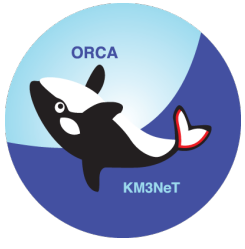
KM3NeT/ORCA

status & perspectives for ν oscillation and mass hierarchy measurements

Piotr Kalaczyński
on behalf of the KM3NeT collaboration

ICHEP 2020 virtual conference
31.07.2020



KM3NeT

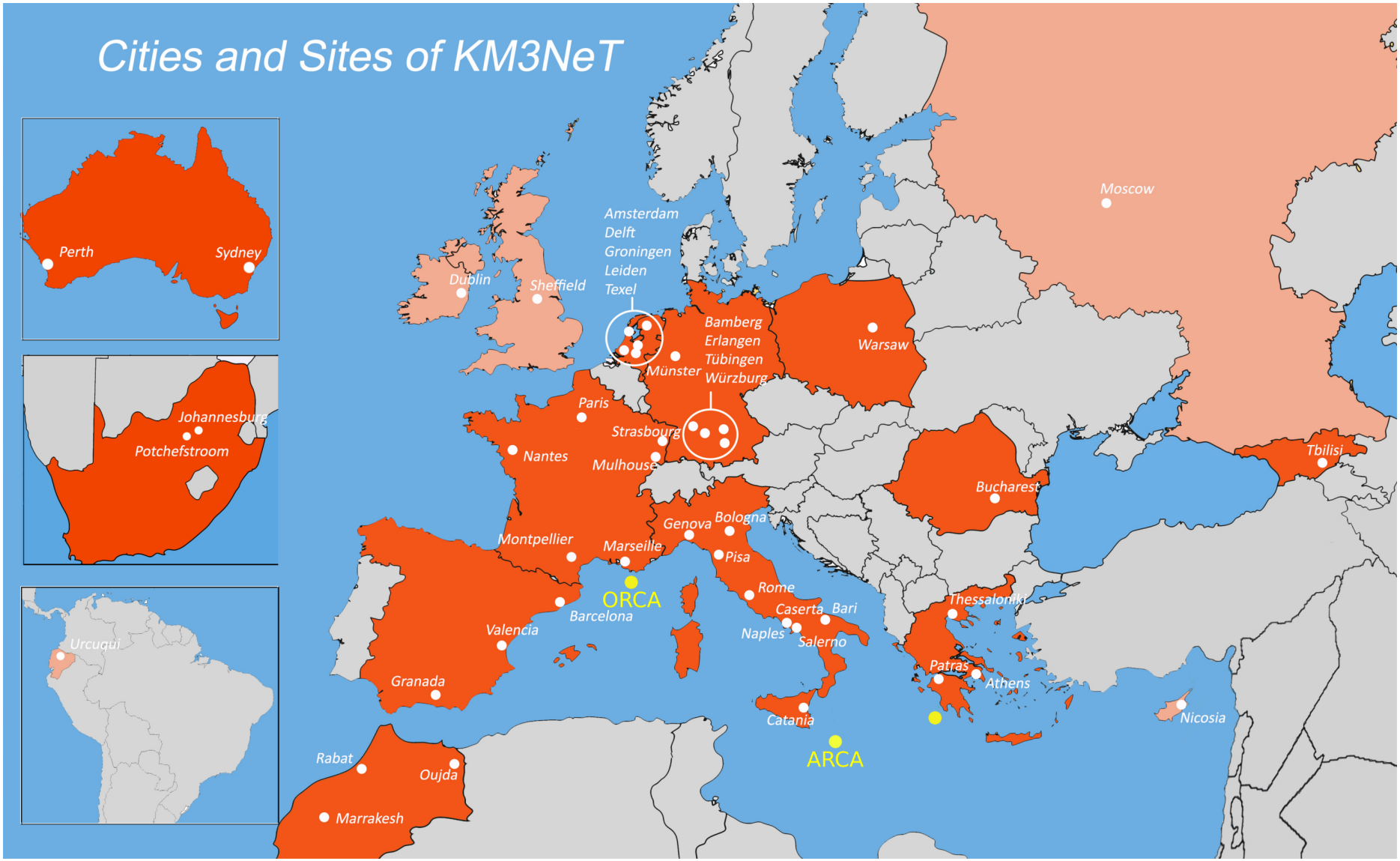
NATIONAL CENTRE FOR NUCLEAR RESEARCH ŚWIERK

Funded by:

NATIONAL SCIENCE CENTRE POLAND
grant 2015/18/E/ST2/00758

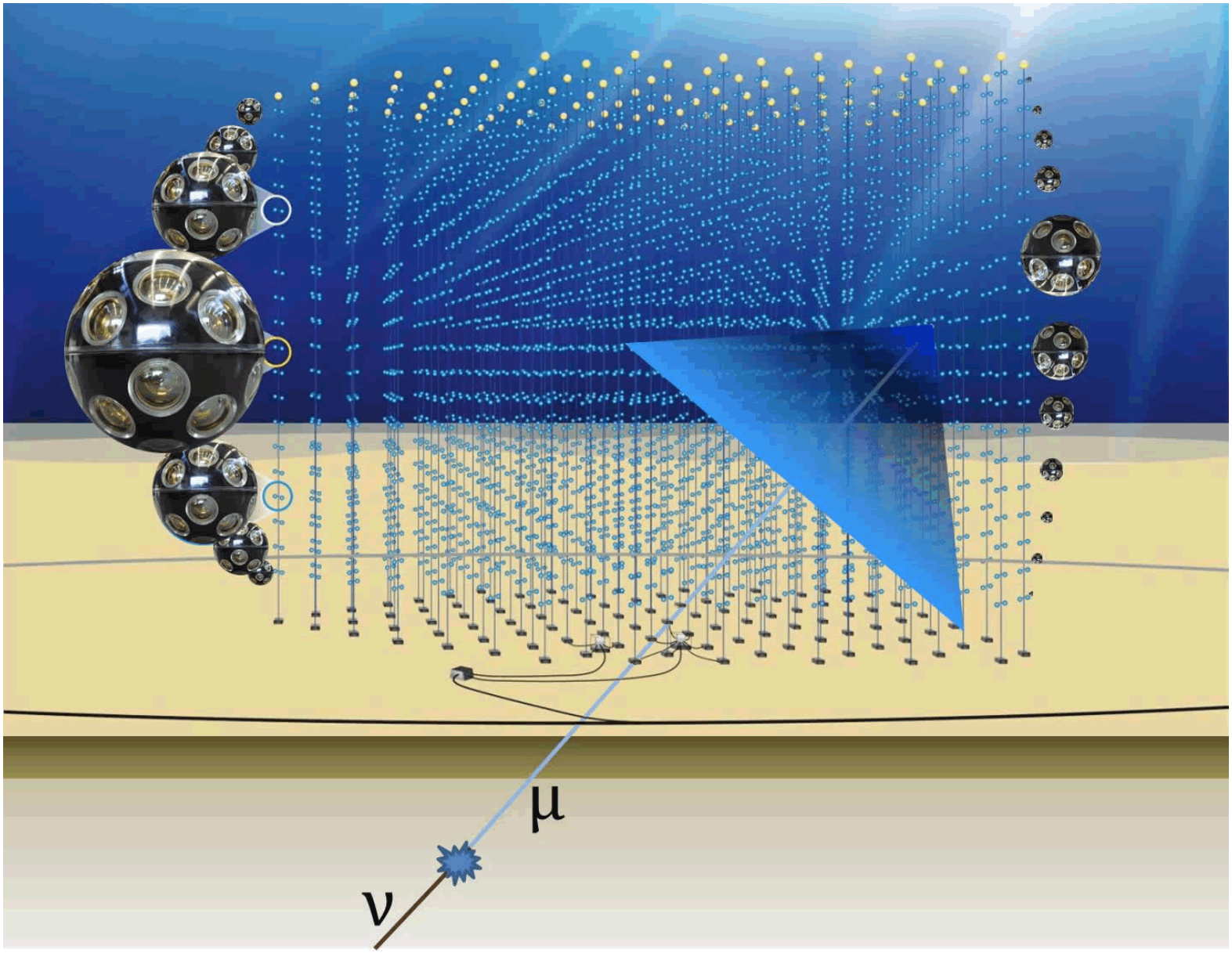
Outline

The KM3NeT Collaboration



KM3NeT – The Cubic Kilometre (km^3) Neutrino Telescope

Principle of detection (upgoing ν_μ example)



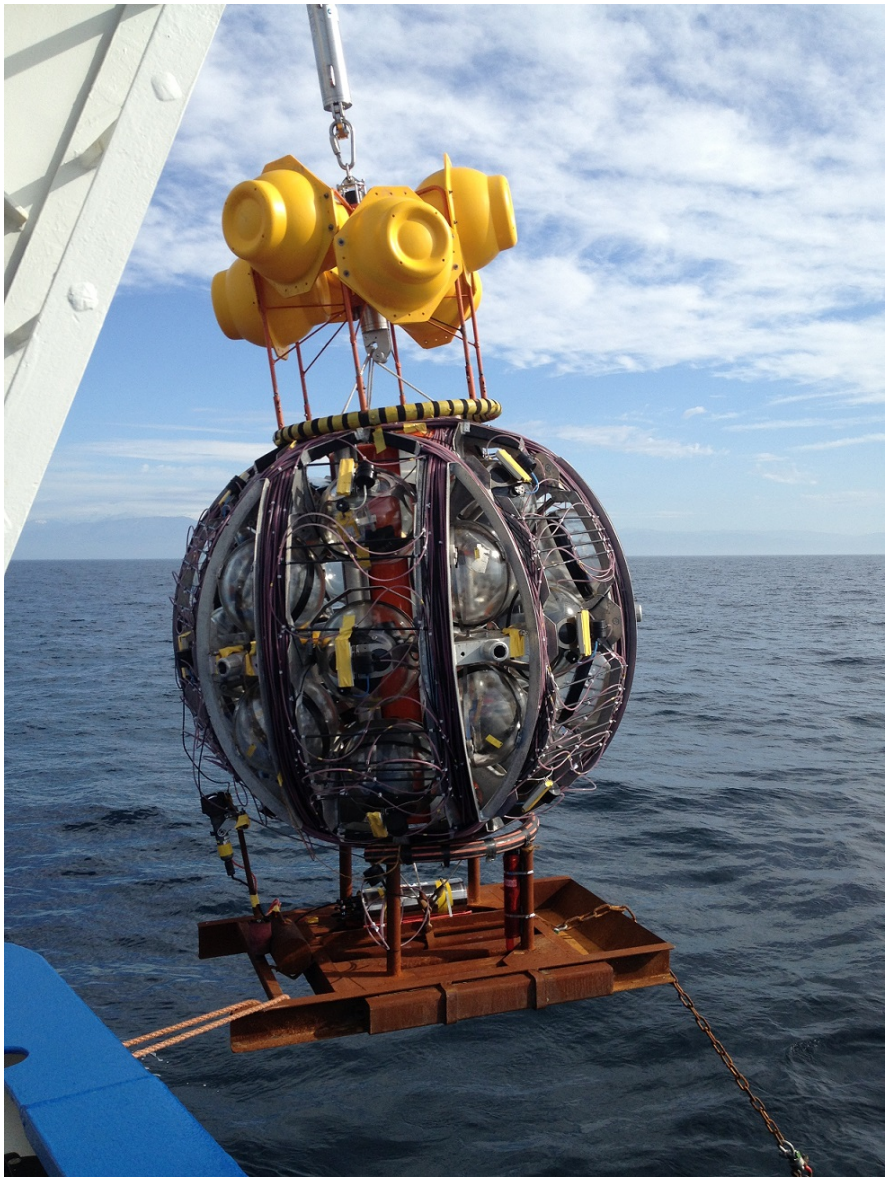
Outline

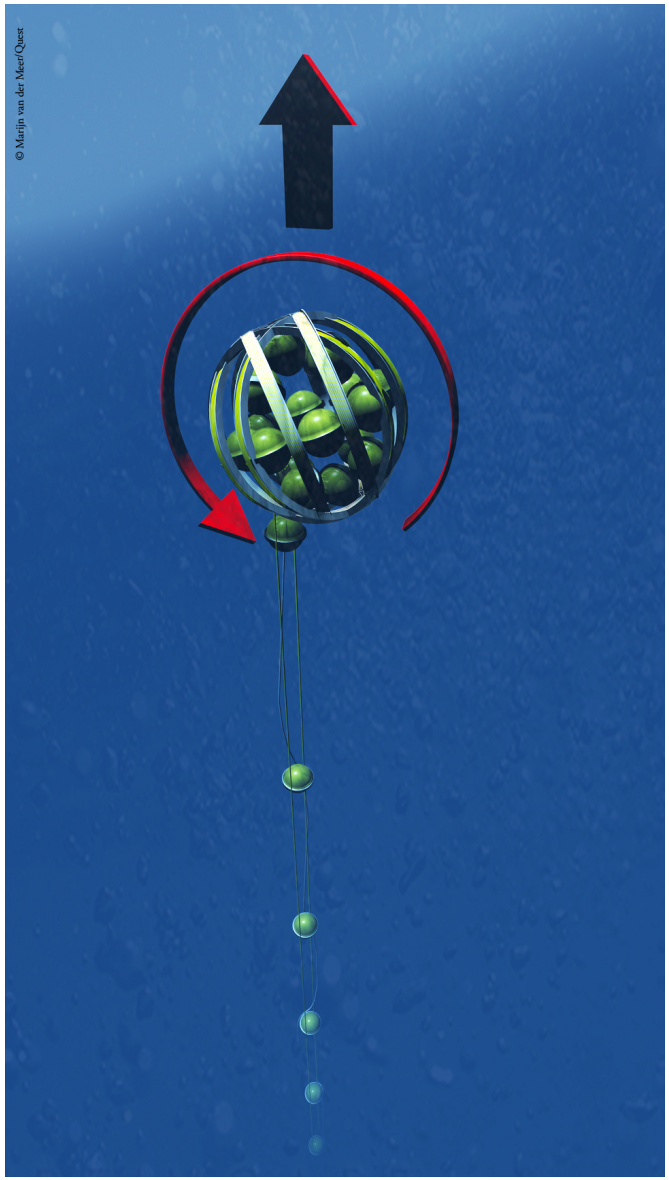
Light sensors

DOM:
Digital Optical Module
(31 PMTs + electronics etc.)

PMT:
Photomultiplier Tube

DOM arrangement

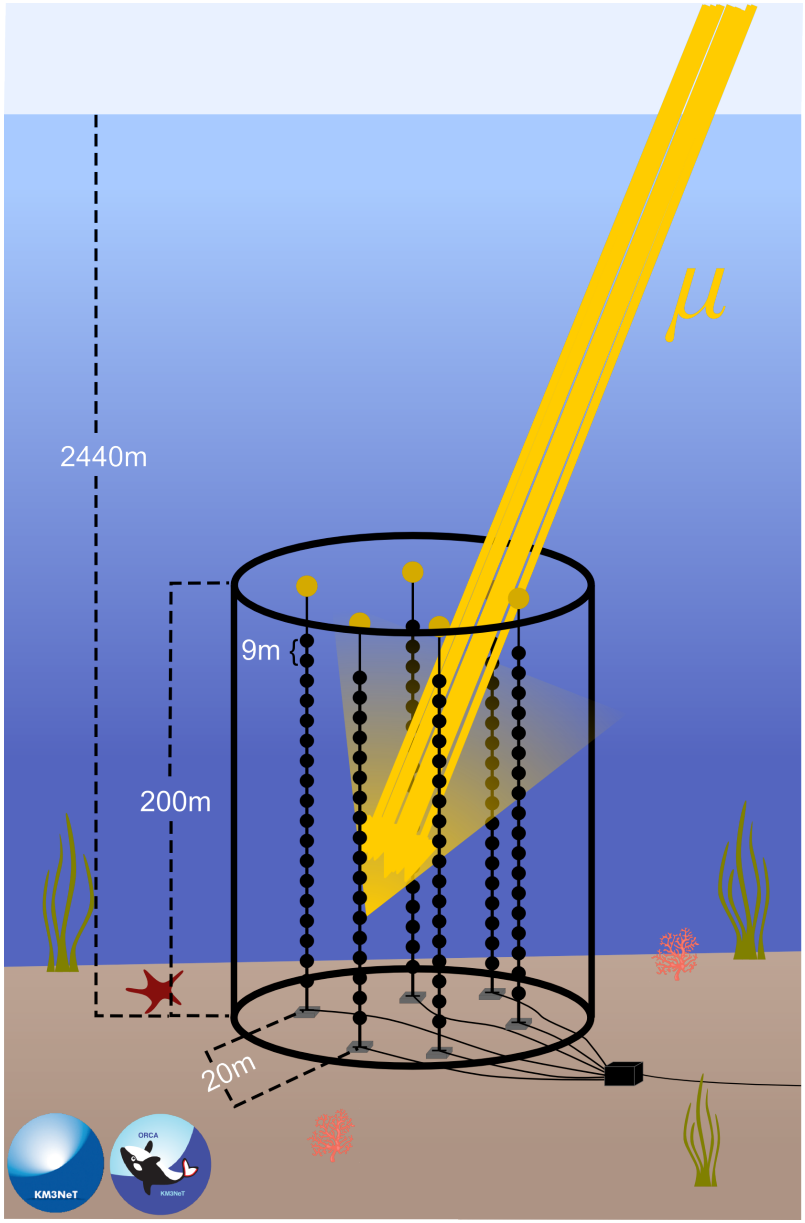




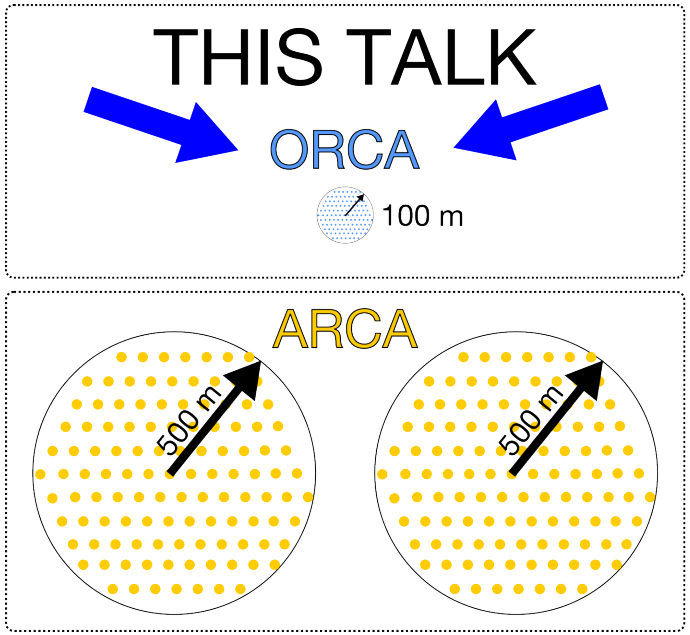
DU: Detection Unit (string with 18 DOMs)

ORCA4 $\Longleftrightarrow$ ORCA with 4 DUs

Detectors



ORCA – Oscillation Research with Cosmics in the Abyss
(main goal: m_ν hierarchy)

