Search for heavy neutrinos in the ND280 near detector of the T2K experiment

Alexander Izmaylov, Sergey Suvorov

High Energy Physics Department Seminar, Troitsk

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Heavy neutral leptons

- Heavy Neutral Leptons (HNL) or heavy sterile neutrinos proposed to solve some problems of the Standard Model (SM) (i.e. $\nu_{\text{MSM}}$ arXiv:050.3065)
- Explain neutrino masses, baryon asymmetry, dark matter

- Different mass regions:
  - $10^9 \div 10^{14}$ GeV: GUT scales, Baryon asymmetry generation
  - $10^2 \div 10^3$ GeV: can study at LHC energy scales
  - $10^{-3} \div 10^2$ GeV: masses of already known leptons and quarks
    This region studied in current work
  - $\sim$ eV: neutrino oscillation anomalies
How to find HNL

• Mixing between HNL and active neutrinos leads to:
  • their production in decays of heavy mesons
  • HNL decays into SM particles

• Two ways for experimental search:
  • direct measurement of meson decays:
    e.g. modified kinematics w.r.t. SM decays with $m_\eta = 0$
    • signal $\sim |U|^2$
  • search for decay products of HNLs originating in intense beam of “ordinary” neutrinos $\rightarrow$ T2K ND280 corresponds to this case
    • signal $\sim |U|^4$
Previous constraints

- Interested in region $100 \text{ MeV} < M_{HNL} < 500 \text{ MeV}$
- Best current limits:
  - **PS191** (CERN experiment, 1980-s)
  - **E949** (BNL, 2015)
- Some hints that the T2K experiment can improve limits
The T2K (Tokai-to-Kamioka) accelerator long-baseline neutrino oscillation experiment

- Study (anti-)neutrino oscillations $\nu_\mu \rightarrow \nu_e$, $\nu_\mu \rightarrow \nu_\mu$
- Neutrino and antineutrino beam from mesons’ decays ($\pi, K$)
HNL in kaon decays

- Other reactions: $N \rightarrow \gamma \nu$, $N \rightarrow \nu \pi^0$, $N \rightarrow 3\nu$.
- We study products of HNL decay with ND280:
  Number of events $\sim |U|^4$
T2K near detector ND280

- Off-axis detector at 280 meters from target station
- Contains:
  - 3 Time Projection Chambers (TPC)
  - 2 Fine Grained Detectors (FGD)
  - Electromagnetic Calorimeter (ECal)
  - Side Muon Range Detector (SMRD)
  - UA1 magnet
- Optimized for tracking and PID at 1GeV
Analysis plan

• Active neutrino interactions → main background for HNL search
• Look for decay in TPC filled with Ar → reduce the impact from active neutrino interactions

• Background: gas interactions and reconstruction failures
  • poor knowledge of Ar cross-section at ~1 GeV
• Optimize cuts to eliminate background
• “Zero signal strategy” – assume all observed events are BG and put C.L. limits on mixing elements
HNL flux simulation

- Use flux from $K\mu 2 \ (K \rightarrow \mu \nu)$
- Reweight $K\mu 2$ flux for HNL:
  - Massive lepton kinematic
  - HNL branching ratio $\Gamma(K \rightarrow lN) = \rho(M_{HNL})\Gamma(K \rightarrow l\nu)|U|^2$

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Flux from reaction $K \rightarrow \mu + N$

Flux from reaction $K \rightarrow e + N$
HNL decay in ND280

- Number of signal events estimated from:
  - HNL flux – \( \phi(\text{HNL}/10^{21} \text{p.o.t/cm}^2) \)
  - detector front area - \( S_{\text{det}} \)
  - probability of HNL decay inside TPC - \( P_{d\text{ecay}}^{TPC} \)
  - decay mode branching ratio - \( Br_{\text{mode}} \)

\[
N_{\text{events}} = \phi(\text{HNL}/10^{21} \text{p.o.t/cm}^2) \cdot S_{\text{det}} \cdot P_{d\text{ecay}}^{TPC} \cdot Br_{\text{mode}}
\]

assume HNL life time \( \tau \gg 1\mu s \) mean free path \( \Lambda = c\beta\gamma\tau \gg 280m \)

