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A search for the decays $B^+ \to e^+\nu_e$ and $B^+ \to \mu^+\nu_\mu$ using hadronic-tag reconstruction

The *BABAR* Collaboration

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Abstract

We report on a search for the rare decay modes $B^+ \to e^+\nu_e$ and $B^+ \to \mu^+\nu_\mu$ with data collected from the *BABAR* detector at the PEP-II e^+e^- storage ring. This search utilizes a new technique in which we fully reconstruct the accompanying B^- in $\Upsilon(4S) \to B^+B^-$ events, and look for a mono-energetic lepton in the B^+ rest frame. No signal candidates are observed in either of the channels, consistent with the expected background, in a data sample of approximately 229 million $B\overline{B}$ pairs. The branching-fraction upper limits are set at $\mathcal{B}(B^+ \to e^+\nu_e) < 7.9 \times 10^{-6}$ and $\mathcal{B}(B^+ \to \mu^+\nu_\mu) < 6.2 \times 10^{-6}$ at the 90% confidence level.

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1 INTRODUCTION

Leptonic decays of B mesons are of interest both for their use in characterizing Standard Model (SM) processes and as probes of possible physics beyond the SM. They are, however, experimentally challenging to observe due to both their small branching fractions and the difficulty of measuring decay modes with neutrinos in the final state. In the SM, these leptonic decays may proceed via tree-level processes mediated by a virtual W^+ boson. The SM branching fraction for this type of decay[1] is given by

$$\mathcal{B}(B^+ \to l^+\nu_l) = \frac{G_F^2 m_B m_l^2}{8\pi}\left(1 - \frac{m_l^2}{m_B^2}\right) f_B^2 |V_{ub}|^2 \tau_B, \tag{1}$$

where G_F is the Fermi coupling constant, m_l and m_B are the lepton and B-meson masses, and τ_B is the B lifetime. Measurements of the leptonic branching fractions can therefore constrain the product of $|V_{ub}|$ and f_B, where $|V_{ub}|$ is the Cabibbo-Kobayashi-Maskawa matrix element parameterizing the $b \to u$ coupling and f_B is a decay constant describing the wavefunction overlap of the two quarks of the B meson. $|V_{ub}|$ has been obtained from analyses of semileptonic B decay modes [2]. A measurement of the branching fractions in Eq. 1 would allow us to experimentally constrain f_B, which can be calculated in lattice QCD with uncertainties of $\sim$15% [3]. Measuring a product $|V_{ub}| \times f_B$, that is inconsistent with measurements using other methods, could be interpreted as evidence for new physics. An enhancement to the branching fraction could be caused by the existence of additional contributions, for example as predicted by supersymmetry [4].

As shown in Eq. 1, the decay rates are helicity suppressed by a factor of m_l^2/m_B^2, yielding SM branching fraction predictions of $\mathcal{O}(10^{-12})$ and $\mathcal{O}(10^{-7})$ for the e and μ modes respectively. The most stringent upper limits on the leptonic decay modes $B^+ \to e^+ \nu_e$ and $B^+ \to \mu^+ \nu_\mu$ are 1.5×10^{-5} [5] and 6.6×10^{-6} [6], respectively, at the 90% confidence level. A preliminary results of $\mathcal{B}(B^+ \to e^+\nu_e) < 5.4 \times 10^{-6}$ and $\mathcal{B}(B^+ \to \mu^+\nu_\mu) < 2.0 \times 10^{-6}$ at the 90% confidence level [7] are also available from the Belle Collaboration.

We search for the decays $B^+ \to e^+\nu_e$ and $B^+ \to \mu^+\nu_\mu$ using a technique in which the accompanying B^- is reconstructed exclusively in one of several hadronic decay modes. This technique has previously been applied to other rare-decay searches [8, 9], but it has not been used previously in a search for $B^+ \to \ell^+\nu_\ell$. Although the hadronic-reconstruction procedure has a relatively low efficiency, this method has the advantages of highly suppressed backgrounds and knowledge of the signal-lepton energy. Because it is very unlikely to observe any background events, an observation of events in the signal region would be highly suggestive of a signal.

The leptonic decay $B^+ \to \tau^+\nu_\tau$ is expected to have a branching fraction of $\mathcal{O}(10^{-4})$ [10]. Although this decay is less suppressed than the e and μ modes, analysis of it is more difficult due to additional neutrinos in the final state. The preliminary result from Belle Collaboration (using a similar tagged-B method) reports first evidence for $B^+ \to \tau^+\nu_\tau$, with a branching fraction of $1.06^{+0.34}_{-0.28}$ (stat) $^{+0.18}_{-0.16}$ (syst) $\times 10^{-4}$ [11]. As the e and μ modes are experimentally cleaner, they may ultimately yield more accurate branching-fraction results than $B^+ \to \tau^+\nu_\tau$ even with the higher suppression.