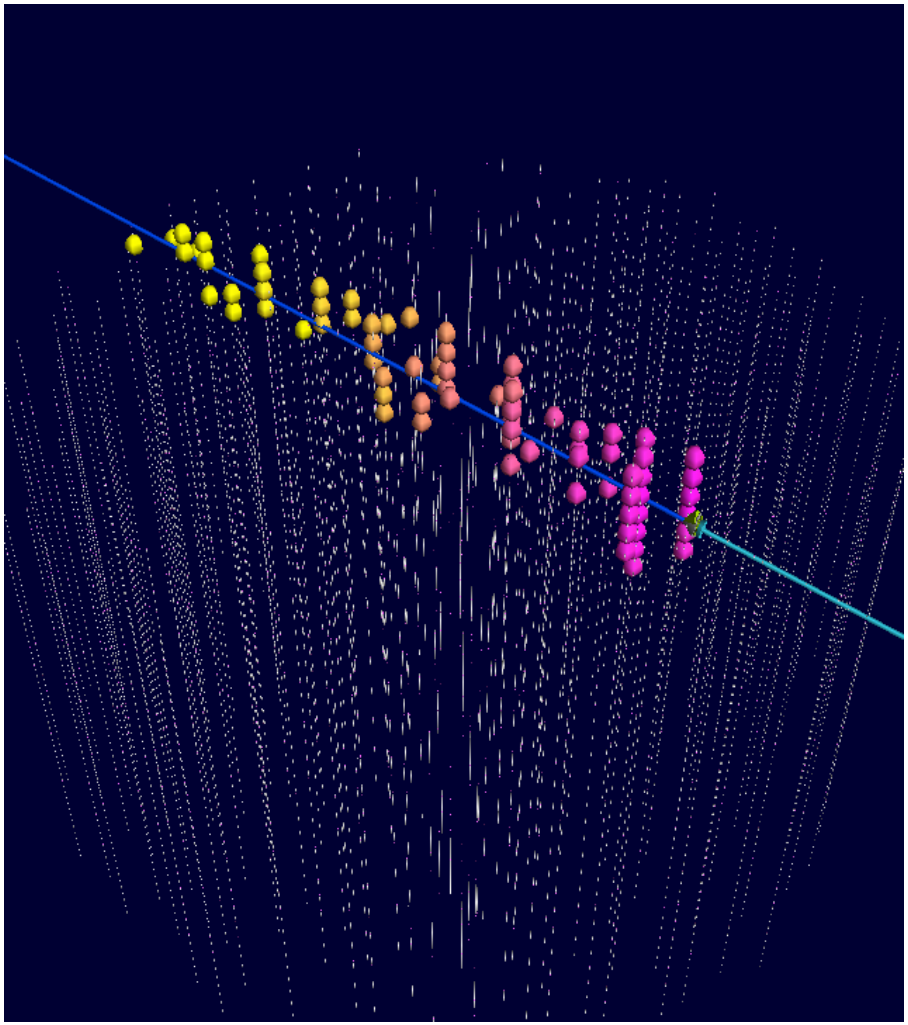


Depth	Volume
2.5 km	0.006 km^3 (6 Mton)
3.5 km	1 km^3 (1 Gton)

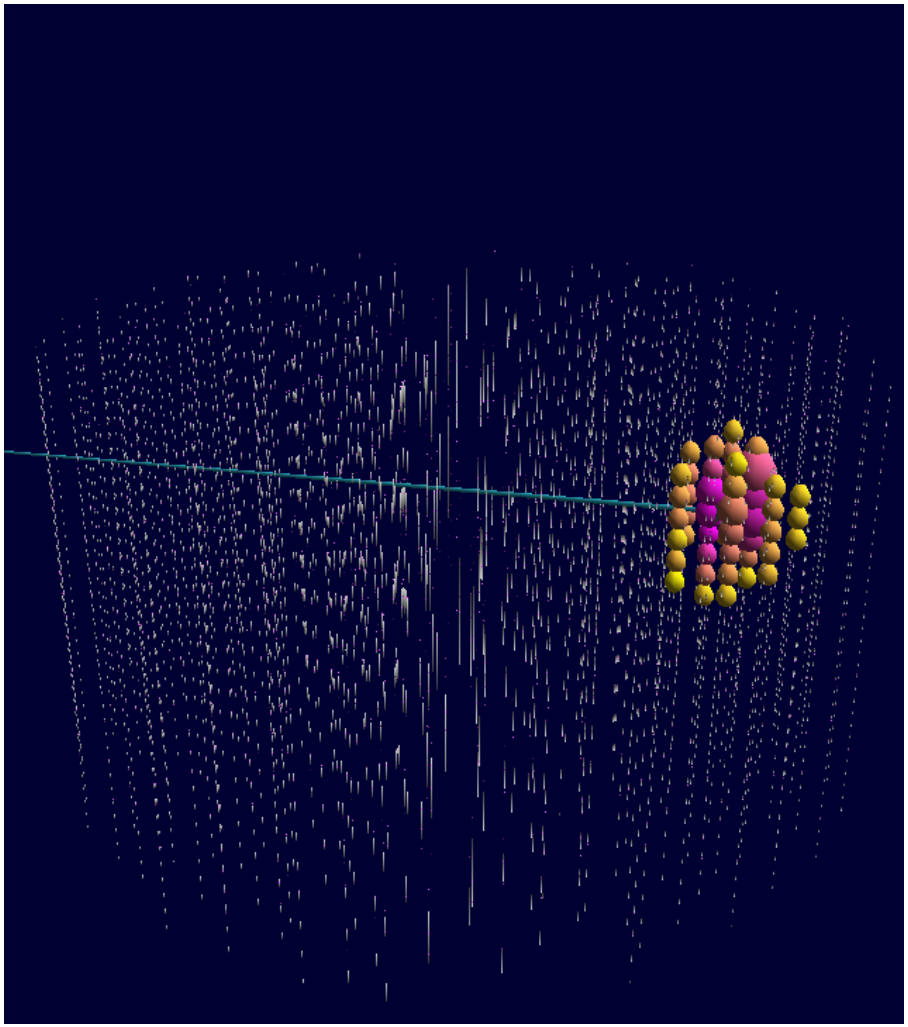
ARCA – Astroparticle Research with Cosmics in the Abyss
(main goal: ν_{astro})

Event topologies (simulated)

tracks
(CC: ν_μ ,ν_τ ($\tau \to \mu$))



showers
(NC: $\nu_{e,\mu,\tau}$, CC: ν_e, ν_τ ($\tau \not\to \mu$))



Ball size $\to$ # hit PMTs on a DOM

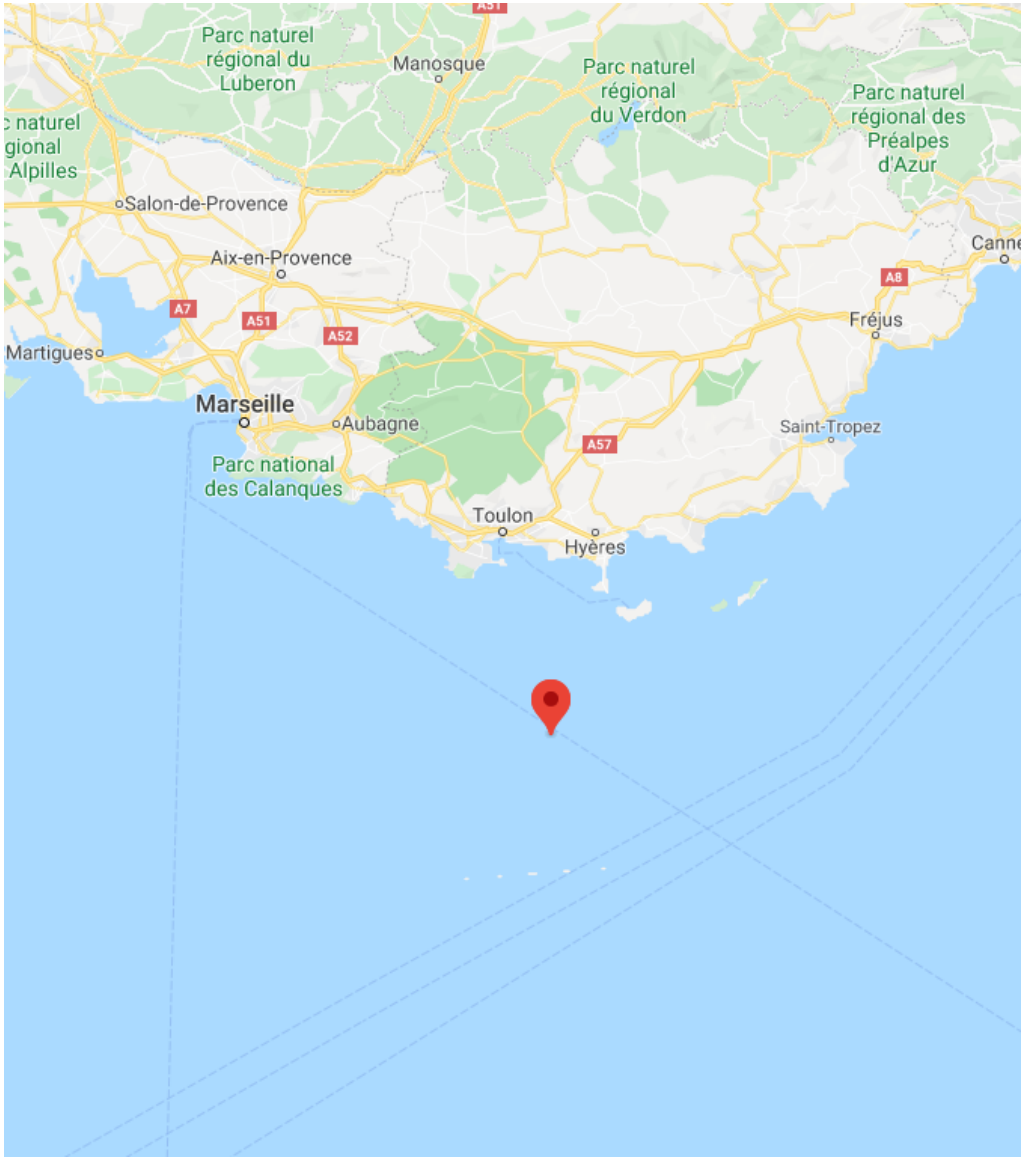
color $\to$ time

Outline

KM3NeT-ORCA

KM3NeT-ORCA:

- **location**:
  - 40 km offshore Toulon (France)
  - coords: 42°48' N 06°02' E
- E_ν **range**: few - 100 GeV
- **configuration**:
  - 6 DUs since January 2020
  - 3 new DUs planned this year
  - full detector: 115 DUs (in 2024)

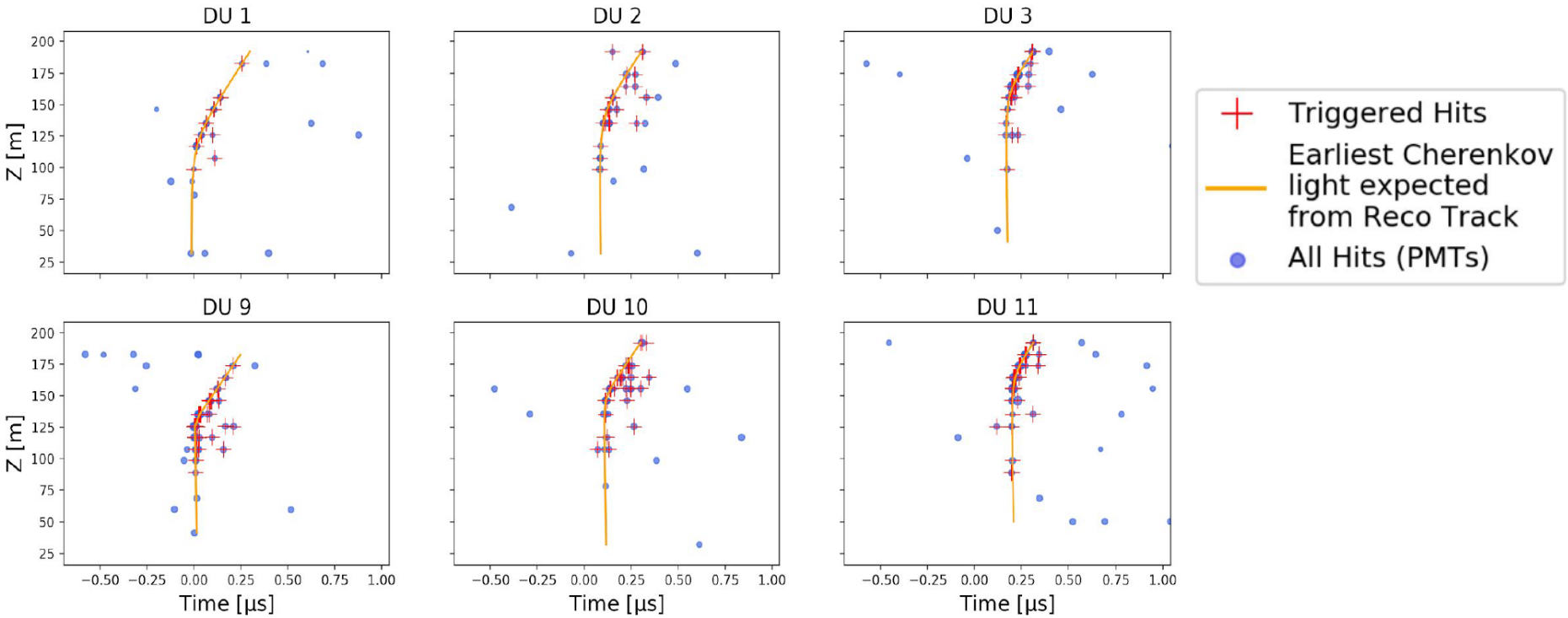


Current status of ORCA

KM3NeT-ORCA:

- First ν candidates (example below)
- COVID-proof operation
- 6 DUs opertional for 6 months celebration:

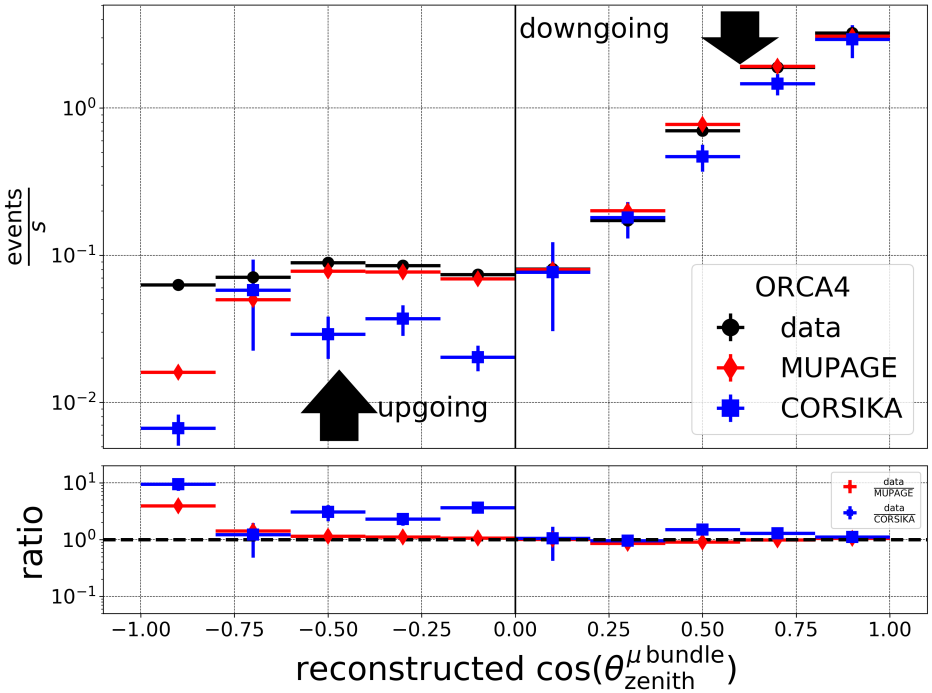
Route 66 6 strings, 6 months

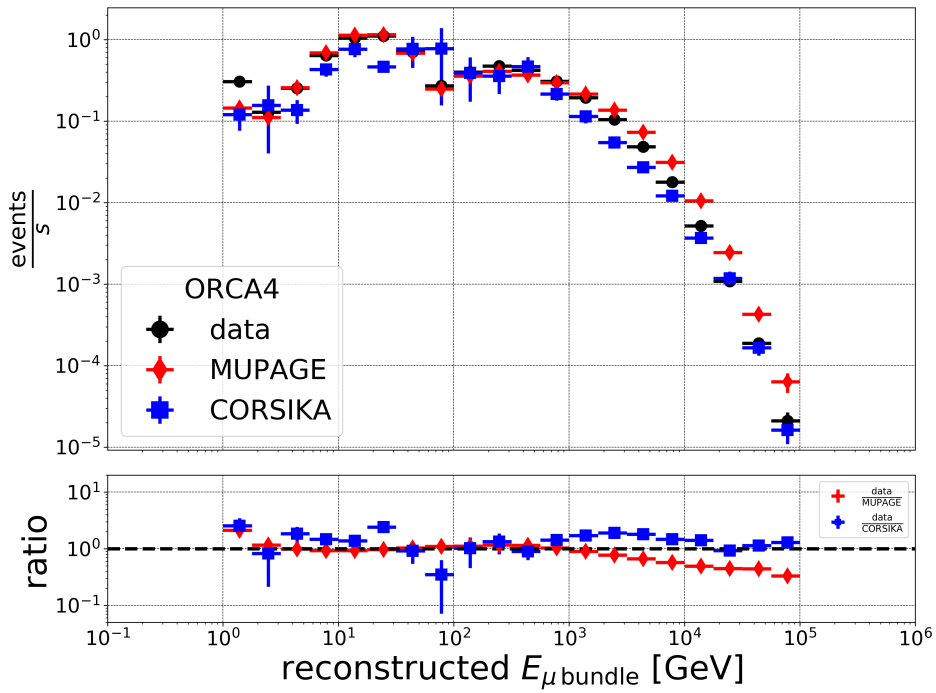


Outline

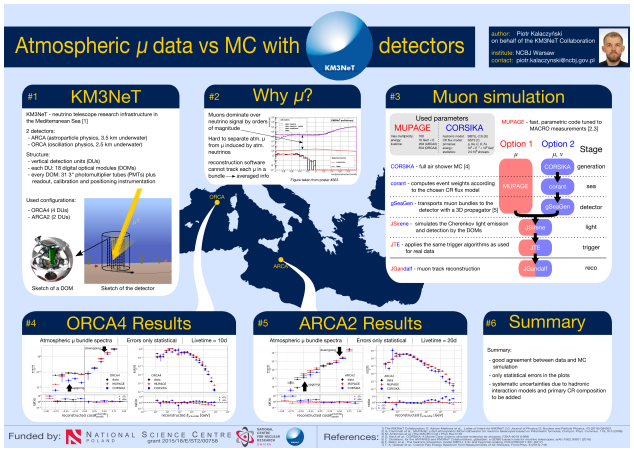
Atmospheric muon rate measurement

author: Piotr Kalaczyński (me ☺)





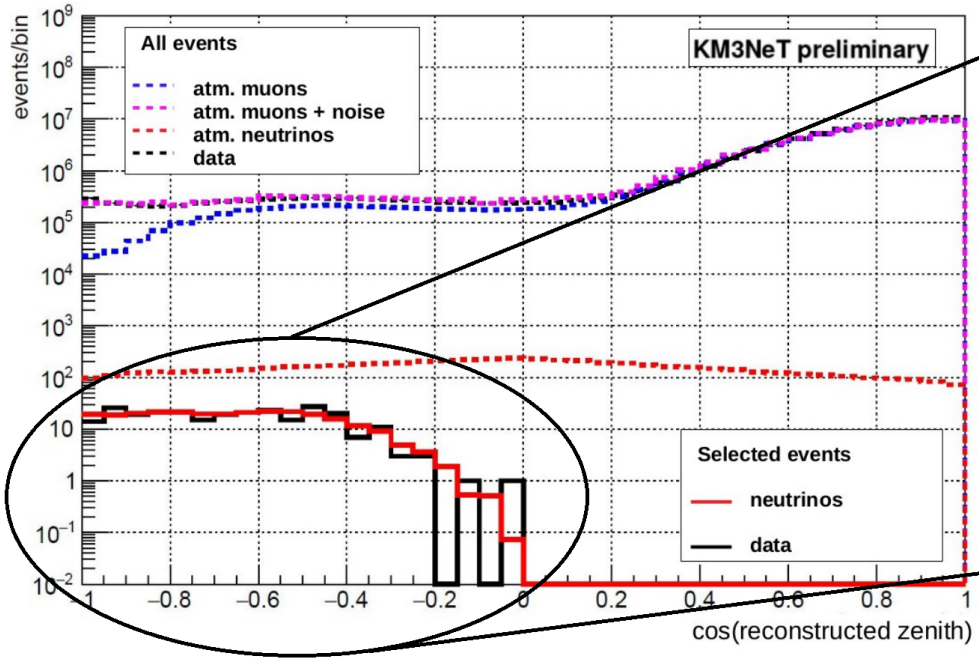
- from poster #316 @Neutrino2020
- **MC**: 35 days (10.2019) with 4 DUs
- **rate**: 455k $\frac{\mu}{\text{day}}$



