Universiteit van Amsterdam

Nikhef

KM3NeT

Physics with KM3NeT-ORCA

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on behalf of the Nikhef-KM3NeT group

What do we know about neutrinos?

- There are 3 weakly interacting neutrino fields
- Interaction eigenstates ≠ mass eigenstates

$$|\nu_\alpha\rangle = \sum_k U^*_{\alpha k} |\nu_k\rangle$$

$$\mathcal{H}|\nu_k\rangle = E_k |\nu_k\rangle$$

Schrödinger →

$$|\nu_\alpha(t)\rangle = \sum_k U^*_{\alpha k} e^{-iE_k t} |\nu_k\rangle$$

Neutrinos oscillate!

- Neutrinos are massive!

$$P_{\nu_\alpha \to \nu_\beta}(L, E) = \sum_{k,j} U^*_{\alpha k} U_{\beta k} U_{\alpha j} U^*_{\beta j} \exp\left(-i \frac{\Delta m^2_{kj} L}{2E}\right)$$

amplitude: $U^*_{\alpha k} U_{\beta k} U_{\alpha j} U^*_{\beta j}$ — frequency: Δm^2_{kj} — $L \approx t$

Six oscillation parameters:

- 2 mass-squared differences — $\Delta m^2_{ij} = m^2_i - m^2_j$
- 3 mixing angles — θ_{ij}
- 1 complex phase — δ_{CP}

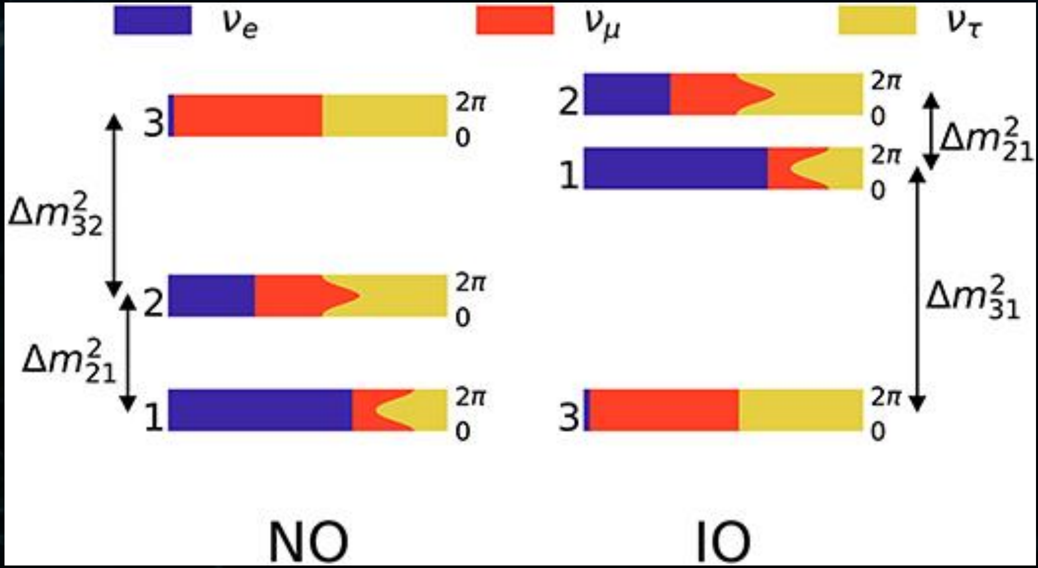
θ_{ij}, δ_{CP} determine size of PMNS matrix elements $U_{\alpha k}$

An unknown: The NMO

3 neutrino mass eigenstates, so in principle 3! orderings possible:

1-2-3	3-1-2	2-3-1	1-3-2	2-1-3	3-2-1

So why this picture?!



DOI: 10.3389/fspas.2018.00036

An unknown: The NMO

3 neutrino mass eigenstates, so in principle 3! orderings possible:

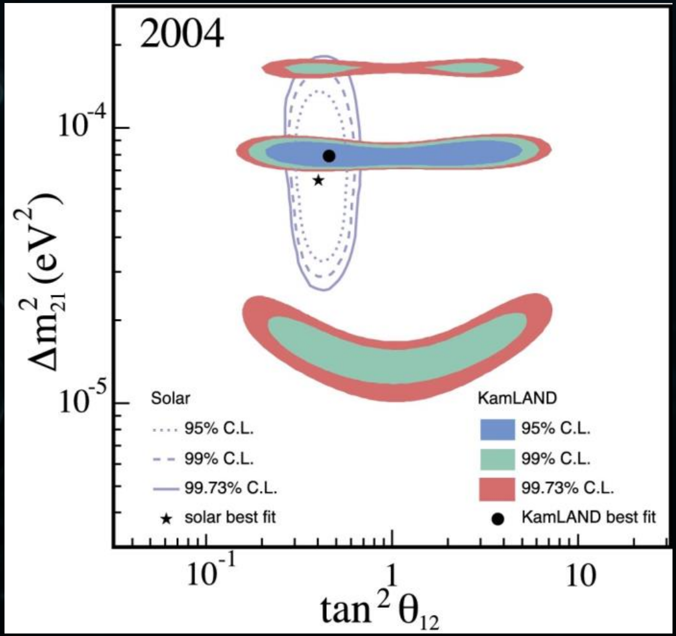
Normal	Inverted				
1-2-3	3-1-2	~~2-3-1~~	~~1-3-2~~	~~2-1-3~~	~~3-2-1~~

So why this picture?!

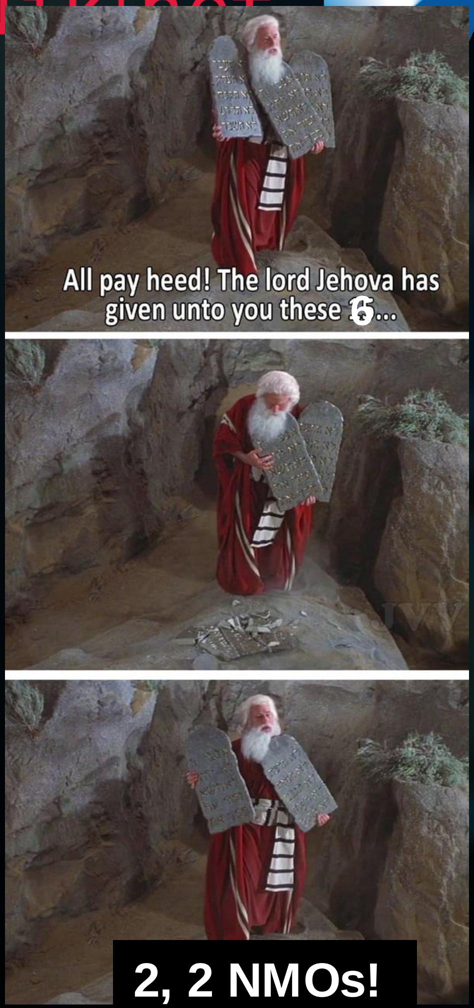
Only $|\Delta m^2_{3l}| > \Delta m^2_{21} > 0$ consistent with data:

- Atmospheric neutrino rates
- Reactor neutrino rates
- Solar neutrino **matter effects**

