Search for Lepton Flavor Violating Decays $\tau^- \to l^- K_s^0$ with the *BABAR* Experiment

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A search for the lepton flavor violating decays $\tau^- \to l^- K_S^0$ ($l = e$ or μ) has been performed using a data sample corresponding to an integrated luminosity of 469 fb^{-1}, collected with the *BABAR* detector at the SLAC PEP-II e^+e^- asymmetric energy collider. No statistically significant signal has been observed in either channel and the estimated upper limits on branching fractions are $\mathcal{B}(\tau^- \to e^- K_S^0) < 3.3 \times 10^{-8}$ and $\mathcal{B}(\tau^- \to \mu^- K_S^0) < 4.0 \times 10^{-8}$ at 90% confidence level.

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In the standard model (SM), lepton-flavor-violating (LFV) decays of charged leptons are forbidden or highly suppressed even if neutrino mixing is taken into account [1–3]. Any occurrences of LFV decays with measurable branching fractions (BFs) would be a clear sign of new physics. No signal has been found in extensive searches for LFV in μ and τ decays (e.g. $\mu \to e\gamma$ [4], $\tau \to \mu\gamma$ [5–7]). However, within the bounds set by searches, some physics models that extend the SM include new sizable LFV processes. For a review, see Ref. [8]. In this paper a search for $\tau^- \to l^- K_S^0$ decays is presented [9].

The $\tau^- \to l^- K_S^0$ BF has been estimated in SM extensions with heavy singlet Dirac neutrinos [10] and in R-parity violating supersymmetric models [11]. In the first case, heavy neutrinos with large mass and large mixing with SM leptons are introduced. Because of the large number of independent angles and phases in the enlarged mixing matrix, the LFV amplitude cannot be precisely evaluated. In the large-mass limit of heavy neutrinos and keeping only the leading terms, theoretical upper bound estimations are of the order 10^{-16} and are thus out of experimental reach. In the second case, couplings of SM leptons to new particles are described using an R-parity violating superpotential. With many new complex couplings, the phenomenology is immensely richer, but at the same time less predictive. While R-parity conserving couplings can affect low-energy processes only through loops, R-parity violating contributions can appear as tree-level slepton or squark mediated processes, competing with SM contributions. So, while LFV decays are highly suppressed in the SM, they can be significantly enhanced in R-parity violating supersymmetry. The previous best experimental upper limits (ULs) for $\tau^- \to l^- K_S^0$ decay branching ratios were measured by the Belle Collaboration using a 281 fb^{-1} data sample: $\mathcal{B}(\tau^- \to e^- K_S^0) < 5.6 \times 10^{-8}$ and $\mathcal{B}(\tau^- \to \mu^- K_S^0) < 4.9 \times 10^{-8}$ at 90% confidence level [12].

The measurement described in this paper is performed using data collected by the *BABAR* detector at the PEP-II asymmetric energy storage ring. Charged particles are detected and their momenta measured by a combination of a silicon vertex tracker (SVT), consisting of 5 layers of double-sided detectors, and a 40-layer central drift chamber (DCH), both operating in a 1.5 T axial magnetic field. Charged particle identification (PID) is provided by the energy loss in the tracking devices and by the measured Cherenkov angle from an internally reflecting ring-imaging Cherenkov detector (DIRC) covering the central region. Photons are measured, and electrons detected, by a CsI(Tl) electromagnetic calorimeter (EMC). The EMC is surrounded by an instrumented flux return (IFR). The detector is described in detail elsewhere [13,14].

The analyzed data sample corresponds to an integrated luminosity of 469 fb^{-1} collected from e^+e^- collisions, 425 fb^{-1} at the $\Upsilon(4S)$ resonance and 44 fb^{-1} at center-of-mass (CM) energy 10.54 GeV. The total number of produced τ pairs $N_{\tau\tau}$ is $(4.31 \pm 0.03) \times 10^8$, calculated using the average τ cross section of 0.919 ± 0.003 nb estimated with KK2f [15]. The Monte Carlo (MC) simulated samples of τ leptons are produced using the KK2f generator [16,17] and Tauola decay library [18,19]. Decays of B mesons are simulated with the EvtGen generator [20], while $e^+e^- \to q\bar{q}$ events, where $q = u$, d, s quarks (referred to as *uds* events) or $q = c$ quark, are simulated with the JETSET generator [21]. The *BABAR* detector is modeled in detail using the GEANT4 simulation package [22]. Radiative corrections for signal and background processes are simulated using PHOTOS [23]. In the following, the simulated signal and background samples will be referred to as signal MC and background MC samples, respectively.