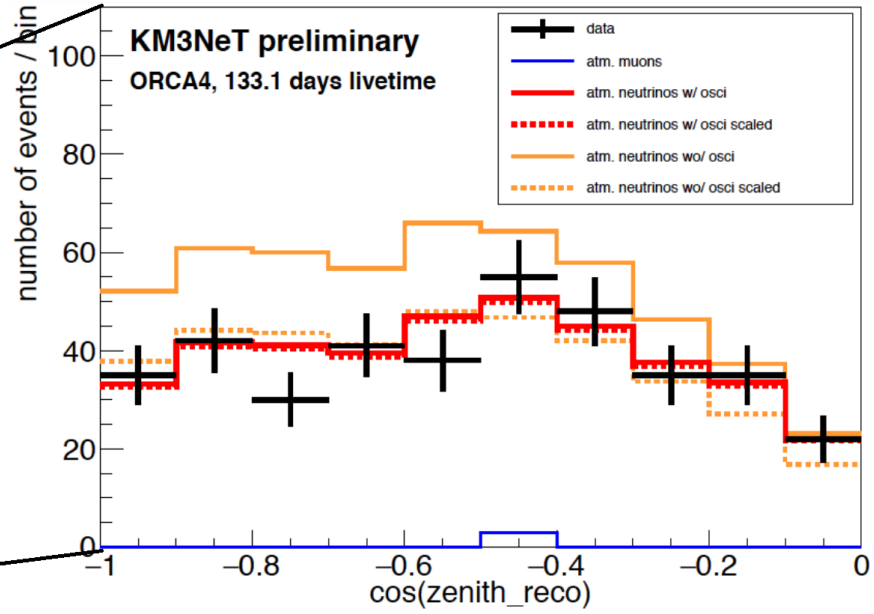
Atmospheric neutrino flux measurement

authors: Luigi Antonio Fusco, Jannik Hofestädt, Dimitris Stavropoulos

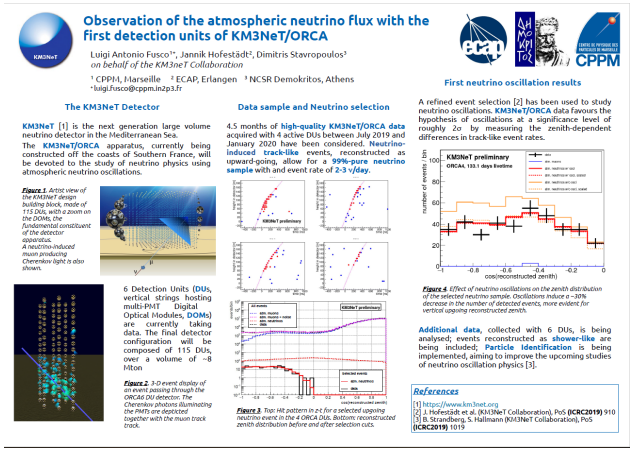
ν_{atm} selection



oscillations



- from poster #363 @Neutrino2020
- **MC**: 4.5 months (07.2019-01.2020) with 4 DUs
- **purity**: 99 %
- **rate**: 3 $\frac{\nu}{\text{day}}$
- oscillations hypothesis favoured $(p = 0.17)$!


Observation of the atmospheric neutrino flux with the first detection units of KM3NeT/ORCA

Luigi Antonio Fusco[1*], Jannik Hofestädt[2], Dimitris Stavropoulos[3]
on behalf of the KM3NeT Collaboration

[1] CPPM, Marseille [2] ECAP, Erlangen [3] NCSR Demokritos, Athens
[*] luigi.fusco@cppm.in2p3.fr

The KM3NeT Detector

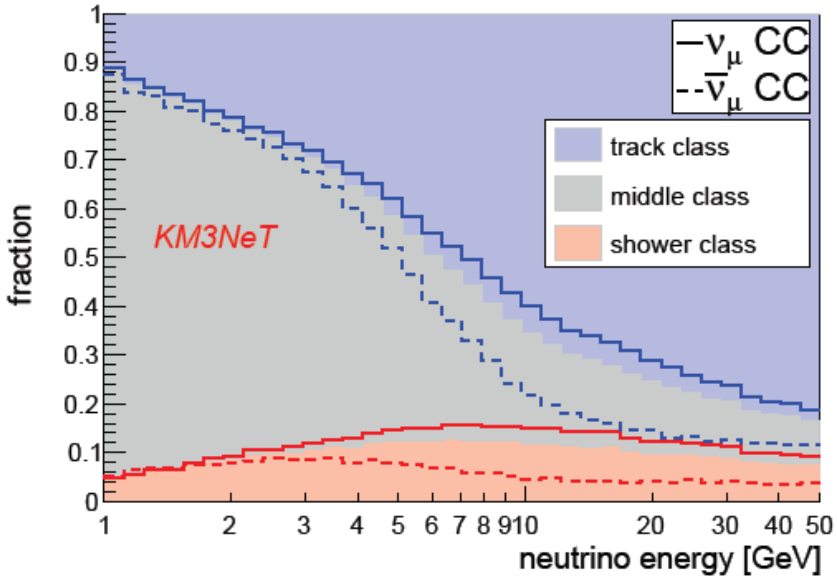
Data sample and Neutrino selection

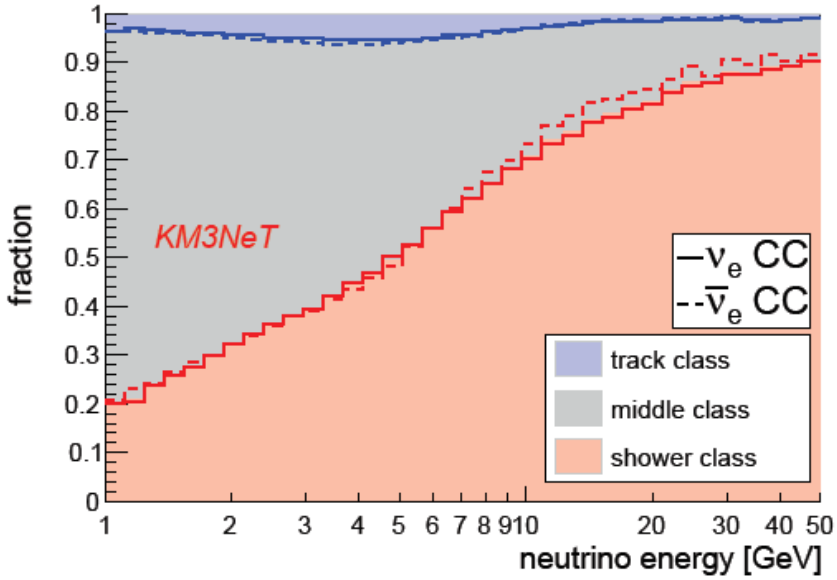
First neutrino oscillation results

References

Outline

Neutrino Mass Ordering (NMO) sensitivity (mini-intro)





- **reco**: max $\mathcal{L}$ (vertex, dir, E, t)
- **cuts**: containment, upgoing, quality
- **background suppression**: random decision forests (RDF)

- **event classes:**
  - **shower**:
    - ★ passes shower selection
    - ★ track score<0.3
  - **middle**:
    - ★ passes shower selection
    - ★ 0.3<track score<0.7
  - **track**:
    - ★ passes track selection
    - ★ track score>0.7

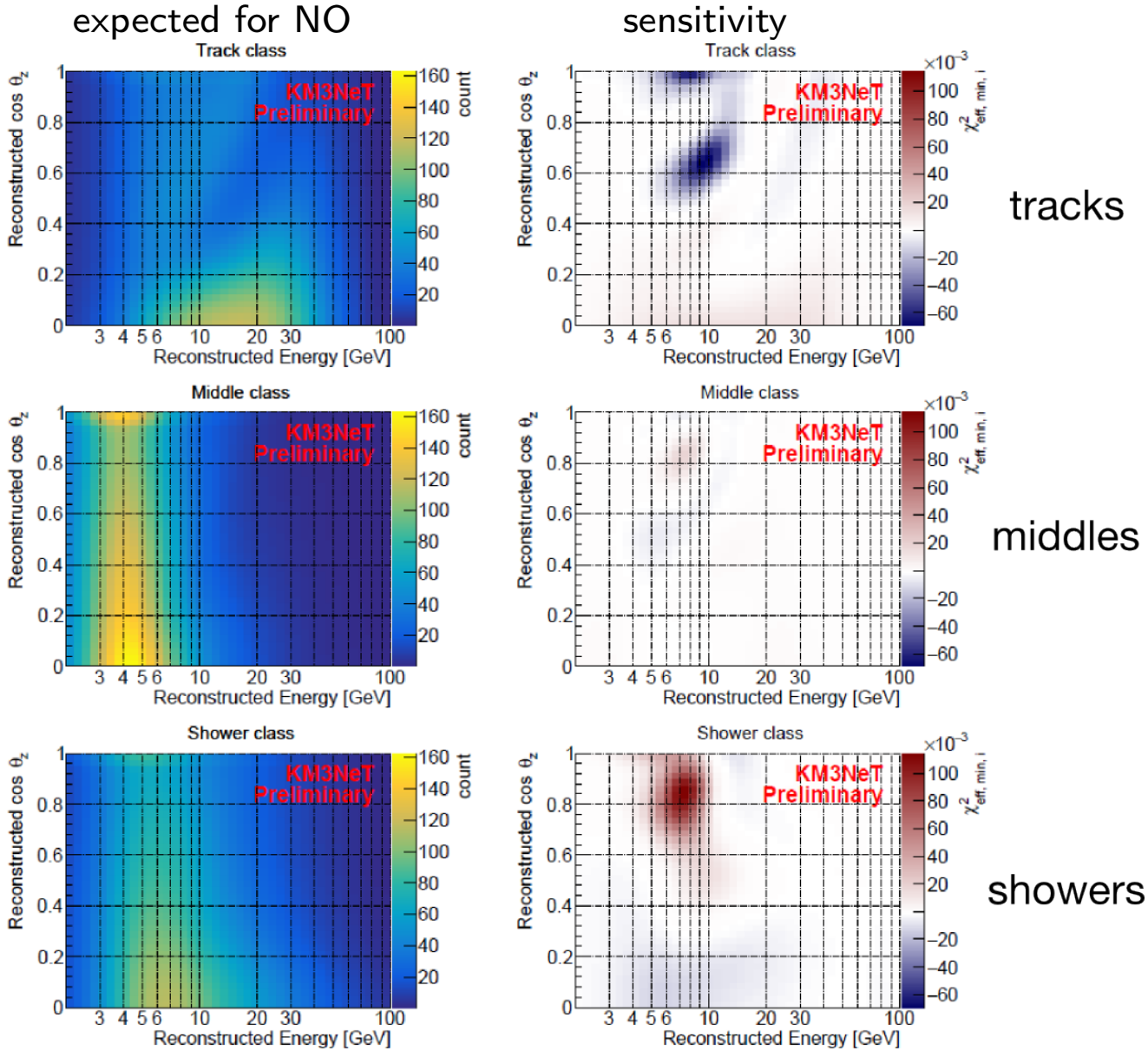
NMO 2D distributions (Asimov dataset)

left:
expected distributions after 3y

right:
sensitivity to the NMO (NO confronted against IO)

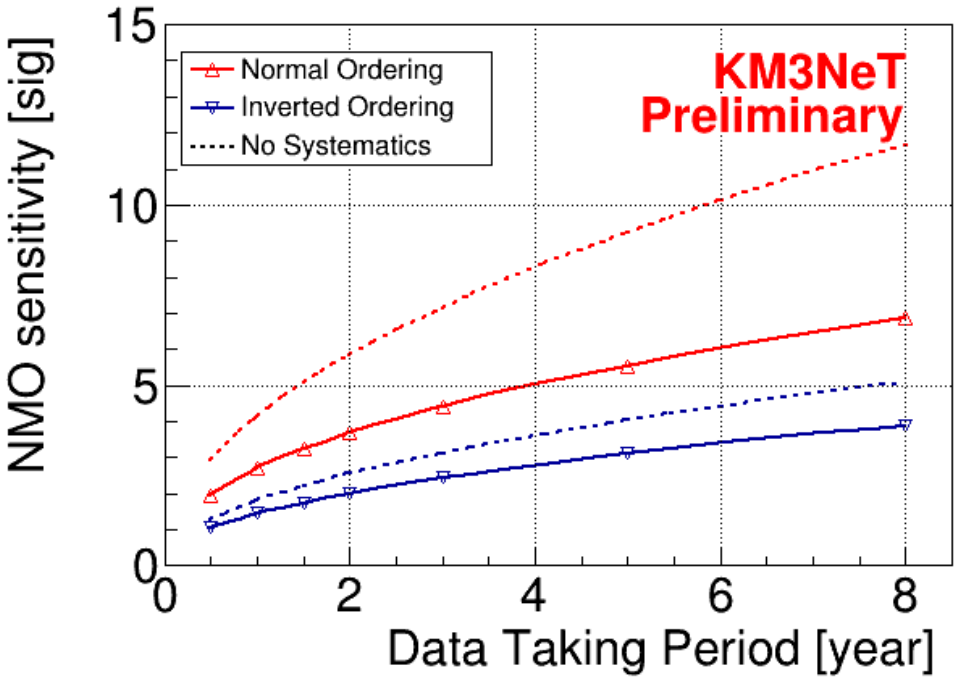
sensitivity obtained by minimizing a Test Statistic

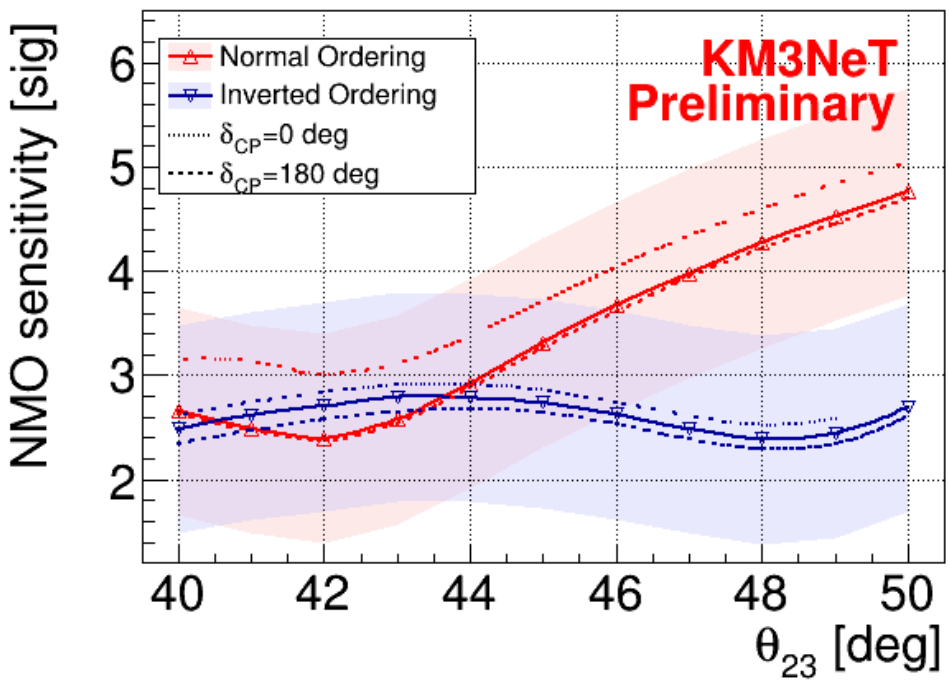
bins: 40x40



NMO sensitivity

author: Mathieu Perrin-Terrin



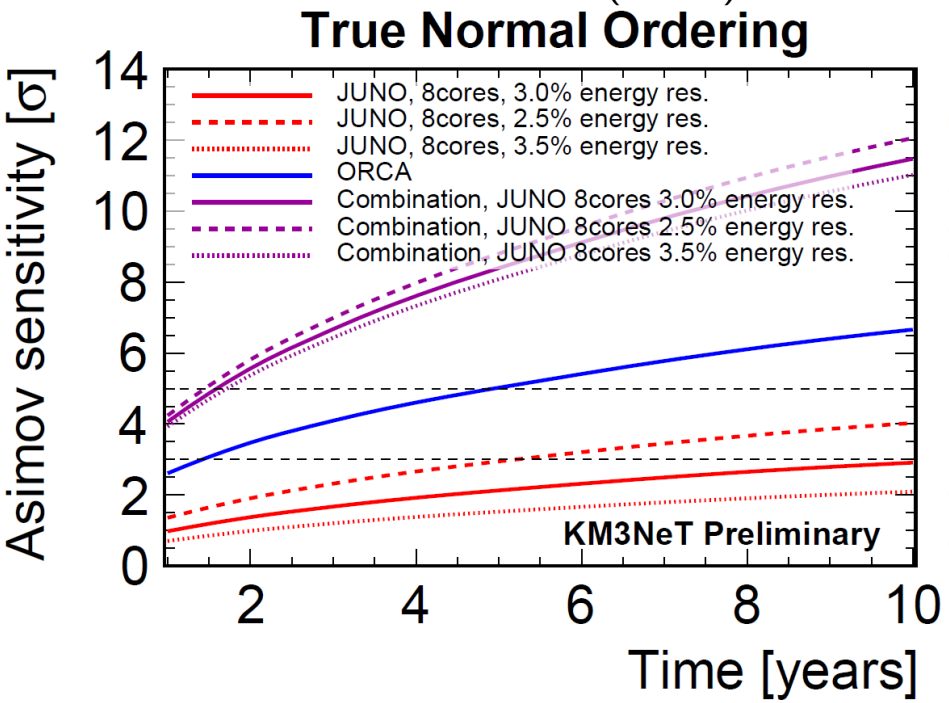


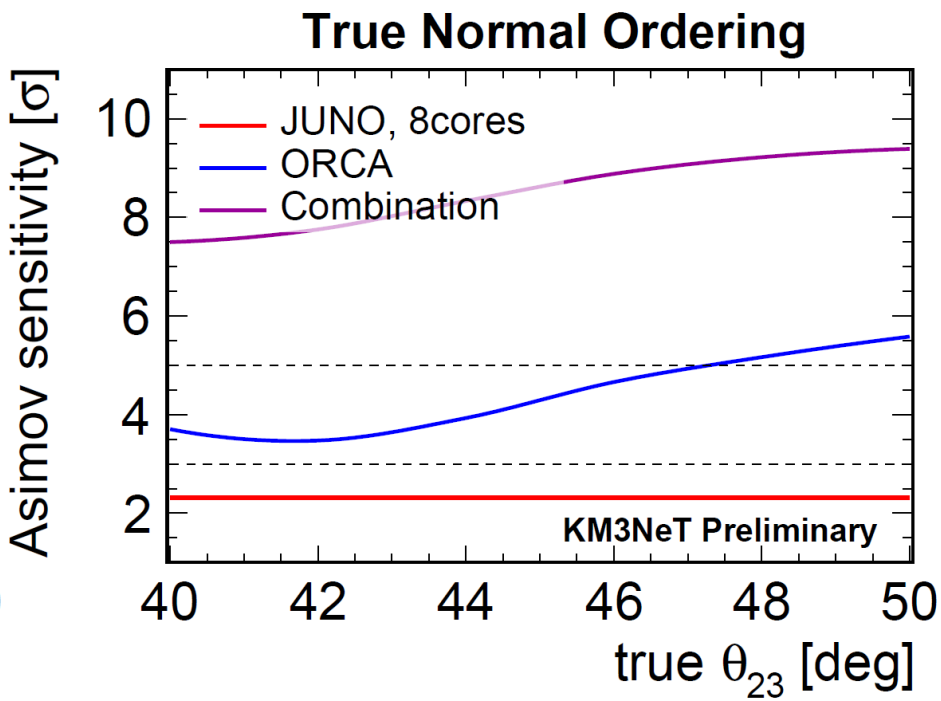
- **parameters**: NuFit 4.1, $\theta_{23} = 48.3°$
- **MC**: 3 yrs of full ORCA (115 DUs)
- for NO: 5σ after 4 yrs

