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In search of New Physics with Lepton Flavor Violation in $\Upsilon(3S) \to e^{\pm}\mu^{\mp}$

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Although unobservable in the standard model, charged lepton flavour violating (LVF) processes are predicted to be enhanced in new physics extensions. We present the final results of a search for electron-muon flavour violation in $\Upsilon(3S) \to e^{\pm}\mu^{\mp}$ decays using data collected with the BaBar detector at the SLAC PEP-II e^+e^- collider operating with a 10.36 GeV centre-of-mass energy. The search was conducted using a data sample of 118 million $\Upsilon(3S)$ mesons from 27 fb^{-1} of data and is the first search for electron-muon LFV decays of a b quark and b antiquark bound state. No evidence for a signal is found and we set a limit on the branching fraction of $\Upsilon(3S) \to e^{\pm}\mu^{\mp}$ and interpret it as a limit on the energy scale divided by the coupling-squared of relevant LFV new physics (NP): $\Lambda_{NP}/g^2_{NP} > 80$ TeV.

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1. Introduction

The Standard Model (SM) of fundamental interactions has proven to be one of the most precise verified physical theories of all times. The problem arises when neutrino oscillation observed by the Super-Kamiokande Observatory [1] and the Canadian Sudbury Neutrino Observatories (SNO) [2] that suggest a neutrino created with a specific lepton flavor (electron, muon, or tau) can later be measured to have a different flavor. Charged lepton flavor violating (LFV) processes are extremely suppressed in the SM by powers of the small neutrino masses. Although mixing between the neutrino flavor eigenstates permits, they are not observable in current experiments. Therefore, observation of charged LFV would be a clear signature of new physics (NP), which validates the argument that the SM requires an extension to the "Beyond Standard Model (BSM)" via new physics. In our calculations, the virtual Υ (with mass $\Upsilon(3S)$ = 10.36 GeV) meson is the potential contributor to the electron muon LFV decay. We took help to find the indirect bound on electron-muon LFV decays of the $\Upsilon(3S)$ (with mass $M_{\Upsilon(3S)}$ = 10.36 GeV) is $\mathcal{B}[\Upsilon(3S) \to e^{\pm}\mu^{\mp}] \leq 2.5 \times 10^{-8}$ using the reported limit on the branching fraction $\mathcal{B}(\mu \to eee < 1.0 \times 10^{-12})$ [3]. The size of the vector boson exchange contribution to the $\mu \to 3e$ decay amplitude can be significantly reduced [4] if there are kinematical suppressions. Such suppressions are possible when the effective vector boson couplings involve derivatives (or momentum factors). Using LFV limits from $\mu - e$ conversions, [5] sets an upper bound at 3.9×10^{-6}. Reference [4] estimates that the contribution of the virtual $\Upsilon(3S) \to e^{\pm}\mu^{\mp}$ to the $\mu \to 3e$ rate would be reduced to a modified bound on $\mathcal{B}[\Upsilon(3S) \to e^{\pm}\mu^{\mp}] \leq 1.0 \times 10^{-3}$.

Our $\Upsilon(3S)$ data was collected with the BABAR detector which is described in detail elsewhere [6, 7] at the PEP-II asymmetric-energy e^+e^- collider at the SLAC National Accelerator Laboratory. The detector was operated from 1999 to 2008 and collected data at the center-of-mass (c.m.) energies of the $\Upsilon(4S)$ (10.58 GeV), $\Upsilon(3S)$ (10.36 GeV), and $\Upsilon(2S)$ (10.02 GeV) resonances, as well as at energies in the vicinity of these resonances.

In our search we investigate a direct search for LFV decays in a sample collected during 2008 (referred to as Run 7) with an integrated luminosity of $27.96 \pm 0.17 fb^{-1}$ [8] which contains 122 million $\Upsilon(3S)$ decays. $\Upsilon(4S)$ data (referred to as Run 6, collected during 2008) with an integrated luminosity of $78.31 \pm 0.35 fb^{-1}$ is used for background estimate. Data taken 40 MeV below the $\Upsilon(4S)$ resonance corresponding to $7.752 \pm 0.036 fb^{-1}$, and data taken 40 MeV below the $\Upsilon(3S)$ resonance corresponding to $2.623 \pm 0.017 fb^{-1}$ constitute as control samples. These are used to evaluate non resonant contributions to the background and to study systematic effects in a signal-free sample. Our search deploys a blind analysis strategy [9] in a sample of $0.93 fb^{-1}$ $\Upsilon(3S)$ decays, to optimize all selection criteria and systematic uncertainties. After excluding the blinded sample, we conduct the LFV search on $27.02 \pm 0.16 fb^{-1}$ data that corresponds to $(117.7 \pm 1.2) \times 10^6 \Upsilon(3S)$ decays.