2 THE *BABAR* DETECTOR AND DATASET

The on-resonance data sample used in this analysis corresponds to an integrated luminosity of $208.7\,\text{fb}^{-1}$, accumulated at the $\Upsilon(4S)$ resonance. The events were recorded by the *BABAR* detector at the PEP-II asymmetric e^+e^- storage ring. In addition to the on-resonance sample, an off-resonance sample of $21.5\,\text{fb}^{-1}$ was recorded approximately $40\,\text{MeV}$ below the $\Upsilon(4S)$ resonance, which is used for studies of backgrounds not originating from the decay of $\Upsilon(4S)$.

The *BABAR* detector is described in greater detail in the literature [12]. Charged-particle tracking and dE/dx measurements for particle identification are provided by both a five-layer double-sided silicon vertex tracker and a 40-layer drift chamber contained within the magnetic field of a 1.5 T superconducting solenoid. A ring-imaging Cherenkov detector (DIRC) provides efficient particle identification. The energies of neutral particles are measured by an electromagnetic calorimeter consisting of 6580 CsI(Tl) crystals. Muon identification is provided by resistive plate chambers. Signal efficiencies and background rates are estimated using a Monte Carlo (MC) simulation of the *BABAR* detector based on GEANT4 [13].

3 ANALYSIS METHOD

The decay $B^+ \to \ell^+\nu_\ell$ produces a mono-energetic charged e or μ in the B^+ rest frame, accompanied by the missing-energy signature of a neutrino. To gain sensitivity to this signature, a B meson from the decay $\Upsilon(4S) \to B\overline{B}$, B_{tag}, is reconstructed in hadronic decay modes $B^+ \to \bar{D}^{(*)0}X^+$, $B^- \to D^{(*)0}X^-$, $B^0 \to D^{(*)-}X^+$ and $\bar{B}^0 \to D^{(*)+}X^-$ [14]. While both charged and neutral B_{tag} candidates are considered for reconstruction, the events where the best B_{tag} candidate (as discussed below) is neutral are vetoed. D^0 candidates are reconstructed in the modes $D^0 \to K^-\pi^+$, $D^0 \to K^-\pi^+\pi^0$, $D^0 \to K^-\pi^+\pi^+\pi^-$ and $D^0 \to K^0_S\pi^+\pi^-$; D^{*0} candidates are formed from a D^0 and either a π^0 or a γ. Similar reconstruction is done for the $D^{(*)\pm}$ candidate. Pions and kaons remaining in the event are combined in subsets with the D candidate to form a B_{tag} candidate, considering the quantity $|\Delta E| = |E_B - E_{\text{beam}}|$, where E_B is the energy of the reconstructed B and E_{beam} is the beam energy, both in the center-of-mass (CM) frame. B_{tag} candidates must satisfy the requirement $|\Delta E| < 0.2\,\text{GeV}$, and the B_{tag} with the lowest value of $|\Delta E|$ is chosen as the candidate. In the case of multiple B_{tag} candidates, the one with a highest *a priori* purity is chosen. The energy-substituted mass

$$m_{ES} = \sqrt{E^2_{\text{beam}} - \vec{p}^{\,2}_B}, \tag{2}$$

where $\vec{p}_B$ is the momentum of the B candidate in the CM frame, is required to be $5.270\,\text{GeV}/c^2 < m_{ES} < 5.288\,\text{GeV}/c^2$. The m_{ES} distribution is shown in Fig. 1. The resolution in m_{ES} is dominated by the spread in E_{beam}, $\sigma_{E_{\text{beam}}} \approx 2.59\,\text{MeV}$.

Event shape requirements are used to suppress the combinatorial backgrounds not originating from the decay of $\Upsilon(4S)$. These requirements are: $R2 < 0.5$, where $R2$ is the ratio of zeroth and the second Fox-Wolfram moment [15]; $|\cos\theta_T| < 0.9$, where θ_T represents the angle between the thrust axis defined by the B_{tag} candidate and by the combination of all other tracks and clusters in the event.

The tracks and clusters not used in the B_{tag} reconstruction are assumed to originate from the decay of the signal B, B_{signal}. Since the CM energy is precisely known, reconstruction of the B_{tag} fully determines the energy and momentum, and thus the rest frame, of the B_{signal} candidate. The signal lepton energy is constrained to be at the kinematic endpoint in the B_{signal} rest frame, producing a distinct experimental signature. Fig. 2 shows a comparison of the lepton-momentum distributions in the B_{signal} rest frame and the CM frame. The B_{signal} rest frame is calculated from the recorded beam energies, and a momentum opposite in direction to the reconstructed B_{tag}. We require the highest momentum track of correct charge in the B_{signal} frame to have a momentum

