes \( \Sigma_i |n \cdot \vec{p}_i|/|\vec{p}_i| \), where the index \( i \) runs over all particles used for \( B_{\text{tag}} \) reconstruction. We require \( \cos \theta_T < 0.9 \) and \( \cos \theta_T < 0.8 \) for \( B^+ \to e^+ \nu \) and \( B^+ \to \mu^+ \nu \), respectively. In the muon mode, we expect a larger continuum background compared to the electron mode due to the higher hadron misidentification rate. Therefore, we apply a more stringent \( \cos \theta_T \) criterion for this mode.

For signal events, we expect no detectable particles left after removing the signal lepton and the particles associated with the \( B_{\text{tag}} \) for a signal event. Therefore, there should be no extra energy deposits in the ECL except for the small contributions from split-off showers and beam background. We define the extra energy (\( E_{\text{ECL}} \)) as the sum of the energy from the neutral clusters not associated with \( B_{\text{tag}} \) or the signal lepton deposited in the ECL. In the \( E_{\text{ECL}} \) calculation, minimum thresholds of 50 MeV for the barrel (32.2° < \( \theta < 128.7° \)), 100 MeV for the forward end-cap (12.4° < \( \theta < 31.4° \)), and 150 MeV for the backward end-cap (130.7° < \( \theta < 155.1° \)) of the calorimeter are required, where \( \theta \) is the cluster’s polar angle relative to the beam direction \[13\]. Higher thresholds are applied for the end-cap regions due to the severity of beam background there. We require \( E_{\text{ECL}} < 0.5 \text{ GeV} \) for both \( B^+ \to e^+ \nu \) and \( B^+ \to \mu^+ \nu \).

We identify signal events with the signal lepton’s momentum in the rest frame of the \( B_{\text{sig}} \) (\( p_{\ell}^B \)). Due to the two-body nature of the signal and the light mass of an \( e \) or a \( \mu \), we expect signal events to peak sharply around 2.64 GeV/c in \( p_{\ell}^B \). By studying the signal MC samples, we demand that each signal event satisfies 2.6 GeV/c < \( p_{\ell}^B \) < 2.7 GeV/c for both \( B^+ \to e^+ \nu \) and \( B^+ \to \mu^+ \nu \).

Dominant backgrounds arise from decays with neutral particles not detected or used in the reconstruction of the \( B_{\text{tag}} \) and a high momentum track that falls in the \( p_{\ell}^B \) signal region. For the \( B^+ \to e^+ \nu \) search, \( B^+ \to \pi^+ K^0 \), \( B^+ \to \ell^+ \nu_\ell \gamma \), and \( B^+ \to \pi^0 \ell^+ \nu_\ell \) decays
in our sample constitute 100% of the background events in the $p_{l}^{B}$ signal region. For the $B^{+} \rightarrow \mu^{+}\nu$ search, $B^{+} \rightarrow \pi^{+}K^{0}$, $B^{+} \rightarrow K^{+}\pi^{0}$, $B^{+} \rightarrow \ell^{+}\nu_{\ell}\gamma$, and $B^{+} \rightarrow \pi^{0}\ell^{+}\nu_{\ell}$ decays constitute $84.7\%$ of the background events in the $p_{l}^{B}$ signal region with the remainder coming from all other $b \rightarrow u\ell^{-}\bar{\nu}_{\ell}$ decays. For an accurate modeling of the background probability density function (PDF) near the $p_{l}^{B}$ signal region, we generate dedicated MC samples for $B^{+} \rightarrow \pi^{+}K^{0}$, $B^{+} \rightarrow K^{+}\pi^{0}$, $B^{+} \rightarrow \ell^{+}\nu_{\ell}\gamma$, and $B^{+} \rightarrow \pi^{0}\ell^{+}\nu_{\ell}$ decays. For the $B^{+} \rightarrow \ell^{+}\nu_{\ell}\gamma$ process, which has not been observed yet, we assume a branching fraction of $B(B^{+} \rightarrow \ell^{+}\nu_{\ell}\gamma) = 5 \times 10^{-6}$.

