NEUTRINO OSCILLATIONS AND NON-STANDARD INTERACTIONS WITH KM3NET-ORCA

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on behalf of the KM3NeT collaboration
KM3NeT-ORCA Detector

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

Total Instrumented Volume ~ 8 Mton

ORCA: Low energy physics ~ few GeV (Neutrino Oscillations)

ORCA: -2450m

Detection Unit (DU)

J. Phys. G43 (2016) no.8, 084001
Event spectra at ORCA

Tracks (NO)

Cascades (NO)

Neutrino events in 3 years (divided by interaction channel):

- $\nu_e$ CC: 14 700
- $\bar{\nu}_e$ CC: 5 700
- $\nu_\mu$ CC: 21 300
- $\bar{\nu}_\mu$ CC: 9 900
- $\nu_\tau$ CC: 2 900
- $\bar{\nu}_\tau$ CC: 1 300
- NC: 6 800

An overall larger statistics-only sensitivity is observed in the shower channel.

$$\chi^2_{stat} = \frac{(N_{E,\cos\theta_z}^{IO} - N_{E,\cos\theta_z}^{NO}) \times |N_{E,\cos\theta_z}^{IO} - N_{E,\cos\theta_z}^{NO}|}{N_{E,\cos\theta_z}^{NO}}$$

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ORCA will determine the neutrino mass ordering with a significance of (2.2-5)$\sigma$ with 3 years of operation depending on the true value of $\theta_{23}$ and $\delta_{\text{CP}}$.

ORCA has strong sensitivity to the atmospheric oscillation parameters compared to current T2K and NOvA allowed regions.

https://pos.sissa.it/358/1019/
Non-Standard Interactions (NSIs)

NSI in neutrino propagation with matter fermions \((f = e, u \text{ or } d\)-quarks) can be modelled as perturbation to SM Hamiltonian.

\[
H = H_{\text{vacuum}} + H_{\text{matter}} + H_{\text{NSI}} = \frac{1}{2E} U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m_{21}^2 & 0 \\ 0 & 0 & \Delta m_{31}^2 \end{pmatrix} U^\dagger + 2\sqrt{2}G_F N_e(x) \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} + 2\sqrt{2}G_F N_f(x) \begin{pmatrix} e_{ee} & e_{em} & e_{et} \\ e_{me} & e_{mm} & e_{mt} \\ e_{te} & e_{tm} & e_{tt} \end{pmatrix}.
\]

In our case, \(f = d\)-quarks.

NSIs modify the oscillation probabilities in matter leading to a departure from the expected signal at the detector. Using the flavour induced distortions, we can put upper bounds on some NSI model parameters.

Muon disappearance (appearance) channel in left (right) in presence of NSI (blue) assuming NO (solid) and IO (dashed) for a fixed baseline.
Correlated NSI Sensitivities:

\[
\begin{bmatrix}
\epsilon_{ee} < 4.2 & \epsilon_{e\mu} < 0.33 & \epsilon_{e\tau} < 3 \\
\epsilon_{\mu\mu} < 0.07 & \epsilon_{\mu\tau} < 0.33 \\
\epsilon_{\tau\tau} < 21
\end{bmatrix}
\]

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.

NSI parameters not appearing on each of the plots are fixed at zero.

With 1 year live time, ORCA will be able to constrain NSI parameters 1 order better than current limits (vide matrix on top).
Sensitivities in the Hybrid NSI model

The exclusion region assuming NO in the hybrid model approximation ($\theta_{12}, \theta_{13},$ and $\Delta m^2_{21} = 0$) is drawn for comparison with current limits from other experiments. With 3 years of live time, ORCA is expected to constrain NSI parameters 4x smaller than IceCube and Super-K limits.

https://pos.sissa.it/358/931/
First results with ORCA 1DU: 125.3 days!

77 neutrino candidates reconstructed as up-going are observed in the considered data sample of 125.3 days of effective livetime, while 67.5 events are expected from atmospheric neutrino simulations and 4 events from atmospheric muon simulations.

https://pos.sissa.it/358/910/pdf
KM3NeT-ORCA is an intermediate energy [3-100 GeV] neutrino telescope with access to large baselines.

ORCA is expected to disentangle the wrong hierarchy within 3 years of operation at $3\sigma$ CL.

ORCA can make precision measurements of atmospheric oscillation parameters.

ORCA is sensitive to other subdominant oscillation effects like NSI.

Currently 4 DUs are in operation. (Stay tuned for first results!)
THANKS
BACKUP
Neutrino Mass Ordering

Mass splittings: Normal Ordering (NO) and Inverted Ordering (IO).

Oscillation pattern distorted by Earth matter effects.

Different event spectra at the detector for either orderings.

Observables: Energy and direction of neutrinos.

Oscillation probabilities in muon disappearance (blue) and appearance (red) channel assuming NO (solid) and IO (dashed). Neutrinos (left) and anti-neutrinos (right). Both contribute to the track channel.
Event Topologies at ORCA

Tracks: $\nu_\mu^{CC}$

\[ \nu_\mu + N^{cc} \rightarrow \text{had} + \mu \]

Cascades: $\nu_e^{CC} \nu^{NC}$

\[ \nu + N^{en} \rightarrow \text{had} \]
\[ \nu_e + N^{en} \rightarrow \text{had} + \text{em} \]

The Cherenkov signature of the outgoing lepton is used as a classifier.
Statistical $\chi^2$ maps:

\[
\chi^2_{stat} = \frac{(N_{E,\cos \theta_z}^{IO} - N_{E,\cos \theta_z}^{NO}) \times |N_{E,\cos \theta_z}^{IO} - N_{E,\cos \theta_z}^{NO}|}{N_{E,\cos \theta_z}^{NO}}
\]

A 20*10 binning scheme in log(E) and cosine zenith to fold in the detector response.

The sign is stored to retain the information of excess or deficit.
Systematics:

\[
\chi^2_S(\varepsilon_{\alpha\beta}) = 2 \sum_{E,\theta_{\varepsilon}} \left( N_{E,\theta_{\varepsilon}}^{\text{model}}(\varepsilon_{\alpha\beta}) \left( 1 + \sum_k f_k^{E,\theta_{\varepsilon}} \zeta_k \right) - N_{E,\theta_{\varepsilon}}^{\text{data}}(\varepsilon_{\alpha\beta} = 0) \right) + N_{E,\theta_{\varepsilon}}^{\text{data}}(\varepsilon_{\alpha\beta} = 0) \ln \left( \frac{N_{E,\theta_{\varepsilon}}^{\text{data}}(\varepsilon_{\alpha\beta} = 0)}{N_{E,\theta_{\varepsilon}}^{\text{model}}(\varepsilon_{\alpha\beta}) \left( 1 + \sum_k f_k^{E,\theta_{\varepsilon}} \zeta_k \right)} \right) + \sum_k \zeta_k^2.
\]

### NH - 8 Mton-years

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NuFit3.2
Sensitivities in the 3-flavour NSI model

NSI parameters that doesn’t appear on the plots are kept fixed at zero.

NO favourable over IO

NO favourable for negatives values
IO favourable for positive values

PoS(ICRC2019)931
Deployment and current status:

Phase 1: 4 ORCA DUs currently online. 2 DUs to be deployed early next year.

Phase 2: 115 ORCA DUs.
Full atmospheric oscillation physics program.

ORCA deployment

22 September 2017: First ORCA string

Video: https://tiny.cc/OrcaDeployment