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A Search for $B^+ \to K^+\nu\overline{\nu}$

The *BABAR* Collaboration

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Abstract

We present a preliminary search for the flavor-changing neutral current decay $B^+ \to K^+\nu\overline{\nu}$ using 56 million $\Upsilon(4S)$ decays recorded with the *BABAR* detector at the SLAC B factory. Identification of the $B^+ \to K^+\nu\overline{\nu}$ final state, with two neutrinos, requires the reconstruction of the companion B in the event. The companion B is reconstructed in the decay mode $B^- \to D^0\ell^-\overline{\nu}\,X$, which provides both high efficiency and good purity. The particles not used in the reconstruction of the companion B are compared with the signature expected for $B^+ \to K^+\nu\overline{\nu}$ decays. Two candidates are found in the data with an expected background of 2.2 events. Under the assumption that all candidates are signal events, an upper limit on the branching fraction for $B^+ \to K^+\nu\overline{\nu}$ of 9.4×10^{-5} at 90% confidence level is determined.

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1 Introduction

The investigation of flavor-changing neutral current (FCNC) decays is of fundamental interest. In the Standard Model (SM) these decays are forbidden at tree level, and occur only in loop diagrams. As a result, their rates are highly suppressed. The SM prediction for the FCNC decay $b \to s\nu\overline{\nu}$ is nearly free from strong interaction effects and has very small theoretical uncertainty. An observation of this decay at a level significantly above the SM prediction would provide unambiguous evidence for new physics.

Within the SM the decay $b \to s\nu\overline{\nu}$ proceeds through W box diagrams and Z penguin diagrams. The expected branching fraction, summed over all neutrino species, is [1]

$$\mathcal{B}(b \to s\nu\overline{\nu}) = \left(4.1^{+0.8}_{-1.0}\right) \times 10^{-5} \quad . \tag{1}$$

At present it does not appear to be feasible to search for the inclusive decay $b \to s\nu\overline{\nu}$; however, the decay $B^+ \to K^+\nu\overline{\nu}$ is tractable.[1] The expected branching fraction for $B^+ \to K^+\nu\overline{\nu}$, summed over all neutrino species, is [2]

$$\mathcal{B}(B^+ \to K^+\nu\overline{\nu}) = \left(0.38^{+0.12}_{-0.06}\right) \times 10^{-5} \quad . \tag{2}$$

The best previous experimental limit is $\mathcal{B}(B^+ \to K^+\nu\overline{\nu}) < 2.4 \times 10^{-4}$ at 90% confidence level [3].

2 The dataset

The data used in this analysis were collected with the *BABAR* detector, which is described elsewhere [4], at the PEP-II storage ring. The integrated luminosity used in this analysis is $50.7\,\mathrm{fb}^{-1}$ recorded at the $\Upsilon(4S)$ resonance, corresponding to 56.3×10^6 $B\overline{B}$ events, and $6.4\,\mathrm{fb}^{-1}$ taken at energies just below $B\overline{B}$ threshold. Simulated data samples for the processes $e^+e^- \to B\overline{B}$, $e^+e^- \to q\overline{q}$ ($q = u,\ d,\ s$ or c) and $e^+e^- \to \tau^+\tau^-$, in quantities comparable to the data, are used to study backgrounds. A sample of 280 000 simulated B^+B^- events with $B^+ \to K^+\nu\overline{\nu}$ and the other B decaying generically have also been analyzed. The simulation of $B^+ \to K^+\nu\overline{\nu}$ decay is based on the form factor model in Ref. [2].

3 Analysis method

The presence of two neutrinos in the final state makes the search for $B^+ \to K^+\nu\overline{\nu}$ difficult, since no kinematic constraints can be applied to the signal B. The strategy adopted in this analysis is to reconstruct exclusively the decay of one of the B mesons in the event, referred to as the "tag" B, and to compare the remaining particle(s) in the event with the signature expected for the decay $B^+ \to K^+\nu\overline{\nu}$. The low multiplicity of the signal decay greatly reduces the combinatorial background in the tag reconstruction, allowing the use of decay modes that would not be sufficiently clean in other circumstances. These considerations lead to the use of the semileptonic decay $B^- \to D^0\ell^-\overline{\nu}\ X$ for the reconstruction of the tag B. The X system is kinematically constrained to be either nothing or a low-momentum pion or photon from a higher mass charm state. The D^0 is reconstructed in the $K^-\pi^+$, $K^-\pi^+\pi^-\pi^+$ and $K^-\pi^+\pi^0$ modes. This method results in roughly 0.5% of B^- decays being reconstructed as tags. Note that particles from