➡ **2 choices remaining**



DOI: 10.1016/j.nuclphysb.2016.04.014



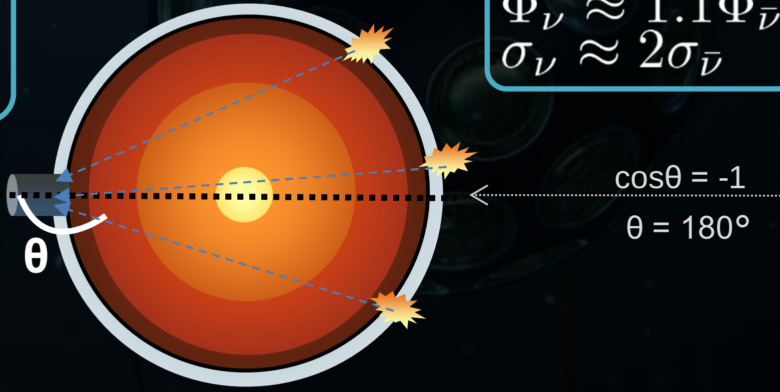
Determining the NMO

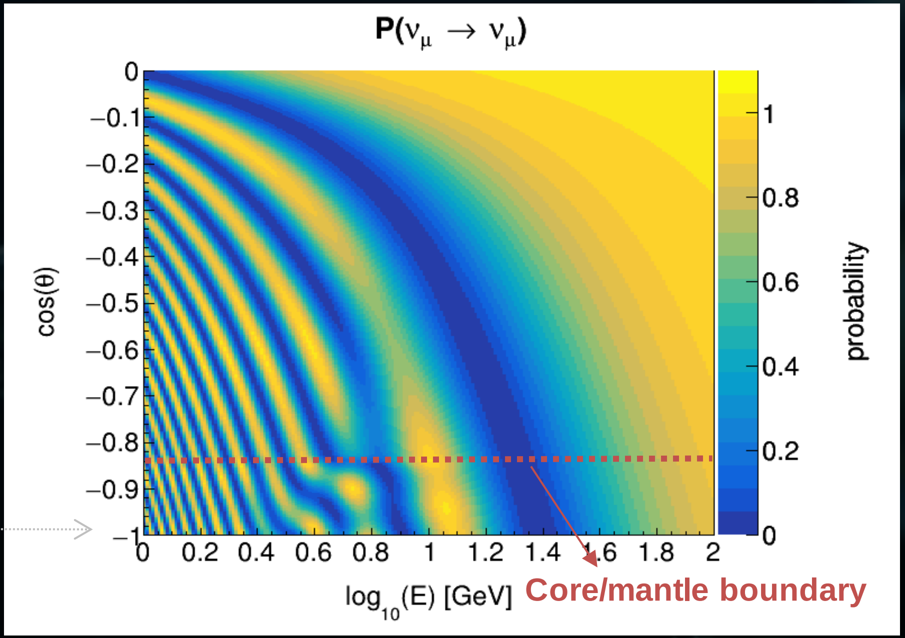
Our method:
Take advantage of matter effects in $P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu)$ and $P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e)$
and use natural $\nu/\bar{\nu}$ event rate asymmetry

- Resonances for ν $(\bar{\nu})$ in NO (IO)
- Long baseline accelerators (e.g. DUNE)
  + atm. neutrino detectors (e.g. KM3NeT)

Can probe vast range of L/E!

$$\Phi_\nu \approx 1.1\Phi_{\bar{\nu}}$$
$$\sigma_\nu \approx 2\sigma_{\bar{\nu}}$$

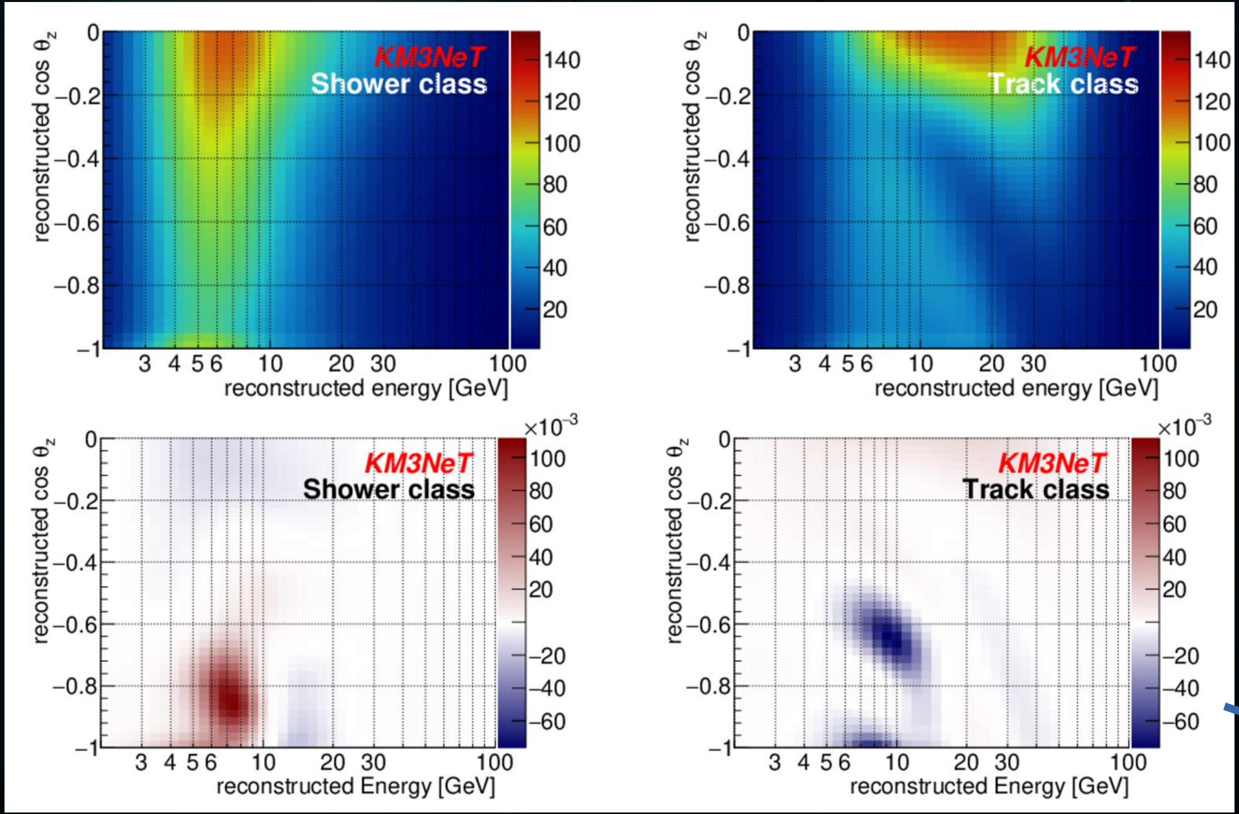




see also 10.1007/JHEP02(2013)082

NMO sensitivity with KM3NeT

DOI: 10.1140/epjc/s10052-021-09893-0



1. Simulate expected event rate
2. Reconstruct events
3. Classify events
   1. Remove noise + atm. $\mu^{\pm}$
   2. Distinguish event topology
4. Calculate Poissonian log-likelihood ratio of NO over IO

Blue: $N_{NO} < N_{IO}$
Red: $N_{NO} > N_{IO}$

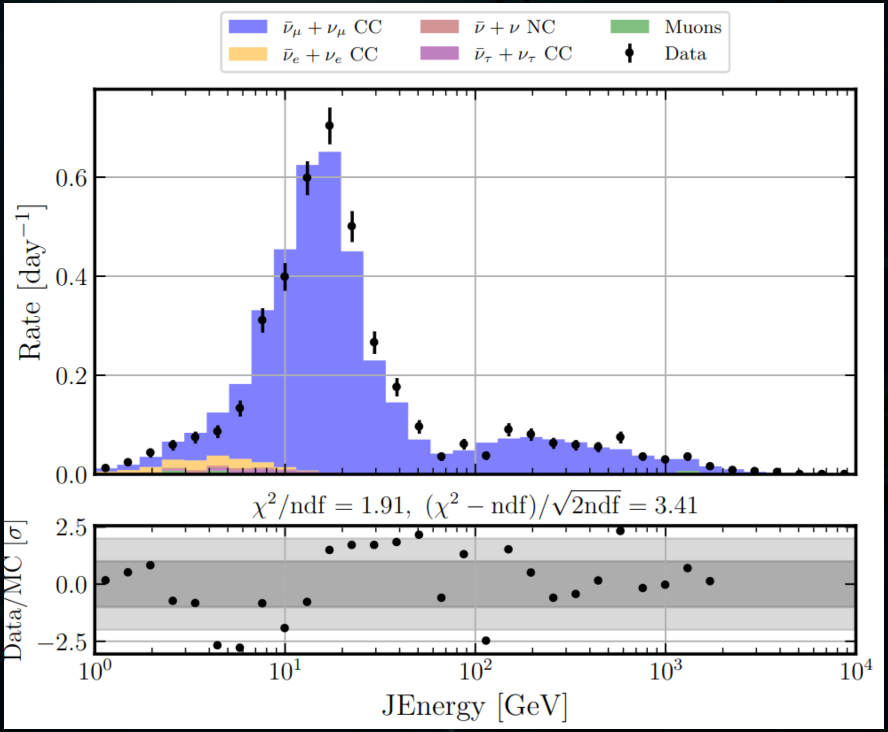
Most sensitivity from **excess of showers and deficit of tracks in 3-15 GeV** for NO w.r.t. IO

