Heavy neutrinos at NA62
based on JHEP 1807 (2018) 105

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XXVII International Workshop on Deep Inelastic Scattering and Related Subjects
I am not an experimentalist.
I do not speak on behalf of the NA62 collaboration.
Nonetheless, we have published estimates on heavy neutrinos at NA62.
One member of our collaboration is an experimentalist at NA62.
Hierarchy problem

Higgs mass

[Ellis et al. 2009]

Only in a small window of $m_h$ can the SM be extended to the $M_P$

![Graph showing perturbativity and stability bounds.]

Higgs-top conspiracy

[Degrazia et al. 2012]

Their mass values happen to put us into a meta-stable vacuum

![Graph showing instability and stability regions.]

The SM is technically natural up to $M_P$
Hierarchy problem

**Higgs mass**

[Ellis et al. 2009]

Only in a small window of $m_h$ can the SM be extended to the $M_P$

**Higgs-top conspiracy**

[Degrassi et al. 2012]

Their mass values happen to put us into a meta-stable vacuum

New Physics

- Heavy NP easily destabilizes the Higgs mass
- NP at the electroweak scales circumvents this problem
- must be coupled feebly enough to have evaded detection

The SM is technically natural up to $M_P$

Relatively light and feebly coupled NP leads to long lived particles
Neutrino masses

Masses differences

- There are two measured mass differences for potentially three light neutrino masses $m_1$, $m_2$, $m_3$
- One neutrino may still be massless $m_{\text{lightest}} = 0$
- The smaller “solar” mass difference is given by $\Delta m_{\text{sol}}^2 = m_2^2 - m_1^2$

Normal ordering

![Normal Ordering Diagram]

Inverted ordering

![Inverted Ordering Diagram]

Parameter

<table>
<thead>
<tr>
<th>Variables</th>
<th>Normal Ordering</th>
<th>Inverted Ordering</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_1^2$</td>
<td>$m_{\text{lightest}}^2$</td>
<td>$m_{\text{lightest}}^2 - \Delta m_{32}^2 - \Delta m_{\text{sol}}^2$</td>
</tr>
<tr>
<td>$m_2^2$</td>
<td>$m_{\text{lightest}}^2 + \Delta m_{\text{sol}}^2$</td>
<td>$m_{\text{lightest}}^2 - \Delta m_{32}^2$</td>
</tr>
<tr>
<td>$m_3^2$</td>
<td>$m_{\text{lightest}}^2 + \Delta m_{31}^2$</td>
<td>$m_{\text{lightest}}^2$</td>
</tr>
</tbody>
</table>

Larger $\Delta m^2$

- $\Delta m_{31}^2 = m_3^2 - m_1^2$
- $\Delta m_{32}^2 = m_3^2 - m_2^2$
Neutrino masses

Masses differences

- There are two measured mass differences for potentially three light neutrino masses $m_1$, $m_2$, $m_3$.
- One neutrino may still be massless: $m_{\text{lightest}} = 0$.
- The smaller "solar" mass difference is given by $\Delta m^2_{\text{sol}} = m_2^2 - m_1^2$.

Normal ordering and inverted ordering diagrams.

Best fit values from the NuFIT 3.1 release by the $\nu$-fit collaboration:

<table>
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<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>(smaller)</td>
<td>$\Delta m^2_{\text{sol}}$</td>
<td>$7.40 \times 10^{-5}$ eV$^2$</td>
</tr>
<tr>
<td>larger</td>
<td>$\Delta m^2$</td>
<td>$2.515 \times 10^{-3}$ eV$^2$</td>
</tr>
<tr>
<td>$\sin^2\theta_{12}$</td>
<td>0.307</td>
<td>0.307</td>
</tr>
<tr>
<td>$\sin^2\theta_{13}$</td>
<td>0.02195</td>
<td>0.02212</td>
</tr>
<tr>
<td>$\sin^2\theta_{23}$</td>
<td>0.565</td>
<td>0.572</td>
</tr>
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Heavy Neutrinos
Low scale seesaw (type I) [Minkowski 1977; Mohapatra et al. 1980; Yanagida 1980; Schechter et al. 1980]

Three right handed neutrinos

\[ \mathcal{L}_{\nu_R} = -\frac{1}{2} \bar{\nu^C_R} M_{ij} \nu_R^j - y_{ai} \bar{\ell} a \varepsilon \phi \nu_R^i + \text{h.c.} \]

- \( M_{ij} \) Majorana mass;
- \( y_{ai} \) Yukawa coupling

Electroweak symmetry breaking

Dirac mass: \( m_{ai} = v y_{ai} \)