We define the sideband of the $p_{l}^{B}$ as 2 GeV/c < $p_{l}^{B}$ < 2.5 GeV/c. The $p_{l}^{B}$ sideband is dominated by the $b \rightarrow c$ and $b \rightarrow u\ell^{-}\bar{\nu}_{\ell}$ decay. Out of all background events in the $p_{l}^{B}$ sideband, each $b \rightarrow c$ and $b \rightarrow u\ell^{-}\bar{\nu}_{\ell}$ decay contributes 55% (60%) and 39% (34%) for the $B^{+} \rightarrow \ell^{+}\nu_{\ell}$ ($B^{+} \rightarrow \ell^{+}\nu_{\ell}\mu$) search. The remaining 6% of the background in the $p_{l}^{B}$ sideband originates from the $B^{+} \rightarrow \ell^{+}\nu_{\ell}\gamma$ decay and the $b \rightarrow s,d$ processes aside from $B^{+} \rightarrow \pi^{+}K^{0}$ or $B^{+} \rightarrow K^{+}\pi^{0}$ for both searches. $B^{+} \rightarrow D^{0}\ell^{+}\nu_{\ell}$ and $B^{+} \rightarrow D^{0}\ell^{+}\nu_{\ell}$ decays are found to be composing the $b \rightarrow c$ decays for the $B^{+} \rightarrow \ell^{+}\nu_{\ell}$ ($B^{+} \rightarrow \mu^{+}\nu_{\ell}$) search at rates of 67% (64%) and 24% (21%), respectively, and are treated separately from the other $b \rightarrow c$ decays.

Continuum events are found to be negligible in both the $p_{l}^{B}$ sideband and $p_{l}^{B}$ signal regions.

We calculate the branching fraction as

$$B(B^{+} \rightarrow \ell^{+}\nu) = \frac{N_{\text{obs}} - N_{\text{bkg}}^{\text{exp}}}{2 \cdot \epsilon_{s} \cdot N_{B^{+}B^{-}}},$$

(2)

where $N_{\text{obs}}$ is the observed yield of the data sample in the $p_{l}^{B}$ signal region, $N_{\text{bkg}}^{\text{exp}}$ is the the expected number of background in the $p_{l}^{B}$ signal region, $\epsilon_{s}$ is the total signal selection efficiency, and $N_{B^{+}B^{-}}$ is the number of $\Upsilon(4S) \rightarrow B^{+}B^{-}$ events in the data sample. Using $B(\Upsilon(4S) \rightarrow B^{+}B^{-}) = 0.513 \pm 0.006$ [4], we estimate $N_{B^{+}B^{-}}$ as $(396 \pm 7) \times 10^{6}$.

We obtain $N_{\text{bkg}}^{\text{exp}}$ by fitting a background PDF based on the background MC sample to the $p_{l}^{B}$ sideband of the data sample. We extrapolate the expected background yield in the $p_{l}^{B}$ signal region by the ratio of the background PDF integration in the $p_{l}^{B}$ sideband and the $p_{l}^{B}$ signal region.

The systematic uncertainties on $N_{\text{bkg}}^{\text{exp}}$ are estimated according to the uncertainties in the background PDF parameters, the branching fraction of background decays, and the statistics of the data sample in the $p_{l}^{B}$ sideband. We vary each source in turn by its uncertainty $(\pm 1\sigma)$ and the resulting deviations in $N_{\text{bkg}}^{\text{exp}}$ are added in quadrature. We calculate the branching fraction uncertainty according to the experimental measurements [4] for the $B^{+} \rightarrow D^{(*)0}\ell^{+}\nu_{\ell}$, $B^{+} \rightarrow \pi^{0}\ell^{+}\nu_{\ell}$, $B^{+} \rightarrow \pi^{0}K^{0}$, and $B^{+} \rightarrow K^{+}\pi^{0}$ modes. For the $B^{+} \rightarrow \ell^{+}\nu_{\ell}\gamma$, an uncertainty of ±50% is applied. For modes where a clear estimate of the background level is not available, we assume a conservative branching fraction uncertainty of ±100%. The values of $N_{\text{bkg}}^{\text{exp}}$ and their uncertainties for each $B^{+} \rightarrow e^{+}\nu$ and $B^{+} \rightarrow \mu^{+}\nu$ are listed in Table [I].

