Searches for neutrino physics beyond the standard model with KM3NeT/ORCA6

Víctor Carretero Cuenca (IFIC, Universitat de València - CSIC) on behalf of the KM3NeT Collaboration

International Conference of High Energy Physics
9/07/2022 (Bologna, Italy)
Table of contents

KM3NeT/ORCA

Neutrino Invisible Decay

Non Standard Interactions

Analysis

ORCA6 first results

Conclusions
KM3NeT/ORCA

- Digital Optical Modules (DOMs) and Detection Units (DUs).
- Currently 11 DUs (out of 115) deployed for KM3NeT/ORCA.
- 7 Mtons of instrumented volume (KM3NeT/ORCA115).
- Detection principle: Cherenkov light produced in neutrino interactions.
- See previous presentation by V. Pestel.
ORCA6 dataset

Same dataset that was described in V. Pestel presentation.

- Only up-going events.
- 1237 neutrino candidates in 354.6 days.
- Only ~30 background events (atmospheric $\mu$) expected.
- Signal dominated by $\nu_\mu$ - CC interactions.

KM3NeT preliminary ORCA6, 354.6 days

Reco. energy, track length based [GeV]

Reconstructed cos($\theta_{zenith}$)
Invisible Neutrino Decay

Summary

- **Motivation:** Proposed as a solution to neutrino deficit. Ruled out as main contribution (oscillation) but not as a *subdominant* process.

- There are several models that can explain this neutrino decay:
  1. **Majoron** Model: $\nu_i \rightarrow \nu_j + J$.
  2. **Dirac** Model: $\nu_i \rightarrow \bar{\nu}_j + \xi$

- Visible or **Invisible** Decay.

- Only $\nu_3$ decays are not well constrained by data.

- A **decay constant** is introduced in the Hamiltonian: $\alpha_3 = \frac{m_3}{\tau_3}$

$$H_T = \frac{1}{2E} \left[ H_{vacuum} + H_{decay} + H_{matter} \right] = \frac{1}{2E} H$$

$$H = U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m_{21}^2 & 0 \\ 0 & 0 & \Delta m_{31}^2 \end{pmatrix} U^\dagger + U \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -i\alpha_3 \end{pmatrix} U^\dagger + \begin{pmatrix} V & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$\Delta m_{31}^2 \rightarrow \Delta m_{31}^2 - i\alpha_3 \quad V = \pm 2E_n e \sqrt{2}G_F$$
Invisible Neutrino Decay
Oscillation effects

Neutrino invisible decay effects:

- Unitarity breaking.
- Atmospheric oscillation damping.

\[ P_{\mu e} + P_{\mu\mu} + P_{\mu\tau} < 1 \]

\[ \alpha_3 = 10^{-5} \text{eV}^2 \]

Oscillation damping
Matter resonance effects play an important role.
Non Standard Interactions

Summary

- **Motivation**: NSI describe the effects at the electro-weak scale of possible new physics at a higher energy scale.

- Additional potential terms in the Hamiltonian.

- The terms have the following **impact**:
  - Diagonal: If different, violation of **leptonic universality**.
  - Off-diagonal: **Flavour-changing neutral currents**.

- Neutrinos could couple to electrons, down quarks or up quarks.

- Not sensitive to the relative coupling strengths. For this analysis, **down quark** coupling is considered.

\[
H = \frac{1}{2E} U \begin{pmatrix}
0 & 0 & 0 \\
0 & \Delta m^2_{21} & 0 \\
0 & 0 & \Delta m^2_{31}
\end{pmatrix} U^\dagger + \sqrt{2} G_F n_e \begin{pmatrix}
1 + \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\
\epsilon_{\mu e}^* & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\
\epsilon_{\tau e}^* & \epsilon_{\tau\mu} & \epsilon_{\tau\tau}
\end{pmatrix}
\]

\[
\epsilon_{\alpha\beta} = \epsilon_{\alpha\beta}^{ee} + \frac{n_u}{n_e} \epsilon_{\alpha\beta}^{\nu e} + \frac{n_d}{n_e} \epsilon_{\alpha\beta}^{d e}
\]
NSI effects most important signature

Main effects are seen near the vertical and for energies > 10 GeV.

\[
\cos \theta = -1
\]
Analysis

- 2D binned analysis in $E_{\text{reco}}$ and $\cos \theta_{\text{reco}}$.