- **inter-DOM spacing**: 20 m
- paper in preparation

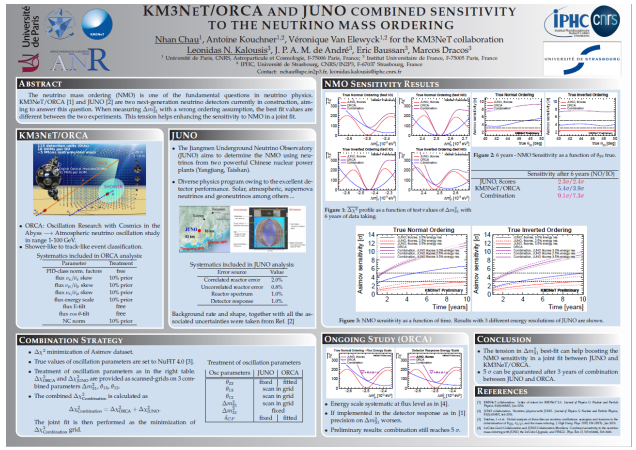
NMO sensitivity for ORCA + JUNO

authors: Nhan Chau and L. Kalousis (JUNO)



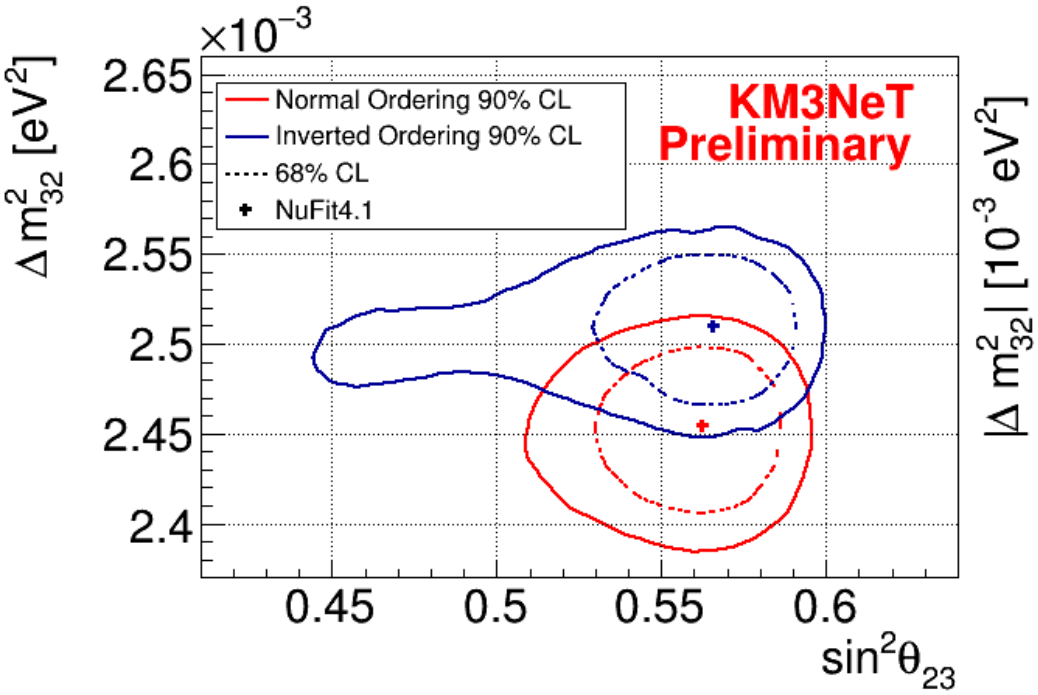


- from poster #480 @Neutrino2020
- tension between the best-fit Δm^2_{31} with a wrong ordering assumption enhances the sensitivity
- **method**: χ^2 minimization of an Asimov dataset
- **parameters**: NuFit 4.0, $\theta_{23} = 49.7°$
- for NO: 5σ after 1 yr (7.5σ after 4 yrs)

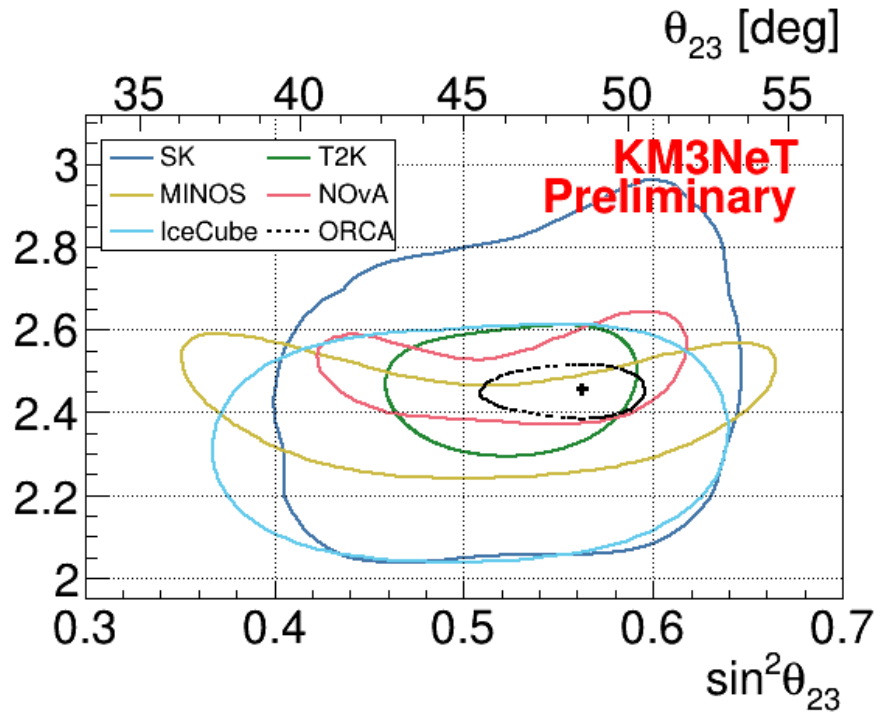


Sensitivity to Δm^2_{32} and θ_{23}

author: Mathieu Perrin-Terrin



Assuming NO

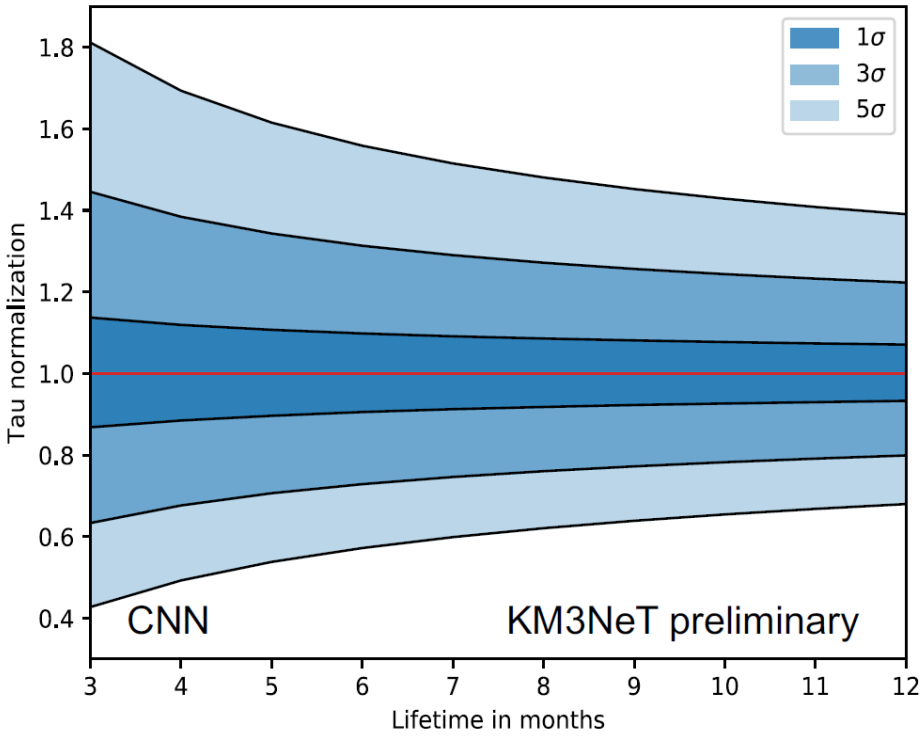


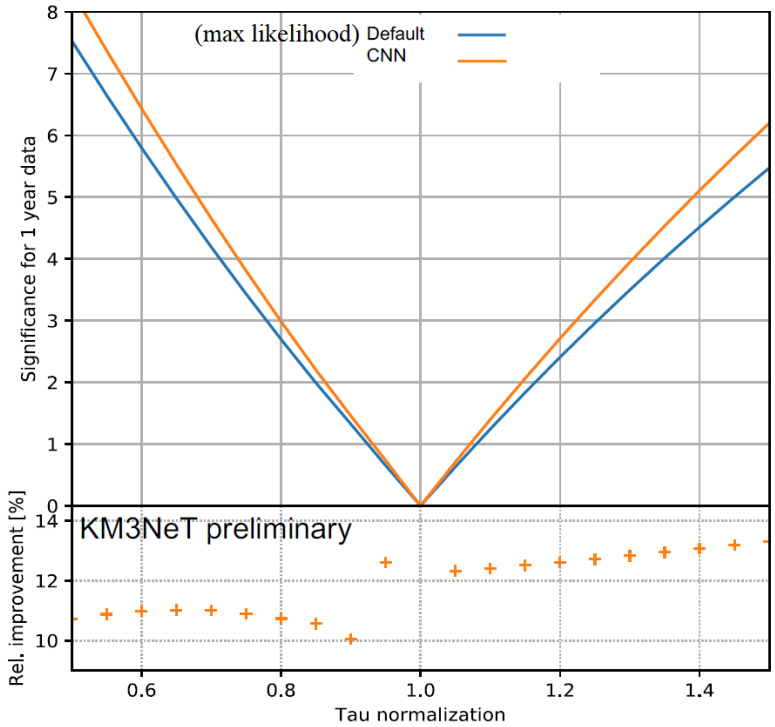
- **method**: max. likelihood
- **parameters**: NuFit 4.1
- **MC**: 3 yrs of full ORCA (115 DUs)

- **inter-DOM spacing**: 20 m
- paper in preparation

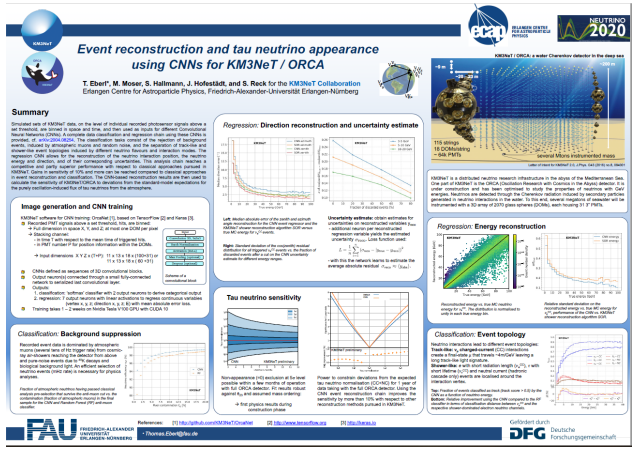
ν_τ appearance

authors: Michael Moser and Thomas Eberl





- from poster #202 @Neutrino2020
- confirmation of τ appearance possible within few months of operation with full ORCA
- Fit robust against θ_{23} and mass ordering
- CNN's outperform max $\mathcal{L}$ by >10 %



Sterile neutrinos (mini-intro)

Sterile ν simplest scenario (3+1):

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{bmatrix} = U_{3+1} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{bmatrix}$$

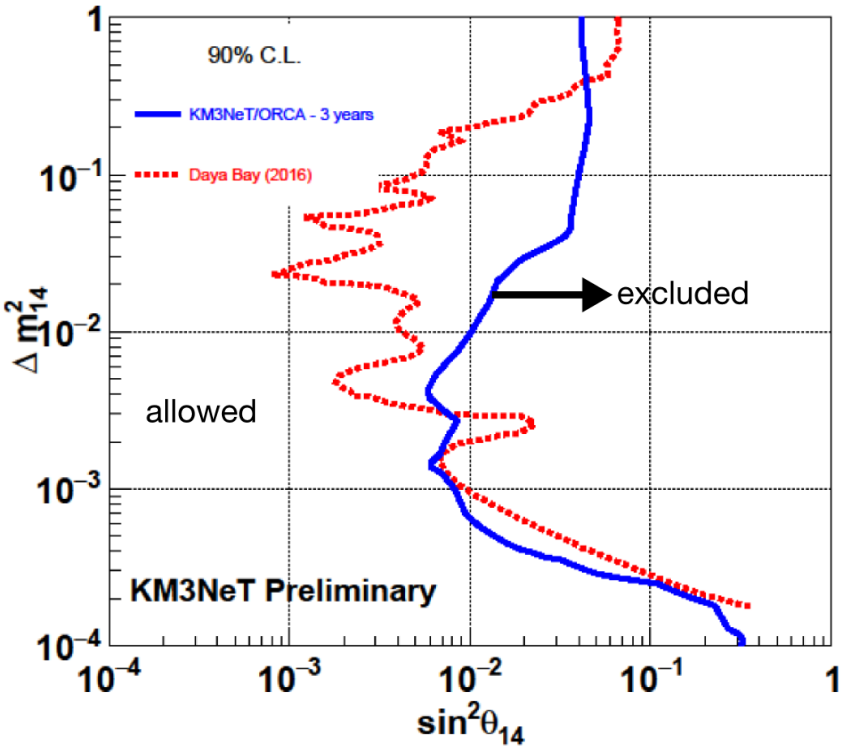
$\hookrightarrow$ new mixing parameters: θ_{i4}, Δm^2_{i4} $(i = 1,2,3)$, δ_{i4} $(i = 1,2,3)$

- standard U_{PMNS}
- sterile

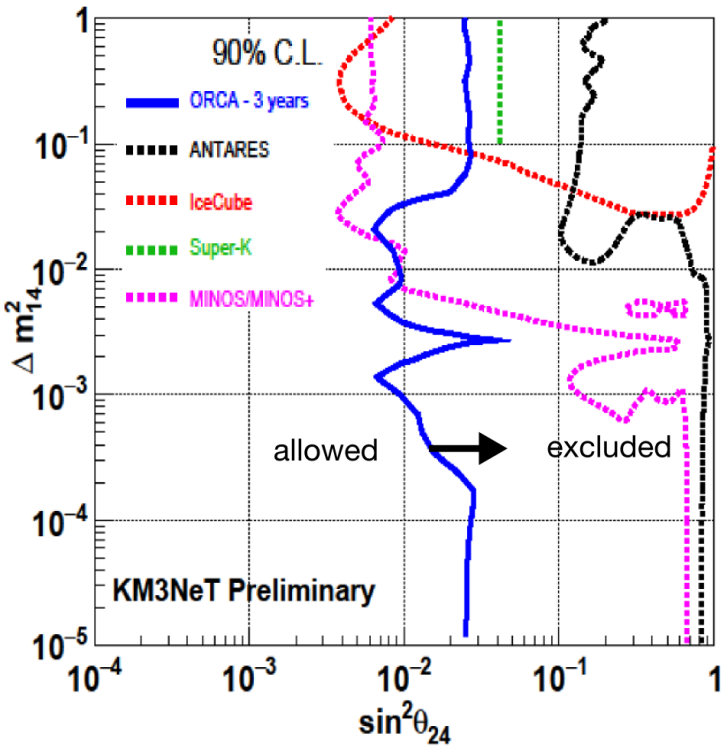
Exclusion limits on sterile mixing parameters

authors: Tarak Thakore, Alba Domi and Joao Coelho

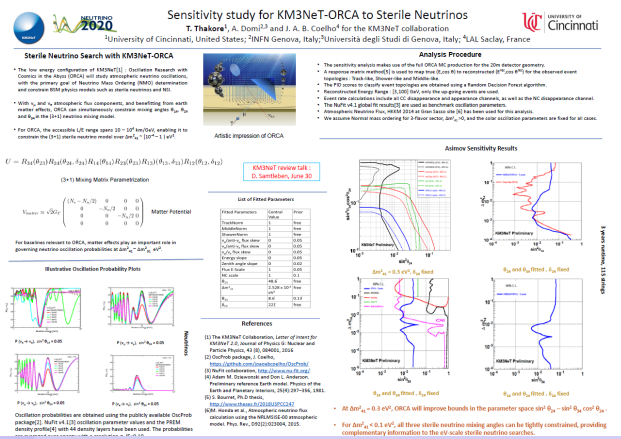
θ_{24} and θ_{34} fitted, $\delta_{24} = 0$



θ_{14} and θ_{34} fitted, $\delta_{24} = 0$



- from poster #179 @Neutrino2020
- **method**: χ^2 minimization of an Asimov dataset
- **MC**: 3 yrs of full ORCA (115 DUs)
- **scenario**: 3+1
- **assumptions**: NO, $\Delta m^2_{41} > 0$, NuFit 4.1 (Δm^2_{21}, θ_{12})



There is more!

See the backup for:

Other analyses:

- Sensitivity to **non-standard interactions** (NSI)
- Astrophysics:
  - Sensitivity to **Core-collapse Supernovae** (CCSN)
  - Indirect search for **dark matter from the Sun**

Potential detector upgrades:

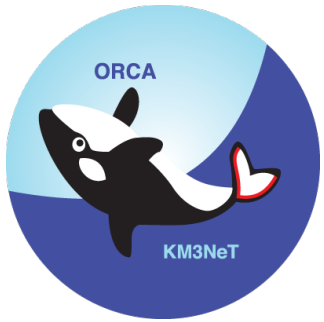
- Denser instrumentation (**Super-ORCA**)
- Neutrino beam (**P2O**)

Outline

Summary

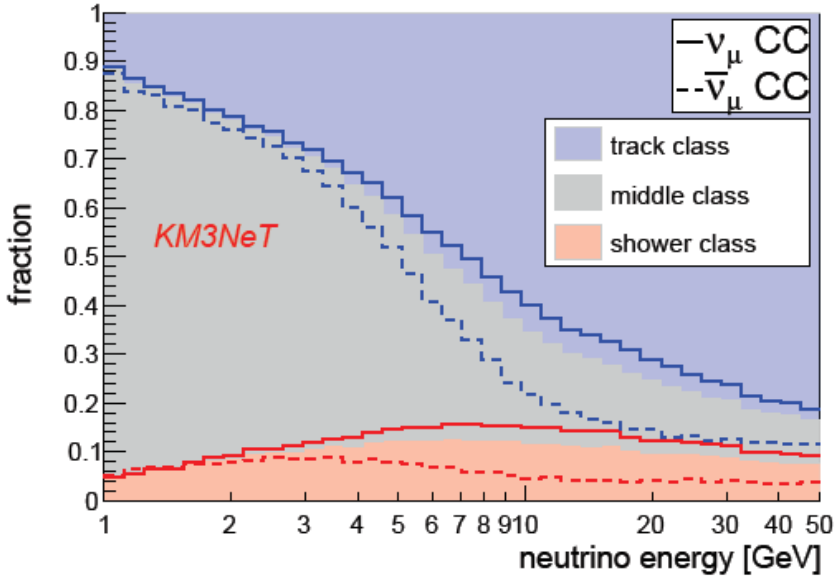
- Detector:
  - ORCA6 running stably
  - new DUs expected this year
- Data analyses and sensitivity studies:
  - first measurements with ORCA4
  - we already see the oscillations!
  - ORCA6 analyses ongoing

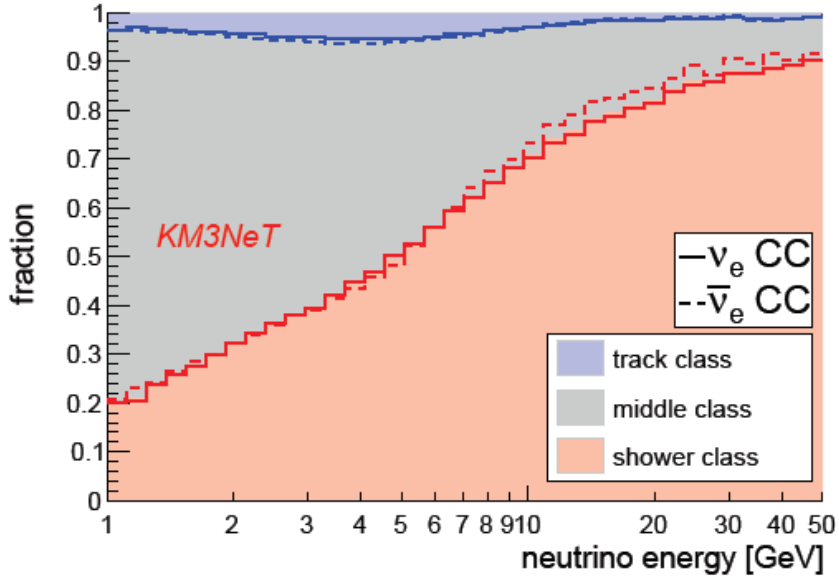
Take-home message:
ORCA lives and bites hard.
Exciting physics ahead!

