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A Search for $B \to \tau\nu$

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Abstract

We search for the decay $B^- \to \tau^- \bar{\nu}_\tau$ in a sample of over 2 million charged B decays using the CLEO detector. We use the channel in which the tau decays leptonically, and combine this lepton with the missing energy and momentum in the event to form a B candidate. A fit to the mass and energy distribution of these B candidates yields -14 ± 46 signal events. This value corresponds to an upper limit of $\mathrm{B}(B^- \to \tau^- \bar{\nu}_\tau) < 2.2 \times 10^{-3}$ at the 90% confidence level.

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I. INTRODUCTION

The purely leptonic decays of mesons are perhaps the simplest of all known decays of hadrons. Unlike all other decays, the final state is unaffected by strong interactions. As a consequence, the rate for these decays can be predicted by many models of particle interactions, and measurement of the rate can provide information about a particular model that can be interpreted easily. In this paper we report on a new search for the leptonic decay $B^- \to \tau^- \bar{\nu}_\tau$[1].

In the Standard Model, the leptonic decays proceed through the annihilation of the constituent quarks in the meson into a virtual W^- boson. For pseudoscalar mesons the branching fraction is given by:

$$\mathrm{B}(P^+ \to \ell^+ \nu_\ell) = \frac{\mathrm{G}_\mathrm{F}^2 m_P m_\ell^2}{8\pi} \left(1 - \frac{m_\ell^2}{m_P^2}\right)^2 f_P^2 \left|V_{qq'}\right|^2 \tau_P \, . \tag{1}$$

where G_F is the Fermi coupling constant, m_P and m_ℓ are the meson and lepton masses, τ_P is the meson lifetime, and $V_{qq'}$ is the appropriate element of the CKM matrix and gives the coupling of the constituent quarks. The one remaining parameter is f_P, the decay constant, which parameterizes the overlap of the quark wave functions within the meson.

In the case of the B^- all of these quantities are well known [1] except for f_B and V_{ub}. The parameter V_{ub} has been the subject of considerable experimental and theoretical effort, but is currently known with an accuracy of only 25% to 30%. The factor f_B, which has similar uncertainty [2], also appears in the theoretical expression for $B\bar{B}$ mixing, and uncertainty in its value currently limits our knowledge of the CKM matrix element parameter V_{td}. The ratio of the $B \to \tau\nu$ branching fraction to the parameter $\Delta m_B/\Gamma_B$ that describes $B\bar{B}$ mixing is sensitive to V_{ub}/V_{td} with little other uncertainty except on the top quark mass. Including ϵ_K, the parameter describing CP violating mixing in the neutral kaon system, in the denominator of this ratio would remove the top quark mass dependence as well.[2]

The branching fraction predicted by the Standard Model is

$$\mathrm{B}(B^- \to \tau^- \bar{\nu}_\tau) = (4.7 \times 10^{-5}) \left(\frac{f_B}{190\mathrm{MeV}}\right)^2 \left|\frac{V_{ub}}{0.003}\right|^2 \tag{2}$$

where we have used the value $\tau_B = 1.6$ ps and where the numbers appearing in the fractions with f_B and V_{ub} represent reasonable values for these parameters [2] [3].

The decay $B^- \to \tau^- \bar{\nu}_\tau$ also probes physics outside the Standard Model [4] [5]. For example, the decay could proceed through annihilation of the b and $\bar{u}$ quarks into a Higgs particle, in models in which separate Higgs doublets generate the masses of the u-type and d-type quarks (Model II) [5]. Such a mechanism could enhance the $B \to \tau\nu$ decay rate significantly. Failure to observe this decay at the predicted level can narrow the possible range of parameters describing the model.

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[1]Charge conjugation is assumed unless otherwise stated.

[2]Here one assumes that the Standard Model accounts for CP violation.

The outline of this paper is as follows. In Section II we briefly describe the detector, data sample, and the general method. In Section III we give the observed yield. Systematic effects on the yield and the efficiency are discussed in Section IV. The result is given in the concluding Section V.

II. DATA SAMPLE, DETECTOR, GENERAL TECHNIQUE

The data used in this search were taken with the CLEO-II detector operating at the Cornell Electron Storage Ring (CESR), and consist of an integrated luminosity of 2.01fb^{-1} taken on the $\Upsilon(4S)$ (2.2 million $B\bar{B}$ events, 6.6 million continuum events) and 0.99fb^{-1} taken at a center-of-mass energy 60 MeV below the resonance.

The CLEO-II detector is described in detail elsewhere [6], and here we give a brief description of the relevant features. It combines a solenoidal spectrometer for charged particle momentum measurement with a CsI crystal calorimeter for accurate photon detection. The charged tracking system consists of three wire chambers with 57 tracking layers in an axial magnetic field of 1.5 T. The acceptance for charged tracks is approximately 92% of 4π. Charged particles are identified through their specific ionization(dE/dx) in the main drift chamber. The CsI calorimeter is crucial for its ability to accurately measure photon energies down to 30 MeV over 98% of 4π. Electrons are identified by dE/dx and energy-momentum balance. Outside of the magnet coil is a muon system consisting of over one meter of steel with three layers of streamer tubes embedded within. Muon candidates are required to penetrate at least three nuclear absorption lengths of steel.