[1] Charge conjugate modes are implied throughout.

the tag B that escape detection will not affect the sensitivity of the analysis to $B^+ \to K^+\nu\overline{\nu}$ events; the reconstructed $D\ell$ needs to be a correct, but not complete, subset of the particles produced in the tag B decay. The feed-down from higher-mass charm states often results in good tags in this sense, and thus in an enhanced tagging efficiency.

The event selection proceeds as follows. Selected hadronic events are required to have an identified electron or muon with a momentum above 1.3 GeV/c in the $\Upsilon(4S)$ rest frame. The electron identification is based on quantities from the electromagnetic calorimeter (EMC), the ring-imaging Cherenkov detector (DIRC) and the gas (DCH) and silicon (SVT) tracking devices. The muon identification uses information from the instrumented flux return (IFR) in addition to the devices listed previously. Loose consistency requirements are placed on the charged particle

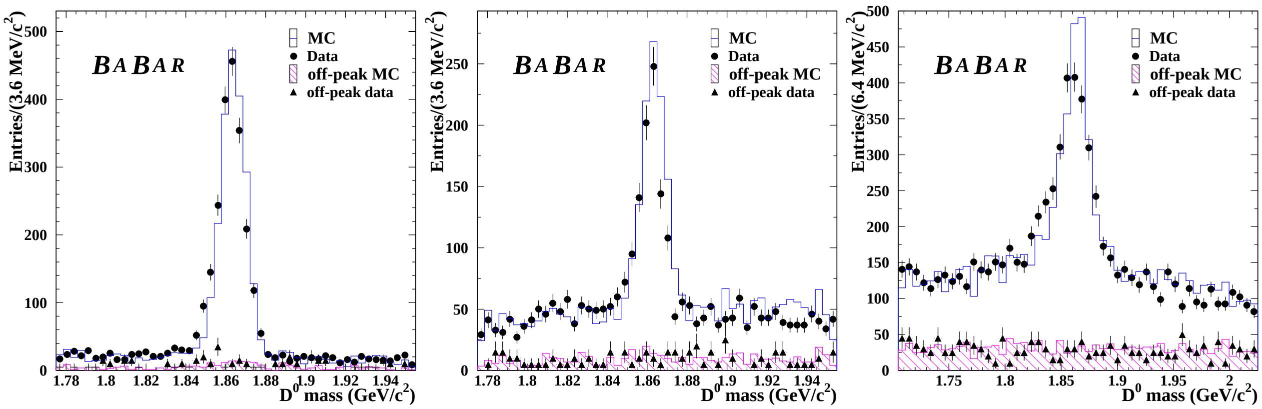

Figure 1: The candidate D^0 invariant mass distributions are shown, from left to right, in the $K^-\pi^+$, $K^-\pi^+\pi^-\pi^+$ and $K^-\pi^+\pi^0$ modes for data (points) and simulation (histogram), for events with no more than three charged tracks and less than 1 GeV of neutral energy not assigned to the tag B candidate. Events are required to have no more than three charged tracks not associated with the tag B in order to mimic the low multiplicity of the signal while maintaining adequate statistics in the plots. The off-resonance distributions have been scaled to the on-peak data luminosity.

vertices for the D^0 and $D^0\ell^-$ candidates. The following kinematic requirements are imposed: $p^*_{D^0} > 0.5\,\mathrm{GeV}/c$, $m_{D^0\ell^-} > 3\,\mathrm{GeV}/c^2$ and $-2.5 < \cos\theta_{B,D\ell} < 1.1$, where $p^*_{D^0}$ is the momentum of the D^0 in the $\Upsilon(4S)$ frame, $m_{D^0\ell^-}$ is the mass of the $D^0\ell^-$ combination and

$$\cos\theta_{B,D\ell} = \frac{2\,E_B E_{D\ell} - m_B^2 - m_{D\ell}^2}{2\,|\vec{p}_B||\vec{p}_{D\ell}|} \quad . \tag{3}$$