From cosmology (BBN) \( \tau < 0.1s \)

Finally:

\[
N_{\text{events}} = \phi(\text{HNL}/10^{21} \text{p.o.t/cm}^2) \cdot S_{\text{det}} \cdot \frac{l_{TPC}}{c\beta\gamma} \cdot \Gamma_{\text{mode}}
\]
Expected sensitivity

\[ |U|^2_{\text{limit}} = \sqrt{\frac{U_{C.L.}}{N_{\text{events}}}} \], no BG \rightarrow U_{C.L.} = 2.44 \text{ (Feldman Cousins)}

- PS191 limits
- Asaka et al prediction (arXiv:1212.1062) ("theoretical estimation")
- Full MC simulation
- Assume $10^{21}$ POT, no background, 100\% efficiency, 90\% C.L.

\[
|Ue|^2 \quad |U\mu|^2 \quad |UeU\mu|
\]
HNL Selection

- Recon two-tracks’ vertex in TPC FV, good quality,
- Tracks of opposite charge
- PID: $e\pi$ or $\mu\pi$
- Invariant mass cut $250 \div 700\ MeV$ for $\mu\pi$ and $140 \div 700\ MeV$ for $e\pi$
- At least one track use vertex TPC
- No other activity in vertex TPC
- No activity in upstream detectors
- Kinematics cuts: tracks opening angle, HNL candidate polar angle.

Example of signal event simulation. HNL decay in TPC1.
HNL Time of Flight

- T2K beam 8 bunches $\sigma \sim 19 \text{ ns}$

- Massive HNL $\Rightarrow dT = \frac{d}{c} \left( \frac{1}{\beta} - 1 \right)$
  
  $d \approx 280 \text{ m}$

Time cut:

$-100 \text{ ns} < T_{\text{vertex}} - T_{\text{bunch}} < 300 \text{ ns}$

limited by electronic gates

Active $\nu$ bunch
HNL bunch

$M_{\text{HNL}} = 460 \text{ MeV}$
HNL Selection Efficiency

- Limited by detector design:
  - Low efficiency at TPC edges
  - Pion interactions
  - Small relative angle between tracks → TPC tracking limitations
Charge conjugated modes

- T2K collects data with different horn polarity $(6.2\nu + 2\bar{\nu})10^{20}POT$
- Assume Majorana cases of HNL, look for both $K^\pm \rightarrow l^\pm N$, $N \rightarrow l^\mp \pi^\pm \rightarrow$ increase statistic for analyse
MC background study

- Use MC to estimate BG. Checks with
  - GENIE \((2.27 \cdot 10^{21} \text{ POT})\)
  - NEUT \((6.5 \cdot 10^{21} \text{ POT})\)

- NEUT \(10^{21} \text{ POT}\) equivalent
  1. \(\mu\pi\) mode \(4.6\)
  2. \(e\pi\) mode \(3.23\)

- GENIE
  1. \(\mu\pi\) mode \(4\)
  2. \(e\pi\) mode \(1.76\)

- NEUT \(\bar{\nu}\)
  1. \(\mu\pi\) mode \(3.4\)
  2. \(e\pi\) mode \(1.3\)

MC estimation at data statistics
For \((6.2\nu + 2\bar{\nu})10^{20} \text{ POT}\)
2010-1015 ND280
\[
\begin{align*}
\mu\pi & \quad 3.34 \\
e\pi & \quad 2.83
\end{align*}
\]
MC background study with NEUT