- Reconstructed events are computed taking into account:
  - Atmospheric flux.
  - Cross-sections.
  - Oscillation probabilities.
  - Effective mass.

- A $\chi^2$ analysis is performed: Poisson log-likelihood and gaussian penalties for systematics.

$$
\chi^2_{\text{total}} = \chi^2_{\text{Stat}} + \chi^2_{\text{Priors}}
$$

$$
\chi^2_{\text{total}} = 2 \sum_{i,j} \left[ (N_{ij}^{\text{mod}} - N_{ij}^{\text{dat}}) + N_{ij}^{\text{dat}} \log \left( \frac{N_{ij}^{\text{dat}}}{N_{ij}^{\text{mod}}} \right) \right] + \sum_k \left( \frac{\epsilon_k - \mu_k}{\sigma_k} \right)^2
$$
Nuisance parameters. The best fit values correspond to the standard oscillation model.

<table>
<thead>
<tr>
<th>Systematic</th>
<th>Pull ($\sigma$)</th>
<th>Best Fit</th>
<th>Post-fit error</th>
<th>C. V.</th>
<th>Prior</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normalisation</td>
<td>1.2</td>
<td>0.88</td>
<td>0.10</td>
<td>1</td>
<td>None</td>
</tr>
<tr>
<td>$\nu_\tau$-CC normalisation</td>
<td>0.15</td>
<td>0.97</td>
<td>0.20</td>
<td>1</td>
<td>0.20</td>
</tr>
<tr>
<td>Cosmic muon normalisation</td>
<td>0.3</td>
<td>1.3</td>
<td>0.9</td>
<td>1</td>
<td>None</td>
</tr>
<tr>
<td>NC normalisation</td>
<td>0.2</td>
<td>0.9</td>
<td>0.5</td>
<td>1</td>
<td>0.5</td>
</tr>
<tr>
<td>$\nu_\mu$/\bar{\nu}_\mu ratio</td>
<td>0.0</td>
<td>0.00</td>
<td>0.05</td>
<td>0</td>
<td>0.05</td>
</tr>
<tr>
<td>$\nu_e$/\bar{\nu}_e ratio</td>
<td>0.0</td>
<td>0.00</td>
<td>0.07</td>
<td>0</td>
<td>0.07</td>
</tr>
<tr>
<td>$\nu_\mu$/\nu_e ratio</td>
<td>0.0</td>
<td>0.000</td>
<td>0.020</td>
<td>0</td>
<td>0.020</td>
</tr>
<tr>
<td>Energy scale</td>
<td>0.0</td>
<td>1.00</td>
<td>0.05</td>
<td>1</td>
<td>0.05</td>
</tr>
<tr>
<td>Spectral index</td>
<td>1.2</td>
<td>0.05</td>
<td>0.04</td>
<td>0</td>
<td>0.3</td>
</tr>
<tr>
<td>$\nu_{up}/\nu_{horiz}$ ratio</td>
<td>0.1</td>
<td>0.002</td>
<td>0.020</td>
<td>0</td>
<td>0.020</td>
</tr>
<tr>
<td>$\Delta m^2_{31}$ [$10^{-3}$eV$^2$]</td>
<td>2.2</td>
<td>1.98</td>
<td>0.24</td>
<td>2.517</td>
<td>None</td>
</tr>
<tr>
<td>$\theta_{23}$ [$^\circ$]</td>
<td>0.8</td>
<td>45</td>
<td>5</td>
<td>49.2</td>
<td>None</td>
</tr>
</tbody>
</table>