Here E_B and $|\vec{p}_B|$ are respectively the energy of and magnitude of the momentum of the B meson in the $\Upsilon(4S)$ frame. E_B is one half of the center-of-mass energy of the e^+e^- initial state, and $|\vec{p}_B|$ is $\sqrt{(E_B^2 - m_B^2)}$. The upper limit on $\cos\theta_{B,D\ell}$ is 1.1 to account for resolution on the measurement (the signal cannot exceed 1). The lower limit is relaxed to increase efficiency for the feed-down from decays of the type $B^- \to D^{*0}\ell^-\overline{\nu}$ and $B^- \to D^{**0}\ell^-\overline{\nu}$. The requirement on $\cos\theta_{B,D\ell}$ is the most important for restricting the kinematics of the $D^0\ell^-$ to be consistent with coming from a semileptonic B decay. In cases where more than one $D^0\ell^-$ candidate is reconstructed, the one with the smallest value of $|\cos\theta_{B,D\ell}|$ is used. The reconstructed D^0 invariant mass distributions are shown in Fig. 1.

Once the tag B is selected, additional requirements are placed on the remaining particles in the event. There must be exactly one charged track in the event that is not part of the tag B, its charge must be opposite to that of the tag lepton, and it must satisfy the particle identification criteria for charged kaons, which are based on information from the DIRC and tracking system. The momentum spectrum, in the $\Upsilon(4S)$ rest frame, for the kaon from $B^+ \to K^+\nu\overline{\nu}$ decays peaks near the upper kinematic limit while the spectrum for background peaks at low momentum; the signal kaon candidate is thus required to satisfy $p^*_K > 1.5\,\mathrm{GeV}/c$ (see Fig. 2). The angle $\theta^*_{K,\ell}$ between the charged lepton and the signal kaon is isotropically distributed in signal events, since these particles originate from different B mesons, while the background from $e^+e^- \to q\overline{q}$ and $e^+e^- \to \tau^+\tau^-$ peaks forward and backward in this angle; we require $-0.9 < \cos\theta^*_{K,\ell} < 0.8$. In addition to the above requirements on charged tracks, we use information from the EMC and IFR to limit additional neutral particles in the event. The $B^+ \to K^+\nu\overline{\nu}$ signal leaves very little neutral energy in the detector and does not contain any neutral hadrons. We therefore require that the number of IFR clusters consistent with neutral hadrons (N_{IFR}) be zero, and that the energy deposited in the EMC, once the daughters from the $D\ell$ have been removed, (referred to as E_{left} or remaining neutral energy) satisfies $E_{\mathrm{left}} < 0.5\,\mathrm{GeV}$ (see Fig. 2).