Seesaw mechanism

\[ m_{\nu} = -m_{ai} M_{ij}^{-1} m_{bj}^T = -\theta_{ai} M_{ij} \theta_{bj}^T, \quad \theta_{ai} = m_{aj} M_{ij}^{-1}, \]

produces tiny masses for the left handed neutrinos

Small mixing into mass eigenstates

\[ \nu \simeq U_{\nu}^\dagger (\nu_L - \theta \nu_R^C), \quad N \simeq \nu_R + \theta^T \nu_L^C, \]

the PNMS matrix \( U_{\nu} \) diagonalises the \( m_{\nu} \)

The neutrino is special

May explain

- Neutrino oscillation data
- Neutrino masses
- Baryogenesis via Leptogenesis
- Dark matter
Low scale seesaw (type I) [Minkowski 1977; Mohapatra et al. 1980; Yanagida 1980; Schechter et al. 1980]

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Coupling of \( N_i \) to the SM

\[ \mathcal{L} \supset -m_W \frac{\bar{N} \theta^* \gamma^\mu e_L}{\sqrt{2} v} W^+_{\mu} - \frac{m_Z}{\sqrt{2} v} \bar{N} \theta^* \gamma^\mu \nu_L Z_{\mu} - \frac{M}{v} \theta_a h \nu_{L\alpha} N + \text{h.c.} \]
### νMSM

**SM is symmetric under** $U(1)_{B-L}$

Majorana mass $M_{ij}$ breaks this symmetry

**The $B - L$ symmetry is restored**

▶ in the limit of $M_{ij} \to 0$

▶ if $\nu_{Ri}$ form pseudo Dirac pairs $\nu_{Ri} + \nu^{C}_{Rj}$
### νMSM

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<td>Majorana mass ( M_{ij} ) breaks this symmetry</td>
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</table>

### The \( B - L \) symmetry is restored

- in the limit of \( M_{ij} \rightarrow 0 \)
- if \( \nu_{Ri} \) form pseudo Dirac pairs \( \nu_{Ri} + \nu_{Rj}^c \)

### Mass matrix

\[
M_{ij} = M \begin{pmatrix}
1 - \mu & 0 & 0 \\
0 & 1 + \mu & 0 \\
0 & 0 & \mu'
\end{pmatrix}
\]

### \( B - L \) violating parameter

\( \epsilon, \epsilon', \mu, \mu' \) are small

- Almost mass degenerate pseudo Dirac pair
- Lighter \( \mathcal{O}(\text{keV}) \) dark matter candidate

### Yukawa coupling

\[
y_{ai} = \begin{pmatrix}
y_e + \epsilon_e & i(y_e - \epsilon_e) & \epsilon'_e \\
y_\mu + \epsilon_\mu & i(y_\mu - \epsilon_\mu) & \epsilon'_\mu \\
y_\tau + \epsilon_\tau & i(y_\tau - \epsilon_\tau) & \epsilon'_\tau
\end{pmatrix}
\]

- Pseudo Dirac pair with coupling \( \mathcal{O}(y) \)
- Dark matter candidate with coupling \( \mathcal{O}(\epsilon') \)
**SM is symmetric under** $U(1)_{B-L}$

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The $B - L$ symmetry is restored

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**Mass matrix**

$$M_{ij} = M \begin{pmatrix} 1 - \mu & 0 & 0 \\ 0 & 1 + \mu & 0 \\ 0 & 0 & \mu' \end{pmatrix}$$

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**Yukawa coupling**

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- pseudo Dirac pair with coupling $\mathcal{O}(y)$
- Dark matter candidate with coupling $\mathcal{O}(\epsilon')$

**Abbreviation**

$$U^2 = \sum_a U^2_a, \quad U^2_a = \sum_i U^2_{ai}, \quad U^2_{ai} = |\theta_{ai}|^2,$$

The ratio $U^2_a/U_2$ becomes independent of other heavy neutrino parameter
Allowed range of $U_{\alpha}^2/U^2$

Normal Ordering

Inverted Ordering

- for arbitrary parameter choices (hashed region)
- in the symmetric limit (filled region).
- The stars mark our benchmark scenarios.

Benchmark scenarios $U_{\alpha}^2/U^2$ in %

<table>
<thead>
<tr>
<th></th>
<th>$U_{ei}^2$</th>
<th>$U_{\mu i}^2$</th>
<th>$U_{\tau i}^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.530 : 84.7 : 14.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>12.0 : 20.5 : 67.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>3.65 : 38.3 : 58.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>100 : 0 : 0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>0 : 100 : 0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>0 : 0 : 100</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Probability contours for the heavy neutrino couplings

Normal Ordering

Inverted Ordering

Coloured areas consistent with neutrino oscillation data at 1 σ, 2σ, 3σ

The Majorana phase is unknown and correspond to the circular structure in the plots
pure $U^2_\tau$

\[
\begin{array}{cccc}
U^2_e : U^2_\mu : U^2_\tau \\
0 : 0 : 1
\end{array}
\]
NA62
Fixed target experiment in the North Area using the CERN SPS with the goal to