The efficiencies $\epsilon_{s}$ are 0.86 × 10^{-3} and 1.02 × 10^{-3} for $B^{+} \rightarrow e^{+}\nu$ and $B^{+} \rightarrow \mu^{+}\nu$, respectively, as summarized in Table [I]. These are determined from MC with their lepton identification efficiencies corrected to the data sample.

The uncertainties of $\epsilon_{s}$ are calculated from the following sources: lepton identification, signal MC statistical error, track finding uncertainties of the signal lepton, $\epsilon_{\text{tag}}$ correction,
TABLE I: Results of the $B^+ \rightarrow \ell^+\nu$ search. $\epsilon_s$ is the signal selection efficiency, $N_{\text{obs}}$ is the number of events observed, $N_{\text{bkg}}^{\text{exp}}$ is the expected yield of background events in the signal region, and $B^{90}$ is the upper limit of the branching fraction at 90% C.L.

| Mode          | $\epsilon_s$ [%] | $N_{\text{obs}}$ | $N_{\text{bkg}}^{\text{exp}}$ | $B^{90}$ |
|---------------|------------------|------------------|-------------------------------|----------|
| $B^+ \rightarrow e^+\nu$ | 0.086            | 0                | 0.10 ± 0.04                  | < 3.4 × 10^{-6} |
| $B^+ \rightarrow \mu^+\nu$ | 0.102            | 0                | 0.26$^{+0.09}_{-0.08}$      | < 2.7 × 10^{-6} |

From the lepton identification efficiency, we obtain 1% uncertainty for both $B^+ \rightarrow e^+\nu$ and $B^+ \rightarrow \mu^+\nu$ searches. The uncertainty due to signal MC statistics is 1.4% for $B^+ \rightarrow e^+\nu$ and 1.3% for $B^+ \rightarrow \mu^+\nu$. Track finding contributes a 0.35% uncertainty. The $\epsilon_{\text{tag}}$ correction includes the statistical uncertainty, the branching fraction uncertainty of signal side $B^+ \rightarrow \bar{D}^{(*)0}\ell^+\nu_\ell$ decays, and the particle identification uncertainty of particles used to reconstruct the $D^{(*)0}$ mesons, resulting in a 4.2% uncertainty.

To account for the difference of $p^B_\ell$ shape in the signal MC and the data sample, we study $B^+ \rightarrow \bar{D}^0\pi^+$ decays as a control sample. The control sample is similar to our signal decay since it is also a two-body decay of a $B^+$ meson. The $\bar{D}^0$ meson is identified in the $\bar{D}^0 \rightarrow K^+\pi^-$ and $\bar{D}^0 \rightarrow K^+\pi^-\pi^+\pi^-$ decay channels. We follow the same

![FIG. 1: The $p^B_\ell$ distributions of the $B^+ \rightarrow \bar{D}^0\pi^+$ control sample study. The points with error bars indicate the background subtracted data and the black histogram shows the MC distribution. The region between the two dashed lines represents the $p^B_\ell$ selection region for the control sample study.](image)
analysis procedure as in the $B^+ \rightarrow \ell^+\nu$ analysis, where the $\pi^+$ from the primary decay of the $B^+$ meson (primary $\pi^+$), is treated as the lepton and the $D^0$ decay products as a whole treated as the invisible neutrino. We compare the distributions of the primary $\pi^+$ momentum in the rest frame of the signal $B$ ($p_B^{\pi}$) between the background subtracted data sample and the control sample MC, which are displayed in Figure 1.