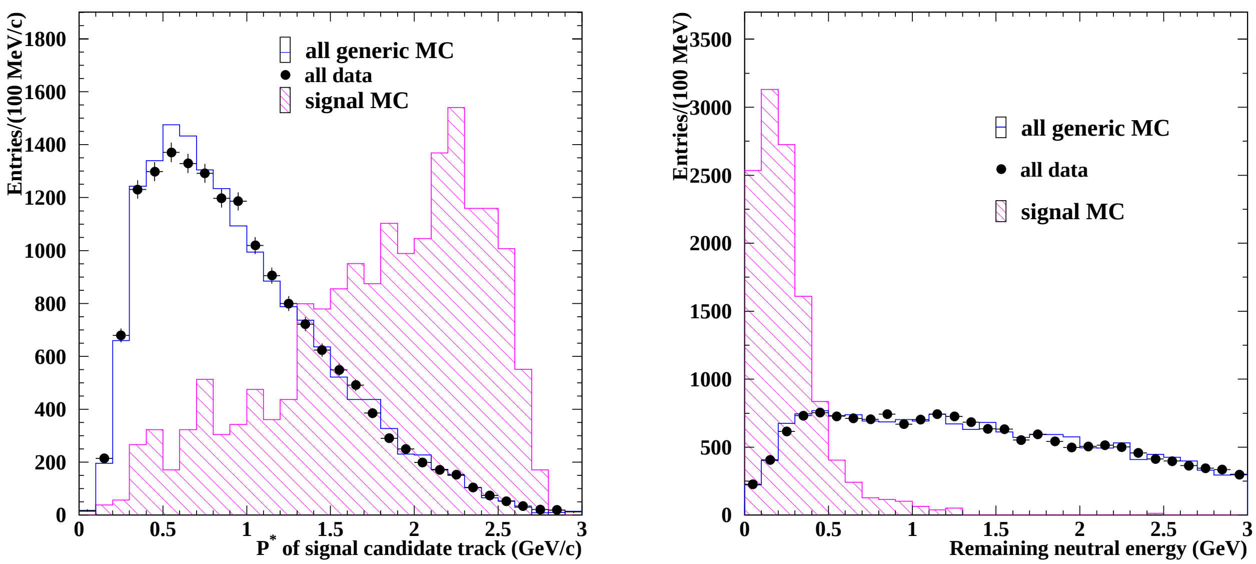

Figure 2: The distributions of p^*_K and E_{left} for simulated signal and background events. Events with no more than three charged tracks and less than 1 GeV of neutral energy not assigned to the tag B candidate are used for the plot on the left whereas the neutral energy requirement is relaxed to be less than 3 GeV for the plot on the right. The generic MC distribution has been scaled to the on-peak data luminosity with an arbitrary scale factor applied to the signal MC distribution.

The yields in the signal and sideband regions at each stage in the application of the selection criteria are given in Table 1 for the on-peak data and background Monte Carlo, along with the efficiency for the signal Monte Carlo. The distribution of events in the search plane defined by the variables[2] E_{left} and $(m_D - m_D^{\mathrm{fit}})/\sigma_D^{\mathrm{fit}}$ is shown in Fig. 3. The signal box is defined by the

[2]The quantities m_D^{fit} and σ_D^{fit} are the mean and sigma from Gaussian fits to the D^0 invariant mass spectrum. Separate values are calculated for each D^0 decay mode in data and simulation.