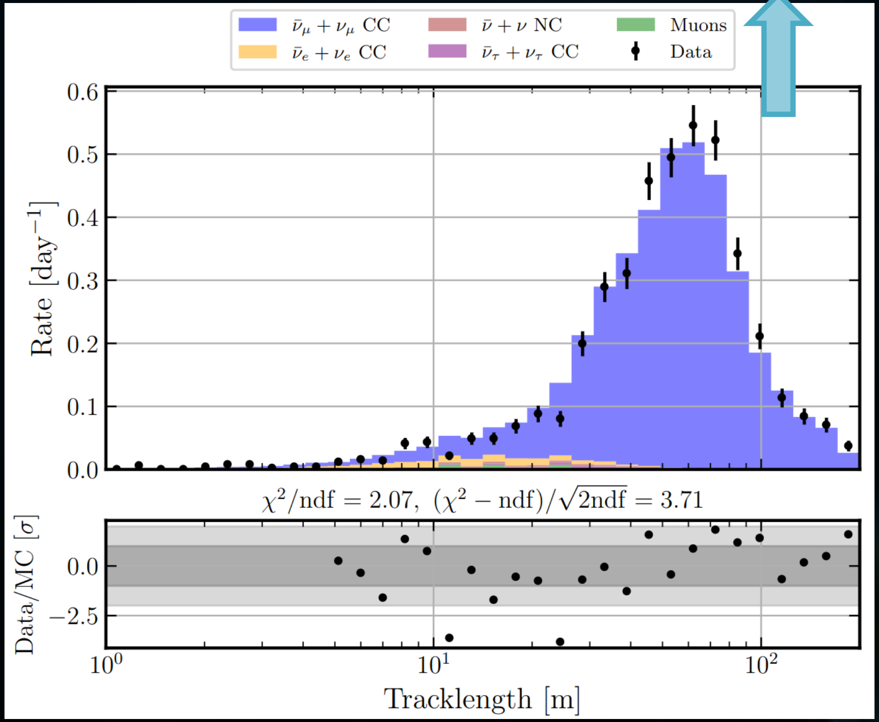
A first look at the data

>10% of KM3NeT-ORCA deployed right now and growing

→ Several neutrinos will be detected as we speak!

~ **4 atm. ν / day**
510 days of livetime
0.3% atm. $\mu^{\pm}$ contamination





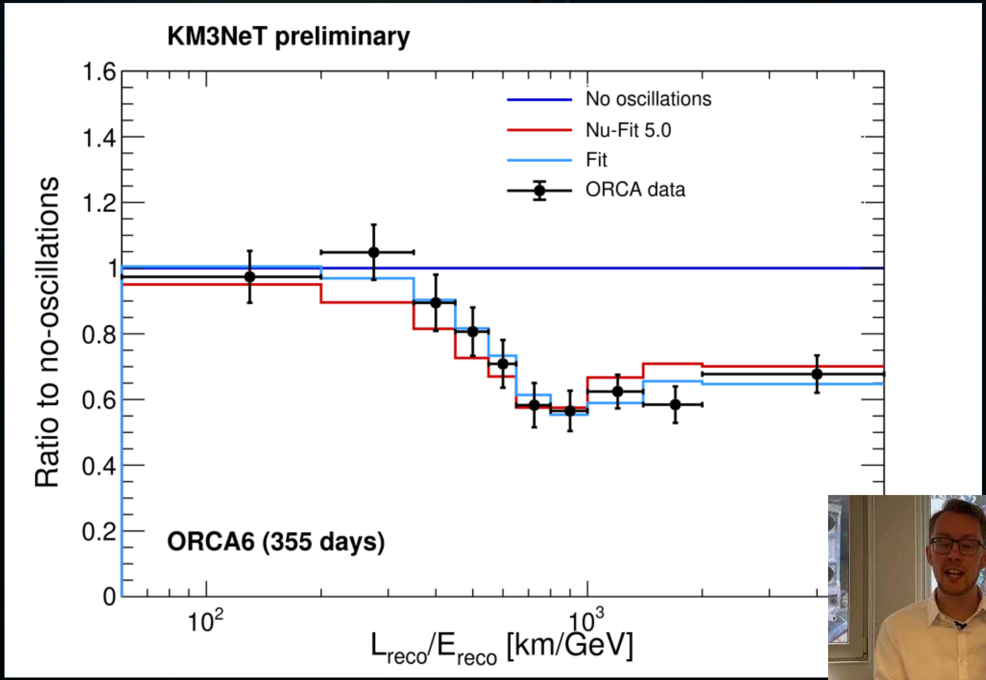
Results for 6 lines of ORCA by Alfonso Lazo

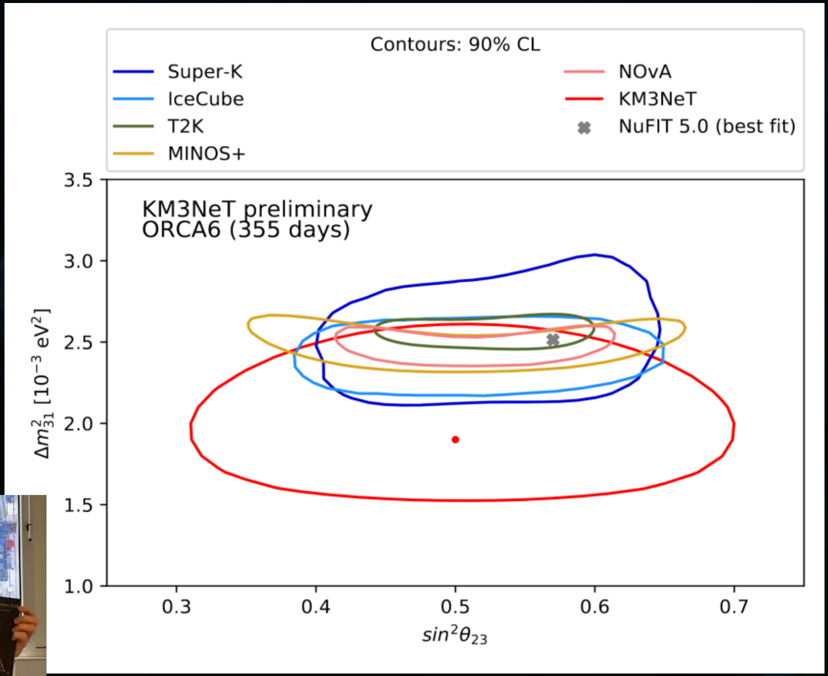
A first look at the data

>10% of lines already deployed and taking data!

First measurements with 355 days of 6 ORCA lines presented in **Lodewijk Nauta**'s Ph.D. thesis

5.9σ preference for oscillations over no oscillations





Ph.D. thesis, L. Nauta (2022)

Improving our analysis framework

First oscillation fits on data were done with a framework developed at Nikhef!

MONA

Question: What does MONA refer to?

a) 

b) 

c) 

Improving our analysis framework

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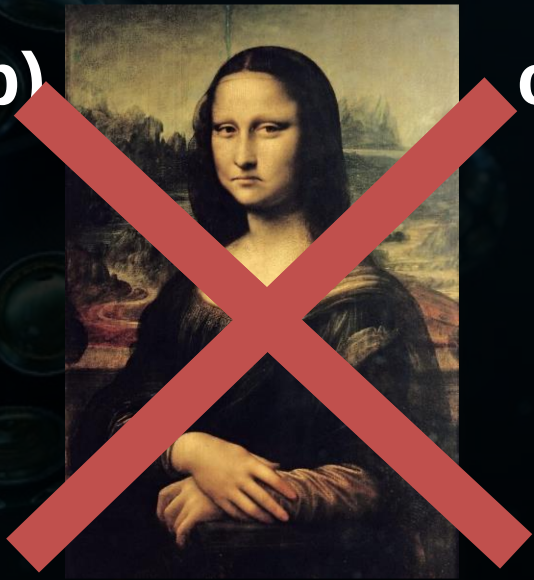
MONA

Question: **What does MONA refer to?**

a) 

b) 

c) 

Improving our analysis framework

First oscillation fits on data were done with a framework developed at Nikhef!

MONA

Mass Ordering Neutrino Analysis

Set up by former Nikhef PostDoc **Bruno Strandberg**

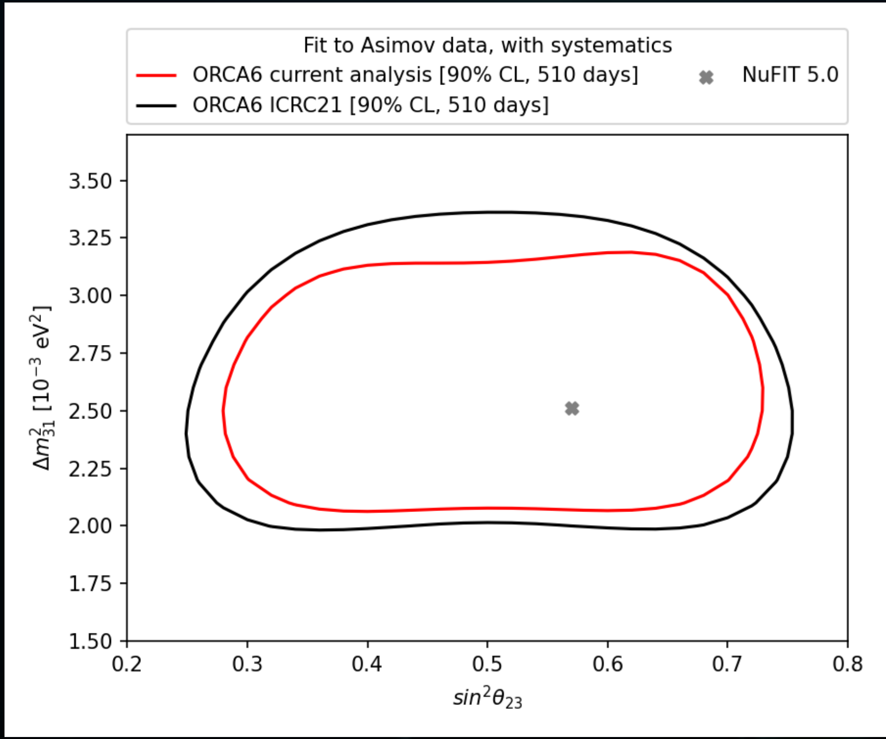
Fully based on **RooFIT** software by Wouter Verkerke

Collaboration and synergy with other Nikhef groups!