For this analysis, two different stages of selection are used. In the first, which we call the loose selection stage, we retain enough data to estimate background distribution shapes. The second, which we refer to as the tight selection, uses criteria that have been chosen to optimize the sensitivity. The sensitivity, or expected UL, is defined as the UL value obtained using the background expected from MC: we choose selection criteria that give the smallest

expected UL. We use loose and tight electron and muon PID selectors for the two stages of selection. The selectors are based on combinations of measurements from the various subdetectors. The average efficiency for the loose electron (muon) selector is 98% (92%) for a laboratory momentum $p_{\rm LAB} > 0.6(1.4)$ GeV/c, whereas the π misidentification rate is less than 10% (6%). The average identification efficiency for the tight electron (muon) selector with a likelihood based algorithm is 93% (80%) for the same momentum range, whereas the π misidentification rate is less than 0.1% (2%). All selection criteria are applied to both channels and quantities are defined in the CM system, unless stated otherwise.

Events are first selected using global event properties in order to reject $b\bar{b}$, $c\bar{c}$, and uds background events with high multiplicity. All tracks (photons) are required to be reconstructed within a fiducial region defined by $0.410 < \theta < 2.540$ ($0.410 < \theta < 2.409$) radians, where θ is the polar angle in the laboratory system with respect to the z axis direction [13]. The overall event charge must be zero. Furthermore, the event must include a K^0_S candidate with an invariant mass within 25 MeV/c^2 of the nominal K^0_S mass [24], reconstructed from two oppositely charged tracks, assuming the pion mass for both. The highest momentum track in the CM frame has to have a momentum between 1.5 and 4.8 GeV/c for both modes. For the electron channel events, the total EMC energy associated with tracks in the laboratory frame has to be less than 9 GeV. The thrust [25] is calculated using tracks and calorimeter energy deposits without an associated charged particle track. The thrust magnitude has to be between 0.85 (0.88) and 0.98 (0.97) for the electron (muon) channel. For each event, two hemispheres are defined in the CM frame using the plane perpendicular to the thrust axis. The hemisphere that contains the reconstructed τ candidate, defined below, is referred to as the signal side and the other hemisphere as the tag side. Candidate τ pair events are required to have three reconstructed charged particle tracks on the signal side. On the tag side, one track only is required for the muon channel, while for the electron channel, events with one or three reconstructed tracks are retained.

The signal τ candidates are reconstructed by combining one K^0_S candidate with the third track of the signal hemisphere, to which mass is assigned according to the considered decay mode. The lepton track is required to be identified as an electron or muon by the loose PID selector. The signal τ candidates are then examined in the two dimensional distribution of ΔE_τ vs ΔM_τ, where ΔM_τ is defined as the difference between the invariant mass of the reconstructed τ and the world average value [24], and ΔE_τ is defined as the difference between the energy of the reconstructed τ and the expected τ energy, half the CM total energy. Only τ candidates with a ΔM_τ value within ± 0.35 GeV/c^2 and a ΔE_τ value within ± 0.4 GeV are retained. The whole decay tree is then fitted requiring that, within reconstruction uncertainties, the K^0_S decay products form a vertex, the K^0_S mass is constrained to the nominal value, and the track and the K^0_S trajectory form a vertex close to the beam interaction region. To improve the energy resolution, a bremsstrahlung recovery procedure is applied for the $\tau^- \to e^- K^0_S$ decay mode only: before the fit, the e^- track candidate is combined with up to three photons with an energy larger than 30 MeV and contained in a cone around the track direction of $\Delta\theta \times \Delta\phi = 0.035 \times 0.050$ rad^2, where θ is the polar angle and ϕ the azimuthal angle in the laboratory system. The constrained fit must have a χ^2 probability larger than 1%. If more than one candidate is found (which occurs in less than 1% of the events), only that with the largest χ^2 probability is retained.