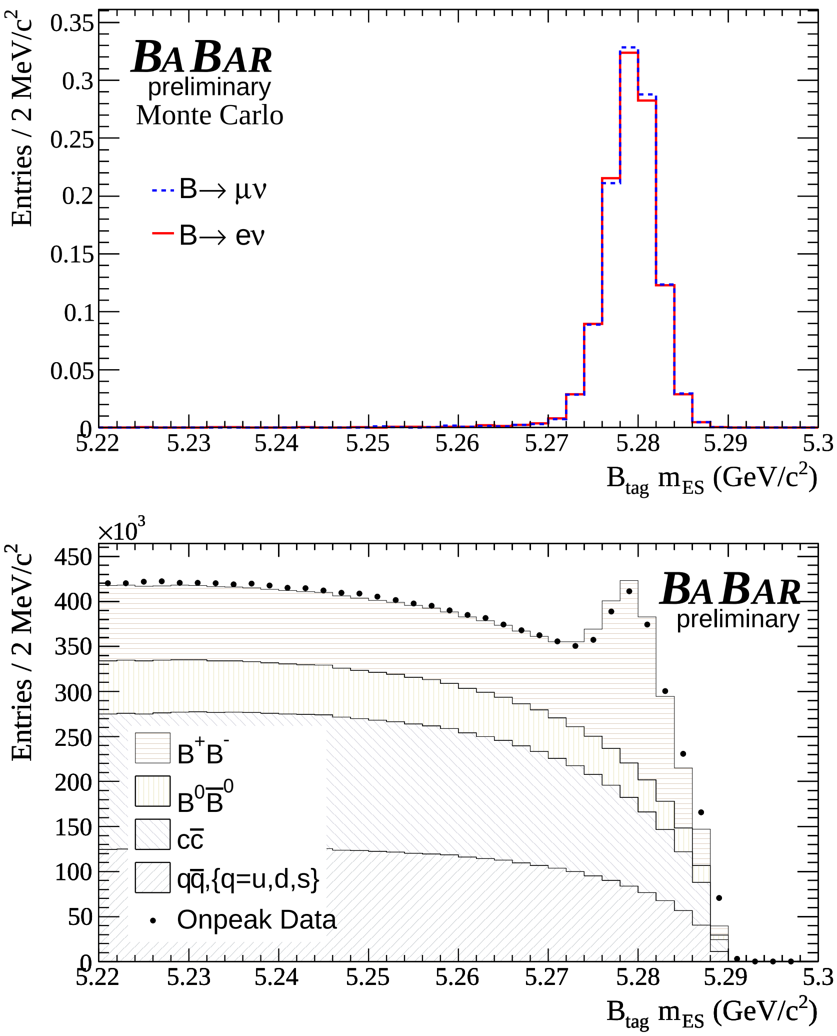

Figure 1: m_{ES} distribution of $B_{\rm tag}$ candidates. Signal MC events are shown on top and background MC events on the bottom. The events are required to have one reconstructed charged B. The signal and background samples are scaled to data luminosity, assuming both the signal mode branching fractions to be 2.0×10^{-6} (*i.e.*, the current upper limit of the mode $B^+ \to \mu^+\nu_\mu$).

$\vec{p^*}$ between 2.54 and 2.72 GeV/c^2. This highest momentum track is also required to satisfy (e or μ) lepton identification requirements, and to survive a veto on kaon particle identification based primarity on DIRC.

The missing momentum in the $B_{\rm signal}$ frame is measured to be

$$\vec{p^*}_{\rm miss} = \vec{p^*}_{\Upsilon(4S)} - \vec{p^*}_{B_{\rm tag}} - \sum_i \vec{p^*}_i, \tag{3}$$

where the sum is of all charged and neutral particles not associated with the reconstruction of the $B_{\rm tag}$, and all quantities are computed in the $B_{\rm signal}$ rest frame. The direction of the missing