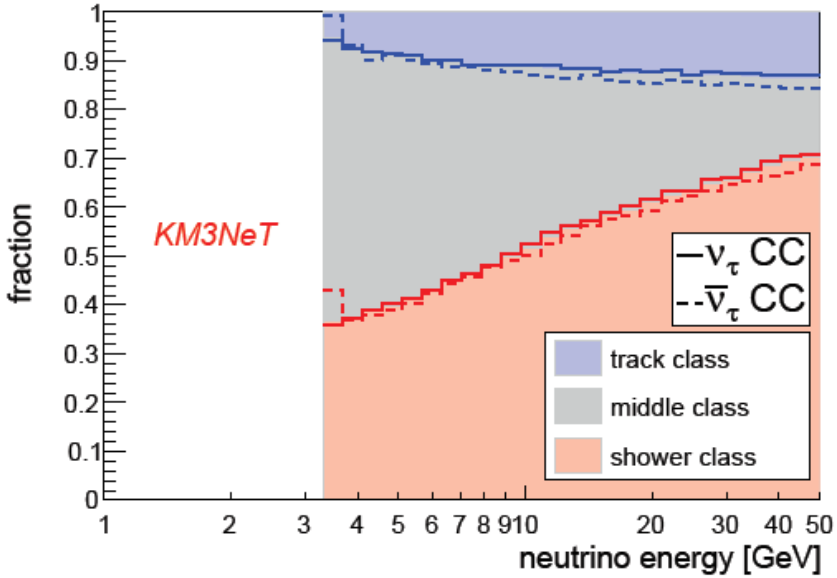


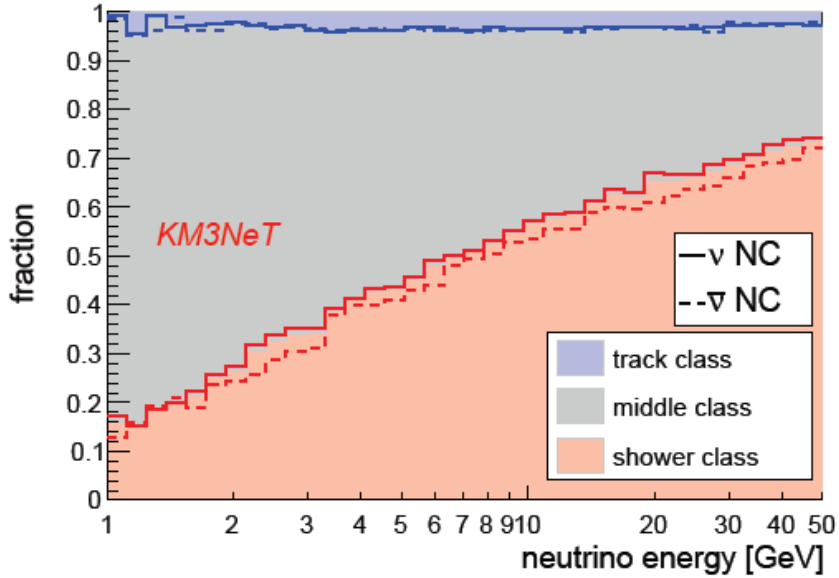
Thank you for your attention. Any questions?

NMO event classification all plots

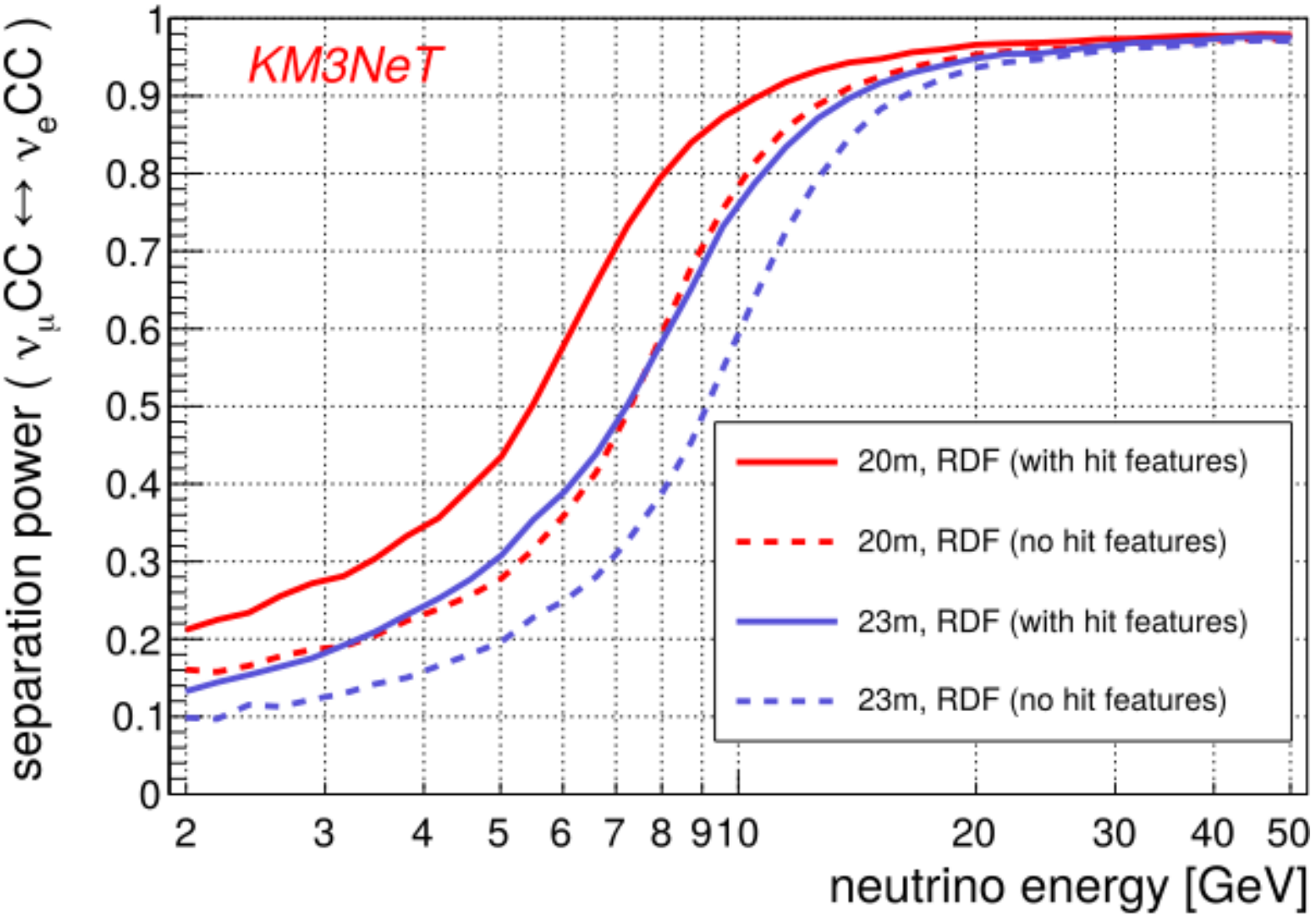




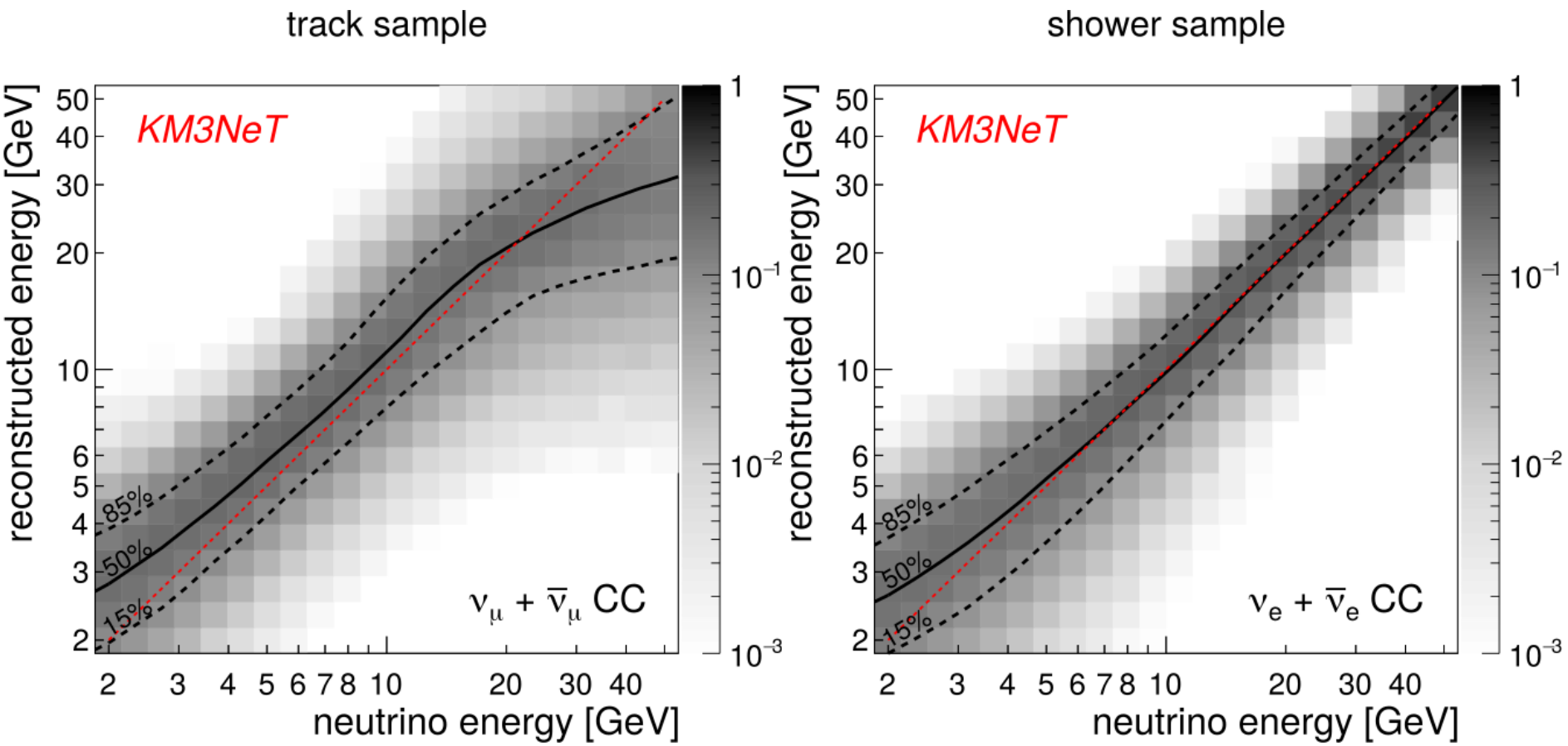




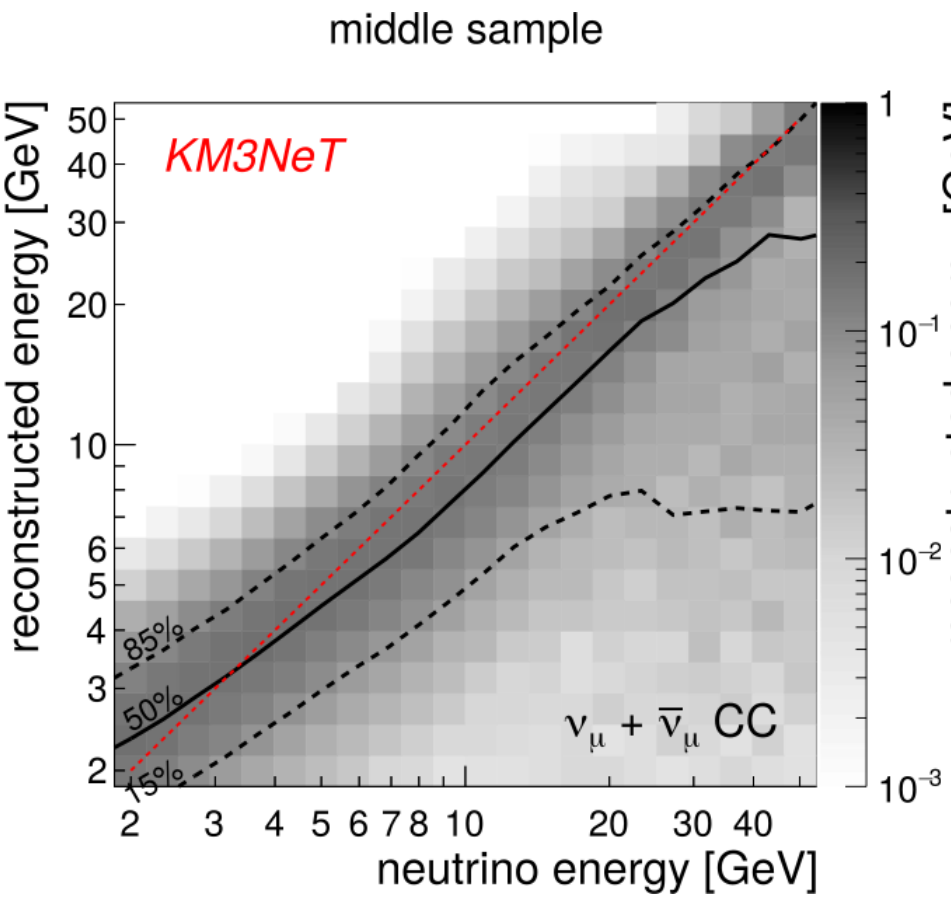
NMO separation power (tracks vs showers)