This search looks for events consistent with $B \to \tau\nu$ followed by $\tau \to \ell\nu\bar{\nu}$. In such events, one observes a lepton plus a number of other particles from the decay of a second B. In particular if the 4-momentum of the lepton is $(E_{\rm lep}, \vec{p}_{\rm lep})$, and the net 4-momentum of all the other detected particles is $(E_{\rm rest}, \vec{p}_{\rm rest})$, then for an ideal event in which all the decay products of the second B are observed and perfectly measured,

- $\Delta E \equiv E_{\rm rest} - E_{\rm beam} = 0$.
- $M \equiv (E^2_{\rm beam} - |\vec{p}_{\rm rest}|^2)^{1/2} = m_B$.
- The missing energy and momenta, defined as $E_{\rm mis} \equiv 2E_{\rm beam} - E_{\rm lep} - E_{\rm rest}$ and $\vec{p}_{\rm mis} \equiv -(\vec{p}_{\rm rest} + \vec{p}_{\rm lep})$ respectively, represent the net energy and momenta of the three unobserved neutrinos. Note that ΔE and M can be viewed as the energy difference and beam-constrained mass of the $B \to \tau\nu$ decay.

This analysis is a search for such events, after suppressing those in which particles are lost or mis-reconstructed, and discarding those events that appear to have come from the continuum. As shown in Figure 1, this procedure leads to a peak for events with a $B \to \tau\nu$ decay; however, there is significant background from $B\bar{B}$ that will have to be subtracted. Continuum events are also present, and are subtracted, using scaled off resonance data, with little statistical impact on the result.

III. YIELD

We first select hadronic events by requiring that there be at least 4 charged tracks, and that the total detected track and shower energy be greater than 15% of the center of mass energy. Between 20% and 90% of this energy must be deposited in the calorimeter. To suppress non-$\Upsilon(4S)$ decays, we select events that are spherical in shape by requiring that the ratio of the second and zero-th Fox-Wolfram moments [7], calculated with charged tracks and neutral calorimeter showers, be less than 0.50. Certain continuum backgrounds are further suppressed by a requirement that $|\cos\theta_{\rm mis}| < 0.95$, where $\theta_{\rm mis}$ is the angle between the missing momentum and the beam line.

We then select events with exactly one identified lepton, which we attribute to the tau decay. Rejecting events with additional leptons reduces the number of events with multiple semileptonic heavy flavor decays, in which multiple neutrinos can fake the signal. To remove events where charged particles were missed we require the sum of the charges of the tracks, ΣQ, to be zero. We also require that the missing energy be less than the beam energy to reduce the continuum contribution from $\tau^+\tau^-$ and $e^+e^-\gamma\gamma$ events.

At this stage we calculate the beam constrained mass M and ΔE. For the purposes of studying cuts and systematic uncertainties, we define a signal region $M > 5.27$ GeV and $-2 \leq \Delta E < 0$ GeV. Also, when we quote signal yields and efficiencies, we count only those events lying in this region. We find a total of 968 events from the on resonance data in this signal region. Continuum events are then subtracted using scaled off resonance data. After this subtraction, 651 ± 40 events remain. The efficiency for a signal event to satisfy all selection criteria and lie in the signal region is $4.1 \pm 0.2\%$, where the error is statistical only. Figure 1 shows the distribution of M versus ΔE at this stage.

We extract the $B \to \tau\nu$ signal by doing a fit in the plane of M versus ΔE over the range $M > 5.15$ GeV and $-2.0 \leq \Delta E < 2.5$ GeV. We fit for the normalizations of three event samples: the $B \to \tau\nu$ signal, the $B\bar{B}$ background in which at least one B has decayed semileptonically, and the $B\bar{B}$ background in which the lepton comes from a secondary decay or a missed pair conversion, or is a hadron that has been mistaken for a lepton. We take the shapes of these three distributions from Monte Carlo.

In the fits, we take special precaution to allow for residual mis-modelling of the energy deposition by neutral hadrons. This is done with a preliminary fit for the contributions by those events in which the measured energy from neutral hadrons is within 500 MeV of their true energy and by those in which it is not. This fit is done only in the region $5.15 < M < 5.22$ GeV/c^2, $-2.0 < \Delta E < -0.5$ GeV or $0.5 < \Delta E < 2.5$ GeV, which is well away from the signal region. We fix the relative normalizations of these two components in the final fit.

Figures 2 and 3 show the ΔE and M distributions respectively for the data and the Monte Carlo after the cut on the other variable. The agreement between the data and the fit is good in the 2 dimensions and in both projections. The fit has a χ^2 of 259 for 267 degrees of freedom. The resulting normalizations of the background samples agree well with the absolute prediction based on luminosity and the $B\bar{B}$ cross section. The fit shows that we should scale the Monte Carlo sample by the factor 0.674 ± 0.008 for best agreement with the data, compared with the absolute prediction of 0.647 ± 0.017. The normalization of events in which the lepton comes from B semileptonic decay relative to those in which it does not is

1.027 ± 0.089, and the normalization of events with well-measured to mis-measured hadronic energy is 0.892 ± 0.042. Finally, the fit finds -14 ± 37 $B \to \tau\nu$ events in the signal region, where the error is statistical only.

