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Searching for Heavy Neutral Leptons using Tau Leptons at BABAR

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In recent years there have been large improvements in constraining the extended Pontecorvo–Maki–Nakagawa–Sakata (PMNS) matrix element, $|U_{\tau 4}|^2$, which describes the mixing between the active ν_τ and an additional heavy neutral lepton (HNL). We present a model-independent search for a HNL, capable of mixing with ν_τ using data from BABAR. A total of 424 fb^{-1} of electron-positron data is analyzed. Upper limits at the 95 % confidence level of $2.31 \times 10^{-2} < |U_{\tau 4}|^2 < 5.04 \times 10^{-6}$ are set, across the mass range $100 < m_4 < 1300$ MeV/c^2. More stringent limits are being placed at higher masses.

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1. Introduction

Heavy Neutral Leptons (HNLs) are additional neutrino states that interact via gravity, but, have no electric charge, weak-hypercharge, or color charge. They can only be detected in experiments because of some small mixing with the active neutrino states.

The Standard Model (SM) must be extended to explain several observational phenomena such as baryon asymmetry in the Universe (BAU), the existence of dark matter, and the non-zero mass of the neutrinos. HNLs are inherent in models explaining the origins of neutrino mass through seesaw mechanisms. One extension, the Neutrino Minimal Standard Model (ν-MSM) [1], proposes three HNLs and can explain the origins of neutrino masses, dark matter [2] and the BAU [3, 4]. Two of the additional HNLs have masses in the MeV/c^2 - GeV/c^2 range. The third HNL is a dark matter candidate with mass in the keV/c^2 range.

In this article, the possibility of a HNL interacting with the τ-lepton, via charged-current weak interactions, is considered. Mixing between the HNL (flavor state denoted as N) mass eigenstate and the active neutrinos is parameterized by the extended Pontecorvo–Maki–Nakagawa–Sakata (PMNS) matrix with additional elements U_{l4}, where l denotes the SM lepton flavor state i.e. e, μ, τ:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_{\mathrm{N}} \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{\mathrm{N}1} & U_{\mathrm{N}2} & U_{\mathrm{N}3} & U_{\mathrm{N}4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

Historically searches that constrain mixing with the tau sector have provided weaker constraints than those that explore mixing with the electron or muon sector [5]. Prior to the presented analysis, limits were specifically loose in the $m_4 \sim 300$ MeV/c^2 to $m_4 \sim 2$ GeV/c^2 range.

2. The *BABAR* analysis

Reference [6] presents new limits on $|U_{\tau 4}|^2$ in the $100 < m_4 < 1300$ MeV/c^2 mass range through a model independent analysis of *BABAR* data. The data sample used corresponds to an integrated luminosity of 424 fb^{-1}. An overview of the *BABAR* detector can be found in Ref. [7].

2.1 Experimental Strategy

The analysis strategy makes no assumptions on the origin or nature of the HNL and seeks the new particle only through observation of missing mass and energy in tau decays. If the decay products of the τ have recoiled against a heavy neutrino, the phase space and the kinematics of the outgoing visible particles are modified with respect to SM τ decay with a massless neutrino. It is assumed that the HNL does not decay within the detector.

At a collision energy of $\sqrt{s} = 10.58$ GeV, $e^+e^- \to \tau^+\tau^-$ produces two τ leptons with well-separated decays in the center-of-mass (CM) frame. Signal event candidates are required to have a “$1-3$ topology," this means that one τ decay must produce three charged particles (the 3-prong), while the other τ decay yields just one charged particle (the 1-prong). In order to select the $1-3$ topology, events are required to have four well-reconstructed charged particles, none must be compatible with coming from a photon conversion. The total charge of all four tracks must be zero.

The decay daughters of the two taus will be spatially well-separated due to the large CM energy relative to the τ masses. It is customary to then divide the event into two hemispheres in the CM frame separated by a plane perpendicular to the thrust axis, calculated using all observed charged and neutral particles in the event. The hemisphere containing just one track is termed the "tag-side." The other hemisphere is termed the "signal-side" and must contain 3 charged tracks, assuming the pion mass hypothesis. The search focuses specifically on the scenario where the signal side tau decays via a 3-prong, pionic τ decay, with an accompanying HNL. This provides access to the region 300< m_4 <1360 MeV$/c^2$, which historically had weak constraints.

