A Search for Heavy Neutral Leptons in tau decays at BABAR

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Motivations

Heavy Neutral Leptons (HNLs) are additional neutrino states. They have mass but are neutral in all respects.

- HNLs are proposed by several beyond Standard Model (BSM) theories to explain three major observational phenomena:
  - Neutrino oscillations and origins of their mass via seesaw models etc. (Phys. Rev. D 23,165);
  - Baryonic asymmetry of Universe (Phys. Rev. Lett. 81, 1359);
- $\nu$-MSM proposes three keV-GeV scale HNLs.

- Experiments generally quote results in parameter space of elements $|U_{ln}|^2 \cdot \nu$. HNL mass hypothesis.
- Tau sector historically less explored...

\[ \sigma(e^+e^- \rightarrow \tau^+\tau^-) = 0.919 \pm 0.003 \text{ nb} \]

\[ \text{Integrated luminosity in runs used} = 424 \text{ fb}^{-1} \]

\[ \rightarrow N_{\tau\tau} \sim 4 \times 10^8 \text{ events} \]
The BABAR Experiment

- Asymmetric $e^+e^-$ collider with $\sqrt{s} = 10.58$ GeV/c² i.e. Y(4S) resonance: 9 GeV electrons collide with 3 GeV positrons.
- **Total luminosity:** 432 fb⁻¹ ($4.7 \times 10^8 \overline{B}B$) on peak.

**Detectors:**
- **Reconstruct tracks:** Silicon Vertex Tracker (SVT) + 40-layer Drift Chamber (DCH), in 1.5-T solenoid.
  - Momentum resolution = 0.47% at 1 GeV/c
- **Measure energy:** Electromagnetic Calorimeter (EMC)
  - Energy resolution = 3% at 1 GeV.
- **PID:**
  - Identify charged pions, kaons and electrons using Ring Imaging Cherenkov detector (DIRC) + ionization loss measurements in the SVT and DCH.
  - Instrumented flux return of solenoid used to identify muons.
The BABAR Search


- Looks only at kinematics, no assumptions on underlying model, except that there must be some small mixing with tau sector:
  - “signal side” : three pronged pionic tau decay ($\tau^- \rightarrow \pi^-\pi^-\pi^+\nu_\tau$) as it allows access to region $100 < m_4 < 1360\text{ MeV/c}^2$ where limits were loose.
  - “tag side” : Second tau decay must be leptonic, due to cleaner environment.

  Branching Fractions:
  - 1-prong (electron or muon) $\sim 34\%$
  - 3-prong (3 pion) $\sim 9\%$

  CPT assumed to hold, combining + and – signal sides.

  $\sigma(e^+e^- \rightarrow \tau^+\tau^-) = 0.919 \pm 0.003\text{ nb}$

  Integrated luminosity in runs used $= 424\text{ fb}^{-1}$

  $\rightarrow N_\tau \sim 4 \times 10^8$ events
**Method**

### SM Tau Decay

\[
\frac{d\Gamma_{\text{tot}}(\tau^{-} \to \nu h^{-})}{dm_h dE_h} = (1 - |U_{\tau4}|^2) \frac{d\Gamma(\tau^{-} \to \nu h^{-})}{dm_h dE_h} \bigg|_{m_\nu=0} + |U_{\tau4}|^2 \frac{d\Gamma(\tau^{-} \to \nu h^{-})}{dm_h dE_h} \bigg|_{m_\nu=m_4}.
\]

### BSM Tau Decay

- Model 3-pronged decay as 2-body with outgoing HNL and hadronic system \((h)\).
- Define \(E_h\) as reconstructed energy and \(m_h\) as the invariant mass of the visible, hadronic products.
- \(E_\tau = \frac{E_{\text{CMS}}}{2}\) in the limit of no ISR. The value of \(E_h\) and \(m_h\) can exist, in principle, in the ranges:

\[
3m_{\pi\pm} < m_h < m_\tau - m_4
\]

and

\[
E_\tau - \sqrt{m_4^2 + q_+^2} < E_h < E_\tau - \sqrt{m_4^2 + q^-_+},
\]

where

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

Templates for each mass in the form of 2D plots of \(E_h, v. m_h\). Boundary of curved region in this plot characteristic of a massive neutrino.