IV. SYSTEMATIC EFFECTS

There are three broad sources of systematic uncertainties in turning the observed number of signal events found into a limit on $\mathrm{B}(B^- \to \tau^- \bar{\nu}_\tau)$. The first is how well the Monte Carlo predicts the efficiency. The second is the uncertainty in the signal yield due to uncertainty in the M versus ΔE distributions of the background. The third is due to details of the fit: its range and binning.

A. Uncertainty in the Signal Efficiency

The signal efficiency consists of two components: the first is the probability that an event in which one B decayed via $B \to \tau\nu$ followed by $\tau \to e(\mu)\nu\bar{\nu}$ satisfies the selection criteria up to (but not including) any requirements on M and ΔE. The second is how uncertainty in the shape of the M and ΔE distributions affect the yield that we extract from the fit.

Uncertainty in the efficiency of the selection criteria is dominated by the requirements that there be exactly one lepton, that the net charge of the event be zero, and that $E_{\mathrm{mis}} < E_{\mathrm{beam}}$. According to the Monte Carlo simulation, the probability that we observe exactly one lepton in the event is 0.425 ± 0.005. This efficiency has two components whose systematic uncertainties we evaluate separately. The first is the probability that the lepton from the $B \to \tau\nu$ decay is reconstructed satisfactorily and is properly identified. According to the Monte Carlo signal, the lepton that we isolate is from the $B \to \tau\nu$ decay over 98% of the time. The systematic error on lepton identification efficiency is 5% from studies of known electron and muon samples in the data. The second component is the probability p_0 that we identify no leptons other than the single lepton from the $B \to \tau\nu$ decay. We measure this efficiency using generic $B\bar{B}$ events, by using the fact that the probability of observing zero leptons in a generic $B\bar{B}$ event (two B decays) is p_0^2. From a sample of $B\bar{B}$ events we find that the Monte Carlo underestimates p_0 by 4 ± 1%, where the error is statistical. We apply this correction to the efficiency, and assign an error of 1%.

Next we consider the probability that the event have net charge zero. Here we compare data with Monte Carlo for the $B\bar{B}$ background in the sideband region, with $M > 5.2$ GeV and $\Delta E > 1.0$ GeV. We find that the fraction of events with zero net charge is 0.5457 ± 0.0023 for the data and 0.5487 ± 0.0010 for the Monte Carlo. The ratio of these is 0.9945 ± 0.0046, and based on this we assign a systematic uncertainty of 1%.

Finally, according to the Monte Carlo the probability that $E_{\mathrm{mis}} < E_{\mathrm{beam}}$ is 0.879 ± 0.015, for signal events. We take 30% of the loss as the systematic error on this, for a contribution of 4%.

We now have each contribution to uncertainty in the fraction of events that satisfy the selection criteria. We add them in quadrature to find a total fractional error of 6.6%.

It is important that the shape of the signal provided by the Monte Carlo correctly represents the shape of the signal in the data. We find that a peak that is too narrow in

ΔE or M could lead to an overestimate of the signal, while one that is too broad could cause us to underestimate a signal that is really there. We check the shape of the signal in M and ΔE using a sample of fully reconstructed B decays to hadrons [8] and to $D^*\ell\nu$. In these events, the fully reconstructed B plays the role of the B that decayed to $\tau\nu$, and we reconstruct ΔE and M for the remaining particles. While the probability of surviving the ΔE, M and the net charge criteria differs for the various samples because of varying contamination by shower fragments from the first B, agreement between data and Monte Carlo is a good check of the signal efficiency. We vary the shape of the signal in a mock data set and repeat the standard fit, using the comparison between the data and Monte Carlo of these parallel samples as a guide to how much variation is reasonable. As an example Figure 4 shows the comparison between data and Monte Carlo for the $D^*\ell\nu$ sample. Widths for ΔE within and M agree between the data and Monte Carlo, and if we vary the width of the signal peak in the mock data as indicated by the errors we find that the yield changes by 6.3%.

The total error in the signal efficiency is then 9.0%, where we have included both the effects of the selection criteria and sensitivity to the shapes of the M and ΔE distributions discussed above.

B. Uncertainty in the Background Shape

A large number of background events populate the signal region. Therefore it is important to understand the background if we hope to extract the signal in a reliable and robust fashion. In background events within the signal region, the lepton attributed to the tau is the product of semileptonic B decay over 90% of the time. There is also a smaller contribution of leptons from the cascade decay $b \to c \to y\ell\nu$ (7%) and misidentified hadrons (1%); these events are suppressed because they tend to have large visible energy. In order for a B decay to enter the signal region, several GeV of energy must go undetected. This happens primarily in two ways. First, additional semileptonic decays can result in loss of energy to unobserved neutrinos. While these events are suppressed by rejecting events with more than one lepton, they occur in 67% of the background. In most of these events, an unidentified soft muon is the culprit. The second cause is neutral hadrons that deposit only a fraction of their energy in the crystal calorimeter. We find that more than 500 MeV of neutral hadronic energy has been missed in 83% of the $B\bar{B}$ background events. For comparison, only 15% of the signal suffers from such a mismeasurement. Most of the background is due to a "conspiracy" between these two effects: one or more lepton is unidentified and some neutral hadronic energy is lost.