After the above selection is applied, backgrounds remain, mainly from Bhabha events for the electron channel and from nonlepton events for the muon channel due to the larger pion to muon misidentification. To improve the background rejection, further requirements are imposed on the K^0_S candidates. For the muon channel, the K^0_S laboratory momentum must be greater than 1.0 GeV/c. For the electron channel, in order to remove events with a photon conversion faking a K^0_S, the invariant mass of the K^0_S daughters, calculated using the momentum from the fit and assigning them the electron mass, is required to be greater than 0.10 GeV/c^2. The K^0_S flight length significance is computed as the three-dimensional distance in the laboratory system between the τ vertex and the K^0_S vertex, divided by its error, and we select events with a flight length significance greater than 3.0. Finally, the K^0_S reconstructed mass is required to be between 0.482 and 0.514 GeV/c^2. The last two criteria are included in the loose selection for the electron channel while, for the muon channel, they are applied at a later stage in order to maintain sufficient statistics in the loose selection sample. The amount of background events due to dimuon and Bhabha processes is negligible after the loose selection has been applied and most of the surviving events come from charm decays, such as $D^- \to K^0_S \pi^-$ and $D^- \to K^0_S \ell^- \nu$, and from combinations in the uds events of a true K^0_S and a fake lepton.

To avoid bias from adapting selection requirements to the data, the tight selection has been optimized in a blind way, without looking at the data in the rectangular region (blinded box) shown in Fig. 1, corresponding to more than ± 5 times the resolution for signal events on ΔE_τ and ΔM_τ, respectively. As discussed above, selection criteria have been chosen to optimize the sensitivity on the upper limit. Therefore, for the tight selection the tighter PID selectors plus the following requirements are applied. The event's missing momentum is computed by subtracting from the e^+e^- momentum all track candidates and all unmatched calorimeter energy deposits. To reject events with tracks and photons lost out of the acceptance, the missing mo-

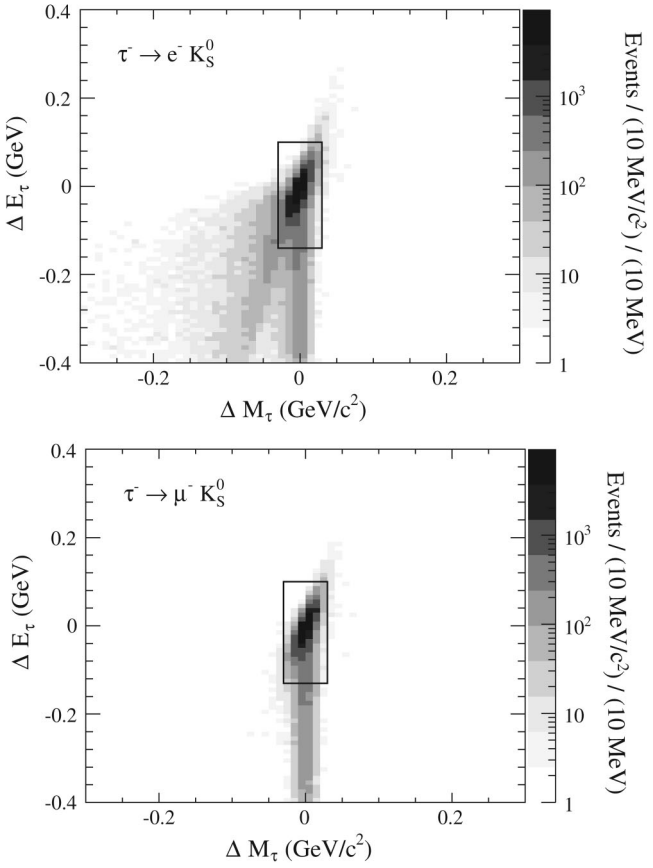

FIG. 1. Candidate distributions for signal MC samples $\tau^- \to e^- K_S^0$ (top) and $\tau^- \to \mu^- K_S^0$ (bottom) in the $(\Delta E_\tau, \Delta M_\tau)$ plane after the loose selection. The rectangle corresponds to the blinded box. The z-axis scale is logarithmic.