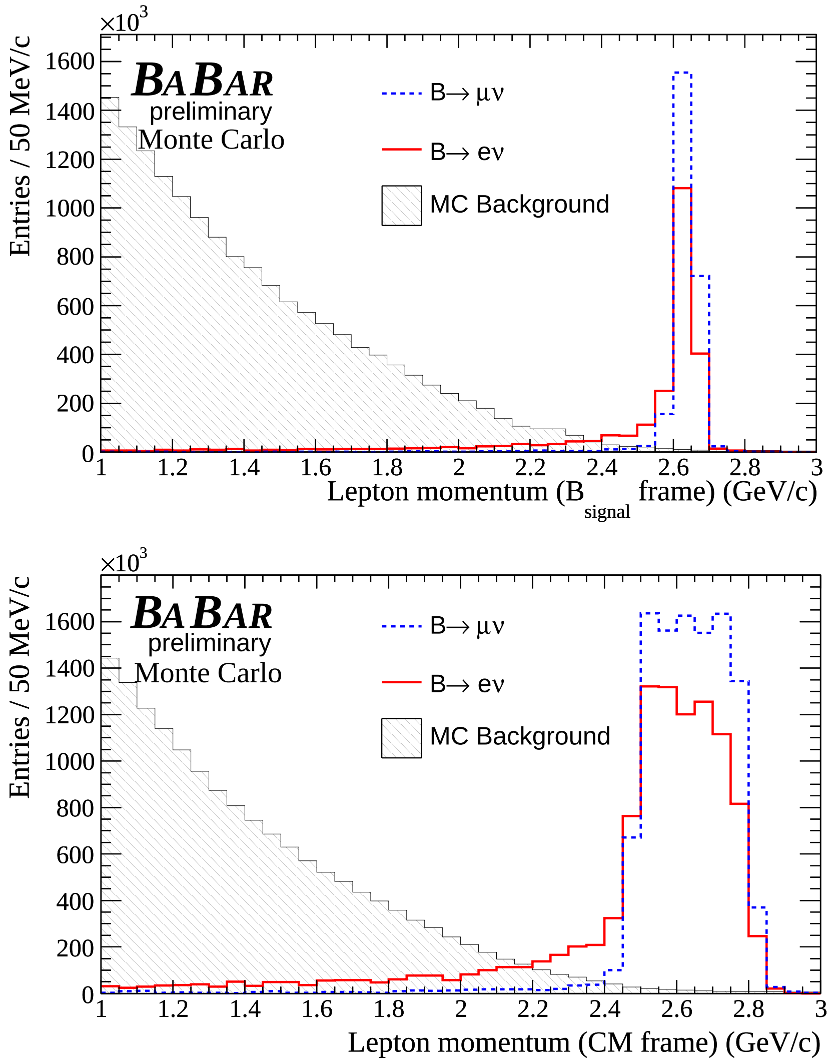

Figure 2: The lepton-candidate momentum distributions in the B_{signal} frame (top) and in the CM frame (bottom) before applying the signal-selection criteria. The resolution gain provided by the B_{tag} reconstruction allows a tighter selection around the signal peak. The signal MC is scaled arbitrarily.

momentum is described by

$$\cos\theta_{p_{\mathrm{miss}}} = \frac{p_{z_{\mathrm{miss}}}}{|\vec{p}_{\mathrm{miss}}|}, \tag{4}$$

where $p_{z_{\mathrm{miss}}}$ is the component of the momentum relative to the axis defined by the e^- (high energy) beam direction, and the momenta are computed in the CM frame. To ensure that the missing momentum is carried by the neutrino rather than a particle passing outside of the detector acceptance, we require $-0.76 < \cos\theta_{p_{\mathrm{miss}}} < 0.92$.

We also require that the missing momentum be consistent with a neutrino recoiling against the signal candidate lepton by requiring $\Delta P^*_{\rm miss} < 0.7\,{\rm GeV/c}$, where

$$\Delta P^*_{\rm miss} = |\vec{p}^{\,*}_{\rm miss} + \vec{p^*}|. \quad (5)$$

This requirement is useful in suppressing semileptonic B decays, where a high momentum lepton may be present.

The amount of extra energy in the event is described by a quantity $E_{\rm extra}$, defined by

$$E_{\rm extra} = \sum_i E_i, \quad (6)$$

where E_i is the CM frame energy of a given particle, and the sum runs over all tracks and clusters not associated with the $B_{\rm tag}$ or the lepton candidate. We select events with $E_{\rm extra} < 1.2\,{\rm GeV}$. The resulting selection efficiencies after applying the above selection criteria are $(0.122 \pm 0.012)\,\%$ and $(0.145 \pm 0.013)\,\%$ for e and μ modes, respectively, where the uncertainties include only MC statistics.

Backgrounds potentially arise either from sources with a peak in $B_{\rm tag}$ m_{ES}, or which are combinatorial in $B_{\rm tag}$ m_{ES}. One source of the nonpeaking background is from the misreconstruction of the decay products of $\tau^+\tau^-$ or $q\bar{q}$ ($q = u, d, s, c$). These backgrounds are strongly suppressed by event shape requirements. Nonpeaking background can also arise from misreconstructed B_{tag} candidates in $B\overline{B}$ events.

No nonpeaking background events in MC ($\tau^+\tau^-$ and $q\bar{q}$ samples are approximately equal to the data luminosity, and $B\overline{B}$ sample is ~ 5 times the data sample) pass the selection criteria. The absence of nonpeaking background is verified by studying the p^* and m_{ES} sidebands ($2.0\,{\rm GeV} < p^* < 2.5\,{\rm GeV}$ and $5.22\,{\rm GeV}/c^2 < m_{ES} < 5.26\,{\rm GeV}/c^2$). The ratios of the number of events in these sidebands are used to extrapolate the background level in the signal region. For B^+B^- events, the nonpeaking contribution is estimated by fitting the m_{ES} distribution with a combination of a Gaussian and an ARGUS function [16]. The background estimate from the sidebands is consistent with the prediction from the MC of no nonpeaking background. As can be seen in Fig. 1, the m_{ES} sideband region is well modeled by background MC up to the uncertainties arising from the relative cross sections of various decay modes. For nonpeaking events, the quantities p^* and m_{ES} are assumed to be uncorrelated in both the signal and sideband regions.