Correct extraction of the signal relies in proper simulation of the shape of the background in the M versus ΔE plane. It is particularly important that the Monte Carlo not have excess background, because this could lead us to miss a signal in the data. We quantify the effect of mis-modelling the background shape by varying the underlying parameters that control the shape and see what effect this has on the observed yield. The range of variation has either been determined by previous analyses at CLEO-II or in dedicated studies of the detector response.

The $b \to c \to y\ell\nu$ branching fraction has been studied in several CLEO analyses. Based on this, we vary this branching fraction in the range $(9.58 \pm 1.69)\%$. This changes the signal yield by ∓ 17 events. The lepton fake probability has been studied both at the $\Upsilon(1S)$ resonance which is nearly free of leptons, and using samples of K^- and π^- particles at the $\Upsilon(4S)$. A conservative error on these studies is $\pm 50\%$. Varying the fake rate by this amount has a ± 1 event effect on the signal yield. We have studied the energy deposited by K_L mesons using samples of charged K^+ mesons from $D \to K\pi$ decay. After correcting for the electromagnetic interactions of the charged particles, we find an uncertainty in the energy deposited in hadronic showers of $\pm 8.0\%$. Changing the simulated energy deposition by this amount changes the signal yield by ± 6 events. We have studied the production rate of neutral K mesons using the K_S yield in the data and Monte Carlo. This study has an uncertainty of $\pm 5\%$, mostly due to uncertainty in the tracking efficiency. Varying the production rate of neutral hadrons by this amount changes the yield by ∓ 12 events. To evaluate uncertainty in the result due to uncertainty in the momentum spectrum of leptons from $b \to c \to y\ell\nu$, we shift the lepton energies by ± 25 MeV. This changes the signal yield by ± 15 events. Finally, mesons decaying through the channel $B \to X\tau\nu$ could contribute additional background. Varying the branching fraction for these modes between 2.0% and 3.0% changes the yield by ∓ 6 events.

We calculate the systematic error due to the background shape by adding in quadrature the variations in the studies listed above. The total is ± 27 events.

As noted above, much of the background arises when energy is lost to extra undetected neutrinos. We would like to confirm that the distribution in ΔE is modeled correctly by the Monte Carlo. One indication of this is the ΔE distribution of events which have not one, but two identified leptons. Figure 5 shows the ΔE shape from these two lepton events. Possible signal contributions to this distribution are small when compared to the statistical error of the continuum subtraction and assuming a signal branching fraction smaller than our limit. This distribution indicates that the background is underestimated by 43 ± 48 events. This gives us confidence that neutrino background is not hiding a signal.

C. Fit Variations

The details of the fit can be varied one by one and a new yield can be compared with the standard fit. Bin sizes are varied by a factor of two, ΔE cutoffs by 1 GeV, mass cutoffs by 100 MeV, and a maximum likelihood fit rather than a χ^2 minimization performed. The effect of such changes is to introduce an average uncertainty of 6 events.

V. CONCLUSION

Table I summarizes the yield and the sources of error on the yield and efficiency. Two final pieces of information are needed to turn these into a limit on $\mathrm{B}(B^- \to \tau^-\bar{\nu}_\tau)$. The number of B^+B^- decays is taken from hadronic production at and below the $\Upsilon(4S)$ cross section. This number has an error of 1.8%. For the tau leptonic branching fraction we use $(35.31 \pm 0.31)\%$. This leads to a central value for the branching fraction of:

TABLE I. A summary of the yield of $B \to \tau\nu$ events and systematic errors.

Signal Yield	-14
Errors	
Statistics	± 37
Background Shape	± 27
Fit Details	± 6
Total	-14 ± 46
Efficiency	$(4.1 \pm 0.4)\%$

$$\begin{aligned} \mathrm{B}(B^- \to \tau^- \bar{\nu}_\tau) &= \frac{\text{Yield}}{\text{Efficiency} \times N_{B^+B^-} \times \mathrm{B}(\tau^- \to \ell^- \nu\bar{\nu})} &(3)\\ &= \frac{-14 \pm 46}{(0.041 \pm 0.004) \times (2.20 \pm 0.04) \times 10^6 \times (0.3531 \pm 0.0031)} &(4)\\ &= (-0.4 \pm 1.4) \times 10^{-3}\,. &(5)\end{aligned}$$

In order to calculate the upper limit, we use a procedure that accounts for the uncertainties in the efficiency and luminosity. In this procedure we determine that value of the branching fraction B such that 90% of all measurements leading to this result would originate from B or less, assuming that all branching fractions are equally likely. This is a Bayesian approach. We find

$$\mathrm{B}(B^- \to \tau^- \bar{\nu}_\tau) < 2.2 \times 10^{-3} \tag{6}$$

at the 90% confidence level.

This value places a constraint on the product $f_B|V_{ub}|$ of 6.8 MeV. It also rules out the existence of a charged Higgs with large values of $\tan\beta$ in models with two Higgs doublets in which the u-type and d-type quarks acquire their masses from different Higgs particles. If we conservatively assume $f_B|V_{ub}| = 0.35$ MeV, the limit implies $\tan\beta < 0.66 \times (m_{\mathrm{H}^-}/1\,\mathrm{GeV})$.