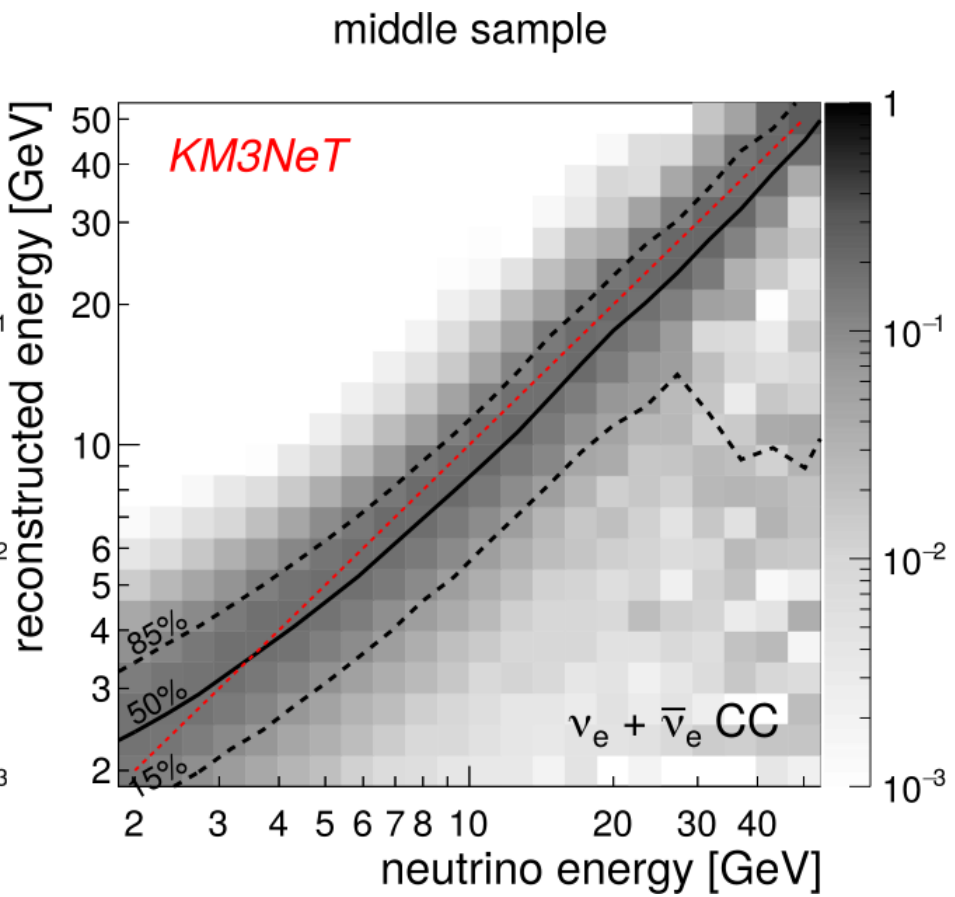


NMO E resolution

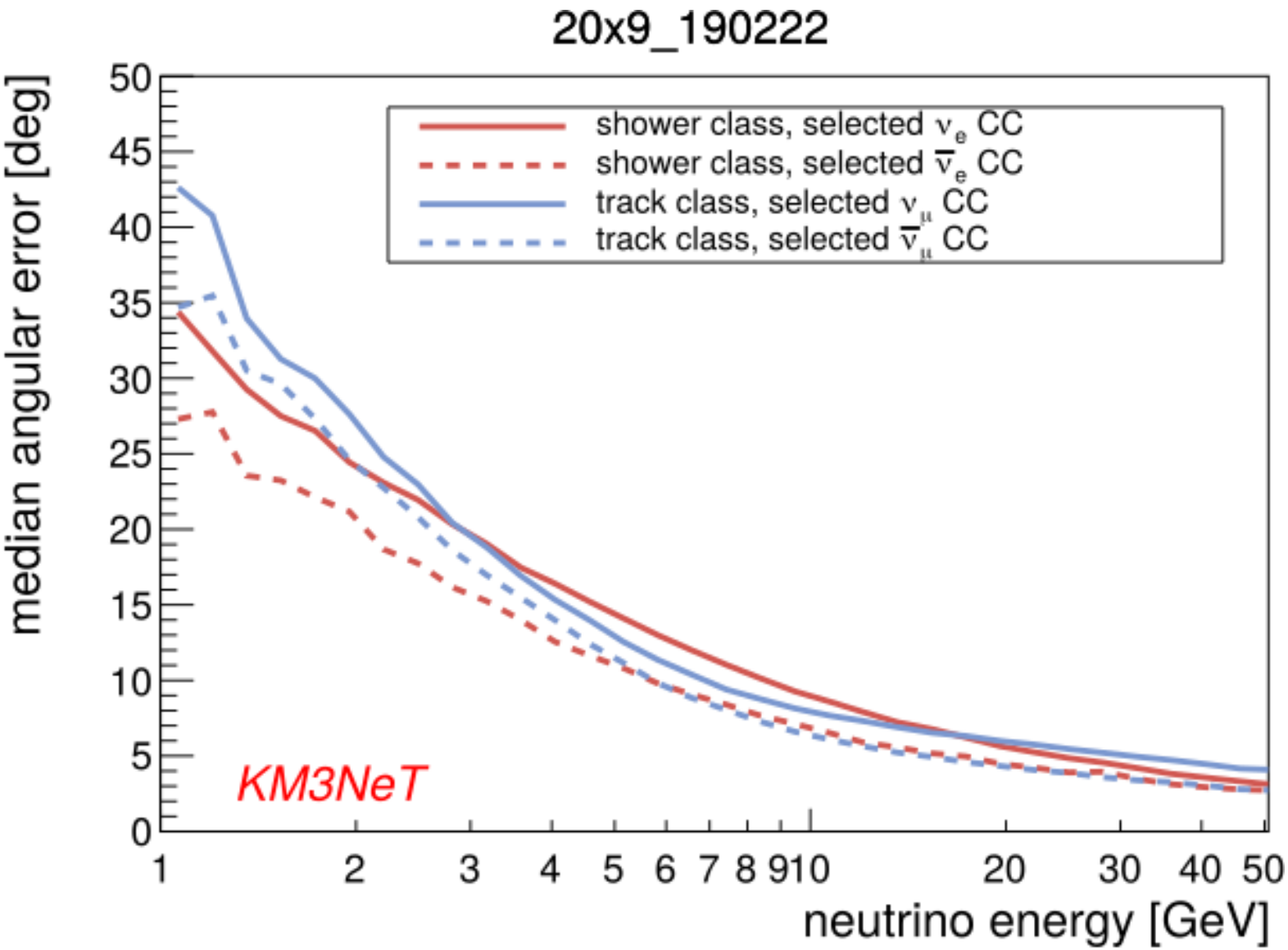


NMO E resolution

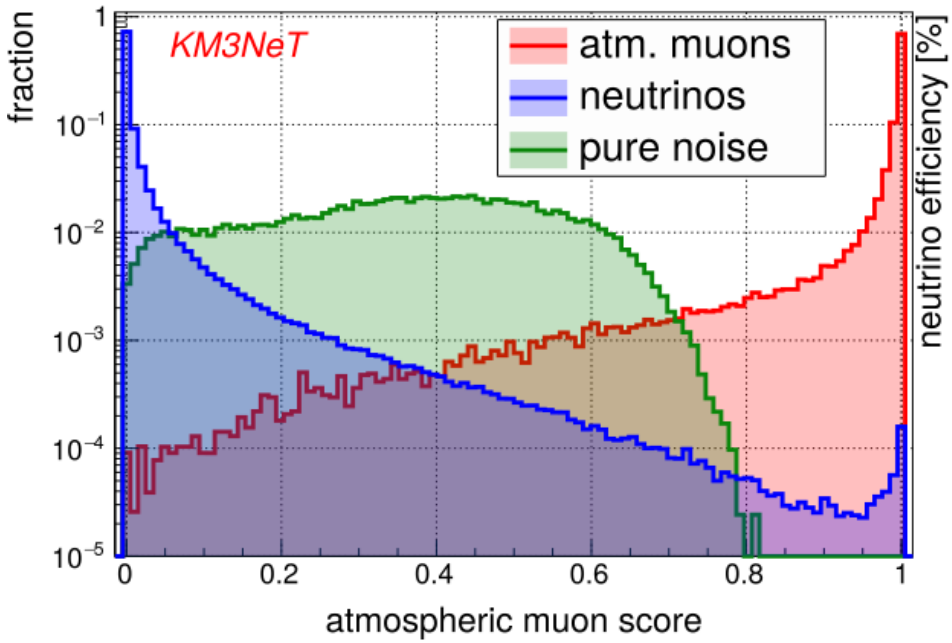


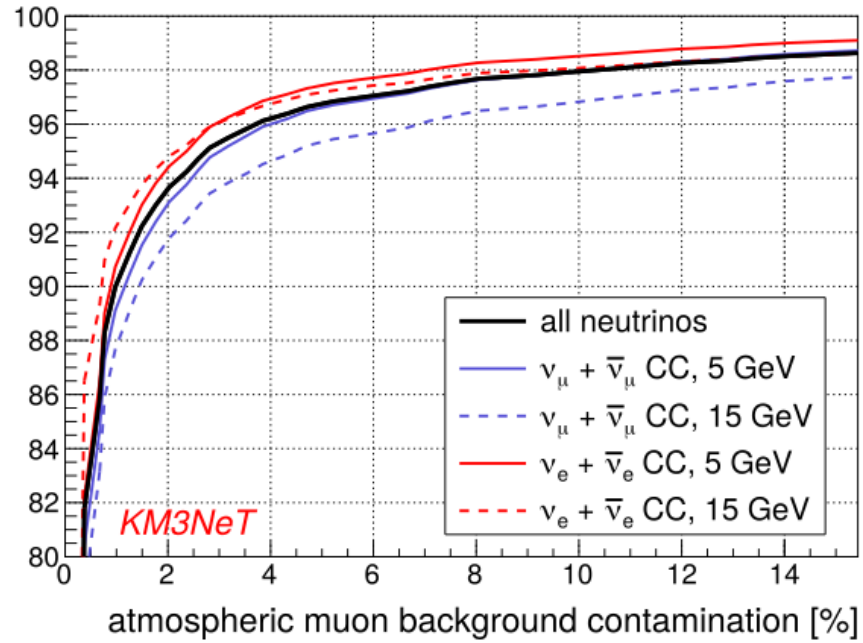


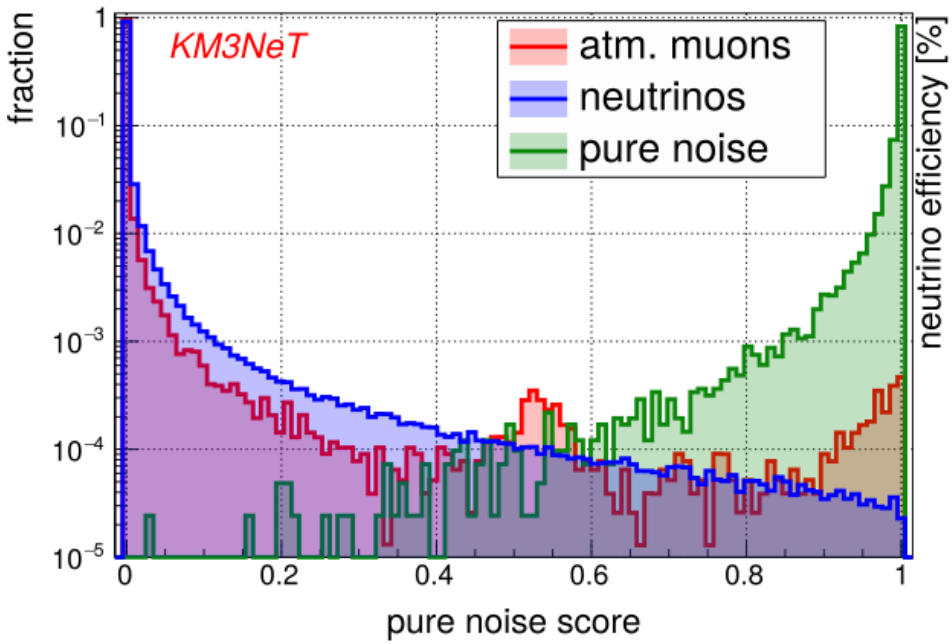
NMO angular resolution

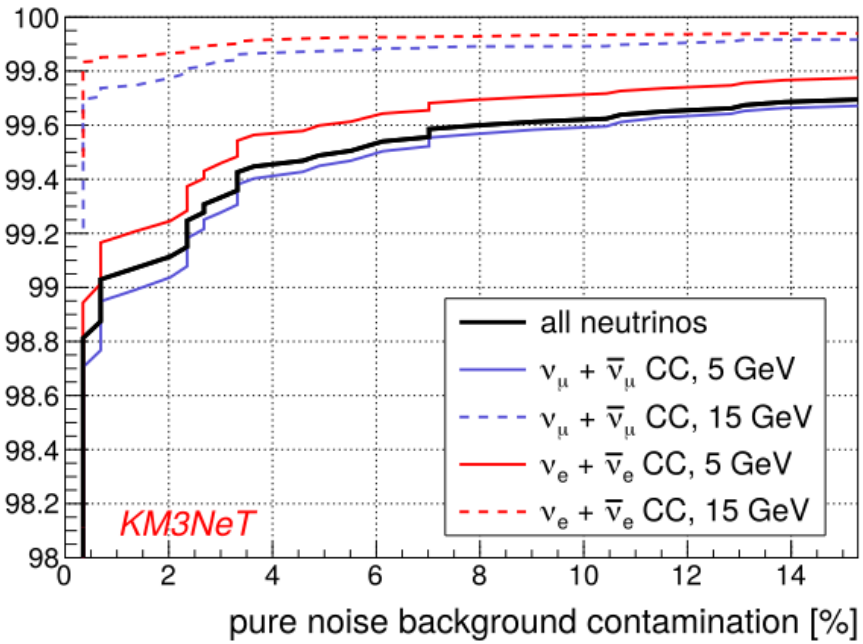


NMO muon and noise suppression









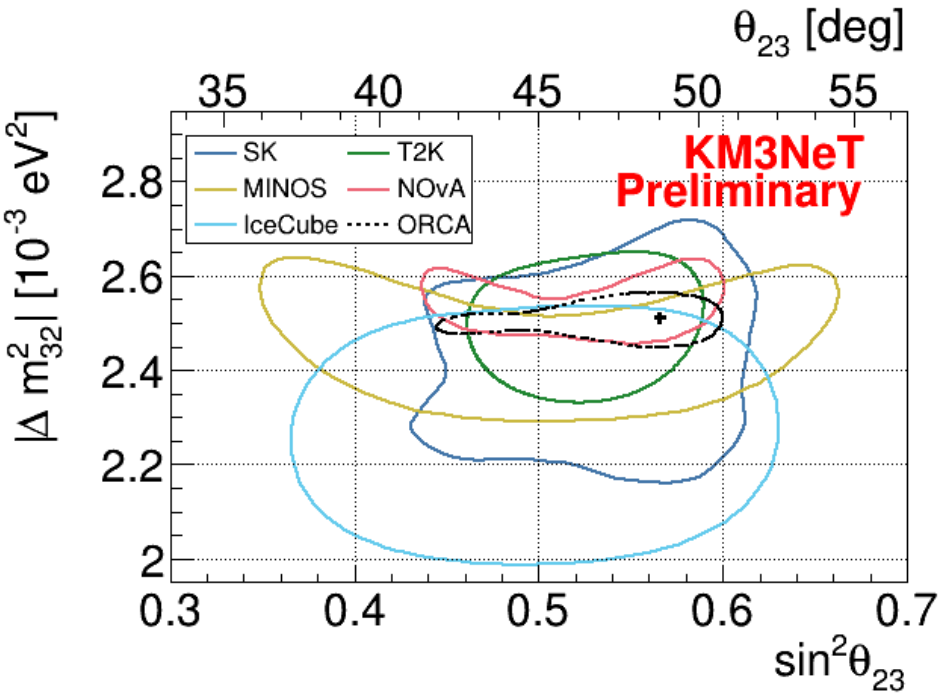
NMO priors

Parameter	Null Hypothesis Values		Constraints
	NO	IO	
Δm^2_{32}	2.528×10^{-3} eV^2	2.436×10^{-3} eV^2	free
δ_{CP}	221.0°, 0°, 180.0°	282.0°, 0°, 180.0°	free
θ_{13}	8.60°	8.64°	$\pm 0.13°$
Δm^2_{21}	7.39×10^{-5} eV^2		fixed
θ_{12}	33.82°		fixed
θ_{23}	[40°–50°]		free

Sensitivity to Δm^2_{32} and θ_{23} priors

Parameter	Null Hypothesis Values		Constraints
	NO	IO	
δ_{CP}	221.0°	282.0°	free
θ_{13}	8.60°	8.64°	$\pm 0.13°$
Δm^2_{21}	7.39×10^{-5} eV^2		fixed
θ_{12}	33.82°		fixed
θ_{23}	[40°–50°]		fixed
Δm^2_{32}	$[2.2 \times 10^{-3}; 2.8 \times 10^{-3}]$ eV^2		fixed

Sensitivity to Δm^2_{32} and θ_{23} comparison for IO



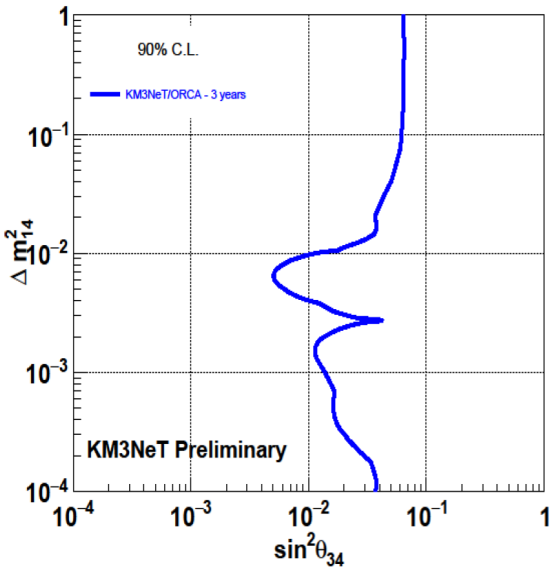
(Assuming IO)

References:

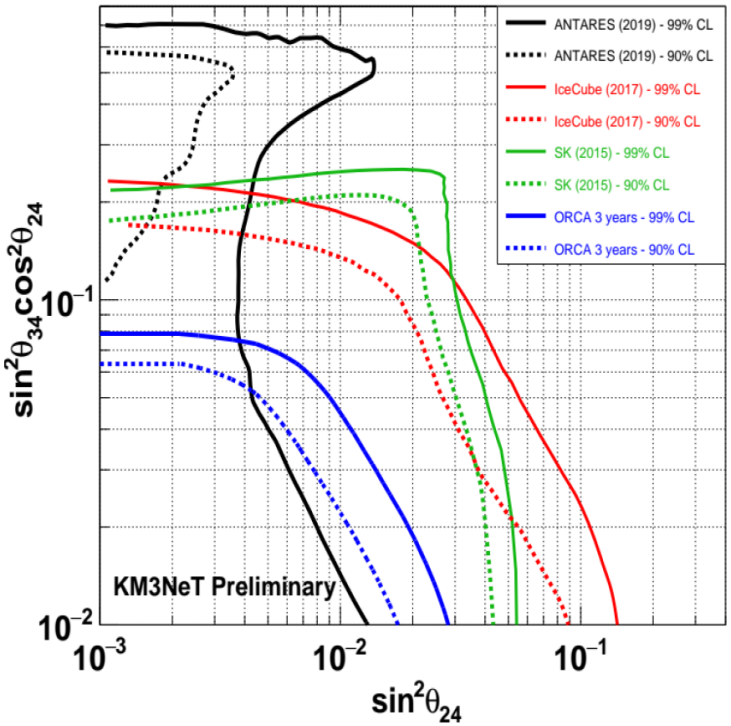
- M. G. Aartsen et al. (IceCube Collaboration), '*Measurement of Atmospheric Neutrino Oscillations at 6–56 GeV with IceCube DeepCore*', Phys. Rev. Lett. 120 (2018), p. 071801, doi:10.1103/PhysRevLett.120.071801
- K. Abe et al., '*Atmospheric neutrino oscillation analysis with external constraints in Super-Kamiokande I-IV*', Phys. Rev. D 97.7 (2018), p. 072001, doi: 10.1103/PhysRevD.97.072001, arXiv: 1710.09126 [hep-ex]
- K. Abe et al., '*Constraint on the matter–antimatter symmetry-violating phase in neutrino oscillations*', Nature 580.7803 (2020), pp. 339–344, doi: 10.1038/s41586-020-2177-0, arXiv: 1910.03887 [hep-ex]
- Adam Aurisano, '*Recent Results from MINOS and MINOS+*', June 2018. doi: 10.5281/zenodo.1286760, url: https://doi.org/10.5281/zenodo.1286760
- M.A. Acero et al., '*First Measurement of Neutrino Oscillation Parameters 543 using Neutrinos and Antineutrinos by NOvA*', Phys. Rev. Lett. 123.15 544 (2019), p. 151803, doi: 10.1103/PhysRevLett.123.151803, arXiv: 545 1906.04907 [hep-ex]

Sterile neutrinos

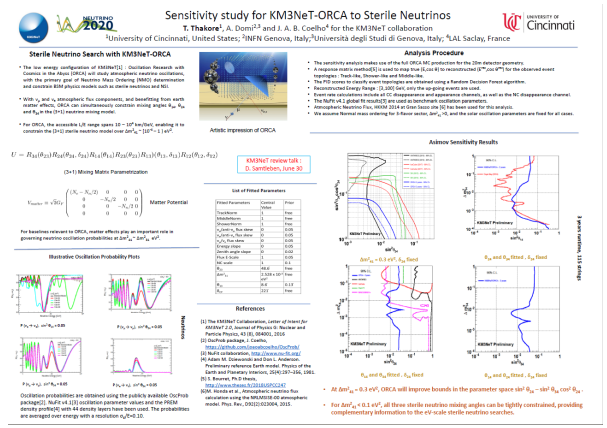
θ_{14} and θ_{24} fitted, $\delta_{24} = 0$



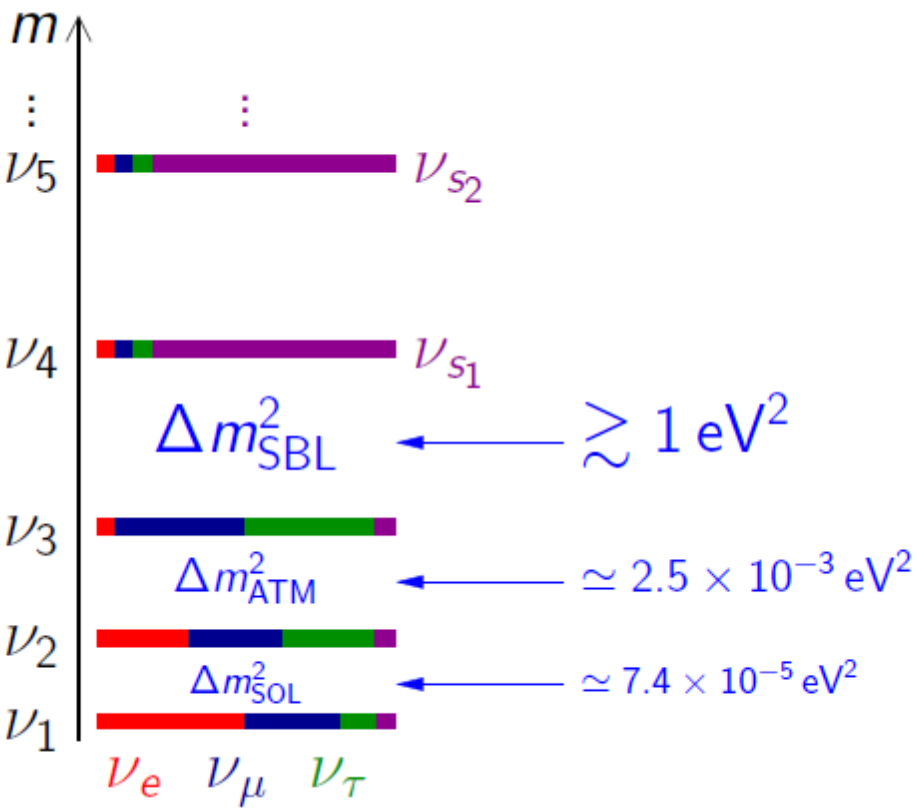
$\Delta m^2_{41} = 0.3\,\mathrm{eV}^2$, $\delta_{24} = 0$



- from poster #179 @Neutrino2020
- **method**: χ^2 minimization of an Asimov dataset
- **MC**: 3 yrs with full ORCA (115 DUs)
- **model**: 3+1
- **assumptions**: NO, $\Delta m^2_{41} > 0$, NuFit 4.1 (Δm^2_{21}, θ_{12})