The most important systematics effects for both analyses are in **bold**, in **blue** for neutrino invisible decay and in **red** for NSI.
$\theta_{23}$ dependency was accounted for, so a 90% contour plot to constrain both of them is computed.
Lower limits for the inverse of the decay constant $1/\alpha_3 = \tau_3/m_3$ in ps/eV at 90% CL.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>L.L.(90%CL) (ps/eV)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>ORCA6</td>
<td>2.4</td>
<td>Data analysis</td>
</tr>
<tr>
<td>ORCA115 (10y)</td>
<td>180</td>
<td>Sensitivity</td>
</tr>
<tr>
<td>T2K, NOvA</td>
<td>2.3</td>
<td>[1]</td>
</tr>
<tr>
<td>T2K, MINOS</td>
<td>2.8</td>
<td>[2]</td>
</tr>
<tr>
<td>K2K, MINOS, SK I+II</td>
<td>290</td>
<td>[3]</td>
</tr>
</tbody>
</table>

- Official results from experiments on this topic are scarce.
- Ref [3] was derived under the two flavour approximation and without matter effects.

\( \epsilon_{\mu\tau} \) effects are more pronounced for **up-going** neutrino directions.
Non Standard Interactions

Results.

KM3NeT/ORCA6 results not far away from the world-leading NSI measurements.

KM3NeT/ORCA6 limit: $-8.7 \times 10^{-3} < \epsilon_{\mu\tau} < 9.0 \times 10^{-3}$

KM3NeT/ORCA115 3-year sensitivity: $-1.7 \times 10^{-3} < \epsilon_{\mu\tau} < 1.7 \times 10^{-3}$ (TBU)
Conclusions

- Preliminary studies of **one year of data** with only a **5%** of the detector yields promising BSM results.
- Neutrino invisible decay constant constrained at 90% CL: $1/\alpha_3 = \tau_3/m_3 > 2.4 \text{ ps/eV}$
- NSI $\epsilon_{\mu\tau}$ parameter constrained at 90% CL: $[-8.7, 9.0] \times 10^{-3}$
- Several **forthcoming** improvements:
  - Analysis of additional half year of data.
  - Shower reconstruction.
  - Particle Identification classification.

- KM3NeT/ORCA keeps growing and the increase in statistics and resolution will enhance our sensitivity and potential to BSM physics.
Backup Slides
Invisible neutrino decay produces a depletion of events that is increased for vertical low energy events.
Most important systematics are $\Delta m^2_{31}$ and spectral index, which yields the biggest pull.
KM3NeT/ORCA115 will improve the current bounds on the invisible neutrino decay by two orders of magnitude, and it will be at least as competitive as future experiments.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>UL (90% CL) [10^{-6}eV^2]</th>
<th>LL (90% CL) [ps/eV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>KM3NeT/ORCA6</td>
<td>280</td>
<td>2.4</td>
</tr>
<tr>
<td>KM3NeT/ORCA115 (10 y)</td>
<td>3.7</td>
<td>180</td>
</tr>
<tr>
<td>T2K, NOvA</td>
<td>290</td>
<td>2.3</td>
</tr>
<tr>
<td>T2K, MINOS</td>
<td>240</td>
<td>2.8</td>
</tr>
<tr>
<td>K2K, MINOS, SK I+II</td>
<td>2.3</td>
<td>290</td>
</tr>
<tr>
<td>MOMENT (10 y)</td>
<td>24</td>
<td>28</td>
</tr>
<tr>
<td>ESSnuSB (5\nu+5\bar{\nu}) y</td>
<td>16 – 13</td>
<td>42 – 50</td>
</tr>
<tr>
<td>DUNE (5\nu+5\bar{\nu}) y</td>
<td>13</td>
<td>51</td>
</tr>
<tr>
<td>JUNO (5 y)</td>
<td>7</td>
<td>93</td>
</tr>
<tr>
<td>INO-ICAL (10 y)</td>
<td>4.4</td>
<td>151</td>
</tr>
</tbody>
</table>
Non Standard Interactions
Oscillation effects

NSI effects most important signature
Mainly effects are seen at very vertical directions.
$\theta_{23}$ interplay with $\alpha_3$

Flipping $\theta_{23}$ octant for high values of $\alpha_3$ in the model reduces the difference with respect to standard oscillations.

This effect implies that as long as $\theta_{23}$ octant is not constrained with precision, sensitivity to $\alpha_3$ could be affected.