**Signal samples made in modified TAUOLA, and passed through G4 + BABAR reco. alg.**
Background and Signal Simulations

- Use MC to estimate expected background contributions
- Detector response modelled using GEANT4, event generator specific to each source
- Three potential sources of non-signal events in data:
  1. SM 3 prong decay to 3 charged pions (\(\tau^- \rightarrow \pi^- \pi^- \pi^+ \nu_\tau\))
  2. Other SM tau decays accidentally tagged as (1)
  3. SM non-tau backgrounds:
     - \(e^+ e^- \rightarrow \Upsilon(4S) \rightarrow B^+ B^-\) and \(e^+ e^- \rightarrow \Upsilon(4S) \rightarrow B^0 \bar{B}^0\)
     - \(e^+ e^- \rightarrow \bar{u}u, \bar{d}d, \bar{s}s\) and \(e^+ e^- \rightarrow \bar{c}c\)
     - \(e^+ e^- \rightarrow \mu^+ \mu^- (\gamma)\)
- HNL: characterized by large missing mass (TAUOLA+KK2F – custom function, mass modified to attribute masses in range 100 – 1300 MeV/c^2)

\[\text{TAUOLA: Comp. Phys. Co. 130, 260–325 (2000)}\]
\[\text{KK2F: Comp. Phys. Co. 64, 275 (1991)}\]
\[\text{JetSet: Comp. Phys. Co. 39, 347 (1986)}\]
Fit Model

Assume each bin \((i, j)\) in 2D plots can be represented by a Poisson sampling function:

\[
\mathcal{L} = \prod_{ij} f(n_{ij}; n_{obs}, \tilde{\theta}) = \prod_{ij} \left( \nu_{\text{HNL}} \right)_{ij} + \left( \nu_{\tau - \text{SM}} \right)_{ij} + \left( \nu_{\text{BKG}} \right)_{ij} \left( n_{obs} \right)_{ij}^{-1} \frac{e^{-(\nu_{\text{HNL}} + \nu_{\text{BKG}} + \nu_{\tau - \text{SM}})_{ij}}}{(n_{obs})_{ij}!} \times \prod_{k} f(\theta_k, \tilde{\theta}_k),
\]

where:

- Potential signal events:
  \[
  \hat{\nu}_{\text{HNL},ij} = n_{\text{HNL},ij}^{\text{reco}} = N_{\tau, \text{gen}} \cdot (|U_{\tau 4}|^2) \cdot p_{\text{HNL},ij},
  \]

- Expected tau SM background events:
  \[
  \hat{\nu}_{\tau - \text{SM},ij} = n_{\tau - \text{SM},ij}^{\text{reco}} = N_{\tau, \text{gen}} \cdot (1 - |U_{\tau 4}|^2) \cdot p_{\tau - \text{SM},ij},
  \]

- Expected non-tau SM background events:
  \[
  \hat{\nu}_{\text{BKG},ij} = n_{\text{BKG},ij}^{\text{reco}} = n_{\tau - \text{other},ij}^{\text{reco}} + n_{\text{non},ij}^{\text{reco}},
  \]

- Use Wilk’s theorem to find limits:
  \[
  q = -2 \ln \left( \frac{\mathcal{L}_{H_0}(|U_{\tau 4}|^2; \tilde{\theta}_0, \text{data})}{\mathcal{L}_{H_1}(|U_{\tau 4}|^2; \tilde{\theta}, \text{data})} \right) = -2 \ln (\Delta \mathcal{L}).
  \]

Potential signal events:

- Expected tau SM background events:

- Expected non-tau SM background events:

- nuisance parameters maximized for a given value of \(|U_{\tau 4}|^2\) i.e. it is the conditional maximum-likelihood. Includes background only case

- maximized (unconditional) likelihood giving the MLE of \(|U_{\tau 4}|^2\) a vector of nuisance parameters which maximize the likelihood.
# Event Selection

- Selection optimized $\tau^\pm \rightarrow l^\pm \nu_l$ (tag) and $\tau^+ \rightarrow \pi^+ \pi^+ \pi^\pm \nu_\tau$ (3h)

<table>
<thead>
<tr>
<th>Cut</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of tracks</td>
<td>Ensure 1+3 prong topology</td>
</tr>
<tr>
<td>Total charge on all 4 charged tracks is 0</td>
<td>Charge conservation</td>
</tr>
<tr>
<td>$p_{CM}^{miss} &gt; 0.9% \sqrt{S}$</td>
<td>Suppresses non-tau backgrounds</td>
</tr>
<tr>
<td>All tracks: $p_{trans} &gt; 250$ MeV/c</td>
<td>To reach DIRC</td>
</tr>
<tr>
<td>All tracks: $-0.76 &lt; \cos(\theta) &lt; 0.9$</td>
<td>Acceptance of DIRC</td>
</tr>
<tr>
<td>1 prong: $\frac{2p}{E} &lt; 0.9%$</td>
<td>Consistent with tau decay</td>
</tr>
<tr>
<td>PID Requirements</td>
<td>Uses Electron and Muon ID algorithms</td>
</tr>
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</table>
Normalization Uncertainties

- Normalization uncertainties affect all bins uniformly.
- Have small effect on overall yield.
- They will be characterized as Gaussian nuisance parameters in the likelihood.