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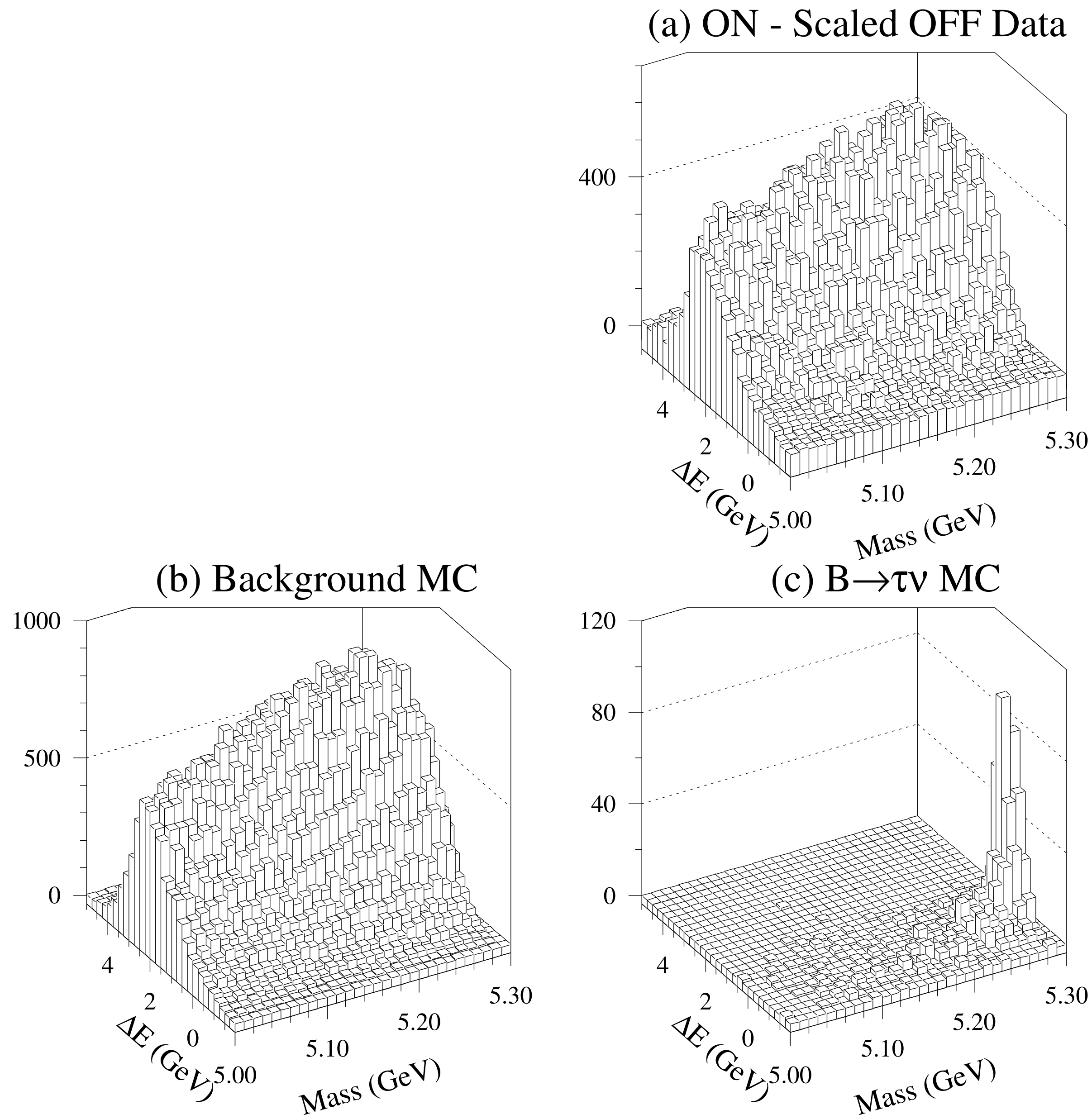

FIG. 1. The ΔE versus M distribution for (a) the $\Upsilon(4S)$ data, (b) the Monte Carlo $B\bar{B}$ background, and (c) the Monte Carlo $B \to \tau\nu$ signal. All other cuts have been applied.