Improving our analysis framework

Evi Nikoloudaki, Dylano van Oijen and Daan van Eijk working on improvements





A very prolific team!

- Many code improvements
- Integration RooFit functionalities
- Comparing response functions
- Scrutinizing systematics

…

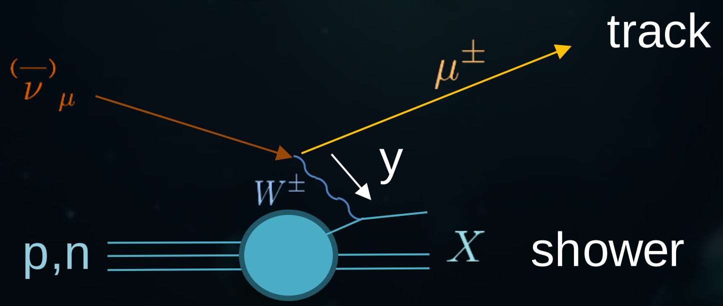
10%-20% improvement in Δm^2_{31} sensitivity
5%-10% improvement in $\sin^2\theta_{23}$ sensitivity

Improved reconstruction

Traditionally only **reconstructed energy and direction** are considered in KM3NeT oscillation studies

But there is more to take advantage of!

Key observable: **Inelasticity** (y)
i.e. the net energy transfer to the nucleus

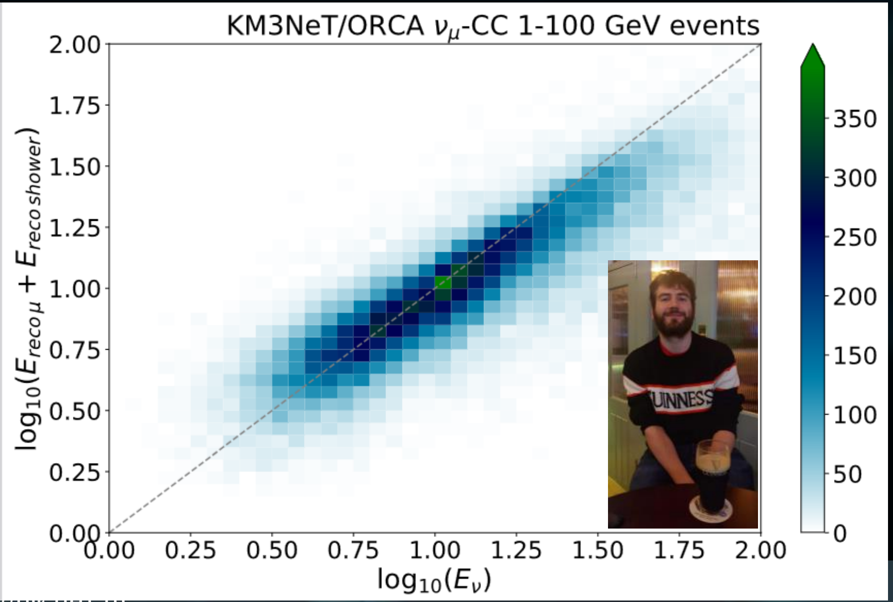


- Could give a handle on $\nu/\bar{\nu}$ distinction!

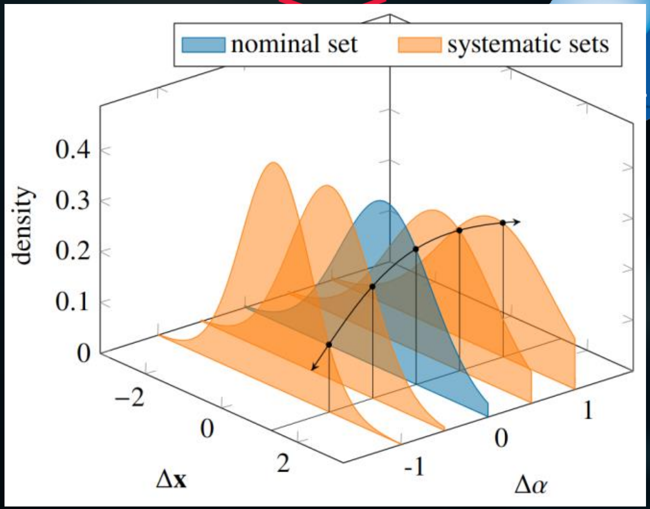
$$\frac{d\sigma_{\bar{\nu}q}}{dy} = \frac{4G_F^2}{\pi}(1-y^2)E^2 \Leftrightarrow \frac{d\sigma_{\nu q}}{dy} = \frac{4G_F^2}{\pi}E^2$$

- Requires **new type of reconstruction**
  - Shower + track fitted simultaneously as distinct components

→ **Brían Ó Fearraigh's Ph.D. thesis**



Improved systematics modeling



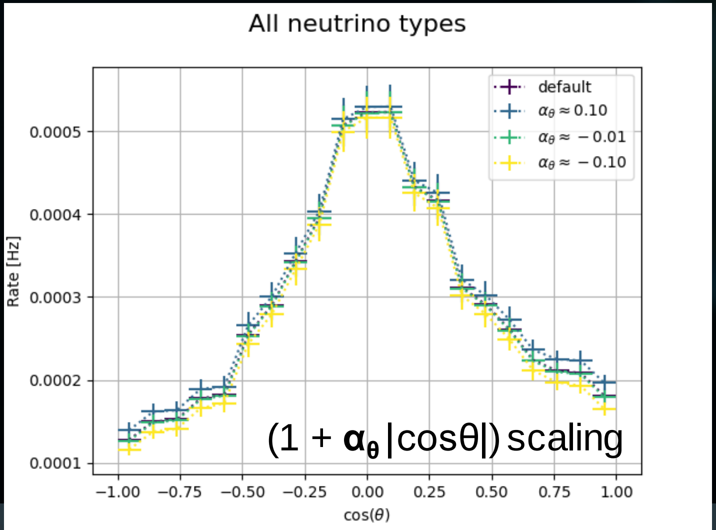
recent IceCube publication: [arXiv:2305.02257]

Systematics are often difficult to model
- Usually no straight-forward way to parametrize detector response in terms of systematics

MC template banks can offer solution:
1. Generate template MC distributions for varying sets of systematic values
2. Determine which template fits the data best

→
- Likelihood-free inference
- Strategy well known from PDF-fitting

Requires procedures for **generic MC-reweighting**
- Not limited to reconstructed observables!



A versatile detector!

Besides NMO, many other topics are being explored!

SM + neutrino oscillations:

- ORCA + JUNO combined NMO sensitivity

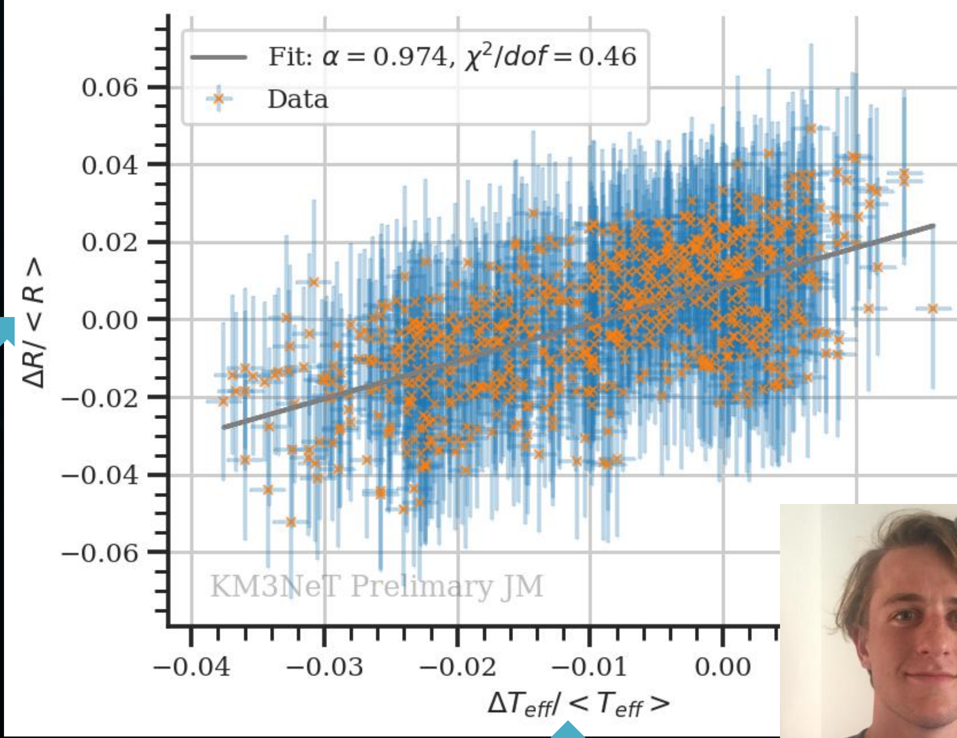
BSM + neutrino oscillations:

- Light sterile neutrino mixing
- Lorentz invariance violation
- Non-Standard Interactions
- Quantum decoherence
- Neutrino decays

Cosmic ray studies:

- Cosmic Ray shadow of the Sun/Moon
- Temperature dependence of muon rate

…



Relative change in atmospheric muon rate

Relative change in effective atmospheric temperature

Jelmer Mulder

Summary and outlook

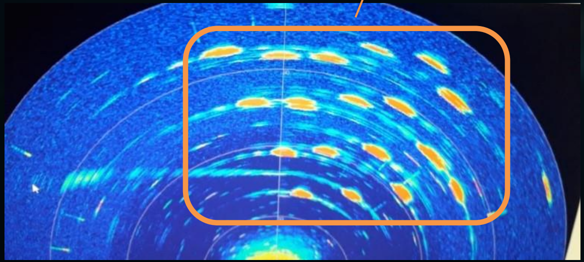
Neutrino properties research is vibrant and brimming at Nikhef!

KM3NeT set to play **important role in NMO determination**

- Possibility to set competitive, potentially leading constraints on Δm^2_{31} and $\sin^2\theta_{23}$
- **Large Nikhef involvement** accross many fronts
  - First constraints from data
  - Development and maintenance of one of main oscillation analysis softwares
  - Improvements in reconstruction, systematics modeling, calibration…

18 strings deployed and growing!

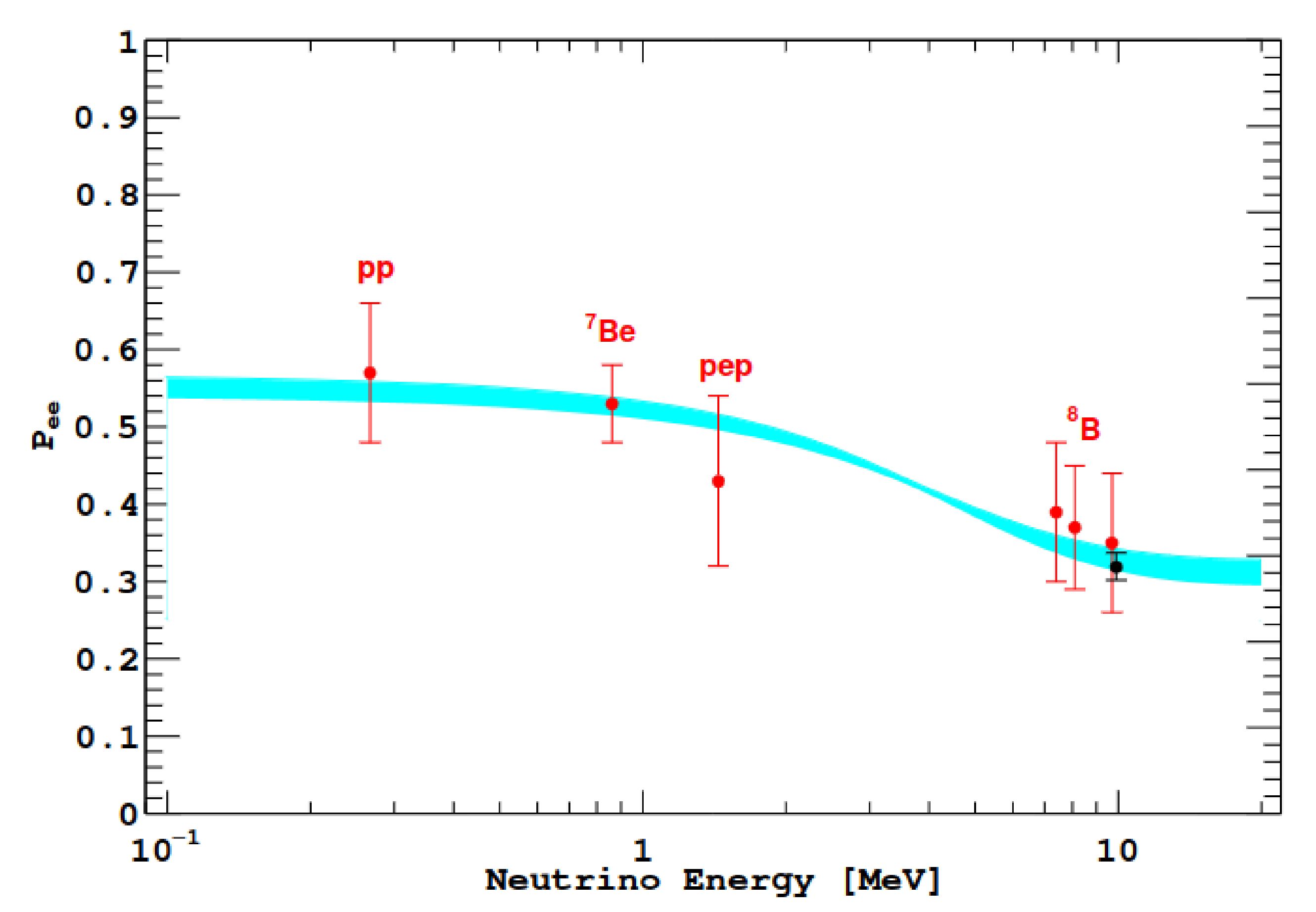
18 strings on sonar!



Ivan Gromov deploying the latest strings!

EXTRA

Adiabatic conversion solar neutrinos



$P(\nu_e \to \nu_e)$ decreases with neutrino energy!

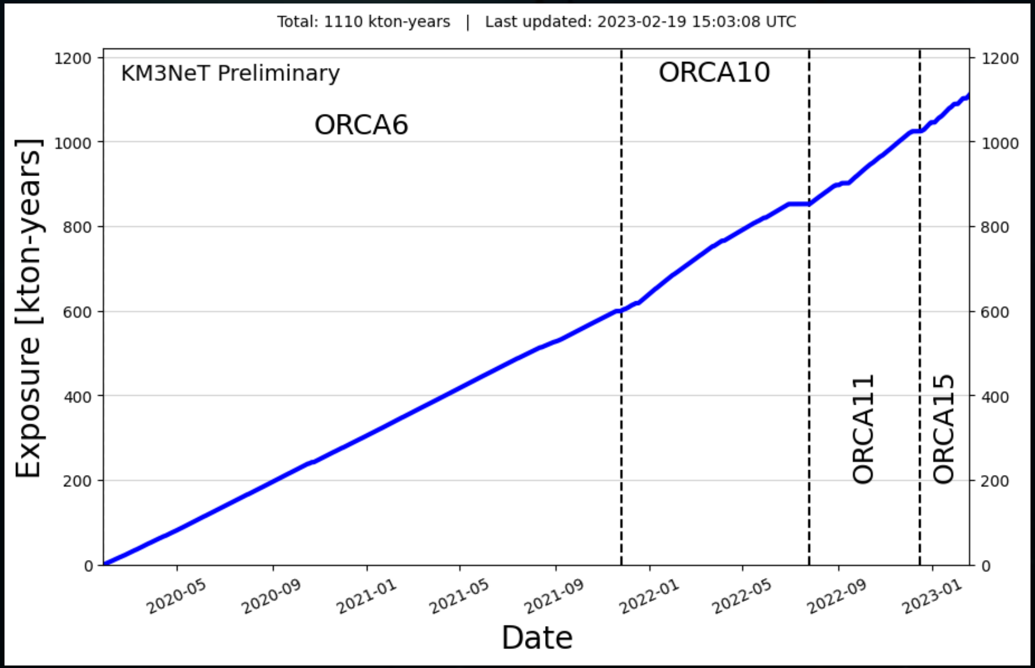
→ Due to matter effects!