Sensitivity study for KM3NeT-ORCA to Sterile Neutrinos

Sterile neutrinos

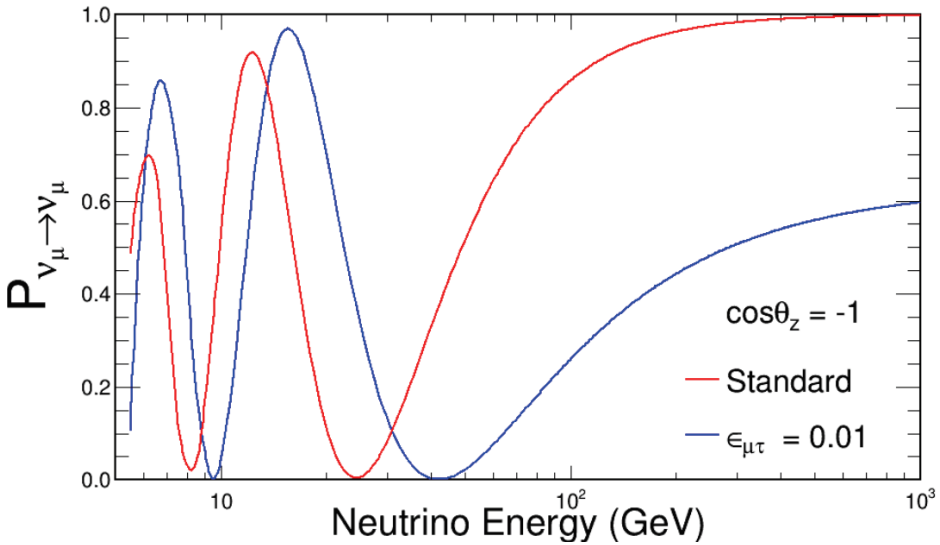


Non-Standard Interactions (NSI) (mini-intro)

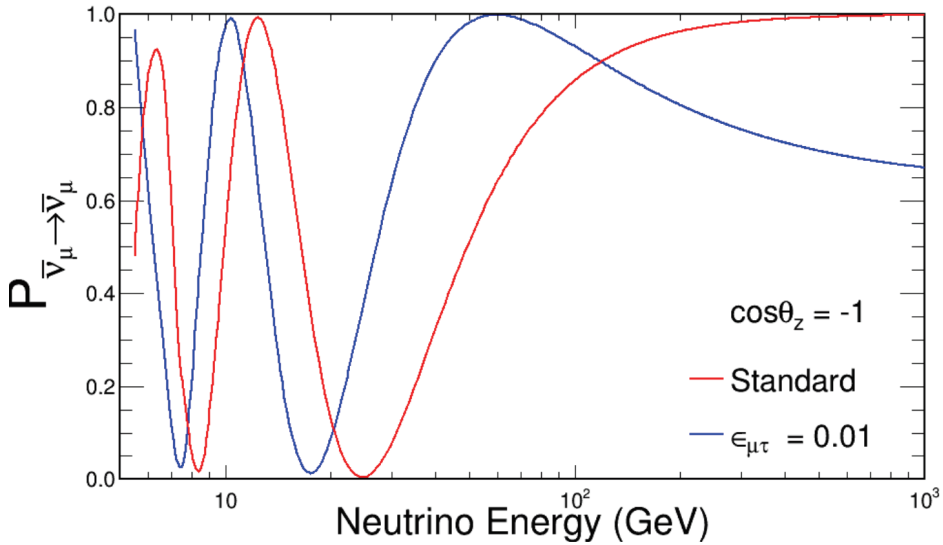
NC NSI of ν_α with matter fermions (e, u, d) distort the standard ($\varepsilon_{\alpha\beta} = 0$) MSW effect:
(arXiv:1907.00991v2)

$$H_{\text{eff}} = \frac{1}{2E} U_{\text{PMNS}} \begin{bmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{bmatrix} U^\dagger_{\text{PMNS}} + \sqrt{2} G_F N_e \begin{bmatrix} 1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon^*_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon^*_{e\tau} & \varepsilon^*_{\mu\tau} & \varepsilon_{\tau\tau} \end{bmatrix}$$

neutrinos

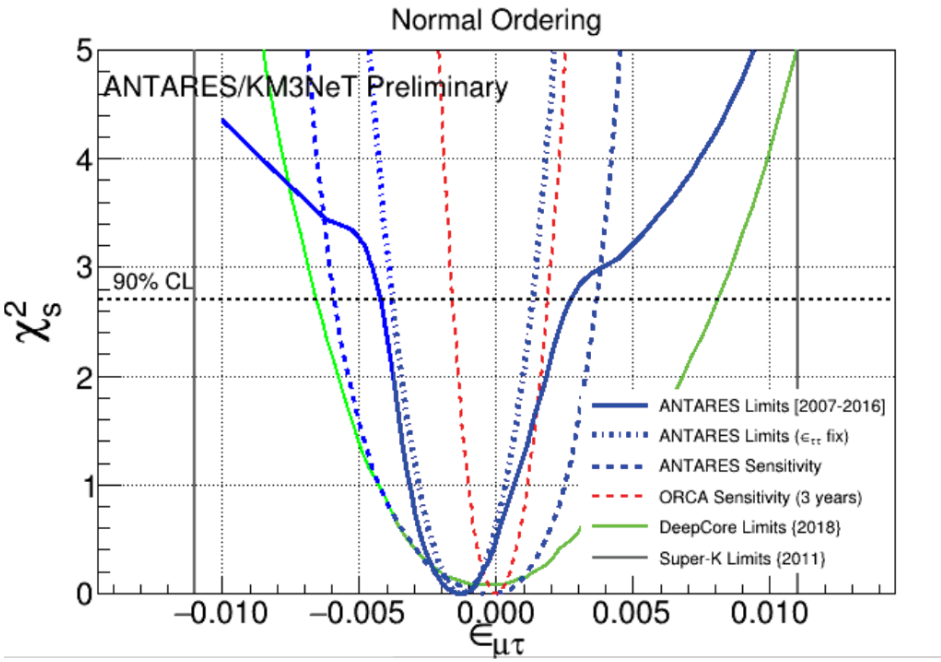


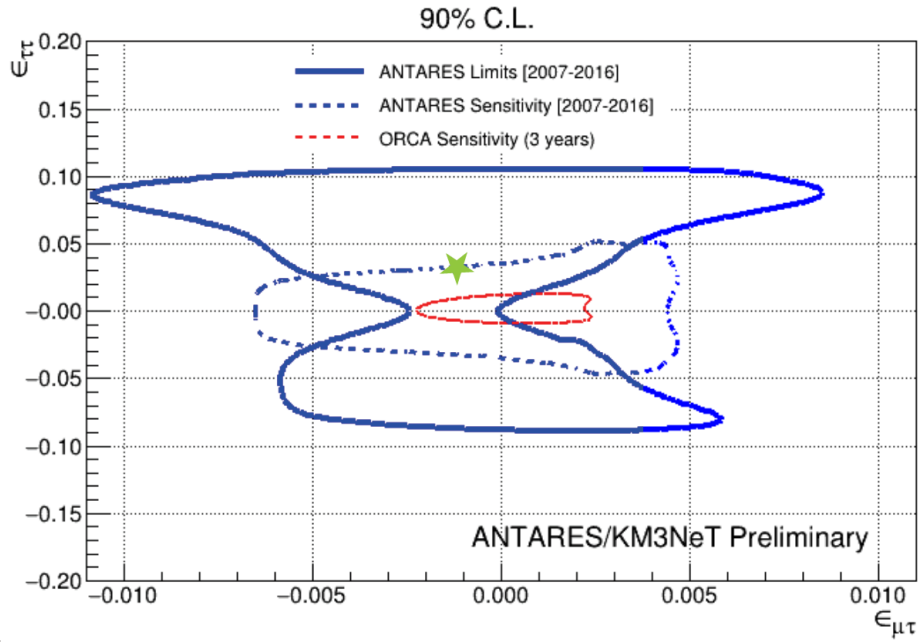
antineutrinos



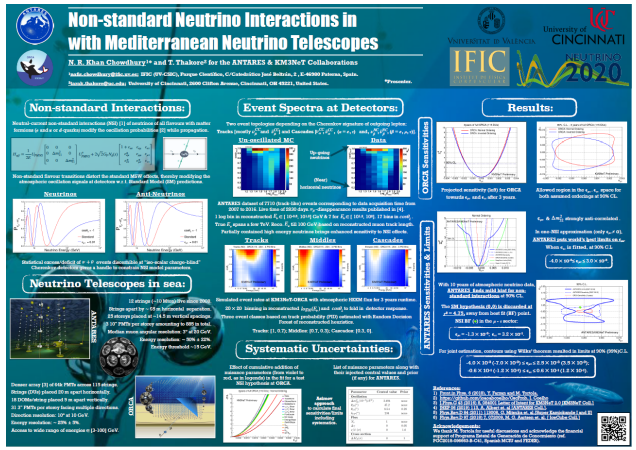
Non-Standard Interactions (NSI)

author: Nafis Rezwan Khan Chowdhury, Tarak Thakore





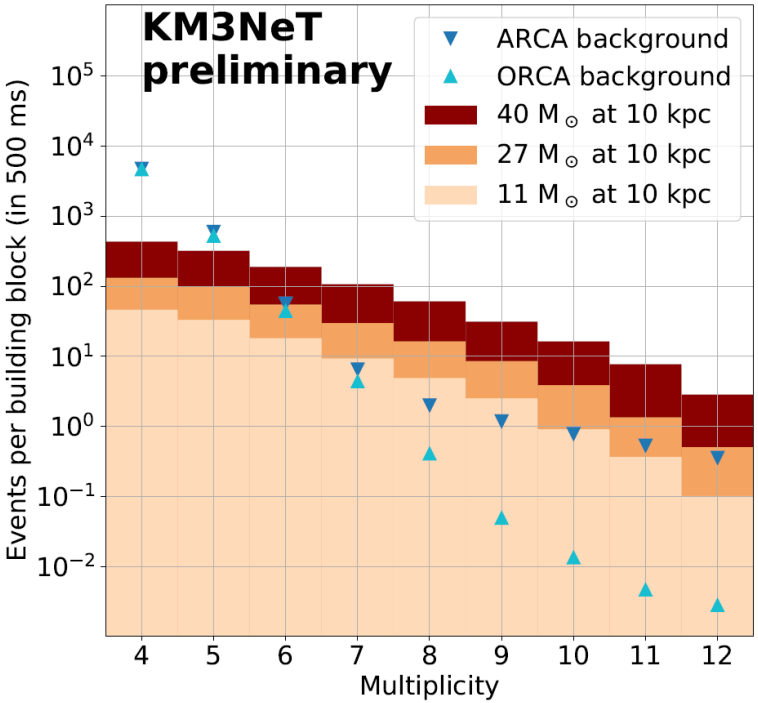
- from poster #178 @Neutrino2020
- **method**: χ^2 minimization of an Asimov dataset
- **MC**: 3 yrs with full ORCA (115 DUs)



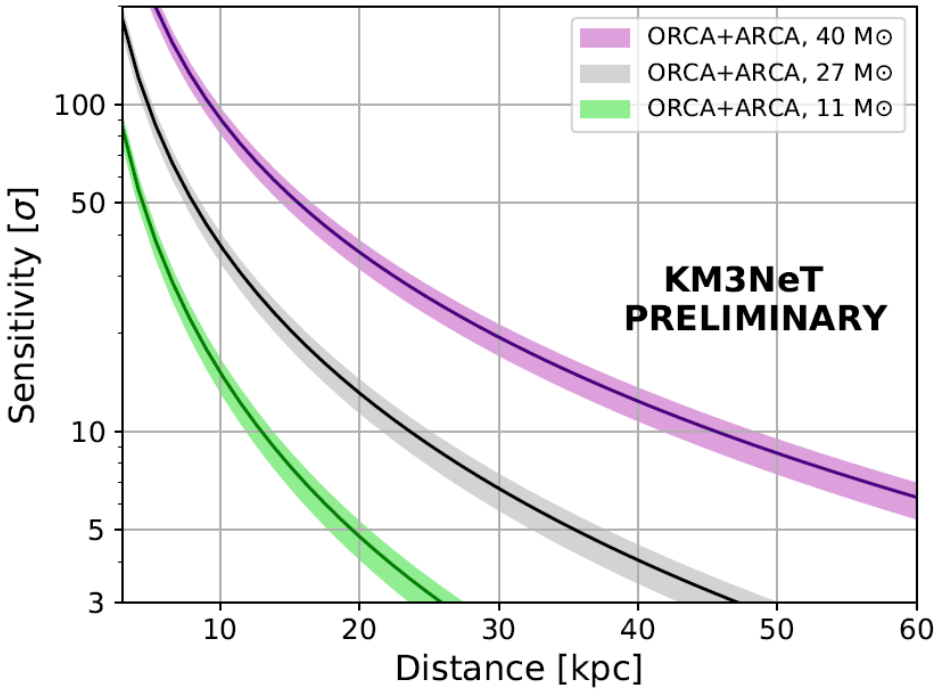
Core-collapse Supernovae (CCSN)

authors: Marta Colomer, Massimiliano Lincetto, Vladimir Kulikovskiy, Damien Dornic and Alexis Coleiro

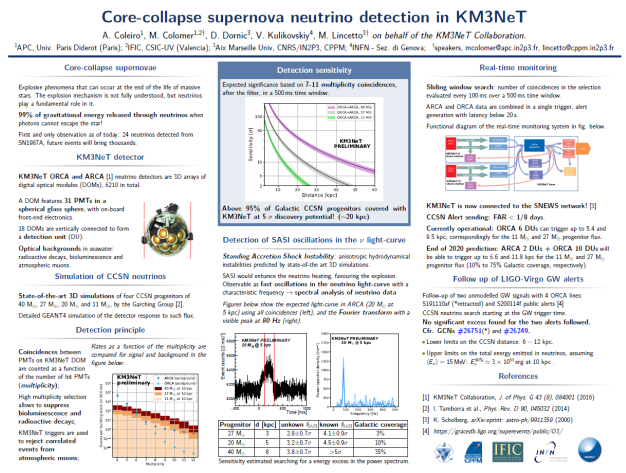
1 building block



full ORCA&ARCA, multiplicity 7-11, 500 ms window



- from poster #245 @Neutrino2020
- **multiplicity** - number of hit PMTs on a DOM
- **mechanism** - MeV ν's under threshold BUT the background rate rises
- >95% of galactic CCSN progenitors at 5σ (20 kpc)
- ORCA6 can trigger up to 5.4 (9.5) kpc for 11 (27) $M_\odot$ progenitors


Core-collapse supernova neutrino detection in KM3NeT

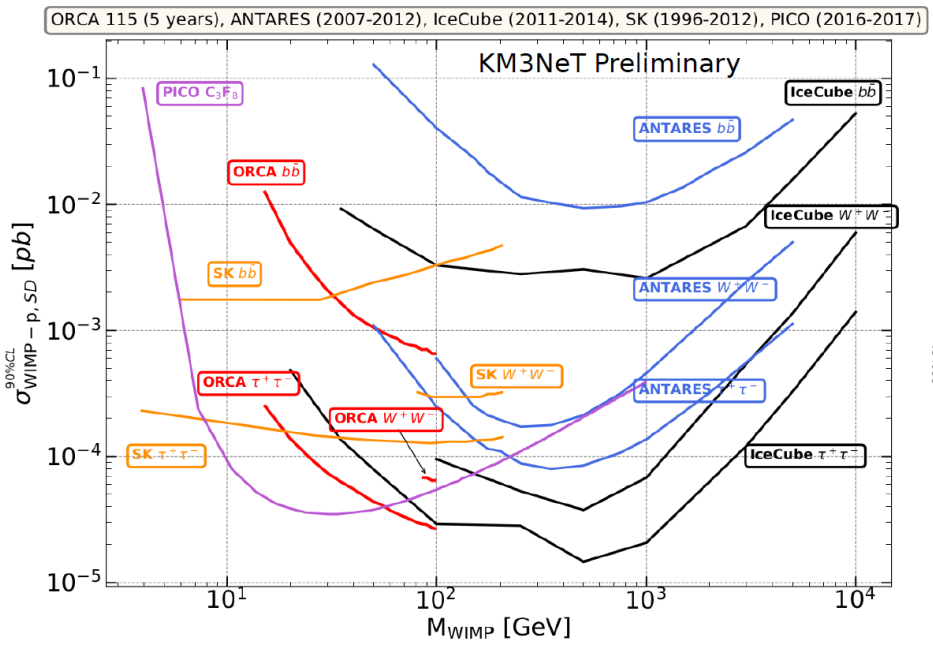
Core-collapse Supernovae (CCSN)

- $\Delta t \simeq 10 - 20\,\text{ms}$ @10 kpc, depending on the progenitor
- dedicated CCSN MC for the signal of a single DOM
- for bgd we use data directly
- No significant excess found for GCN #26751(retracted) and #26249 alerts

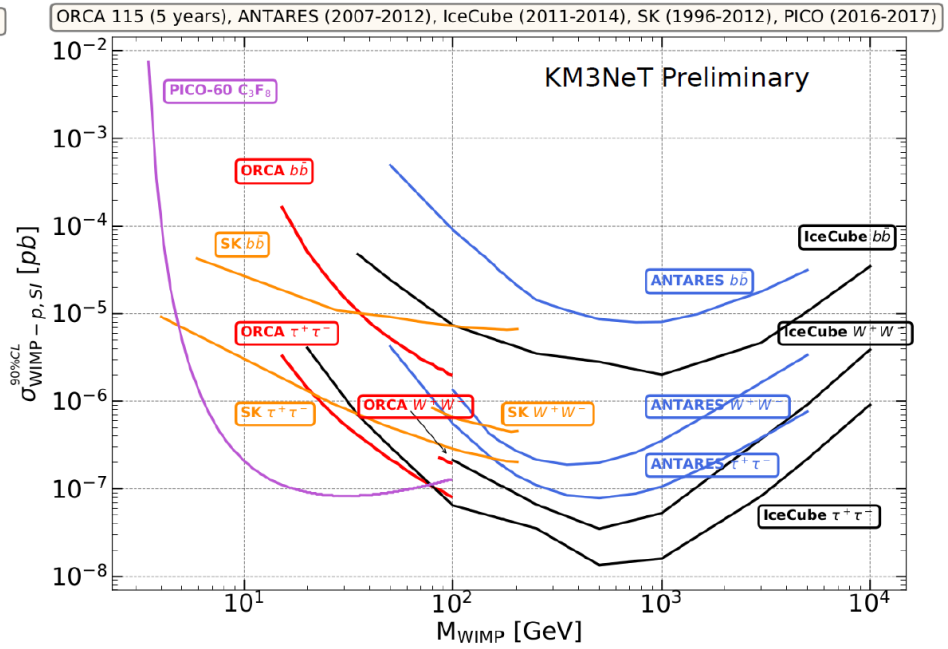
Dark matter (DM) from the Sun

authors: Daniel Lopez-Coto, Sergio Navas and Juande Zornoza

spin-dependent (coupling to splin; mainly for odd A)