In peaking background events, $B_{\rm tag}$ is correctly reconstructed, but the $B_{\rm signal}$ decays via a non-signal mode. The most likely backgrounds are $b \to u\ell\nu_\ell$ events and two-body decays with a misidentified π, where the signal lepton may be near the kinematic endpoint. The total B^+B^- background (nonpeaking and peaking together) is estimated by counting the number of events in the MC sample that pass the selection criteria. Requirements on the signal-lepton momentum and the missing momentum are especially important in discerning the signal events. After rescaling as discussed below, the B^+B^- contribution to the background is estimated to be $0.115^{+0.131}_{-0.075}$ and $0.229^{+0.167}_{-0.142}$ events per $209\,{\rm fb}^{-1}$, for e and μ modes respectively. Since the contributions from the other background types are found to be negligible, the above quantities are taken as the total background estimates.

4 SYSTEMATIC STUDIES

The study of the lepton-momentum sidebands reveals a slight discrepancy between the m_{ES} peaking B^+B^- yields in data and in MC. To estimate the $B_{\rm tag}$ yield in the samples, the m_{ES} distribution for the on-resonance data sample is studied after subtracting the normalized off-resonance m_{ES} distribution from it. To compensate for the CM energy difference, the off-resonance m_{ES} distribution is shifted by $\sim 20\,\text{MeV}$, matching the kinematic endpoints of the two distributions. The precise values of the required energy shift are determined by comparing the on-resonance and off-resonance CM energy distributions. By fitting a sum of a Gaussian and an ARGUS function to the background subtracted m_{ES} distribution, we determine the parameters for the shape of the nonpeaking contribution. Another set of such parameters is estimated by a similar fit using a simulated $B\overline{B}$ sample. These parameters are used to fit the signal region in the data and MC $B\overline{B}$ samples. The yields are calculated by integrating the Gaussian component of the resulting fits, resulting in a range of values for the yield (see Table 1). The scaling factor, which is the ratio of the data and the MC yields, is calculated to be $0.908 \pm 0.013(stat) \pm 0.015(syst)$, where the systematic error arises from the uncertainties involved in the fitting procedure. It is notable that while the yield itself has a large uncertainty of $\sim 8.8\,\%$, the ratio between the data and MC yields are less dependent on the exact shape of the nonpeaking contribution. Applying the correction factor to quantities determined from the $B\overline{B}$ MC sample introduces a systematic error. However, the signal efficiency and the background estimates determined from MC samples are statistically limited.

Table 1: The peaking $B\overline{B}$ yields resulting from using different ARGUS function shapes for describing the combinatorial contribution. The yields are expressed in B^+B^- pairs per fb^{-1}.

ARGUS shape source	MC yield	Data yield	correction
From Data	2253.38	2018.25	0.896
From MC sample	2581.89	2380.38	0.922
Average			0.908±0.013

Tracking efficiency uncertainties are considered, introducing an additional $0.8\,\%$/track systematic error on the signal efficiency and the background estimate. The lepton-identification efficiencies for data and MC are compared and correction factors of 0.96 ± 0.01 and 0.962 ± 0.015 are determined for e and μ respectively. This correction factor affects all quantities determined from MC samples, introducing a systematic uncertainty. The misidentification rate of leptons as pions is also studied. The difference between the misidentification rates between data and MC introduces a correction factor to background estimates. In the case of muons, the pion misidentification rate is estimated to be $(5.0 \pm 0.5)\,\%$ for MC and $(5 \pm 1)\,\%$ for data. For the electron identification, the discrepancy is larger with misidentification rates of $(0.01 \pm 0.01)\,\%$ in MC and $(0.05 \pm 0.02)\,\%$ in data. This difference requires the number of background events, estimated from MC, to be scaled appropriately. However, as all MC events that pass the selection criteria are verified to have a correct lepton identification, we do not include a misidentification-rate correction to the background estimate. Additional systematic errors, associated with the quantities E_{extra} and ΔP^*_{miss}, are estimated by varying the selection criteria by $100\,\text{MeV}$. The variations in the signal efficiencies are found to be very small, requiring no further additions to the systematics.

The efficiencies and the background estimates, after applying all corrections, are listed in Table 2. The ϵ_{tag} and ϵ_{sig} correspond to the efficiencies of the B_{tag} reconstruction in the signal region and the signal-lepton selection respectively. The ϵ_{tot} represents the product of these two quantities. The quantities N_{bg}, N_{SM} and N_{obs} represent, respectively, the number of estimated background events, the expected number of signal events according to the SM branching fractions and the number of signal candidates observed in the data.