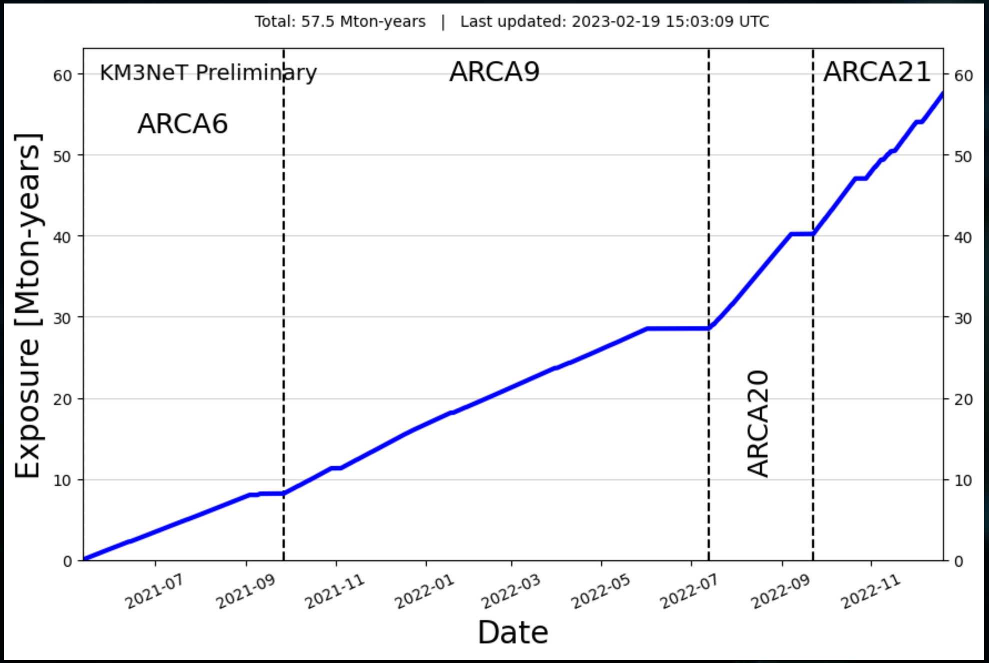
Only occurs in ν_e-oscillations, because $\Delta m_2 > \Delta m_1$

Cumulative exposure

~10% of both detectors deployed as of January 2023

→ Already collecting useful data!





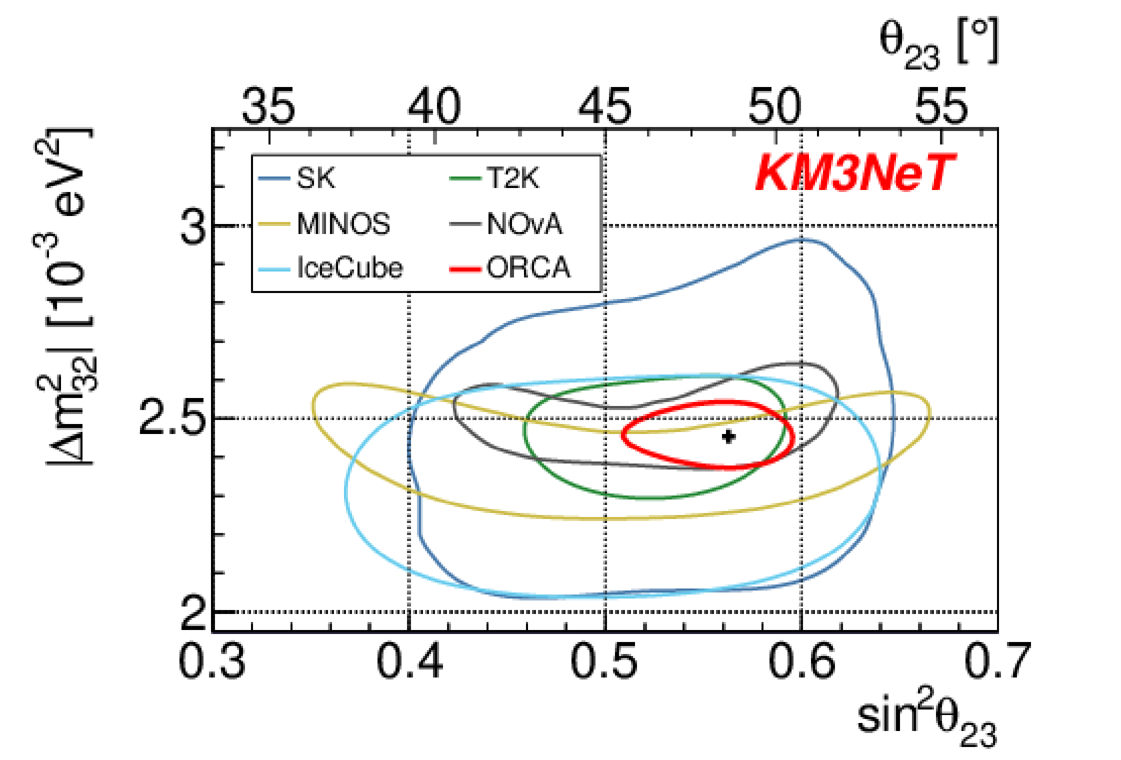
Figures by João Coelho

NMO sensitivity

3σ NMO determination
in 1.3 (5) years if true NMO = NO (IO)

>95% CL constraint on θ_{23}-octant
after 6 years for $|\sin^2\theta_{23} – 0.5| < 0.05$

DOI: 10.1140/epjc/s10052-021-09893-0



Tau-neutrino appearance

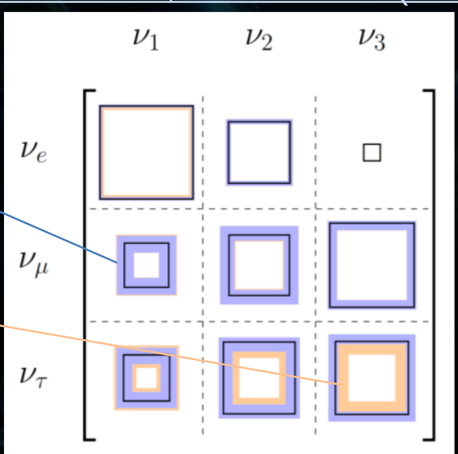
KM3NeT will provide one of the largest atmospheric tau-neutrino datasets (>3k events / yr) !

Allows unprecedented constraints on ν_τ-normalisation (= observed / expected ν_τ rate)

→ Probe PMNS unitarity! Ph.D thesis, S. Hallmann (2021)