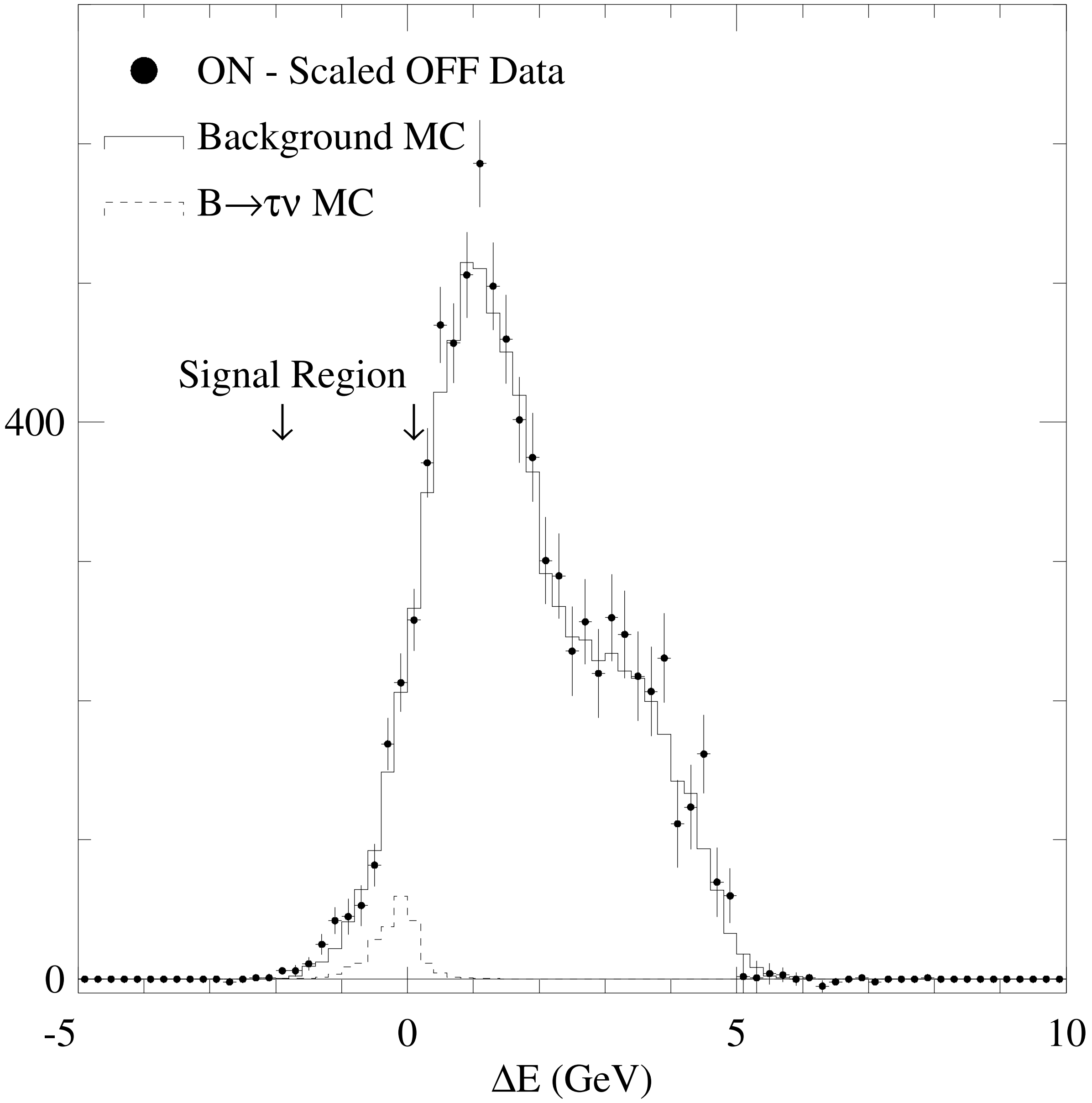

FIG. 2. The ΔE distribution after all other cuts including $M > 5.27$GeV. The signal Monte Carlo is shown with normalization appropriate for a branching fraction of 5.0×10^{-3} and is not included in the Background Monte Carlo distribution.