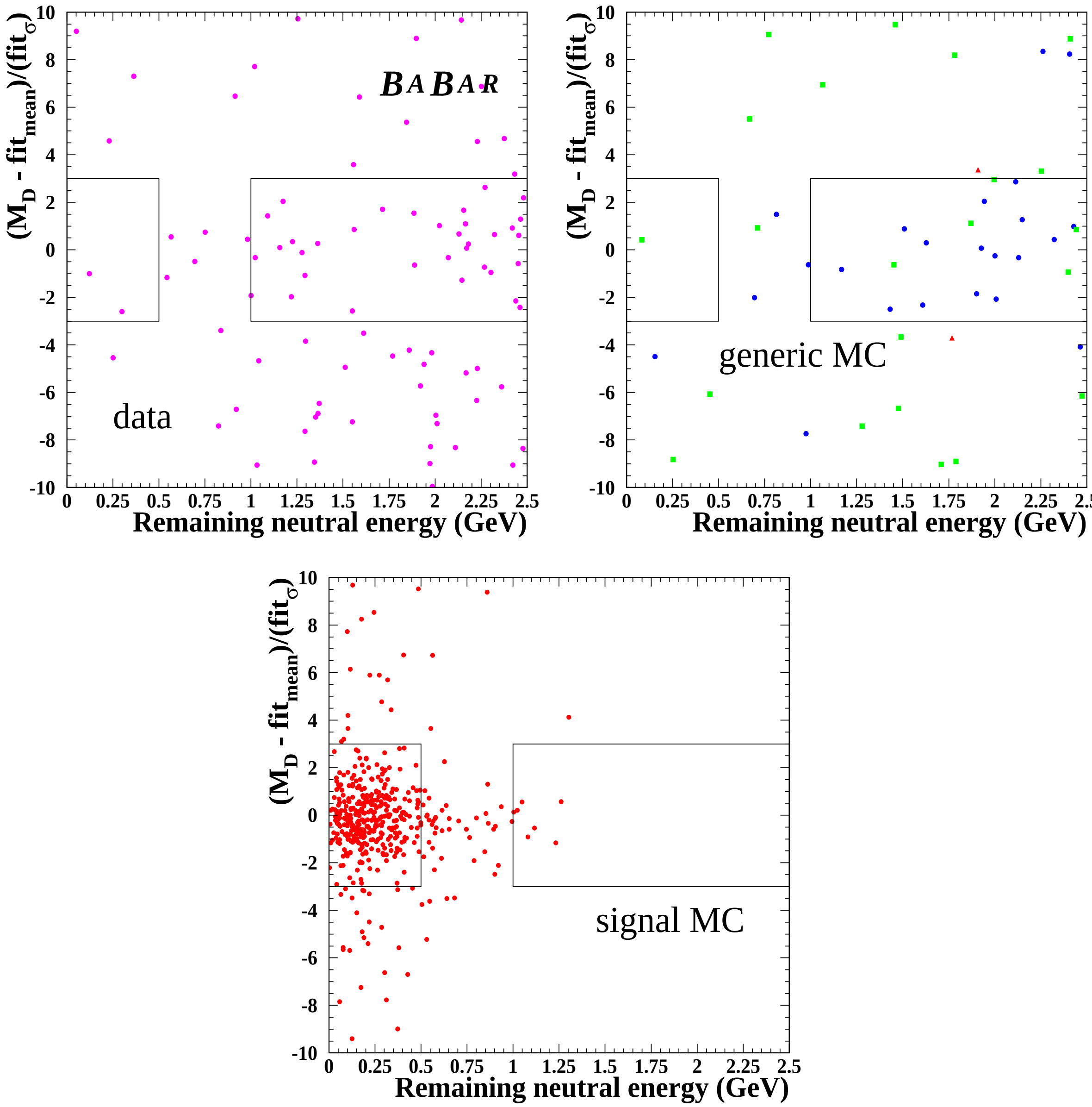

Figure 3: The distribution of events in the $(m_D - m_D^{\rm fit})/\sigma_D^{\rm fit}$ versus $E_{\rm left}$ plane for on-peak data, generic $B\overline{B}$ and continuum Monte Carlo and signal Monte Carlo. In the generic Monte Carlo plot the circles show the contribution from $B\overline{B}$ events, the squares show the contribution from $c\overline{c}$ and the triangles show the contribution from $u\overline{u}/d\overline{d}/s\overline{s}$. The MC has not been scaled to the data luminosity.

Table 1: The number of events passing the selection criteria for on-peak data, on-peak Monte Carlo contributions, off-peak data, off-peak Monte Carlo contributions and $B^+ \to K^+\nu\overline{\nu}$ signal Monte Carlo efficiency. The number of events in the Monte Carlo sample are scaled to the equivalent luminosity in data. The values include the correction factors for tag efficiency, $E_{\rm left}$ and $N_{\rm IFR}$ referred to in the text.

	On-peak (50.7 fb^{-1})		Off-peak (6.4 fb^{-1})		signal MC
Requirement	data yield	MC yield	data yield	MC yield	effic $\cdot 10^4$
Tag, no extra tracks	8998	8525.7	415	389.9	34.3
Kaon identification	717	707.4	49	46.8	24.3
$\cos\theta^*_{K,\ell}$	485	486.2	32	25.0	20.9
p^*_K	101	89.4	7	5.1	14.2
$N_{\rm IFR}$	79	72.5	6	4.4	12.0
$E_{\rm left}$ sideband	34	27.4	3	1.4	0.2
D^0 mass sideband	4	7.1	1	0.8	2.0
Signal box	2	2.2	0	0.3	10.3

requirements $E_{\rm left} < 0.5\,{\rm GeV}$ and $|m_D - m_D^{\rm fit}| < 3\sigma_D^{\rm fit}$. The expected background from the Monte Carlo is 2.2 events.

In order to minimize experimental bias, the signal region was hidden until the selection criteria were finalized. In order to evaluate how well the simulation describes the data, we define auxiliary samples. Two sideband regions are studied: the D^0 mass sideband, defined by the conditions $|m_D - m_D^{\rm fit}| > 3\sigma_D^{\rm fit}$ and $E_{\rm left} < 0.5\,{\rm GeV}$, and a sideband where the additional neutral energy is required to be in the range $1.0 < E_{\rm left} < 2.5\,{\rm GeV}$. The D^0 mass sideband contains incorrectly reconstructed B decays and continuum events whereas the $E_{\rm left}$ sideband is sensitive to correctly reconstructed B tags where the other B leaves only a single detected charged track and substantial missing energy, often in the form of neutral hadrons. The event yields in these regions are also listed in Table 1.

In addition to the sideband samples, we use "double-tagged" events, in which both B^+ and B^- mesons are reconstructed as $B \to D\ell\nu X$, to quantify the uncertainty in the efficiency of several of our signal criteria. We reconstruct double-tagged events by finding a suitable $D^0\ell^-$ candidate where the D^0 decays to $K^-\pi^+$, and then looking for a second $\overline{D}^0\ell^+$ candidate in any of the accepted $\overline{D}^0$ modes. No particle is assigned to more than one of the $D\ell$ candidates. In addition it is required that the event contain no charged tracks that are not assigned to a $D\ell$ candidate.