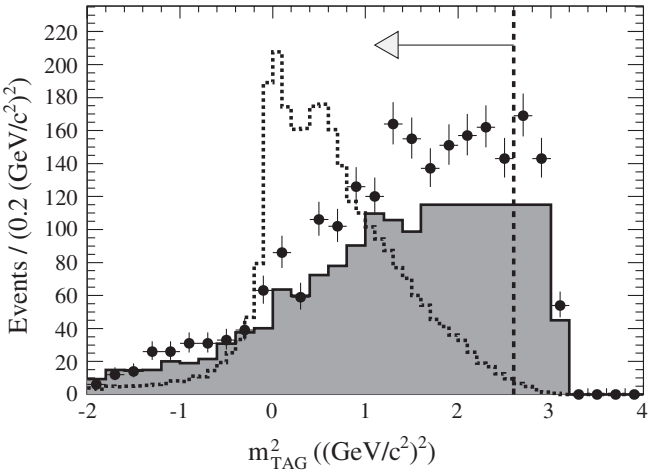

FIG. 2. Distributions of $m^2_{\rm TAG}$ after the loose selection for the $\tau^- \to e^- K_S^0$ channel. The data distribution is shown by solid circles with error bars, background MC with a filled histogram and signal MC with a dashed line. The signal MC distribution is normalized arbitrarily, while the background MC is normalized to the data luminosity. The vertical dashed line and the arrow indicate the applied requirement.

mentum is required to have a transverse component greater than 0.1(0.2) GeV/c for the electron (muon) channel and the cosine of its polar angle in the laboratory system must be smaller than 0.95. In a τ pair event, when neglecting radiation, the tag-side τ has the same momentum as the signal-side τ but the opposite direction. In addition, assuming that the tag τ decays to a one neutrino (hadronic) mode, the event's missing momentum corresponds to the neutrino momentum. These two assumptions determine the tag τ 4-momentum $\hat{p}_{\rm TAG}$, and the neutrino 4-momentum $\hat{p}_\nu$, respectively, and we define the squared invariant mass $m^2_{\rm TAG}$ as $(\hat{p}_{\rm TAG} - \hat{p}_\nu)^2$. As shown in Fig. 2, $m^2_{\rm TAG}$ peaks at small values for signal events and extends to higher values for background events. The tail on the right for the signal sample is due to tag τ decays to (leptonic) modes with two neutrinos, while the tail on the left for the background sample is due to events with missing energy from lost photons or tracks. The variable $m^2_{\rm TAG}$ is required to be smaller than 2.6 $({\rm GeV}/c^2)^2$ for both channels. Shapes for data and MC agree within error but a discrepancy is observed in the normalization. This does not affect the results because the final number of background events is obtained using the data sample. The *uds* background events are further reduced by requiring less than six photons on the tag side. Signal events have missing momentum due only to the undetected neutrino(s) from the tagging τ decay. Therefore, only for the $\tau^- \to \mu^- K_S^0$ channel, the cosine of the angle between the missing momentum and the signal τ candidate is required to be negative, to further reject nonleptonic backgrounds and improve the sensitivity.

For the final step of analysis, we define another discriminating variable, $\chi^2_{\rm FULL}$, as the χ^2 of the geometrical and kinematical fit for the whole decay tree, with additional constraints of ΔM_τ and ΔE_τ equal to 0. Most signal events have $\chi^2_{\rm FULL}$ values in the range 0–50, and we consider this range in the following. In Fig. 3 we show the distributions of $\chi^2_{\rm FULL}$ for data and signal MC inside the blinded box after the tight selection. An analytic curve describing the background, as detailed in the following, is also presented. The overall efficiency ε in this range of $\chi^2_{\rm FULL}$, after the tight selection, and inside the blinded box is 9.4% for the $\tau^- \to e^- K_S^0$ mode and 7.0% for the $\tau^- \to \mu^- K_S^0$ mode. The total signal efficiency is estimated by dividing the number of selected signal MC events by the total number of generated $\tau^- \to l^- K_S^0$ decays and includes the $K_S^0 \to \pi^+\pi^-$ BF.