Uncertainty with unitarity constraint

Uncertainty without unitarity constraint



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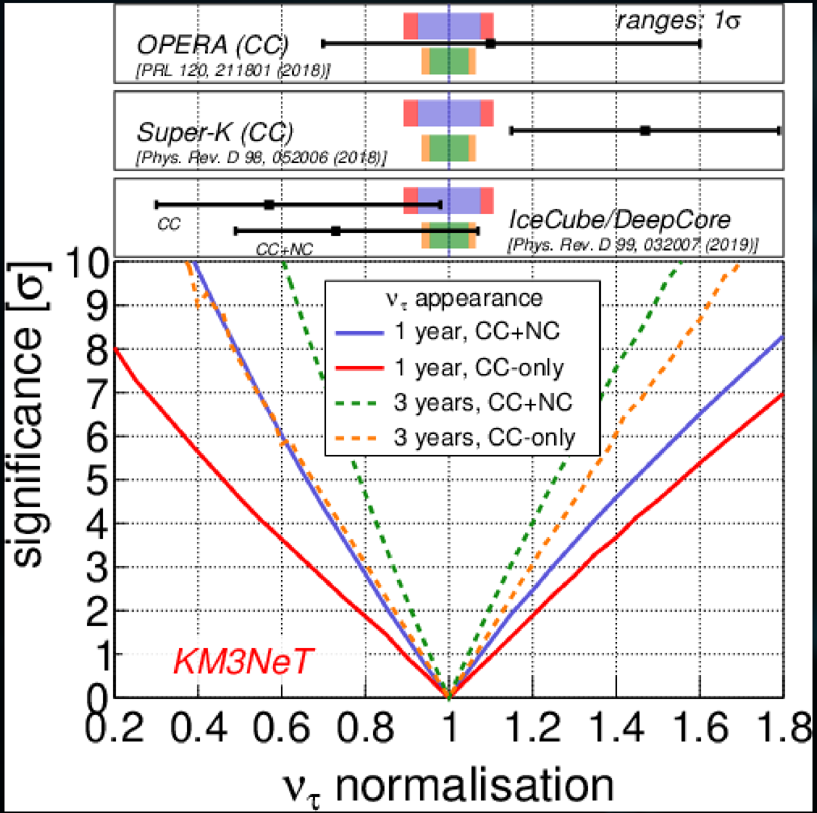
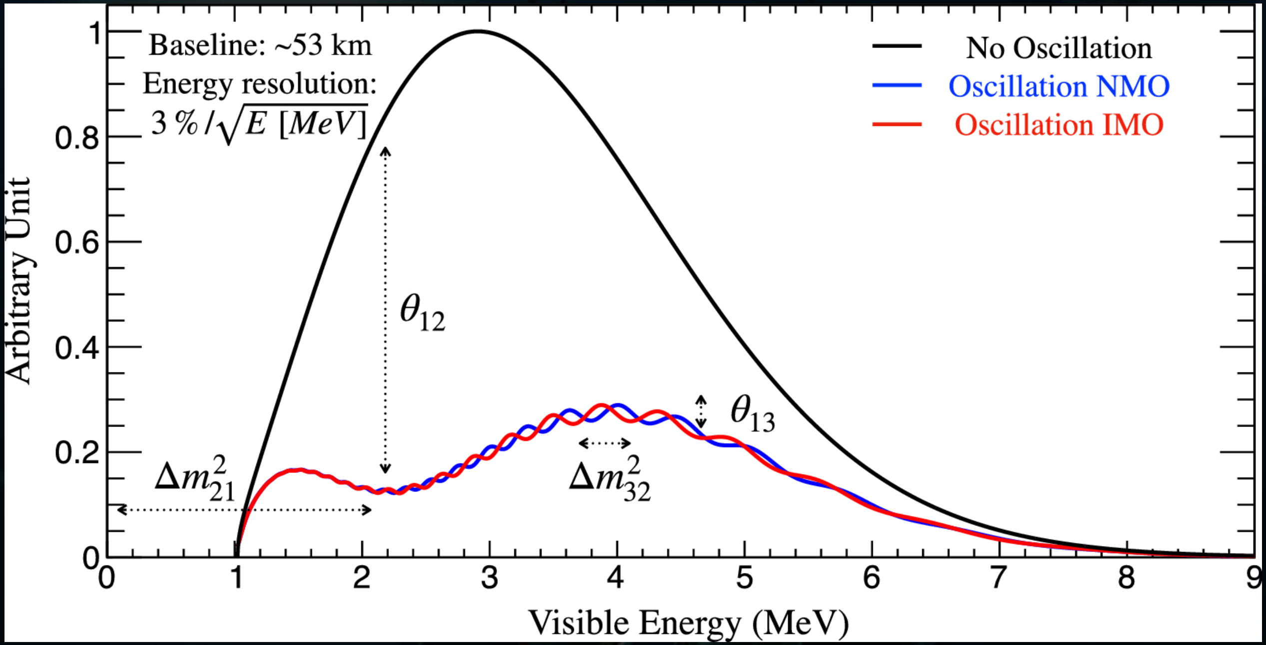


First constraints with ORCA data @ ICRC 2023 !

JUNO status

DOI: 10.1016/j.ppnp.2021.103927



Summer 2022

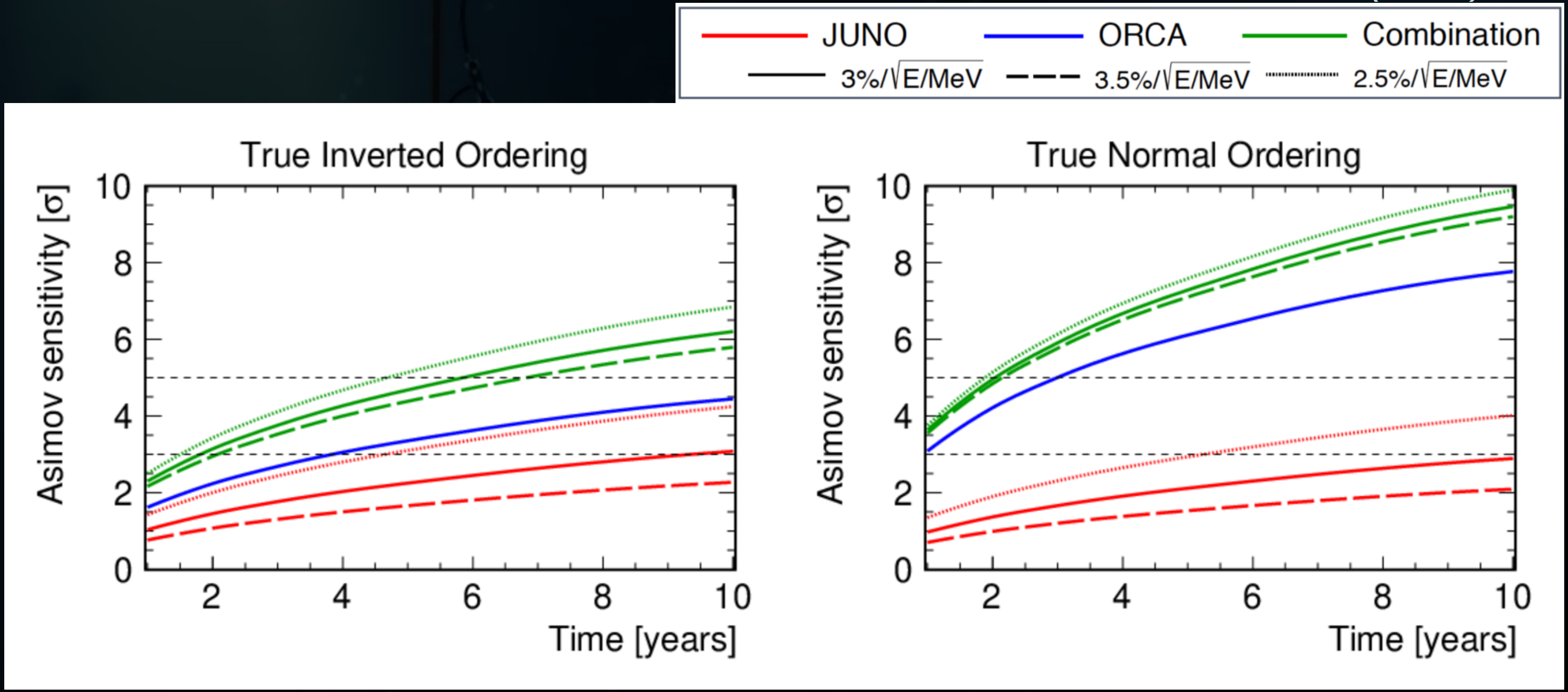
approved	civil construction	detector construction	detector completion
2013	*2015*	*2022*	*2023*

From *ICHEP 2022 talk*
by Jie Cheng

Combined NMO sensitivity

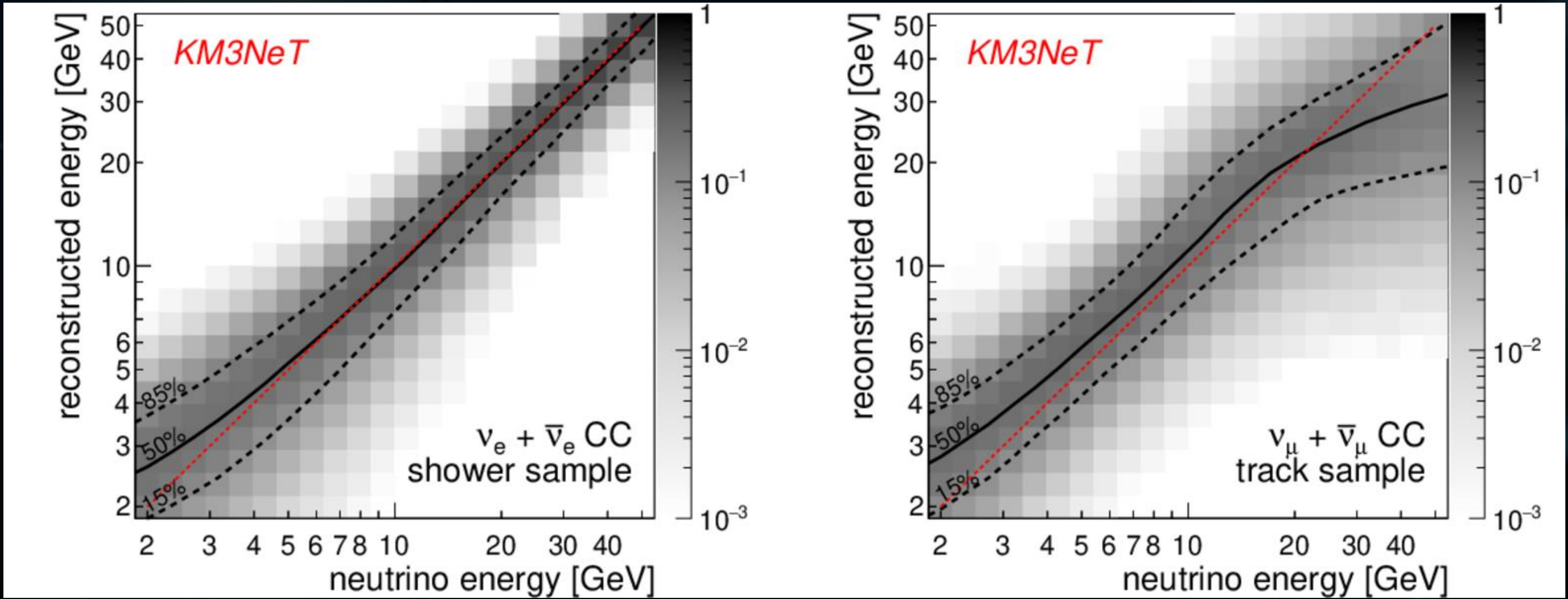
Great enhancement in combination with JUNO:
→5σ determination of NMO after 6 years

