PROCEEDINGS OF SCIENCE

Searching for Heavy Neutral Leptons using Tau Leptons at BABAR

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A model independent search for a Heavy Neutral Lepton (HNL), capable of mixing with the τ neutrino, is presented. A total of 424 fb^{-1} of BABAR data is analyzed. No significant signal is seen. Upper limits at the 95 % confidence level are set on the extended Pontecorvo–Maki–Nakagawa–Sakata (PMNS) matrix element, $|U_{\tau 4}|^2$, which depend on the HNL mass hypothesis and vary from 2.31×10^{-2} to 5.04×10^{-6}, across the mass range $100 < m_4 < 1300$ MeV$/c^2$. More stringent limits being placed at higher masses.

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1. Motivations

Many extensions to the Standard Model (SM) predict Heavy Neutral Leptons (HNLs). These beyond Standard Model particles possess mass, and interact via gravity, but are "neutral" meaning they have no electric charge, no weak hyper-charge, no weak isospin, and no color charge. They interact only with the active neutrinos via mixing.

1.1 Inconsistencies between Standard Model and Observation

There remains a need to extend the SM to explain a number of observational phenomena including: the baryon asymmetry in the Universe (BAU), the existence of dark matter, and the non-zero mass of the neutrinos. The Neutrino Minimal Standard Model (ν-MSM) [1] is one extension which proposes three HNLs and can explain the origins of neutrino masses, dark matter [2] and the BAU [3, 4]. ν-MSM is compatible with all current measurements. Two of the additional HNLs have masses in the MeV/c^2 - GeV/c^2 range and the third is a the dark matter candidate and has mass in the keV/c^2 range. Heavy Neutral Leptons with masses from $O(100\ \text{MeV}/c^2)$ up to a few $O(\text{GeV}/c^2)$ can be produced in decays of SM particles.

1.2 Incorporating Neutrino Mass into the Standard Model

To include neutrino mass in the SM one could add a term which couples neutrinos to the Higgs field, analogous to that for charged leptons. This requires that the Yukawa coupling for the neutrinos be much smaller than for the charged leptons and that right-handed neutrinos have no Majorana mass, despite there being no symmetry preventing it. Furthermore, the neutrino masses and mixing angles would be expected to have a similar hierarchy as for quarks, which we know not to be the case. The SM does, however, allow for a dimension-five operator, the Weinberg operator, which leads to Majorana masses of the neutrinos after electroweak symmetry breaking and is gauge invariant:

$$\mathcal{L}_5 = \frac{c^{[5]}}{\Lambda} L^T \cdot \tilde{H}^* C^\dagger \tilde{H}^\dagger \cdot L + h.c. \tag{1}$$

where Λ is the scale at which the particles responsible for lepton number violation become relevant degrees of freedom; $c^{[5]}$ is a flavor-dependent Wilson coefficient; and C is the charge-conjugation matrix. If the neutrinos are Majorana particles, there are a multitude of models, collectively referred to as "See-Saw Models", which can generate Majorana mass terms for left-handed fermions below the electroweak symmetry breaking scale as well as accounting for the smallness of the neutrino masses without need for extremely small Yukawa couplings. These models are categorized by "types": Type I, with a singlet fermion; Type II, with heavy triplet scalars; and, Type III Seesaw, with triplet fermions.

One feature inherent models that explain neutrino masses is the existence of additional HNL states. Constraints exist from cosmic surveys for eV-scale Seesaw [5] and Big-Bang Nucleo-synthesis (BBN) [6]. More natural solutions remain at the GeV or TeV scale. At the GeV-scale, the Yukawa coupling is of $O(10^{-5})$, and is in reach of existing experiments. At the TeV-scale direct searches become less effective, since the Yukawa coupling is smaller ($O(10^{-6})$).

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2. The BABAR analysis

A recent analysis from BABAR [7] presents new limits on the square of the extended Pontecorvo Maki Nakagawa Sakata (PMNS) matrix element, $|U_{\tau 4}|^2$, in the $100 < m_4 < 1300$ MeV/c^2 mass range. An overview of the BABAR detector can be found in Ref. [8]. The data sample used corresponds to an integrated luminosity of 424 fb^{-1}.

2.1 Experimental Strategy

The analysis strategy was based on Ref. [9], the idea that a HNL can interact with the tau via charged-current weak interactions is explored. If the decay products of the τ have recoiled against a heavy neutrino, the phase space and the kinematics of the visible particles would be modified with respect to SM τ decay with a massless neutrino. It is assumed that the HNL does not decay within the detector.

This search studies the 3-prong, pionic τ decay, giving access to the region 300< m_4 <1360 MeV/c^2, which historically has weaker constraints. Denoting the three charged pions as a hadronic system h^-, the decay can be considered a two-bodied:

$$\tau^- \to h^-(E_h, \vec{p}_h) + \nu(E_\nu, \vec{p}_\nu), \tag{2}$$

where ν describes the outgoing neutrino state. The allowed phase space of the reconstructed energy, E_h, and invariant mass, m_h, of the hadronic system varies as a function of the mass of the HNL. As the HNL gets heavier the proportion of the original τ-lepton's energy going to the visible pions diminishes.

In the center-of-mass 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:

$$E_\tau - \sqrt{m_4^2 + q_+^2} < E_h < E_\tau - \sqrt{m_4^2 + q_-^2}, \tag{3}$$

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. A HNL signal is sought by comparing the observed event yield density in the (m_h, E_h) plane 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. Only channels in which the non-signal (tag) τ decays leptonically are used in this analysis since these provide a cleaner environment.