We estimate the number of background events in the signal region using the number of MC background events in the range 0–50 of $\chi^2_{\rm FULL}$ after the loose selection multiplied by the ratio of numbers of MC background events after tight and loose selections in the full range of $\chi^2_{\rm FULL}$. We apply a 10% correction to normalize the MC to the levels of background seen in data outside the blinded box

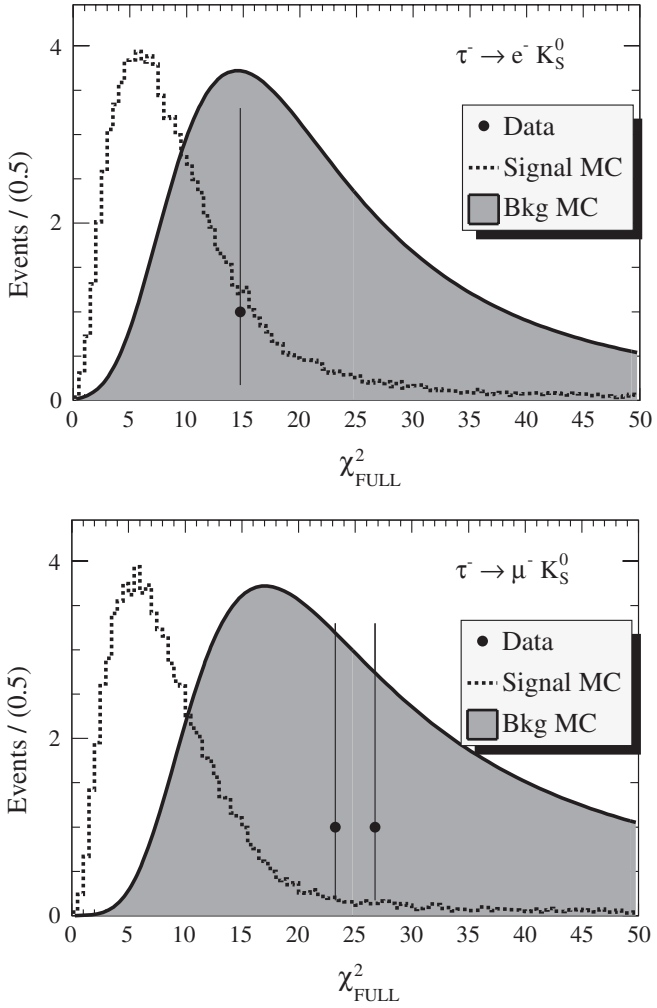

FIG. 3. Distributions of $\chi^2_{\rm FULL}$ after the tight selection for the $\tau^- \to e^- K^0_S$ (top) and $\tau^- \to \mu^- K^0_S$ (bottom) channel. The data events are shown by solid circles with error bars. The signal MC distributions are shown by dashed lines, while the background shapes are shown with filled histograms. The signal and background MC distributions are normalized arbitrarily.

after the tight selection. Total backgrounds of 1.0 ± 0.4 and 5.3 ± 2.2 events are expected for $\tau^- \to e^- K^0_S$ and $\tau^- \to \mu^- K^0_S$ respectively. Finally, the signal region is unblinded and 1 and 2 events are found for electron and muon modes, respectively, as already shown in Fig. 3.

Since no excess above the expected background level is found, 90% confidence level limits have been determined according to the modified frequentist analysis (or CL_S method) [26,27]. This method is more powerful than a simple UL estimation based on numbers of observed and expected events as it takes into account the different distributions of one or more discriminating variables between signal and background. The discriminating variable used in this analysis is $\chi^2_{\rm FULL}$. The signal $\chi^2_{\rm FULL}$ distribution is simply provided by the MC sample as already shown in Fig. 3, but this cannot be done for the background as too few events survive the tight selection, but also the loose one. Therefore we obtain smooth background shapes by fitting the product of a Landau function and a straight line to the MC background distributions after the loose selection. Any distortions on the shapes that could be introduced by the tight selection are negligible compared to the uncertainties of the shapes themselves. The resulting curves are presented in Fig. 3. The adopted test-statistic is the likelihood ratio $Q = \mathcal{L}(S+B)/\mathcal{L}(B)$, where $\mathcal{L}(B)$ and $\mathcal{L}(S+B)$ are, respectively, the likelihood to find the observed events in the hypothesis of background only and of background plus a given amount of signal. The latter, and consequently Q, are functions of the hypothesized signal BF. The confidence level CL_S is defined as the ratio CL_{S+B}/CL_B, where CL_{S+B} and CL_B are estimated using an ensemble of simulated data sets, generated from signal plus background or background only. The generation is iterated with a varying hypothetical value of the number of signal events, depending on the BF. CL_{S+B} and CL_B are then the probabilities that the test-statistic would be less than the $Q_{\rm exp}$ values observed in data, under the respective hypothesis. Signal hypotheses corresponding to $CL_S < \alpha$ are rejected at the $1-\alpha$ confidence level. This method avoids that a negative fluctuation of the background is translated into a large improvement of the exclusion limit and allows to include uncertainties directly on signal and background distributions. The ULs on BFs at 90% confidence level are calculated as