In this analysis, the 1-prong track must be identified as either an electron or muon leptonic channel i.e. $\tau^- \to e^-\bar{\nu}_e\nu_\tau$ or $\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau$, or their charge conjugates. These leptonic channels have a total branching fraction of $\sim 35\%$ and are chosen to suppress low-multiplicity $q\bar{q}$ background events. Each 1-prong channel is analyzed separately. The electrons are selected using a likelihood method and the muons are found using a set of selection criteria that employ information from all five sub-detectors. The final result combines data from both leptonic channels and both charge conjugates of the signal channel.

The analysis proceeds by denoting the three charged pions on the signal side as a single hadronic system h^- or h^+, the decay can be considered a two-bodied:

$$\tau^- \to h^-(E_h, \vec{p}_h) + \nu(E_\nu, \vec{p}_\nu), \tag{1}$$

where ν describes the outgoing neutrino HNL state (an analogous expression can be written for h^+). The allowed phase space of the visible reconstructed energy, E_h, and invariant mass, m_h, of the hadronic system varies as a function of the mass of the invisible HNL. Therefore, as the HNL gets heavier the proportion of the original τ-lepton's energy going to the visible pions is reduced.

In the CM frame the τ-lepton energy is assumed to be $\sqrt{s}/2$. Then E_h must fall between two extremes that define the kinematically allowed values:

$$E_\tau - \sqrt{m_4^2 + q_+^2} < E_h < E_\tau - \sqrt{m_4^2 + q_-^2}, \tag{2}$$

where

$$q_\pm = \frac{m_\tau}{2}\left(\frac{m_h^2 - m_\tau^2 - m_4^2}{m_\tau^2}\right)\sqrt{\frac{E_\tau^2}{m_\tau^2} - 1} \pm \frac{E_\tau}{2}\sqrt{\left(1 - \frac{(m_h + m_4)^2}{m_\tau^2}\right)\left(1 - \frac{(m_h - m_4)^2}{m_\tau^2}\right)};$$

and $3m_{\pi^\pm} < m_h < m_\tau - m_4$. As the HNL mass increases, the allowed phase space of the visible system is reduced in the E_h, m_h plane. We then seek a HNL signal by comparing the observed event yield density in 2D histograms of the measured (m_h, E_h) to a set of template 2D histogram distributions for the background, obtained by simulating all τ known decays as well as non-τ background events, and the potential HNL signal for different m_4 mass values

2.2 Signal and Background Simulations

In this analysis, SM backgrounds can be divided into three groups 1) true SM tau decay to a SM ν_τ plus three charged pions, this is an irreducible background; 2) true SM tau decays to other SM τ channels with three charged pions plus some neutral particles e.g. π^0, these can be reduced via event selections; or , 3) non-τ SM backgrounds such as those originating from muon-pairs, $B\bar{B}$ or $q\bar{q}$ particles, these will be the sub-dominant source of backgrounds and are significantly reduced through event selection. In all three cases, the expected yields were estimated from Monte Carlo (MC) simulations which are passed through a GEANT4[8] model of the detectors followed by the same reconstruction routines as applied to the data.

All τ-pair events are simulated using the KK2F [9] generator and TAUOLA [10] which uses the averaged experimentally measured τ branching rates as listed in Ref. [11]. Several non-τ backgrounds are also studied, including $e^+e^- \to \Upsilon(4S) \to B^+B^-$ and $B^0\,\bar{B}^0$) which are simulated using EvtGen [12]; $e^+e^- \to q\bar{q}$ which are simulated using JETSET [13] [14] and $e^+e^- \to \mu^+\mu^-(\gamma)$ which are simulated using KK2F [15]. A total of 26 signal samples were simulated, one for each of the HNL masses across the range 100 MeV/c^2 < m_4 < 1300 MeV/c^2, at 100 MeV/c^2 increments. For each of these HNL masses, both a τ^+ and τ^- signal channel were simulated. Signal samples were produced within the BABAR software environment using KK2F and TAUOLA.