DOI: 10.1007/JHEP03(2022)055

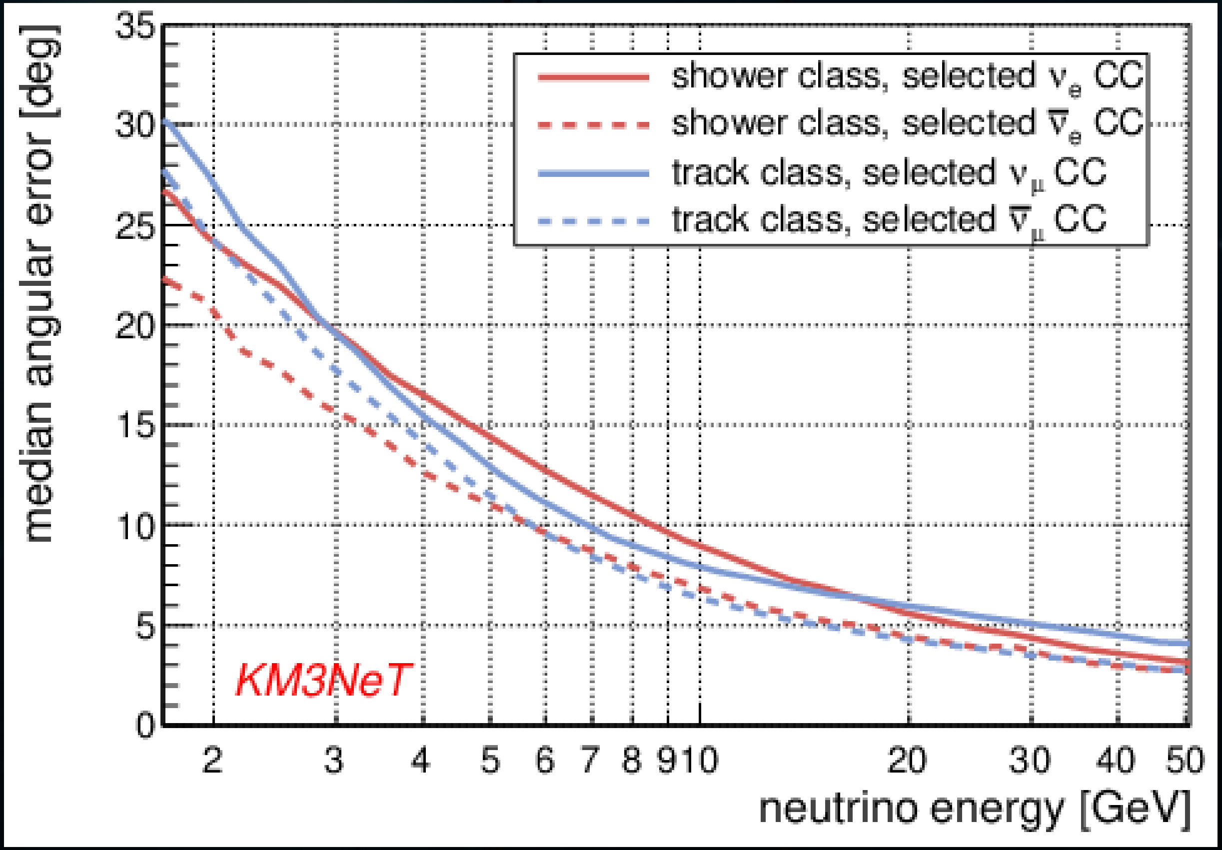


Detector Performance

$\Delta E / E \sim 25\%$ for ν_e @ 10 GeV
$\Delta E / E \sim 35\%$ for ν_μ @ 10 GeV



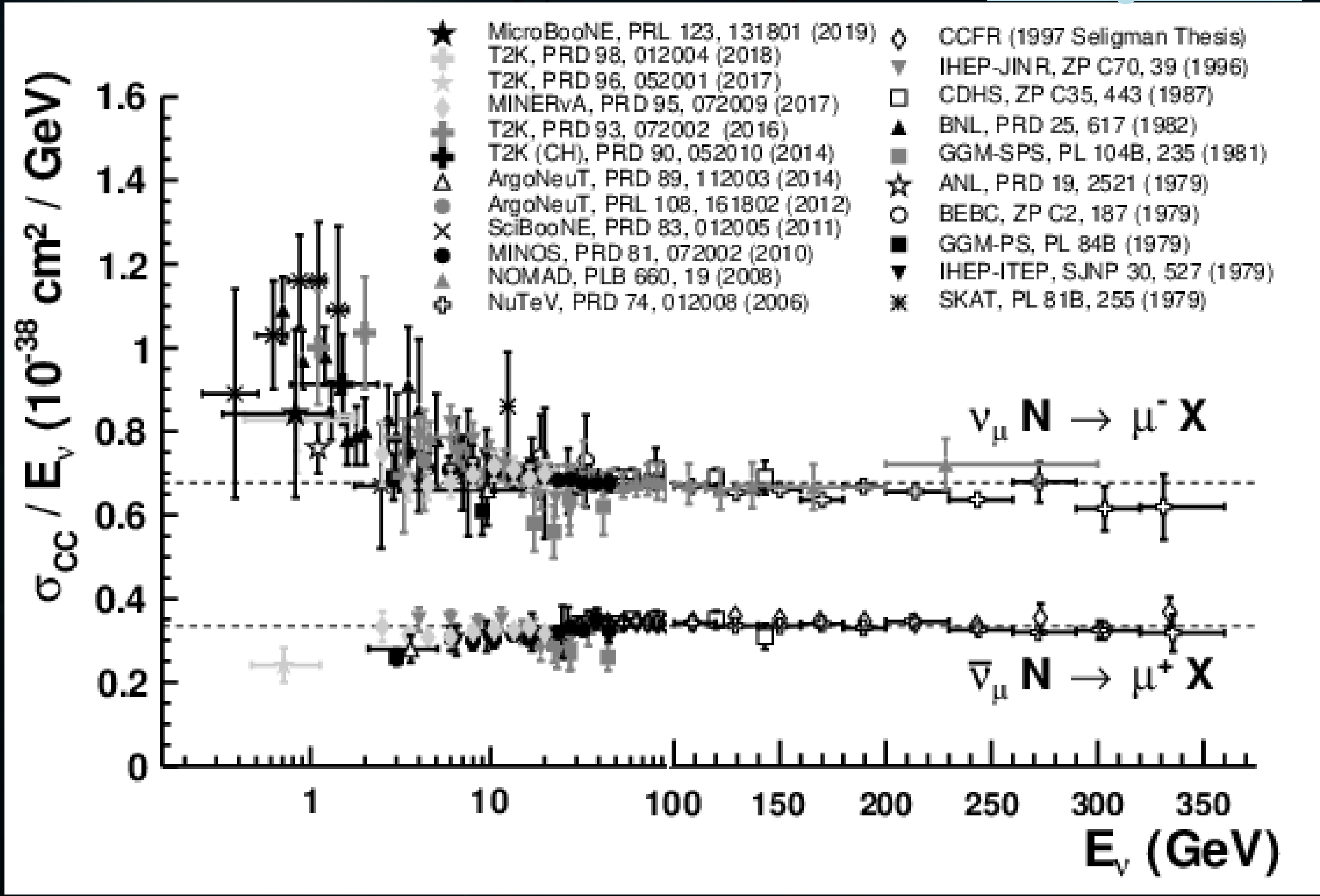
Detector Performance



9.3° / 7.0° / 8.3° / 6.5°
for ν_e / ν_e / ν_μ / ν_μ @ 10 GeV

Neutrino cross-sections

PDG figure 52.1



$\sigma_\nu : \sigma_\nu \sim 2 : 1$

Event classification

Particle Identification based on Random Decision Forests; 3 scores:

1) muon score, 2) noise score, 3) track score