• BG origin for $\mu \pi$ mode:
  1. $\mu \pi$ 41%
  2. $\mu \pi + X$ 23%
  3. $\mu \rho + (X)$ 7.7%
  4. $\pi^- \pi^+ + X$ 2.6%
  5. $\eta \rightarrow \pi^+ \pi^- \pi^0$ 2.6%
  6. $\Lambda \rightarrow \pi^- \rho + X$ 2.6%
  7. $K^0 S \rightarrow \pi^+ \pi^-$ 5.2%
  8. $K^0 L \rightarrow \mu \pi + X$ 2.6%
  9. $\delta - ray$ spoils $\mu$ track 10.3%

• BG origin for $e \pi$ mode:
  1. $\pi^0 \rightarrow 2\gamma \rightarrow e^- e^+ + X$ 46%
  2. $\delta - ray$ from $\mu$ 14%
  3. $\mu \pi$ 14%
  4. $\delta - ray$ spoils $\mu$ track 26%
Systematics

- Predicted events in ND280:

\[ N_{\text{events}} = \varphi(HNL) \cdot \frac{V_{TPC}}{c\beta\gamma} \cdot \Gamma_{\text{decay}} \cdot Eff_{\text{det}} \]

- \( \varphi(HNL) \) - HNL flux, affected by kaon flux systematics
- \( V_{TPC} \) - fiducial volume of TPC
- \( \Gamma_{\text{decay}} \) - HNL decay width for current mode
- \( Eff_{\text{det}} \) - detector efficiency, affected by detector systematics
Flux systematics

- Largest impact from $K^+$ multiplicity measurements (NA61)
  - also affects from focusing, target position etc.
- Expect uncertainties $\leq 30\%$
## Detector Systematics

<table>
<thead>
<tr>
<th></th>
<th>$\mu\pi$</th>
<th>$e\pi$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Variation-Like</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Distortions of magnetic field</td>
<td>0.17%</td>
<td>0.13%</td>
</tr>
<tr>
<td>TPC momentum scale</td>
<td>0.1%</td>
<td>0.1%</td>
</tr>
<tr>
<td>TPC momentum resolution</td>
<td>0.99%</td>
<td>0.74%</td>
</tr>
<tr>
<td>TPC $dE/dx$ particle ID</td>
<td>0.43%</td>
<td>1.67%</td>
</tr>
<tr>
<td><strong>Efficiency-like</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TPC cluster efficiency</td>
<td>&lt;&lt;1%</td>
<td>&lt;&lt;1%</td>
</tr>
<tr>
<td>TPC tracking efficiency</td>
<td>0.3%</td>
<td>3%</td>
</tr>
<tr>
<td>TPC charge ID efficiency</td>
<td>5.95%</td>
<td>6.22%</td>
</tr>
<tr>
<td>TPC-FGD matching efficiency</td>
<td>0.69%</td>
<td>0.82%</td>
</tr>
<tr>
<td>Pion secondary interactions</td>
<td>2.67%</td>
<td>2.43%</td>
</tr>
<tr>
<td>Global Vertexing</td>
<td>0.87%</td>
<td>0.79%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>7.48%</td>
<td>8.11%</td>
</tr>
</tbody>
</table>
$|U|^2$ limits with ND280

- MC efficiency, background, systematics $\Rightarrow$ $|U|^2$ limits
- $(6.2\nu + 2\bar{\nu})10^{20} POT$ statistics (2010-2015 ND280 data)
- $|U|^2$ limits estimated from observed events (Feldman Cousins):

$$U = U_n \left(1 + E \frac{\sigma^2}{2}\right) \left(1 + \left(E \frac{\sigma}{2}\right)^2\right)$$

where $k_n$ is CL limit for observed $n$ events (no syst),

$E = k_n - n$,

$\sigma$ - acceptance RMS
$|U|^2$ limits based on MC

- Red - previous PS191 limit, scaled to HNL Majorana nature
- Green – 90% CL ND280 estimation

$(6.2\nu + 2\bar{\nu})10^{20} POT$ statistics
(2010-2015 ND280 data)

$\nu^+\nu^+\nu^- 10^{20} POT$ statistics
(2010-2015 ND280 data)