Table 2: Efficiencies and background estimates, used for calculating the branching fractions, after applying all corrections. The first error is statistical, the second is systematic.

Quantity	$B \to \mu^+ \nu_\mu$	$B \to e^+ \nu_e$
$\sigma_{B\bar{B}}$	1.05nb	
$\mathcal{L}$	$208.7 fb^{-1}$	
$N_{B\bar{B}}$	229.953×10^6	
$\epsilon_{\rm tag}$ (%)	$0.239 \pm 0.013 \pm 0.004$	$0.247 \pm 0.013 \pm 0.004$
$\epsilon_{\rm sig}$ (%)	$60.5 \pm 4.0 \pm 1.0$	$49.4 \pm 3.8 \pm 0.8$
$\epsilon_{\rm tot}$ (%)	$0.145 \pm 0.013 \pm 0.003$	$0.122 \pm 0.012 \pm 0.003$
$N_{\rm bg}$	$0.229^{+0.167}_{-0.142} \pm 0.007$	$0.115^{+0.131}_{-0.075} \pm 0.004$
$N_{\rm SM}$	~ 0.03	$\sim 3 \times 10^{-7}$
$N_{\rm obs}$	0	0

5 PHYSICS RESULTS

Fig. 3 shows the momentum distribution of the signal lepton in the B_{signal} frame for data and background MC. The absence of events in the signal region is consistent with SM expectations.

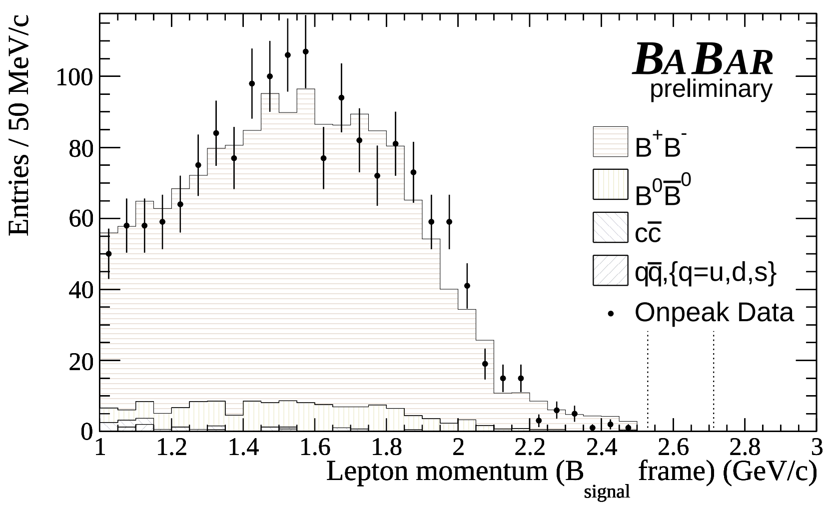

Figure 3: Signal-lepton momentum in $B_{\rm signal}$ frame after all signal selection criteria. No events in data are present in the signal region.

The branching fraction $\mathcal{B}$ is given by

$$\mathcal{B}(B^+ \to l^+\nu_l) = \frac{N_{\rm obs} - N_{\rm bg}}{2 \cdot N_{B^+B^-} \cdot \epsilon_{tot}}, \tag{7}$$

where $N_{\rm obs}$ is the number of events that pass the selection, $N_{\rm bg}$ is the estimated background count, $N_{B^+B^-}$ is the number of B^+B^- pairs in the data sample, and $\epsilon_{\rm tot}$ is the total efficiency of the selection given by signal MC. The upper limit on $\mathcal{B}$ at the 90% confidence level is determined using a frequentist procedure that incorporates systematic uncertainties in the signal efficiency and expected number of background events [17]. This procedure yields $\mathcal{B}(B^+ \to e^+\nu_e) < 7.9 \times 10^{-6}$ and $\mathcal{B}(B^+ \to \mu^+\nu_\mu) < 6.2 \times 10^{-6}$ at the 90% confidence level.

6 SUMMARY

We have set the branching fraction upper limits for rare leptonic decays $B^+ \to e^+ \nu_e$ and $B^+ \to \mu^+ \nu_\mu$ to be 7.9×10^{-6} and 6.2×10^{-6} respectively, at the 90% confidence level. Both results are consistent with the Standard Model and represent improvements to the most stringent published upper limits to date.

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A Appendix

Appended are additional plots of interest.