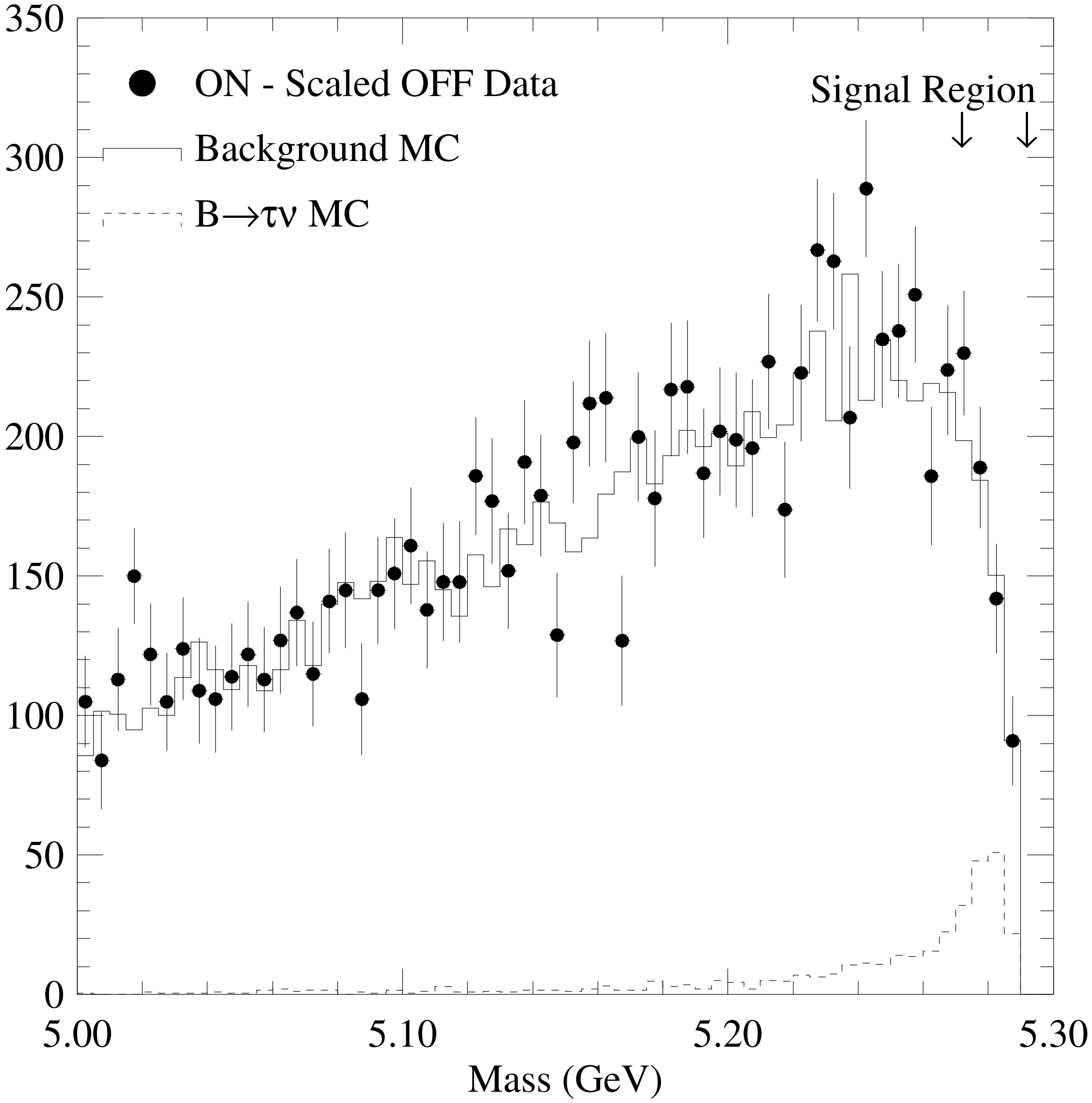

FIG. 3. The mass distribution after all other cuts including $-2.0 < \Delta E < 0.0$ GeV. The signal Monte Carlo is shown with normalization appropriate for a branching fraction of 5.0×10^{-3} and is not included in the Background Monte Carlo distribution.