$\nu^+\nu^+\nu^- 10^{20} POT$ statistics
(2010-2015 ND280 data)
Conclusion

- MC study of HNL production and decays in ND280
- Developed HNL selection → study efficiency and BG with MC
- Studied detector systematics
- $|U|^2$ expected limits estimated with MC
- Ready for data analysis

Able to improve previous limits in high mass region
$|U\tau|$ limits

- $|U\tau|$ element is poor studied
- Reaction $N \rightarrow l^- l^+ \nu_{e,\tau}$ through NC provide study $|Ue|\sqrt{|Ue|^2 + |U\tau|^2}$, assume $|U\mu| \ll |Ue|$

**N** $\rightarrow$ $\nu_{e,\mu,\tau} \rightarrow e,\mu$

Expected sensitivity to $|Ue|\sqrt{|Ue|^2 + |U\tau|^2}$

| $|U\tau|$ constrictions |
|-------------------------|

based on CHARM
DELPHI
NOMAD

\[ M_f \text{ [GeV]} \]

\[ u_{\tau}^2 \]

\[ 10^{-4} \]

\[ 10^{-5} \]

\[ 10^{-6} \]

\[ 10^{-7} \]

\[ 10^{-8} \]

\[ 10^{-9} \]

\[ 10^{-10} \]

\[ 0.2 \]

\[ 0.25 \]

\[ 0.3 \]

\[ 0.35 \]

\[ 0.4 \]

\[ 0.45 \]

\[ 0.5 \]

Mass, GeV
BackUP
Pile up

- Possible pile up sources:
  - No activity in upstream detector
  - No activity in TPC with HNL candidate vertex

- Study real data for pile up value
- Chose the maximum pile up from all runs for each TPC
  - 3.3%    TPC1
  - 3.2%    TPC2
  - 2.8%    TPC3
Invariant mass resolution

\[ M = 0.36 \text{GeV} \]

\[ M = 0.46 \text{GeV} \]
BG

$\eta \rightarrow \pi^+ \pi^- \pi^0$

$\pi^0 \rightarrow 2\gamma \rightarrow e^-e^+ + X$
HNL decay

2-body decay:

\[ N \rightarrow e^- \pi^+ \]
\[ N \rightarrow \mu^- \pi^+ \]

3-body decay:

\[ N \rightarrow \mu^+ e^\pm \nu_{e,\mu} \]
\[ N \rightarrow l^- l^+ \nu_l \]

NC

\[ N \rightarrow l^- l^+ \nu_{e,\mu,\tau} \]
3-body mods

Assume $10^{21}$ POT, no background, 100% efficiency, 90% C.L
Angle cuts

Opening angle of HNL candidate daughters

Polar angle HNL candidate
PID cuts

Muon PID (low momentum only)

N
0.5
0.4
0.3
0.2
0.1
0.05
0.0

0.7 0.75 0.8 0.85 0.9 0.95 1 1.05 1.1
(L +L )/(1-L )
p m

0.7 0.75 0.8 0.85 0.9 0.95 1 1.05 1.1

L

0.7 0.75 0.8 0.85 0.9 0.95 1 1.05 1.1
(L +L )/(1-L )
μ μ

0.7 0.75 0.8 0.85 0.9 0.95 1 1.05 1.1
(L +L )/(1-L )
π π

Pion PID (low momentum only)

N
0.5
0.4
0.3
0.2
0.1
0.05
0.0

0.7 0.75 0.8 0.85 0.9 0.95 1 1.05 1.1
(L +L )/(1-L )
μ μ

0.7 0.75 0.8 0.85 0.9 0.95 1 1.05 1.1
(L +L )/(1-L )
π π

0.7 0.75 0.8 0.85 0.9 0.95 1 1.05 1.1
L

0.7 0.75 0.8 0.85 0.9 0.95 1 1.05 1.1
L

Muon PID

Pion PID

Integral

Integral

Integral

Integral
Vertex spatial reconstruction resolution

[Graphs showing distribution of data points across X, Y, and Z dimensions.]
Recon vertex Z

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$10^{15}$