The reconstructed invariant masses of the D^0 and $\overline{D}^0$ candidates in double-tagged events that satisfy the above criteria are shown in Fig. 4 for data and for Monte Carlo. After subtracting combinatorial background, the number of double-tagged events satisfying the requirement that $|m_D - m_D^{\rm fit}| < 3\sigma_D^{\rm fit}$ for each D candidate is 148 ± 15 in data and 175 ± 16 in the Monte Carlo sample.[3] The number of double-tagged events per fb^{-1} in the data is 0.85 ± 0.11 times the rate in the simulation. This factor is roughly the square of the data/Monte Carlo efficiency ratio for the tag efficiency (including the requirement that there be no additional charged tracks associated with the tag - see the first entry in Table 1). The signal efficiency is therefore corrected by a factor 0.92 ± 0.06, where the uncertainty is taken as a systematic error.

[3]The number of events in the Monte Carlo sample has been scaled to the on-peak data luminosity.

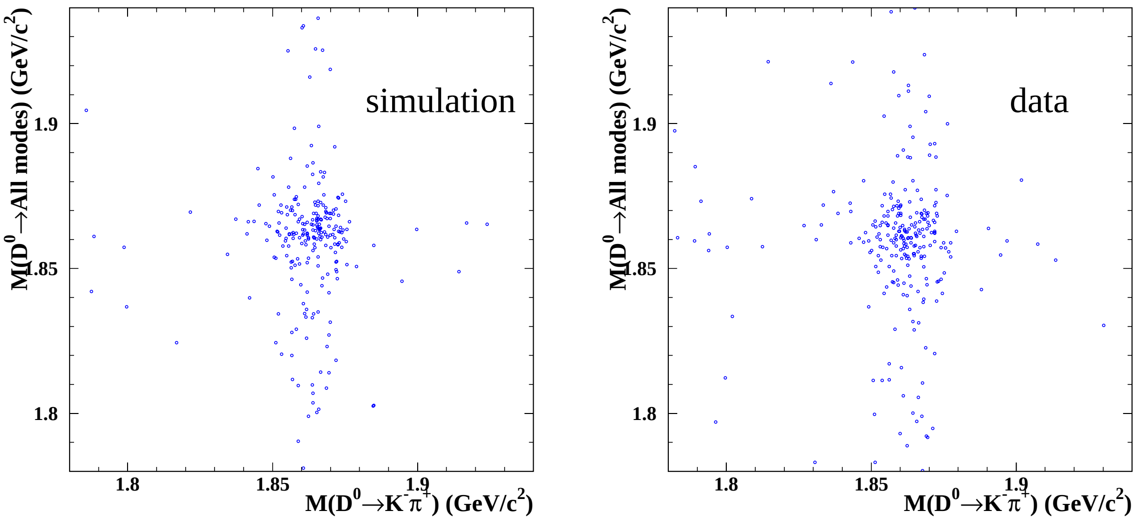

Figure 4: Mass of the $\overline{D}^0$ candidate decaying to all three modes considered versus the $D^0 \to K^-\pi^+$ mass for events in which both B mesons are reconstructed in the $D\ell\,\nu X$ decay mode and no additional charged particles are recorded. The plot on the left (right) shows the results from the simulation (on-peak data).