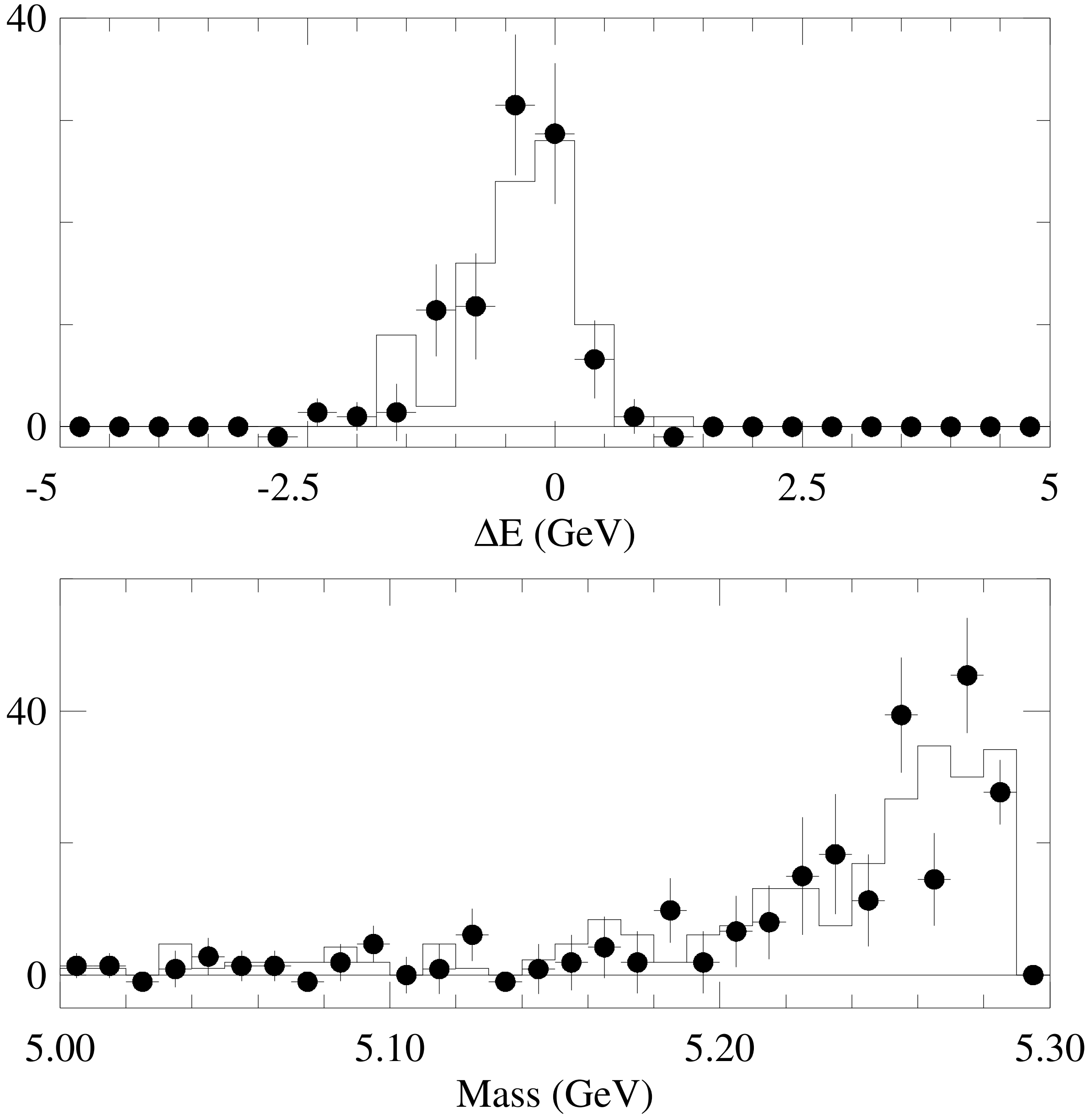

FIG. 4. The distributions of ΔE (top) and M (bottom), for the $B \to D^*\ell\nu$ sample, each after all other cuts except $\Sigma Q = 0$. The circles are the data, and the histogram is the Monte Carlo. The Monte Carlo is normalized to the data using the number of reconstructed $D^*\ell\nu$ decays.

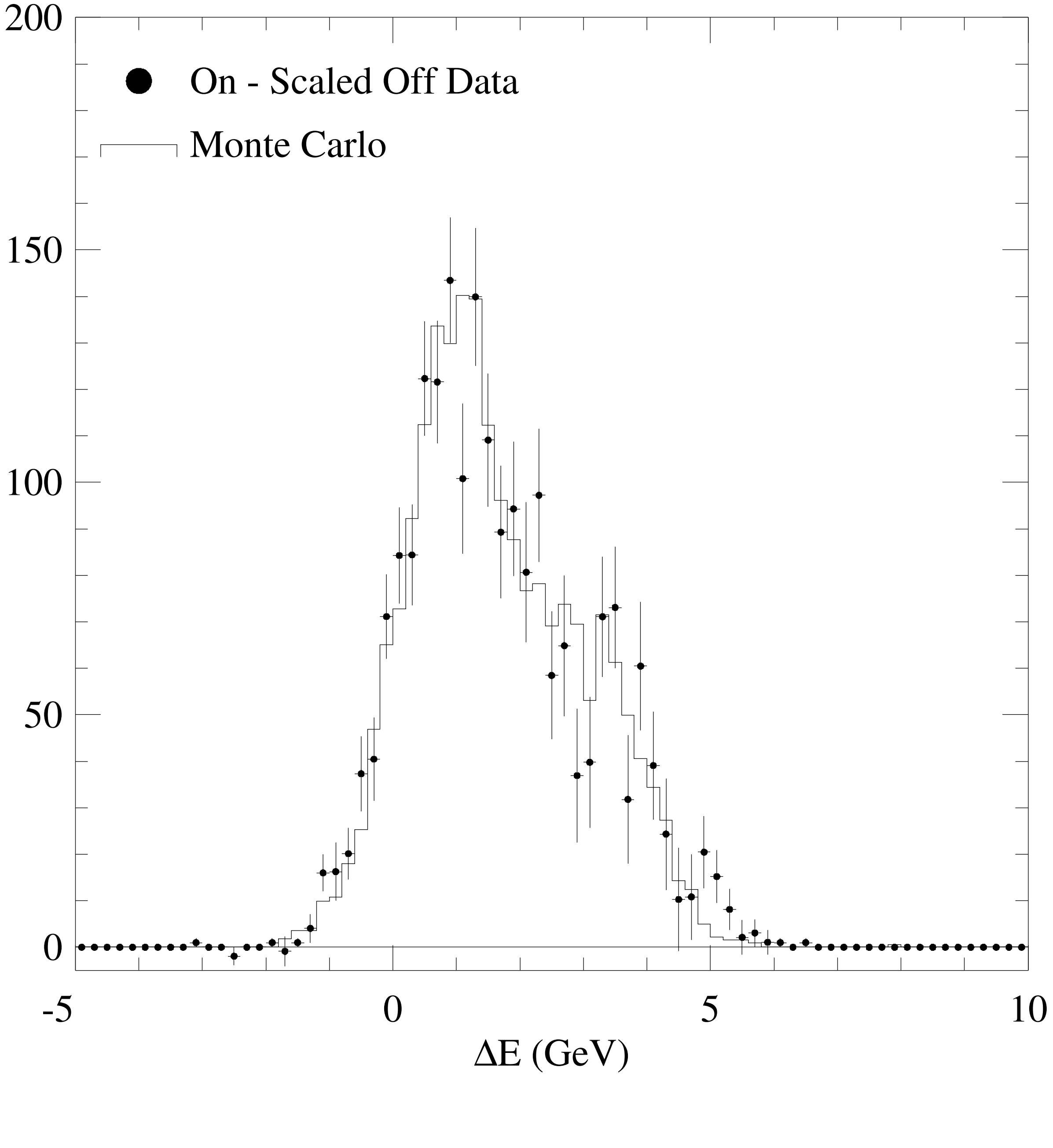

FIG. 5. The ΔE distribution after all other cuts including mass greater than 5.27 GeV. Two leptons rather than the standard one lepton are required.