- measure the very rare kaon decay $K^+ \rightarrow \pi^+ \nu\bar{\nu}$
- extract a 10\% measurement of the CKM parameter $|V_{td}|$

Hidden sectors at NA62
- it can also be used to search for hidden new physics $\chi$

Target mode
- only $K^+$ induced processes

Dump mode
- D- and B-meson induced processes dominate
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- Target mode
- only $K^+$ induced processes
- Dump mode
- $D$- and $B$-meson induced processes dominate
Heavy Neutrinos in the Target mode

Acceptance of $K^+ \rightarrow \ell^+ N$

<table>
<thead>
<tr>
<th>HNL mass [MeV/c^2]</th>
<th>Acceptance</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>0.35</td>
</tr>
<tr>
<td>200</td>
<td>0.30</td>
</tr>
<tr>
<td>250</td>
<td>0.25</td>
</tr>
<tr>
<td>300</td>
<td>0.20</td>
</tr>
<tr>
<td>350</td>
<td>0.15</td>
</tr>
<tr>
<td>400</td>
<td>0.10</td>
</tr>
<tr>
<td>450</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Result

| HNL mass [MeV/c^2] | UL on $|U_{14}|^2$ at 90% CL |
|--------------------|---------------------------|
| 50                 | $10^{-5}$                 |
| 100                | $10^{-6}$                 |
| 150                | $10^{-7}$                 |
| 200                | $10^{-8}$                 |
| 250                | $10^{-9}$                 |
| 300                | $10^{-10}$                |
| 350                | $10^{-11}$                |
| 400                | $10^{-12}$                |
| 450                | $10^{-13}$                |

5 days of operation in 2015

<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+ \rightarrow \ell^+ N$</td>
<td>$K^+ \rightarrow \mu^+ N$, $K^+ \rightarrow e^+ N$</td>
<td>$\pi^+ \rightarrow e^+ N$</td>
<td>$\pi^+ \rightarrow e^+ N$</td>
<td>$K^+ \rightarrow \mu^+ N$</td>
</tr>
</tbody>
</table>
Heavy Neutrinos in the Dump mode

Simulation
- Toy Monte Carlo of the dump mode
- Zero background assumption

Run 3 (2021–2023)
- $10^{18}$ proton on target (POT)
- Corresponds to about 80 days of data taking

Production of heavy neutrinos via $2 \times 10^{15}$ $D$- and $10^{11}$ $B$-mesons

\[
n_N \simeq 2N_{\text{POT}} \left( \chi_c \sum_{D_j=D^+, D^0, D_s} f_{D_j} \text{BR} (D_j \to XN_i) + \chi_b \sum_{B_k=B^+, B^0, B_s} f_{B_k} \text{BR} (B_k \to XN_i) \right),
\]

- $\chi$ production cross section normalization
- $f$ production fractions of mesons

Number of reconstructed events

\[
N_{\text{obs}} = n_N \sum_{f, f'=e, \mu, \tau, \pi, K} \text{BR} (N_i \to f^+ f'^- X) \mathcal{A}_i \left( f^+ f'^- X, M_i, U_{e, \mu, \tau}^2 \right) \varepsilon (f^+ f'^- X, M_i),
\]

- $\mathcal{A}_i$ geometrical acceptance
- $\varepsilon$ efficiency (trigger, reconstruction, selection); assumed to be 100%!
Branching Fractions

For scenario A: $U_{ie}^2 : U_{i\mu}^2 : U_{i\tau}^2 = 1 : 160 : 27.8$

The dominant modes are

$$N_i \rightarrow 3\nu, \pi^0 \nu, \pi^\pm \ell^\mp, \rho^0 \nu, \rho^\pm l, \ell^+ \ell^- \nu$$

The detector is able to reconstruct all final states having two charged tracks.
Results for NA62

\[ U_{2i} : U_{2e}^2 : U_{2\mu}^2 : U_{2\tau}^2 \]

- \( 1 : 160 : 27.8 \)
- \( 1 : 1.71 : 5.62 \)
- \( 1 : 10.5 : 15.9 \)
- \( 1 : 0 : 0 \)
- \( 0 : 1 : 0 \)
- \( 0 : 0 : 1 \)
pure $U_e^2$
pure $U_T^2$

$U^2_{\tau}$

$M_i$ [GeV]

$U^2_e : U^2_\mu : U^2_\tau$

0 : 0 : 1
Conclusion

- Heavy neutrinos constitute a minimal extension to the SM
- They can easily have properties detectable at current or future experiments
- Fixed target experiments are a powerful tool to unveil hidden sectors
- Although not designed for this purpose NA62 is at the moment the leading experiment for masses between the Kaon and the $D$-meson mass (shown at the example of heavy neutrinos)
- There is an opportunity for fixed target experiments dedicated to new physics
References