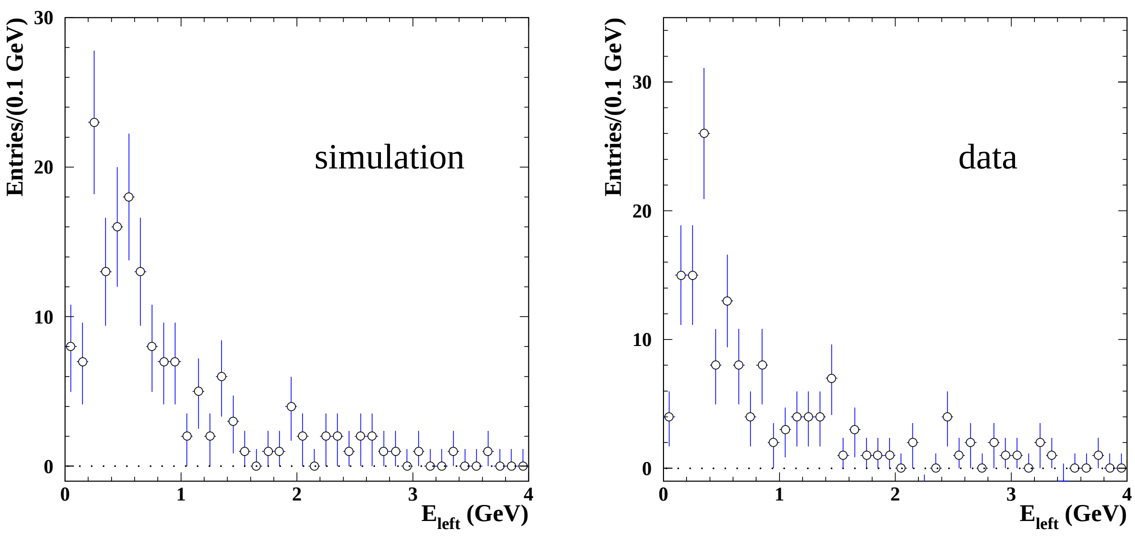

Figure 5: The distribution of E_{left} for "double-tagged" events where both B mesons are reconstructed in the $D\ell\,X$ decay mode and no additional charged particles are recorded. The plots on the left (right) show the distribution from simulation (on-peak data).

Table 2: A summary of the systematic uncertainties on $\mathcal{B}(B^+ \to K^+\nu\overline{\nu})$. $\delta\epsilon/\epsilon$ is the relative uncertainty on the overall efficiency.

Quantity	$\delta\epsilon/\epsilon[\%]$
$B\overline{B}$-counting	1.1
Tagging efficiency	6.0
K selection	2.0
$\cos\theta^*_{K,\ell}$	–
$E_{\rm left}$	4.3
$N_{\rm IFR}$	3.6
K momentum	1.8

The double-tagged events also allow a study of how well the variables $N_{\rm IFR}$ and $E_{\rm left}$ are simulated. Figure 5 shows the distribution of the $E_{\rm left}$ variable in the double-tagged events; the D^0 mass sidebands have been used to subtract the combinatorial background. The mean values of $E_{\rm left}$ in the data and simulation are $0.91 \pm 0.08\,\mathrm{GeV}$ and $0.84 \pm 0.07\,\mathrm{GeV}$, respectively. The fraction of double-tagged events satisfying the requirement $N_{\rm IFR} = 0$ is 0.87 ± 0.03 in data and 0.93 ± 0.02 in simulation. These comparisons are used to adjust the simulated signal efficiencies and assign systematic errors.

Systematic uncertainties on the efficiency of selection criteria based on the total number of events with $\Upsilon(4S)$ mesons, tagging efficiency, K selection and momentum, $E_{\rm left}$ and $N_{\rm IFR}$ have all been studied. The total relative uncertainty on the selection efficiency is found to be $\delta\epsilon/\epsilon = 8.7\%$ where the tagging efficiency and $E_{\rm left}$ contribute the largest uncertainties. The systematic uncertainties are summarised in Table 2.

4 Physics results

The signal region was unblinded to reveal two events, consistent with the 2.2 events predicted with the simulation. The number of $B^+ \to K^+\nu\overline{\nu}$ candidates in the data is thus compatible with the background expectation. For the purpose of setting an upper limit, each candidate is assumed to be signal. The Poisson upper limit for 2 events is 5.3. This upper limit must be modified to account for the uncertainty in the efficiency. Using the prescription advocated in [5] increases the upper limit to 5.4 events, from which we find

$$\mathcal{B}(B^+ \to K^+\nu\overline{\nu}) < 9.4 \times 10^{-5} \quad \text{(preliminary)} \tag{4}$$

at 90% confidence level.

The background at present appears to be mostly combinatorial, based for example on the lack of any D^0 peak in the continuum in Fig. 1. Further refinements may enable this background to be suppressed; the combinatorial component of the background can also be subtracted in the future.

The approach used in this analysis can easily be extended to $\overline{B}^0 \to \overline{K}^0\nu\overline{\nu}$ and $B \to K^*\nu\overline{\nu}$ as well as to $B^+ \to \tau^+\nu$.

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