2.2 Signal and Background Simulations

All SM background yields are estimated from Monte Carlo (MC) simulations which are passed through the same reconstruction and digitization routines as the data.

All τ-pair events are simulated using the KK2F [10] generator and TAUOLA [11] which uses the averaged experimentally measured τ branching rates as listed in Ref. [12]. 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 [13]; $e^+e^- \to q\bar{q}$ which are simulated using JETSET [14] [15] and $e^+e^- \to \mu^+\mu^-(\gamma)$ which are simulated using KK2F [16].

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 process, 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 to observe the selected events in each bin:

$$\mathcal{L} = \prod_{\text{charge}}^{+-}\left(\prod_{\text{channel}}^{e\mu}\left(\prod_{\text{bin}}^{ij}\left(\frac{1}{n_{\text{obs},ij}!}\left[N_{\tau,\text{gen}}\cdot|U_{\tau 4}|^2\cdot p_{\text{HNL},ij}+N_{\tau,\text{gen}}\cdot(1-|U_{\tau 4}|^2)\cdot p_{\tau-\text{SM},ij}+n^{\text{reco}}_{BKG,ij}\right]^{(n_{\text{obs}})_{ij}}\times\right.\right.\right.$$
$$\left.\left.\left. exp\left[-(N_{\tau,\text{gen}}\cdot|U_{\tau 4}|^2\cdot p_{HNL,ij}+N_{\tau,\text{gen}}\cdot(1-|U_{\tau 4}|^2)\cdot p_{\tau-SM,ij}+n^{\text{reco}}_{BKG,ij})\right]\right)_{\text{bin}}\times\prod_k f(\theta_k,\tilde{\theta}_k)\right)_{\text{channel}}\right)_{\text{charge}}, \tag{4}$$

where n_{obs} is the number of observed events in the bin ij, $N_{\tau,\text{gen}}$ is the number of generated τ's, $p_{HNL(\tau-SM),ij}$ is the probability of a reconstructed event being in a given bin in the HNL $(\tau - SM)$ 2D template and $n^{\text{reco}}_{BKG,ij}$ is the expected number of non-τ background events. The final product is a set of Gaussian nuisance parameters. The expression involves a product over all bins, ij, over the two 1-prong channels, and over both τ-lepton charges (±).

A test statistic, q, can be defined as:

$$q = -2\ln\left(\frac{\mathcal{L}_{H_0}(|U_{\tau 4}|^2_0;\hat{\hat{\theta}}_0,\text{data})}{\mathcal{L}_{H_1}(|\hat{U}_{\tau 4}|^2;\hat{\theta},\text{data})}\right) = -2\ln(\Delta\mathcal{L}), \tag{5}$$

where $\mathcal{L}$ in both the numerator and denominator describes the maximized likelihood for two instances. The denominator is the maximized (unconditional) likelihood giving the maximum likelihood estimator of $|U_{\tau 4}|^2$ and the set of nuisance parameters ($\hat{\theta}$); $\hat{\theta}$ is a vector of nuisance parameters that maximize the likelihood. In the numerator the nuisance parameters are maximized for a given value of $|U_{\tau 4}|^2$. The analysis aims to find the value of $|U_{\tau 4}|^2$ that minimizes this quantity at the 95 % confidence level.

2.4 Uncertainties

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

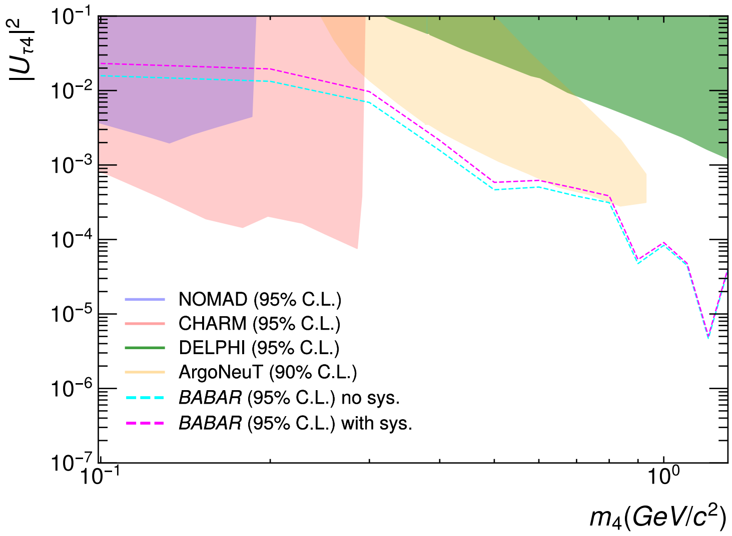

Figure 1: Upper limits at 95% C.L. on $|U_{\tau 4}|^2$. The magenta line represents the result when uncertainties are included. The magenta line is expected to be a very conservative upper limit.

Inefficiency in the MC modelling must also 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 [12] average of $m_{a_1} = 1230 \pm 40$ MeV/c^2 and a Breit-Wigner averaged width of $\Gamma_{a_1} = 420 \pm 35$ are used. Reference [12] 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. In order 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 upper limit at the 95% confidence level provided by this analysis using the described binned likelihood technique. The magenta line represents the upper limit when all systematic uncertainties are considered. The dominant systematic uncertainty is that due to the assumptions made within our simulation.

3. Conclusions

This article has documented new upper limits on $|U_{\tau 4}|^2$ set by BABAR. The technique presented can be applied future searches. The results presented are competitive with projections for experiments coming online in the next few years.

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