<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>Contribution</th>
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<tbody>
<tr>
<td>Luminosity</td>
<td>0.44% [BABAR]</td>
</tr>
<tr>
<td>Cross-section</td>
<td>0.31% [Data]</td>
</tr>
</tbody>
</table>
| Branching fraction of 1-prong tau decays | Electron: 0.23% [PDG]  
      Muon: 0.23% [PDG]                                                      |
| Branching fraction of 3-prong tau decays | 3 pions: 0.57% [PDG]                                                          |
| PID Efficiency                           | Electron: 2% [BABAR]  
      Muons: 1%  
      Pions: 3%                                                            |
| $q\bar{q}$ and Bhabha Contamination      | 0.3% [Control region analysis]                                               |
| Bin Size                                 | < 1% [Alter bins, check results]                                             |
| Tracking Efficiency                      | N/A                                                                          |
| Detector Modelling                       | N/A                                                                          |
| Tau Mass uncertainty                     | N/A                                                                          |
| Tau Energy                               | N/A                                                                          |
Systematic Shape Uncertainties

- $\tau^- \rightarrow \pi^- \pi^+ \nu_\tau$ is mediated by the $a_1$ resonance 97% of the time.
- Dominant shape systematic in signal and tau backgrounds are from modelling of the hadronic tau decays in TAUOLA.
- Experimental (PDG) uncertainties large:
  - $m_{a_1} = 1230 \pm 40$ MeV/$c^2$
  - $\Gamma_{a_1} = 420 \pm 35$ MeV/$c^2$ (we use PDG estimates 250 – 600 MeV/$c^2$)
- To account for this looked at templates with mass and width varied to these extremes and re-calculated the likelihood
- $\Gamma_{a_1}$ error has largest effect:
  - Shift in RMS of $\sim 6 – 7\%$ in $m_h$ and $\sim 1 – 3\%$ in $E_h$.
  - Shift in mean values for $E_h$ and $m_h$ shift by only $\sim 1 – 2\%$. 

$m_4 = 0$ MeV/$c^2$ $m_4 = 500$ MeV/$c^2$ $m_4 = 1000$ MeV/$c^2$

$m_{a_1} = 1230$ MeV/$c^2$ $m_{a_1} = 1270$ MeV/$c^2$ $m_{a_1} = 1190$ MeV/$c^2$
Our results

Binned likelihood fit incorporating nuisance parameters.

Dominant systematic from modelling uncertainties in hadronic tau decays.

Presents new upper limits on $|U_{\tau4}|^2$ at 95 % C.L. between 100 MeV/c$^2$ – 1300 MeV/c$^2$:

- World-leading constraints at time of acceptance for publication.

In 2021-2023 there have also been new results in this region from:

- Bojarska et al.: Phys. Rev. D 104, 095019 (indirect use of CHARM electron and muon result)
Summary

- Heavy Neutral Leptons offer ways of explaining several observational phenomena.
- The possible masses of the additional neutrino state is model dependent and can range from eV/c² up to very heavy masses.
- In the last few years, several new results have been published including results from collider-based experiments and neutrino experiments.
- Constraints in tau sector now comparable to those in the electron and muon sector.
- Many of these results are not from new experiments, they are in fact new studies using old data.

- This talk has given details on the latest analysis from BABAR which presents new upper limits on $|U_{\tau 4}|^2$ at 95 % C.L. between 100 MeV/c² – 1300 MeV/c² in the range $10^{-6} < |U_{\tau 4}|^2 < 10^{-2}$. 
Example Signal Simulations

- Plots illustrate in 1D projections and final 2D templates for $\tau^- \rightarrow \pi^- \pi^+ \pi^- \mu_X$
- Phase space changes with HNL mass

$m_4 = 100 \, \text{MeV}/c^2$

$m_4 = 500 \, \text{MeV}/c^2$

$m_4 = 700 \, \text{MeV}/c^2$

$m_4 = 1000 \, \text{MeV}/c^2$

largest sensitivity for large masses
Example 2D Plots

Data Total = 1273291
MC Total = 1283654

Non-tau Backgrounds

$\tau^+ \rightarrow e\nu_e$ (tag)

$\tau^- \rightarrow \pi^- \pi^- \pi^+ + HNL$ (sig)

SM-tau Backgrounds