We estimate the $p_B^{\ell}B$ shape correction factor as the ratio of the $p_B^{\ell}$ selection efficiencies between the background subtracted data sample and the MC sample. The obtained $p_B^{\ell}B$ shape correction factor is $0.953 \pm 0.034$. The $\epsilon_s$ was corrected according to the mean value of the $p_B^{\ell}B$ shape correction factor and we quote the 3.6% uncertainty as the $p_B^{\ell}B$ shape uncertainty. With this correction applied to the MC sample, the data and the MC agree within 0.3$\sigma$.

The total systematic uncertainty related to $\epsilon_sN_{B^+B^-}$ is 6.1% for both $B^+ \rightarrow e^+\nu$ and $B^+ \rightarrow \mu^+\nu$. The multiplicative uncertainties related to $\epsilon_sN_{B^+B^-}$ are summarized in Table II.

| Source                | $B^+ \rightarrow e^+\nu$ | $B^+ \rightarrow \mu^+\nu$ |
|-----------------------|---------------------------|-----------------------------|
| $N_{B^+B^-}$          | 1.8                       | 1.8                         |
| Lepton ID             | 1.0                       | 1.0                         |
| MC statistics         | 1.4                       | 1.3                         |
| Tracking efficiency   | 0.35                      | 0.35                        |
| $\epsilon_{\text{tag}}$ correction | 4.2                      | 4.2                         |
| $p_B^{\ell}B$ Shape   | 3.6                       | 3.6                         |
| Total                 | 6.1                       | 6.1                         |

In the $p_B^{\ell}B$ signal region, we observe no events for both searches as shown in Figure 2. We set 90% C.L. branching fraction upper limits using the POLE program [28] based on a frequentist approach [29]. In the calculation, we assume a Gaussian distribution of $N_{\text{exp}}^{\text{bkg}}$, with a conservative assumption by choosing the larger deviation of the asymmetric uncertainty in $N_{\text{exp}}^{\text{bkg}}$. We obtain upper limits of the branching fraction for each mode as $\mathcal{B}(B^+ \rightarrow e^+\nu) < 3.4 \times 10^{-6}$ and $\mathcal{B}(B^+ \rightarrow \mu^+\nu) < 2.7 \times 10^{-6}$ at 90% C.L, which include the systematic uncertainties.

In summary, we have searched for the leptonic decays $B^+ \rightarrow e^+\nu$ and $B^+ \rightarrow \mu^+\nu$ with hadronic tagging method using a data sample containing $772 \times 10^6 B\bar{B}$ events collected by the Belle experiment. We find no evidence of $B^+ \rightarrow e^+\nu$ and $B^+ \rightarrow \mu^+\nu$ processes. We set the upper limits of the branching fraction at $\mathcal{B}(B^+ \rightarrow e^+\nu) < 3.4 \times 10^{-6}$ and $\mathcal{B}(B^+ \rightarrow \mu^+\nu) < 2.7 \times 10^{-6}$ at 90% C.L, which are by far the most stringent limits obtained with the hadronic tagging method. Given the low background level demonstrated in this search, we expect more stringent constraints on the new physics models to be set by Belle II [30], the next generation $B$ factory experiment.
FIG. 2: The unbinned maximum likelihood fits of the total background PDF to data. The upper plot is for the $B^+ \rightarrow e^+ \nu$ search and the lower plot is for the $B^+ \rightarrow \mu^+ \nu$ search. The points with error bars are the experimental data, where the error bars correspond to $\pm 1\sigma$ Poisson confidence intervals. The dashed blue line shows the background PDF in the sideband region and the dotted red line in the signal region. The distribution of signal MC, displayed as the black histogram, is scaled by $10^6$ and 40 times the SM expectation for $B^+ \rightarrow e^+ \nu$ and $B^+ \rightarrow \mu^+ \nu$, respectively.

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