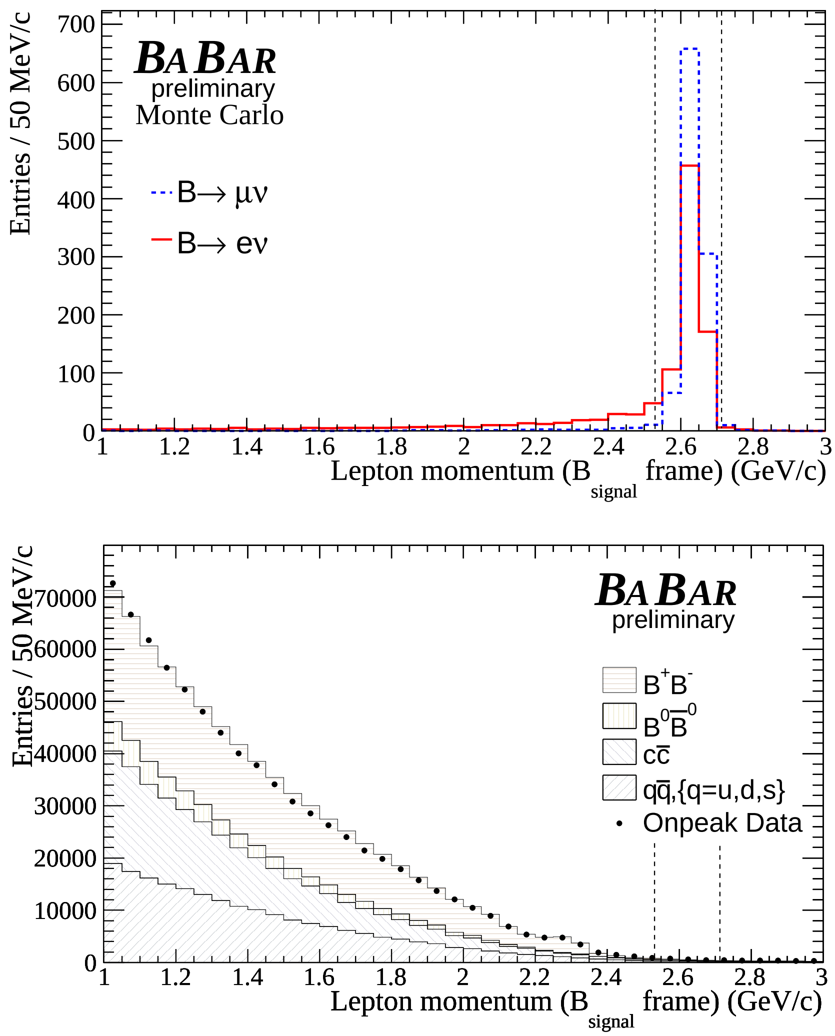


Figure 4: The distribution of the lepton candidate momentum in the B_{signal} frame. The events are required to pass all reconstruction cuts. The signal $B^+ \to \mu^+ \nu_\mu$ and the backgrounds are scaled to onpeak data luminosity, assuming SM predictions for branching fractions. The signal $B^+ \to e^+ \nu_e$ is scaled with respect to $B^+ \to \mu^+ \nu_\mu$ by the relative luminosity of the sample size.