$$\mathcal{B}(\tau^- \to l^- K^0_S) < \frac{s_{90}}{2\varepsilon N_{\tau\tau}}, \tag{1}$$

where s_{90} is the limit for the signal yield at 90% confidence level, and ε and $N_{\tau\tau}$ are already defined above. The dominant systematic uncertainties on the signal efficiency for the electron (muon) channel come from possible data/MC differences in the efficiency of the PID requirements, 0.4% (5.1%) and of the tracking reconstruction, 1.7% (1.6%). Other sources of systematic uncertainty for the efficiency are: data/MC differences in K^0_S reconstruction efficiency (1.0%), the beam energy scale and the energy spread (less than 0.2%). The efficiency errors from MC statistics are negligible compared with the systematics ones. The uncertainty for the total number of τ pairs comes from the error on the luminosity and on the τ cross section values (0.7%). We assume these uncertainties are uncorrelated and combine them in quadrature to give a total signal uncertainty of 2.1% and 5.5%, respectively, for the electron and muon channels. For each bin of the signal $\chi^2_{\rm FULL}$ distribution, we consider the total uncertainties on the signal yield, and for the background distributions the uncertainties on the expected background levels. The uncertainties are treated as fully correlated between the bins as they are mainly due to normalization uncertainties. The analysis results are summarized in Fig. 4 presenting CL_S for the observed events versus the BFs, with the horizontal line defining the UL at 90% confidence level.

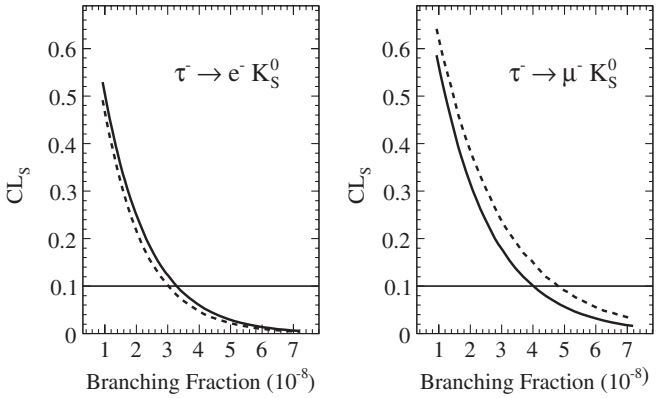

FIG. 4. Observed (full line) and expected (dashed line) CL_S as a function of the BFs (10^{-8}) for the decays $\tau^- \to e^- K_S^0$ and $\tau^- \to \mu^- K_S^0$.

From Fig. 4, the ULs on the BFs at 90% confidence level are determined to be: $\mathcal{B}(\tau^- \to e^- K_S^0) < 3.3 \times 10^{-8}$ and $\mathcal{B}(\tau^- \to \mu^- K_S^0) < 4.0 \times 10^{-8}$. The CL_S obtained using the number of expected background MC events, instead of data, are shown in the same figure and the BF values at 90% confidence level can be regarded as the sensitivities: 3.0×10^{-8} for the electron channel and 4.8×10^{-8} for the muon one.