2. Sample Selections and Analysis Strategies

In search of $\Upsilon(3S) \to e^{\pm}\mu^{\mp}$ events, we require exactly two oppositely charged primary particles, an electron and a muon each with an energy close to half the total energy of

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the e^+e^- collision in the centre of mass (CM) frame E_B. There are two main sources of background comes from muon pairs events in which one of the muons is misidentified, decays in flight, or generates an electron in a material interaction. The other type of event is Bhabha events in which one of the electrons is misidentified. Background from tau pairs that decays to $e^+e^- \to \tau^+\tau^- 2\nu 2\bar{\nu}$ efficiently removed with the kinematic requirements described below. Generic $\Upsilon(3S)$ decays to two charged particles where there is particle misidentification are also a potential background. In the search, we use the optimized PID selection "super tight" for electron and "tight" and for muon. Each track is also required to fail the "loose" pion selector as well as the "loose" kaon selector. The lepton momenta must satisfy the condition which is defining a circle of radius of 0.1 centered at (1,1) in the $\frac{p_e}{E_{Beam}}$ vs $\frac{p_\mu}{E_{Beam}}$ plane. Events must lie within that circle namely, we require $(\frac{p_e}{E_B}-1)^2+(\frac{p_\mu}{E_B}-1)^2 < 0.01$. All other selection criteria have been applied for the signal, $\Upsilon(3S)$ data sample, and continuum backgrounds (estimated from Run6 data). The signal efficiency, as determined from signal MC, is $23.42\pm0.13(stat)\%$. Figure 1 shows the $e\mu$ invariant mass distribution of the data candidates and background events, as well as the potential signal, after all selection requirements have been applied. No events from the generic(3S) MC sample survive the selection.

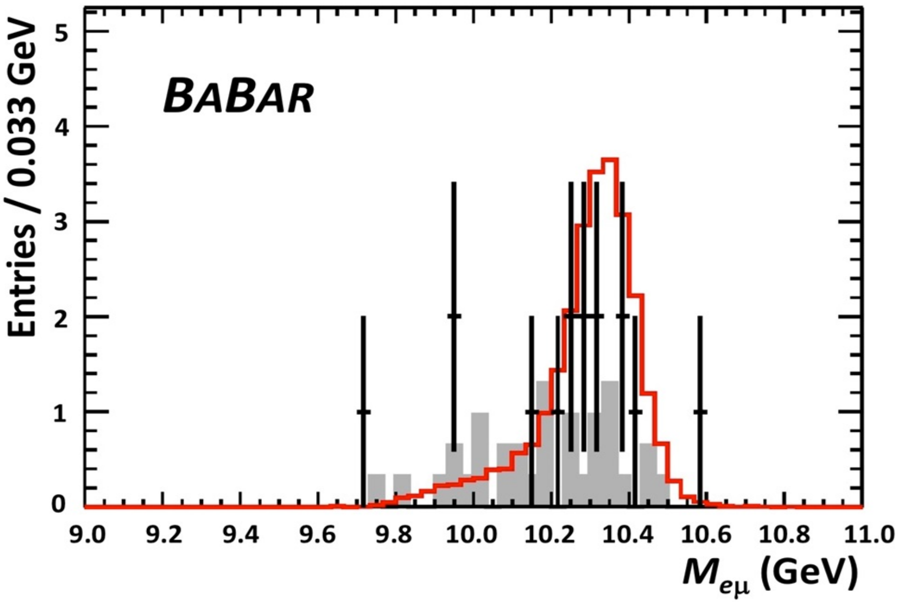

Figure 1: The invariant mass distribution of the $e\mu$ is showing the events that survived all selection criteria. The data sample is presented as the histogram in black with error bars and the open red histogram represents the signal MC with arbitrary normalization. The grey histogram shows the estimate of the continuum background from the Run 6 control sample data with the rate scaled to the amounts expected at 10.36 GeV for a data sample of 27.02 fb^{-1} and the mass scaled to 10.36/10.58 [10].

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For the uncertainty study, we reverse the two major kinematic requirements in the control sample of τ-pair events. The two specific cuts that used to be reversed are the EB-normalized lepton momentum cut and the requirement on the angle between the two

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tracks. This τ control sample study measures the systematic uncertainty associated with particle identification, tracking, kinematics, trigger selection criteria, and all other effects except those associated with the two major kinematic requirements used to select the control sample. The signal efficiency is $23.4 \pm 0.8\%$.

3. Results and Discussions

After unblinding the data, we find $N_{cand} = 15$ candidate events and have an expected background of 12.2 ± 2.3 events from a sample of $117.7 \pm 1.2 \times 10^{6}\Upsilon(3S)$ mesons. We calculate the branching fraction from $\mathcal{B}[\Upsilon 3S \to e^{\pm}\mu^{\mp}]$ is $1.0 \pm 1.4(stat) \pm 0.8(syst) \times 10^{-7}$ where the statistical uncertainty is that from N_{cand}, and all other uncertainties are included in the systematic uncertainty. As this result is consistent with no signal, we set an upper limit $\mathcal{B}[\Upsilon 3S \to e^{\pm}\mu^{\mp}] < 3.6 \times 10^{-7}$ at 90% confidence level (CL) on the branching fraction by using the "CLs" method, a modified frequentist method described in reference [11]. This is the first reported experimental upper limits on $\mathcal{B}[\Upsilon 3S \to e^{\pm}\mu^{\mp}]$. It can be interpreted as a limit on New Physics (NP) using the relationship $\frac{(\frac{g^2_{NP}}{\Lambda_{NP}})^2}{(\frac{4\pi\alpha_{3S}Q_b}{M_{\Upsilon 3S}})^2} = \frac{\mathcal{B}[\Upsilon(3S)\to e^{\pm}\mu^{\mp}]}{\mathcal{B}[\Upsilon(3S)\to \mu^{\pm}\mu^{\mp}]}$ and ignore small kinematic factors. In the relation, Q_b = - $\frac{1}{3}$ is the b-quark charge and α_{3S} is the fine structure constant at the $M_{\Upsilon(3S)}$ energy scale. Using the branching fraction of $\mathcal{B}[\Upsilon(3S) \to \mu^{\pm}\mu^{\mp}] = 2.18 \pm 0.21$ [12] gives a 90% C.L. upper limit of $\frac{\Lambda_{NP}}{g^2_{NP}} > 80$ TeV.

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