Search for neutrino non-standard interactions with 10 years of ANTARES data and perspectives for KM3Net/ORCA

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ANTARES

- Total Instrumented Volume: ~8 Mton
- Instrumented Volume: ~15 m
- Depth: ~375 m ~100 m
- Orientation: ~65 m

ANTARES (completed in 2008)
- 12 strings of 25 storeys each
- 3 10” PMTs per storey (885 total)
- ~10 MTon

ORCA: Low energy physics ~ few GeV (Neutrino Oscillations)
KM3NeT/ORCA & ARCA

ORCA: Low energy physics ~ few GeV
Neutrino Oscillations, Supernovae ….

ARCA: High energy physics ~ GeV - PeV
High energy astronomy, DM searches …

ORCA instrumented Volume ~ 5 Mton

- 115 strings
- 18 DOMs / string
- 31 PMTs / DOM
- Total: 64k PMTs

Detection Unit (DU)
aka “string/line”

KM3NeT DOM
housing 31 3” PMTs
Event Topologies

Tracks: $\nu^C_C$, $\nu^C_C$ (muonic decay)  
Showers: $\nu^C_C$, $\nu^C_C$, $\nu^{NC}$

Position, time and charge pattern within the detector used to reconstruct particle direction and energy.

The Cherenkov signature of the outgoing lepton is used for Particle IDentification (PID).
Non-Standard Interactions (NSIs)

- The neutrino propagation Hamiltonian in presence NSIs:

\[
H = \frac{1}{2E} U_{PMNS} \begin{bmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{bmatrix} U_{PMNS}^\dagger + \begin{bmatrix} A_{CC} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} + \sqrt{2} G_F N_d(x) \begin{bmatrix} \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^{*}_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon^{*}_{e\tau} & \epsilon^{*}_{\mu\tau} & \epsilon_{\tau\tau} \end{bmatrix}
\]

\[\text{Vacuum} \quad \text{SM MSW} \quad \text{NSI}\]

- Signature at detector: a statistical excess/deficit of \((\nu + \bar{\nu})\) events from anomalous flavour transitions expected with standard oscillations predictions.
ANTARES Limits

* ANTARES dataset corresponding to 2007-2016 (both years included) has been used.

** ANTARES Preliminary best-fit points

- $\epsilon_{\mu\tau} : -1.3 \times 10^{-3}$
- $\epsilon_{\tau\tau} : 3.2 \times 10^{-2}$

$\chi^2$/d.o.f.: 152.36/136.

World's best limits!

3 year projected sensitivities towards NSI parameters at ORCA.
Outlook

ANTARES has produced significant results in constraining many new physics scenarios by studying neutrinos at the abyss of the Mediterranean Sea.

KM3NeT will make further improvements.
6 ORCA (and 1 ARCA) strings are operational. (Stay tuned for first results!)
Backup
Computation of event numbers

Model specific
Detector specific

Atmospheric Flux
Oscillated events
Interacting events
Detected events
Reconstructed events
Classified events
Event topologies

Oscillation
Cross-section
Flux

Tracks
Showers
Energy resolution

- Energy resolution for different interaction channels.
Event classes based on track probability estimated with Random Decision Forest (RDF) of reconstructed heuristics.

1 = Perfect Track
0 = Perfect Shower
Systematics:

\[-2\log \mathcal{L}_{NSI} = 2 \sum_{i \in \{\text{bins}\}} \left[ N_i^{NSI}(\bar{\theta}, \bar{s}) - N_i^{SM}(\bar{\theta}, \bar{s}) + N_i^{SM} \log \frac{N_i^{SM}(\bar{\theta}, \bar{s})}{N_i^{NSI}(\bar{\theta}, \bar{s})} \right] + \sum_{k \in \{\text{syst}\}} \frac{(s_k - \hat{s}_k)^2}{\sigma_k^2}\]

<table>
<thead>
<tr>
<th>parameters</th>
<th>treatment</th>
<th>true values</th>
<th>priors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Track norm.</td>
<td>fitted</td>
<td>1</td>
<td>free</td>
</tr>
<tr>
<td>Shower norm.</td>
<td>fitted</td>
<td>1</td>
<td>free</td>
</tr>
<tr>
<td>Middle norm.</td>
<td>fitted</td>
<td>1</td>
<td>free</td>
</tr>
<tr>
<td>$\nu_\mu/\nu_e$ skew</td>
<td>fitted</td>
<td>0</td>
<td>5%</td>
</tr>
<tr>
<td>$\nu_\mu/\bar{\nu}_\mu$ skew</td>
<td>fitted</td>
<td>0</td>
<td>5%</td>
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<tr>
<td>$\nu_e/\bar{\nu}_e$ skew</td>
<td>fitted</td>
<td>0</td>
<td>5%</td>
</tr>
<tr>
<td>Flux Escale</td>
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<td>10%</td>
</tr>
<tr>
<td>NC scale</td>
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<td>5%</td>
</tr>
<tr>
<td>Energy slope</td>
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<tr>
<td>Zenith slope</td>
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<tr>
<td>$\delta_{CP}(^\circ)$</td>
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<td>221</td>
<td>free</td>
</tr>
<tr>
<td>$\Delta m^2_{31}/10^{-3}eV^2$</td>
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<td>2.528</td>
<td>free</td>
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<tr>
<td>$\theta_{13}(^\circ)$</td>
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<td>0.13</td>
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<tr>
<td>$\theta_{23}(^\circ)$</td>
<td>fitted</td>
<td>48.6</td>
<td>free</td>
</tr>
</tbody>
</table>

List of systematics

\[\begin{align*}
\text{Stats} & \quad \checkmark \quad \text{: Allowed} \\
\text{TrackNorm} & \quad \checkmark \quad \text{: Allowed} \\
\text{ShowerNorm} & \quad \times \quad \text{: Excluded} \\
\text{MiddleNorm} & \quad \checkmark \quad \text{: Allowed} \\
\text{FluxEscale} & \quad \checkmark \quad \text{: Allowed} \\
\text{NC Scale} & \quad \times \quad \text{: Excluded} \\
\text{EnergySlope} & \quad \checkmark \quad \text{: Allowed} \\
\text{ZenithSlope} & \quad \checkmark \quad \text{: Allowed} \\
\theta_{13} & \quad \checkmark \quad \text{: Allowed} \\
\theta_{23} & \quad \times \quad \text{: Excluded} \\
\Delta m^2_{31} & \quad \checkmark \quad \text{: Allowed} \\
\theta_{13} & \quad \checkmark \quad \text{: Allowed} \\
\delta_{CP} & \quad \times \quad \text{: Excluded} \\
\theta_{23} & \quad \times \quad \text{: Excluded} \\
\end{align*}\]
Correlated NSI Sensitivities

90% CL contours in different NSI phase spaces.

The region inside the closed curves are the region allowed by ORCA after 3 years of data taking.

https://pos.sissa.it/358/931/