ULs are also determined by exploiting another technique that gives a similar but worse sensitivity for the UL, so it is used only as a cross-check. For this method, selection criteria on the same quantities were slightly tightened to reduce the background as much as possible, and signal candidates are counted inside the elliptical region shown in Fig. 5. The final signal efficiencies with these selections are 9.1% for the $\tau^- \to e^- K_S^0$ mode and 6.1% for the $\tau^- \to \mu^- K_S^0$ mode. The level of background in the signal ellipse is estimated by extrapolating the event densities found in two sideband regions of ΔM_τ, as defined in Fig. 5. The ΔM_τ background distribution is modeled as a linear function plus a Gaussian function to account for the peak related to the decay mode $D^- \to K_S^0 \pi^-$. This is fitted at the loose selection stage, where there are sufficient statistics in the sidebands to estimate the shape. Then the fitted background distribution is normalized according to the number of data events in the sidebands after the tight selection. The final estimated number of background events in the signal region is $0.59 \pm (0.19 \oplus 0.17)$ and $0.30 \pm (0.17 \oplus 0.05)$ for the electron and muon channels, respectively, where the last number is the systematic uncertainty accounting for the observed differences between estimated and real MC sample events inside the signal region at the loose selection stage. When the signal region is unblinded, we find inside the elliptical signal region only one event for each channel. Using the signal efficiencies, the estimated residual backgrounds, and the number of observed events ULs on the BFs at 90% confidence level for this cross-check are calculated with the POLE program [28]. Uncertainties are included assuming that efficiency and background values have a Gaussian distribution, and that they are not correlated. The resulting ULs are $\mathcal{B}(\tau^- \to e^- K_S^0) < 4.8 \times 10^{-8}$ and $\mathcal{B}(\tau^- \to \mu^- K_S^0) < 7.6 \times 10^{-8}$.

In conclusion, a search for the lepton flavour violating decays $\tau^- \to l^- K_S^0$ has been performed using a data sample of 469 fb^{-1} collected with the *BABAR* detector at the SLAC PEP-II electron-positron storage rings. No statistically significant excess of events is observed in either channel and the resulting ULs are $\mathcal{B}(\tau^- \to e^- K_S^0) < 3.3 \times 10^{-8}$ and $\mathcal{B}(\tau^- \to \mu^- K_S^0) < 4.0 \times 10^{-8}$ at 90% confidence level. These results are the most restrictive ULs on the BFs of these decay modes, and can be used to constrain

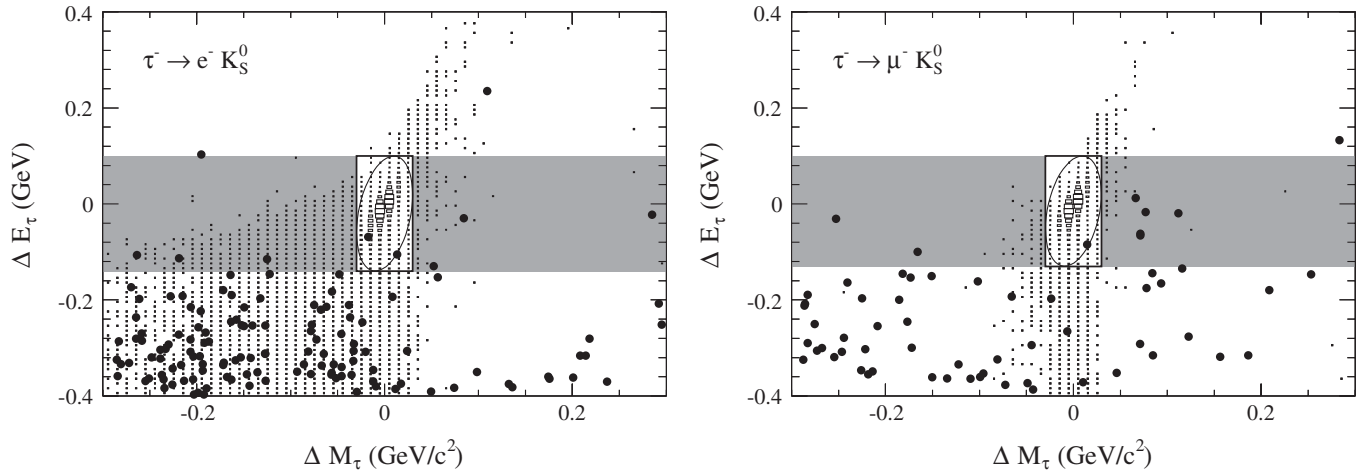

FIG. 5. Candidate distribution in the (ΔE_τ, ΔM_τ) plane after all selections for cross-check method ($\tau^- \to e^- K_S^0$ on the left, $\tau^- \to \mu^- K_S^0$ on the right). Data candidates are indicated by solid circles. The boxes show the signal MC distribution with arbitrary normalization. The blinded box, used for both methods, corresponds to the rectangle. The gray bands and the ellipse indicate the sidebands used for extrapolating the background and the signal region for the cross-check measurement. The z-axis scale is linear.

parts of the theoretical phase space in several models of physics beyond the standard model.

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