2.3 Analysis Procedure

A binned likelihood approach is taken. It is assumed that the contents of a given bin, i, j, in the (m_h, E_h) data histogram are distributed as a Poisson distribution and may contain events emanating from any of the SM background processes, and potentially HNL signal events. The likelihood to observe the selected candidates in all the (m_h, E_h) bins is the product of the Poisson probability of observing the selected events in each bin. A set of Gaussian nuisance parameters is also included to account for yield uncertainties. Shape uncertainties are incorporated separately and discussed in the following section. Wilk's theorem [16] is then utilized to converge on a value of $|U_{\tau 4}|^2$ which minimizes the likelihood at the 95 % confidence level.

2.4 Systematic Uncertainties

Uncertainties on the normalization are parameterized as Gaussian nuisance parameters in the fit, these include: luminosity (0.44 %), $\sigma(ee \to \tau\tau)$ (0.31 %), leptonic branching fractions (~ 0.2 %), 3-prong branching fraction (0.57 %), PID Efficiency (e : 2%, μ: 1%, π: 3%).

In addition, inefficiency in the hadronic tau MC modeling must be accounted for. For many hadronic τ decay channels the relative uncertainties from experimental results are large. A τ-lepton decay to three charged pions is mediated by the $a_1(1260)$ resonance which decays through the intermediate $\rho\pi$ state. In the MC samples used in this analysis the PDG [11] average of m_{a_1} = 1230 ± 40 MeV/c^2 and a Breit-Wigner averaged width of $\Gamma_{a_1} = 420 \pm 35$ are used. Reference [11] quotes the estimated width to be between 250 - 600 MeV/c^2. The uncertainty associated with the a_1 resonance represents the dominant contribution to the systematic error in the analysis. To understand the effects of the uncertainty on the a_1 mass on the final results in this analysis several additional MC simulations were built, in which the m_{a_1} was varied to $\pm 1\sigma$ of the experimental average.

2.5 Results

Figure 1 shows the results from the presented analysis. A model-independent search for heavy neutral leptons (HNL) found new upper limits at the 95 % C.L on the $|U_{\tau 4}|^2$ which vary from

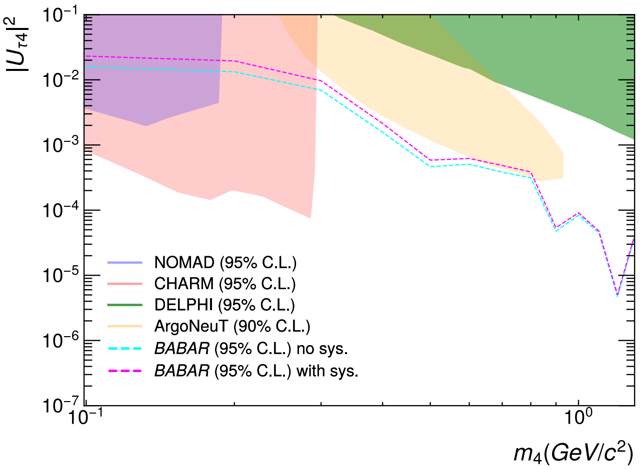

Figure 1: Upper limits at 95% C.L. on $|U_{\tau4}|^2$. The magenta line represents the result when uncertainties are included. The magenta line is expected to be a very conservative upper limit.

2.31×10^{-2} to 5.04×10^{-6}, across the mass range $100 < m_4 < 1300\ \mathrm{MeV}/c^2$. More stringent limits are placed on higher neutrino masses. These improve on the previous upper limits from NOMAD [17], CHARM [18] and DELPHI [19]. In 2021 the ArgoNeuT experiment[20] also published limits in this region, the BABAR result improves on those limits. In a recent publication Barouki *et al.* [21] showed even tighter bounds. In addition, a recent recasting of the CHARM data, which utilizes data from the electron and muon searches to indirectly constrain the tau sector, has also improved constraints in the same region [22]. Constraints also exist from cosmic surveys for eV-scale Seesaw [23] and Big-Bang Nucleo-synthesis (BBN) [24].

2.6 Conclusions

The result presented significantly improved limits on the existence of HNLs in the relevant mass range. There have been several new results in the same parameter region and in the electron and muon sectors. No evidence for the existence of HNLs mixing with any of the three active neutrinos has been found. The search for HNLs continues at facilities around the world and we expect even further improved limits in the coming years. In the $5-10$ year time frame we expect new results from Belle-II, FASER and NA62 [25]. Looking further ahead, significant improvements are expected from the proposed facilities: the FCC-ee [26] and the ILC.

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