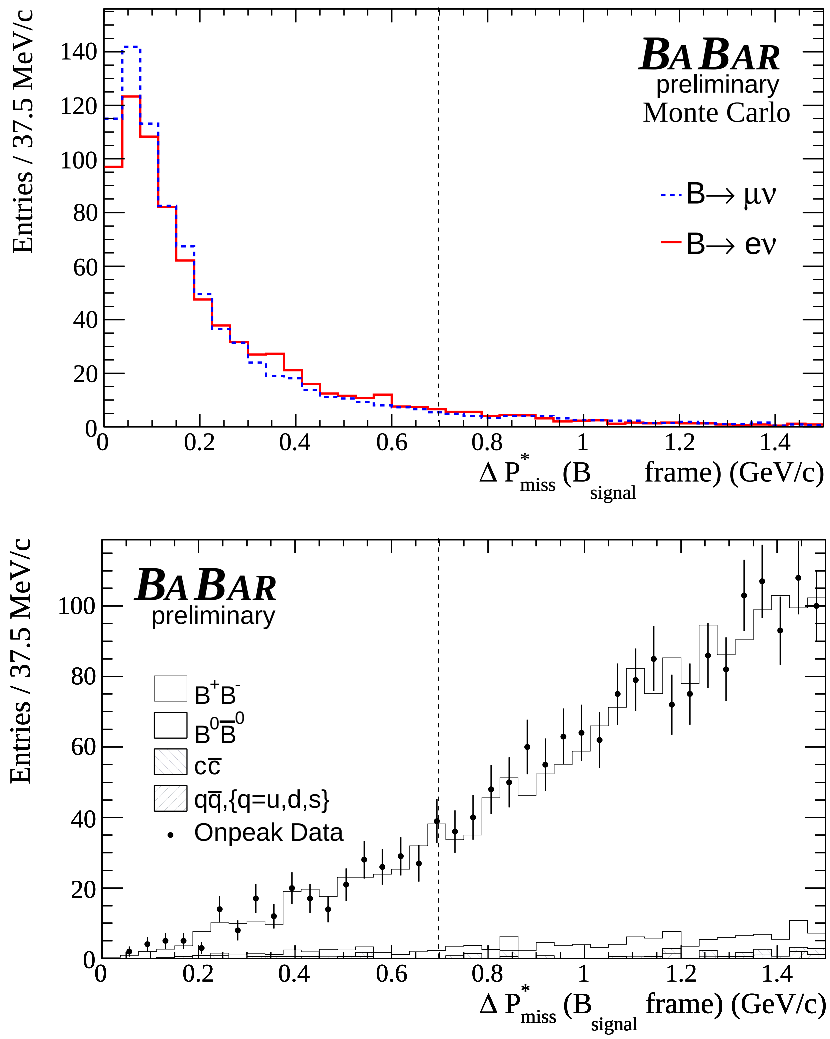
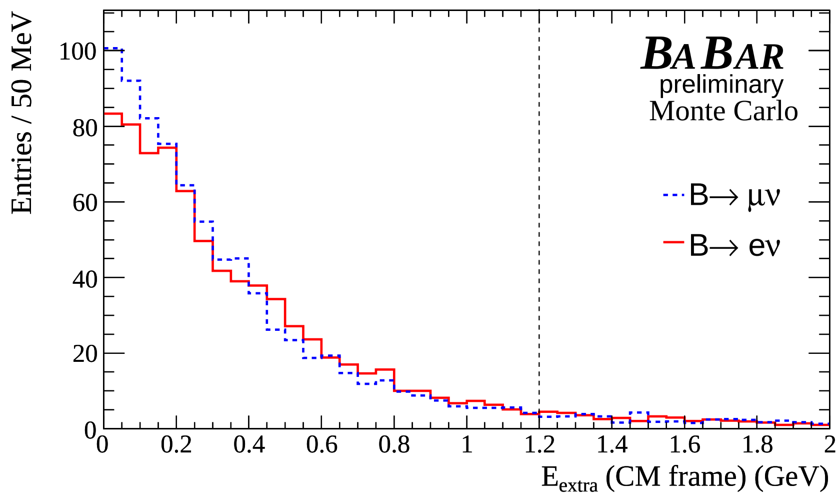


Figure 5: The distribution of ΔP^*_{miss}, for signal and background samples. The events are required to pass all reconstruction and signal cuts (with a relaxed requirement of $p^* > 2.0\,\text{GeV}$ to increase background statistics). The signal $B^+ \to \mu^+ \nu_\mu$ and the backgrounds are scaled to onpeak data, assuming SM predictions for branching fractions. The signal $B^+ \to e^+ \nu_e$ is scaled with respect to $B^+ \to \mu^+ \nu_\mu$ by the relative luminosity of the sample size.



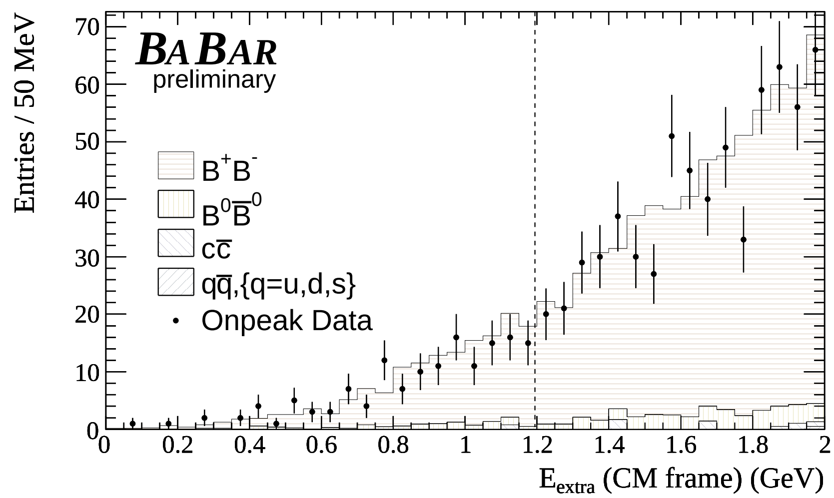


Figure 6: E_{extra}, the total energy not accounted for by the signal lepton candidate, distribution. The events are required to pass all reconstruction and signal cuts (with a relaxed requirement of $p^* > 2.0\,\text{GeV}$ to increase background statistics). The signal $B^+ \to \mu^+ \nu_\mu$ and the backgrounds are scaled to onpeak data luminosity, assuming SM predictions for branching fractions. The signal $B^+ \to e^+ \nu_e$ is scaled with respect to $B^+ \to \mu^+ \nu_\mu$ by the relative luminosity of the sample size.