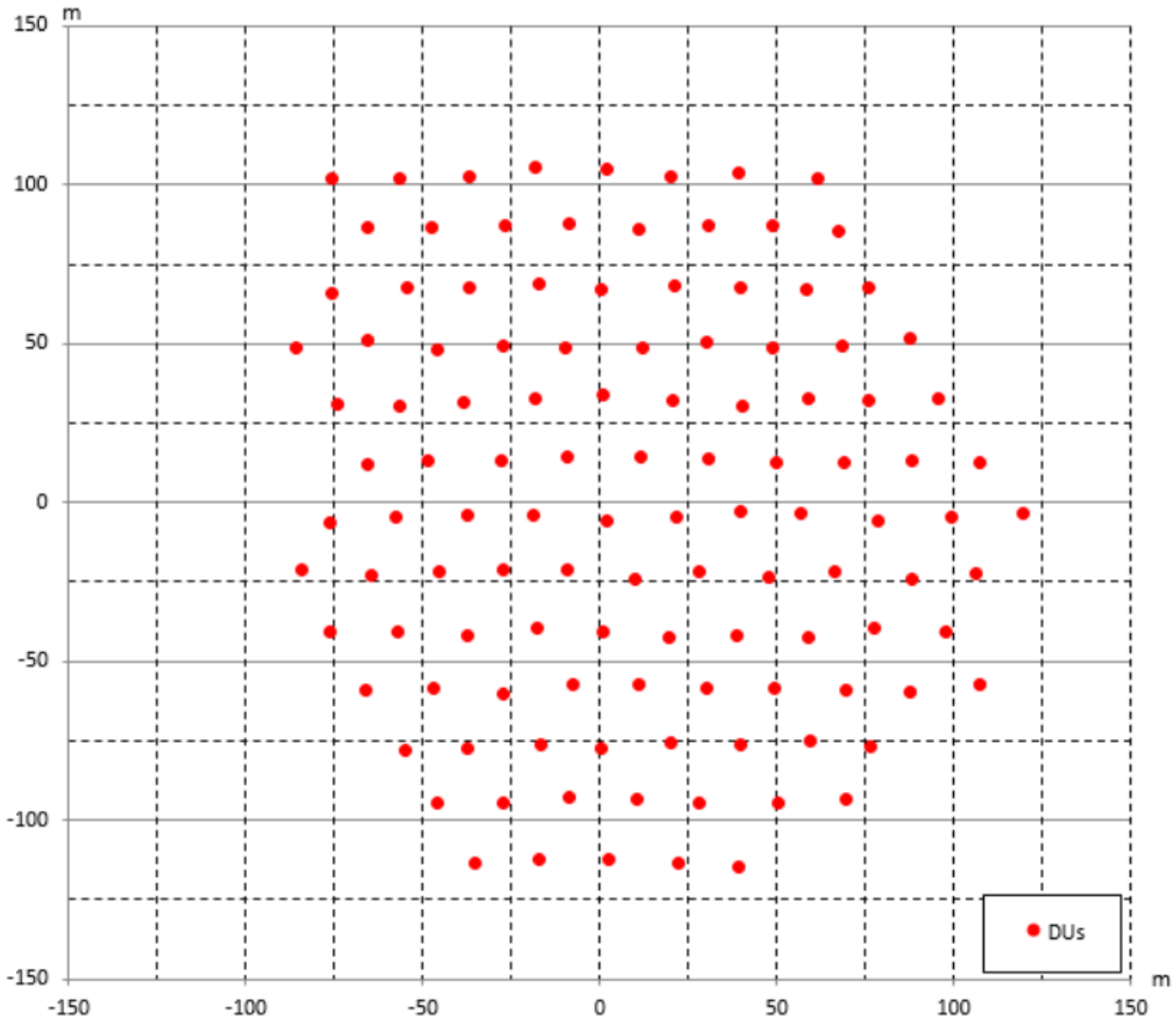


spin-independent (coupling to mass)



- **search**: indirect
- **DM particle**: WIMP (neutralino χ)
- **method**: $\log \mathcal{L}$ maximization
- **MC**: 5 yrs with full ORCA (115 DUs)
- **used topology**: only tracks

The actual ORCA footprint

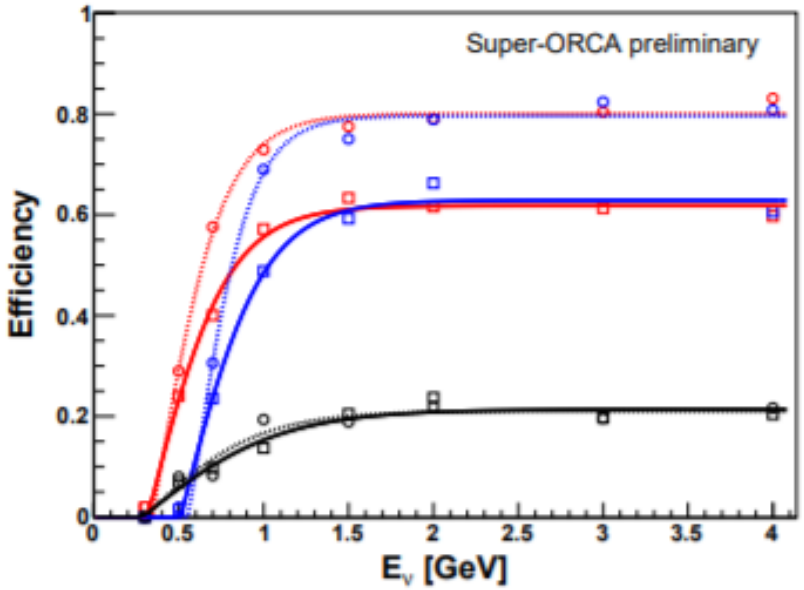


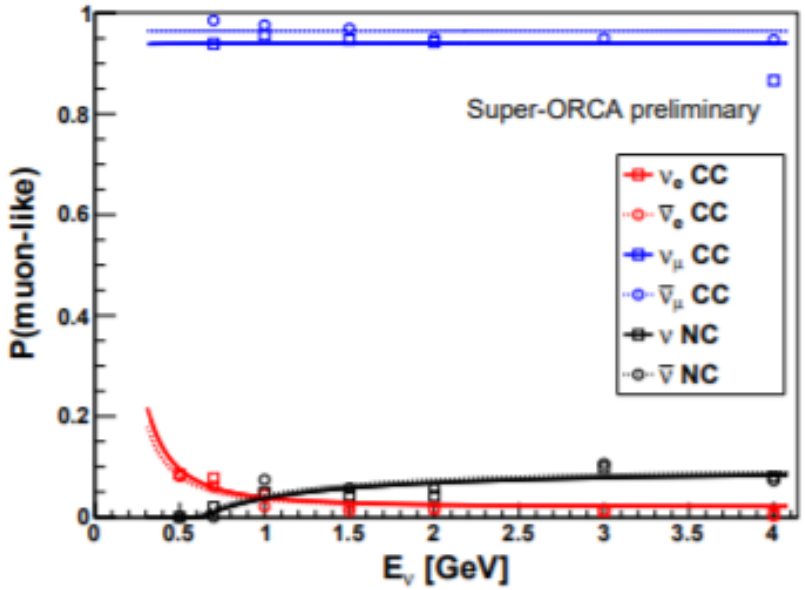
Super-ORCA

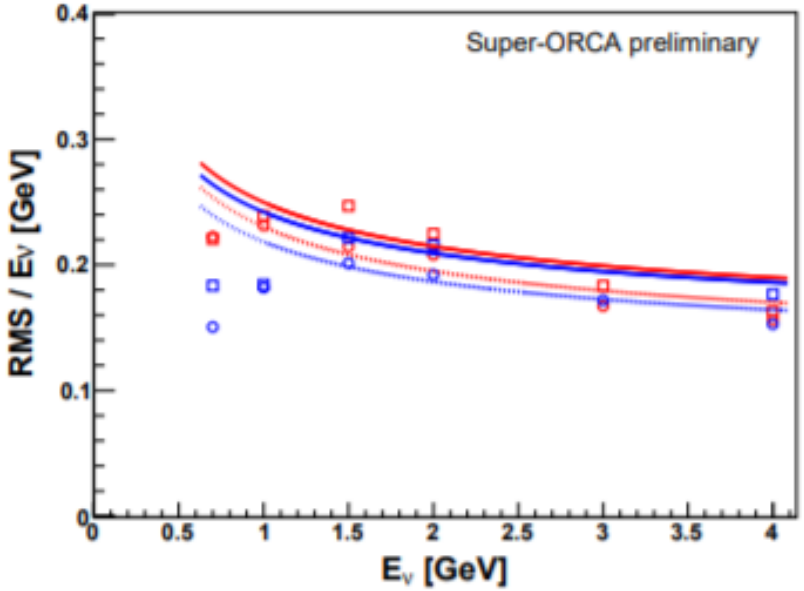
More details in PoS(ICRC2019)911

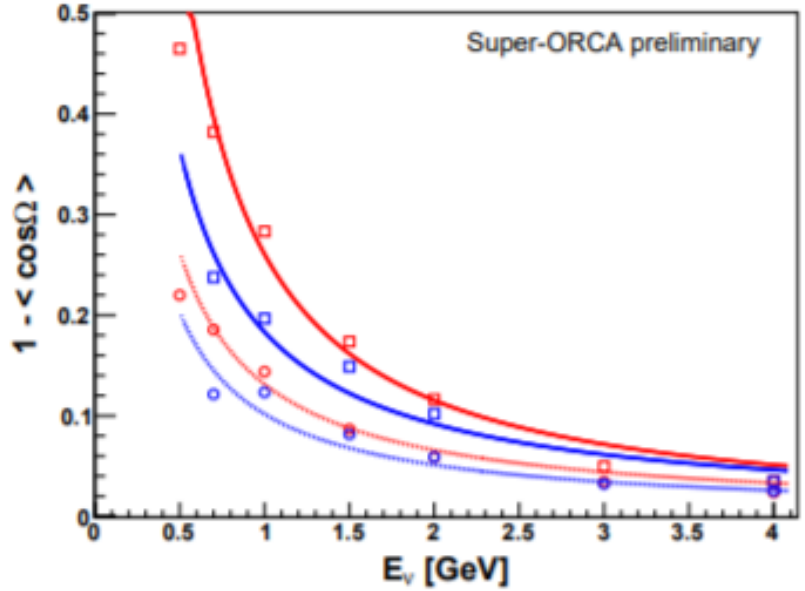
- ~10x denser
- improved E (sub-GeV!) and θ resolution
- **Sensitivity**: χ^2 minimization of an Asimov dataset and simultaneous fit of several nuisance parameters

Super-ORCA expected detector performance

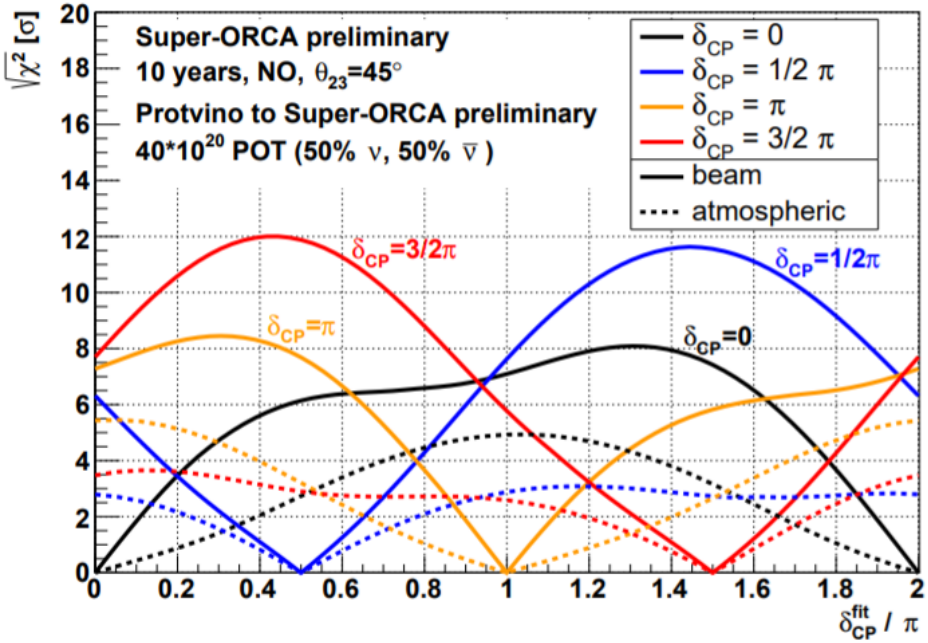




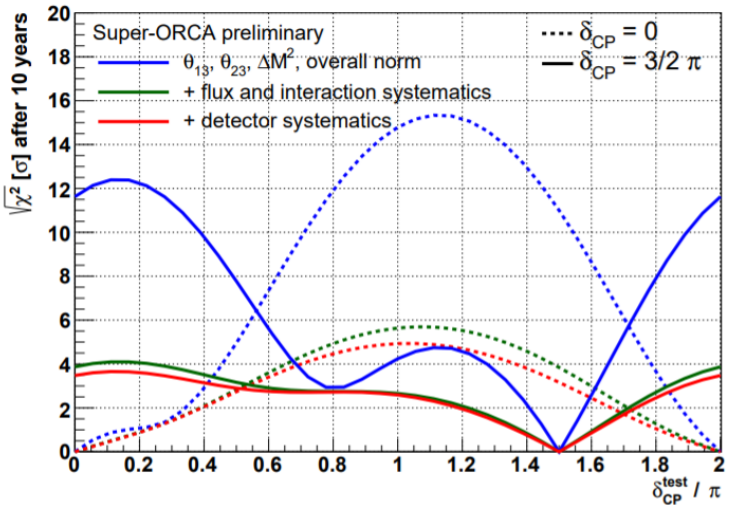


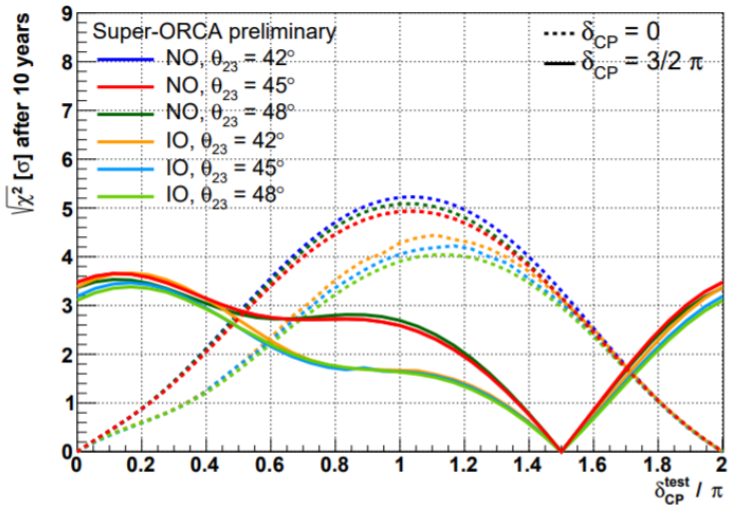


Super-ORCA expected δ_{CP} sensitivity

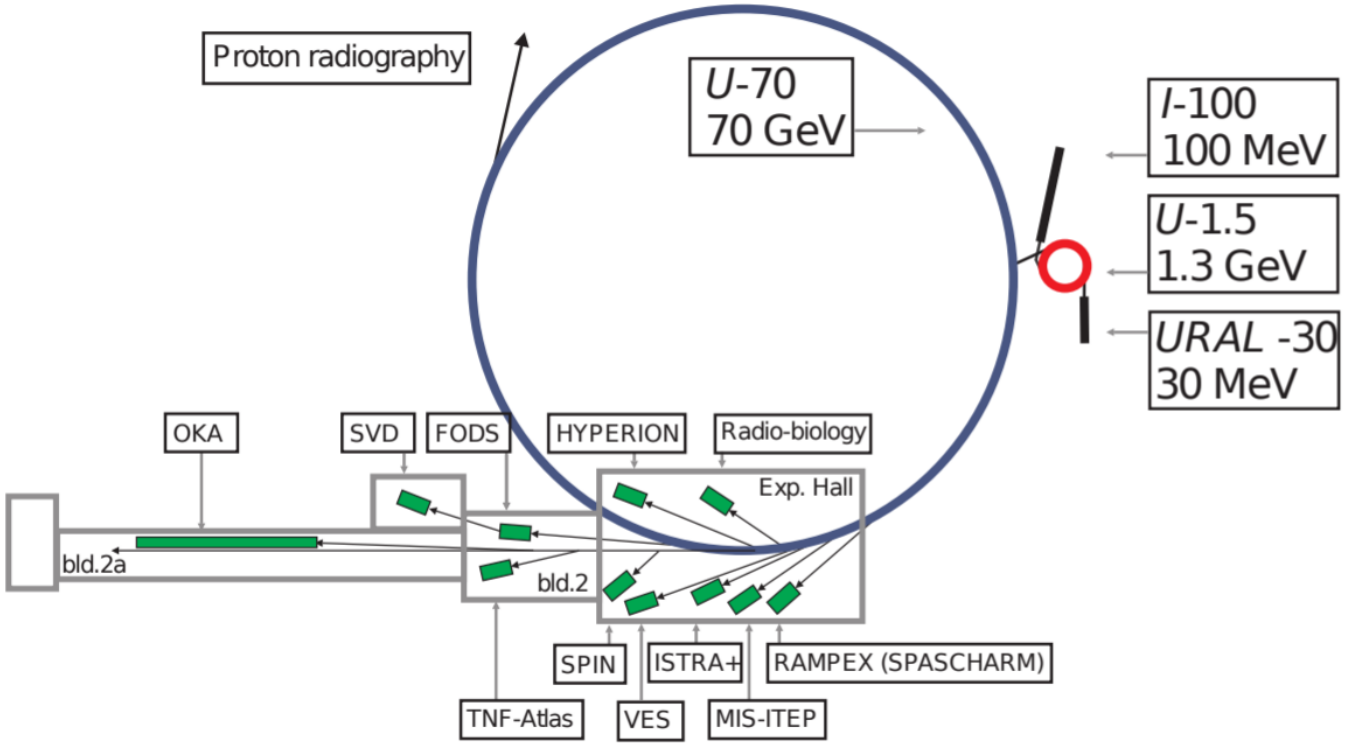


- **beam power**: 450 kW
- **beam time**: 5 y in ν + 5 y in $\bar{\nu}$ mode





Protvino accelerator



- beam power up to 450 kW
- ν and $\bar{\nu}$ mode possible as in T2K
- **P2O LoI:** Eur. Phys. J. C (2019) 79: 758 (arXiv:1902.06083)

P2O near detector

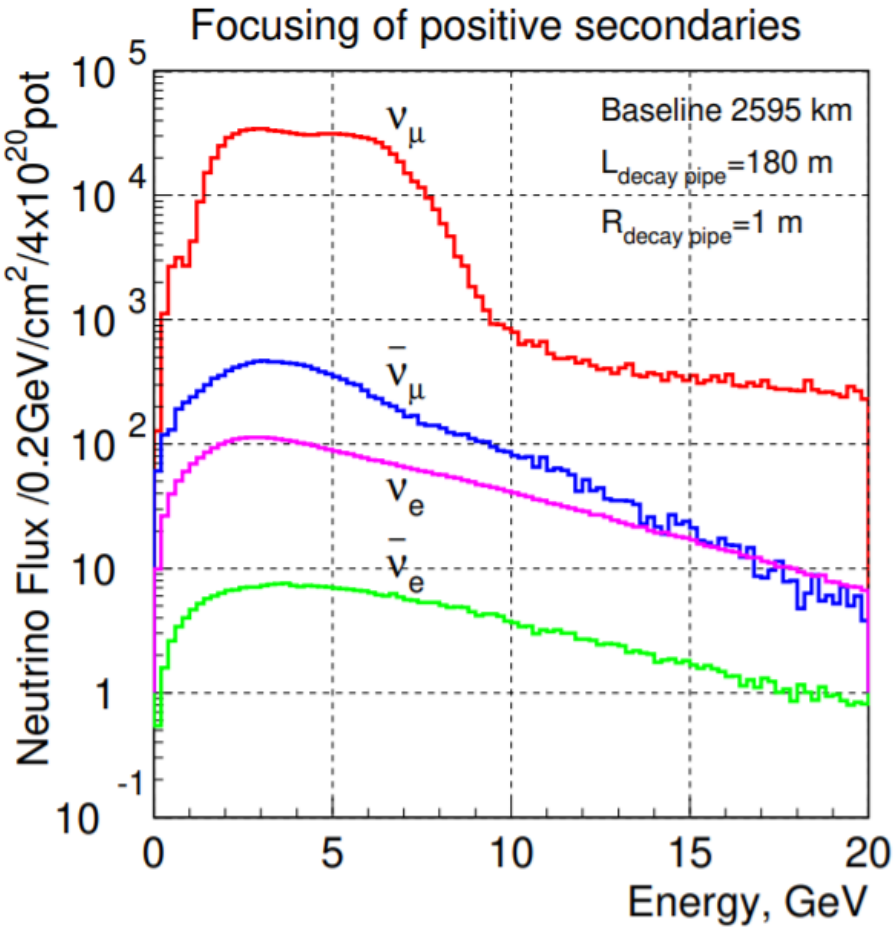
Considered detector designs:

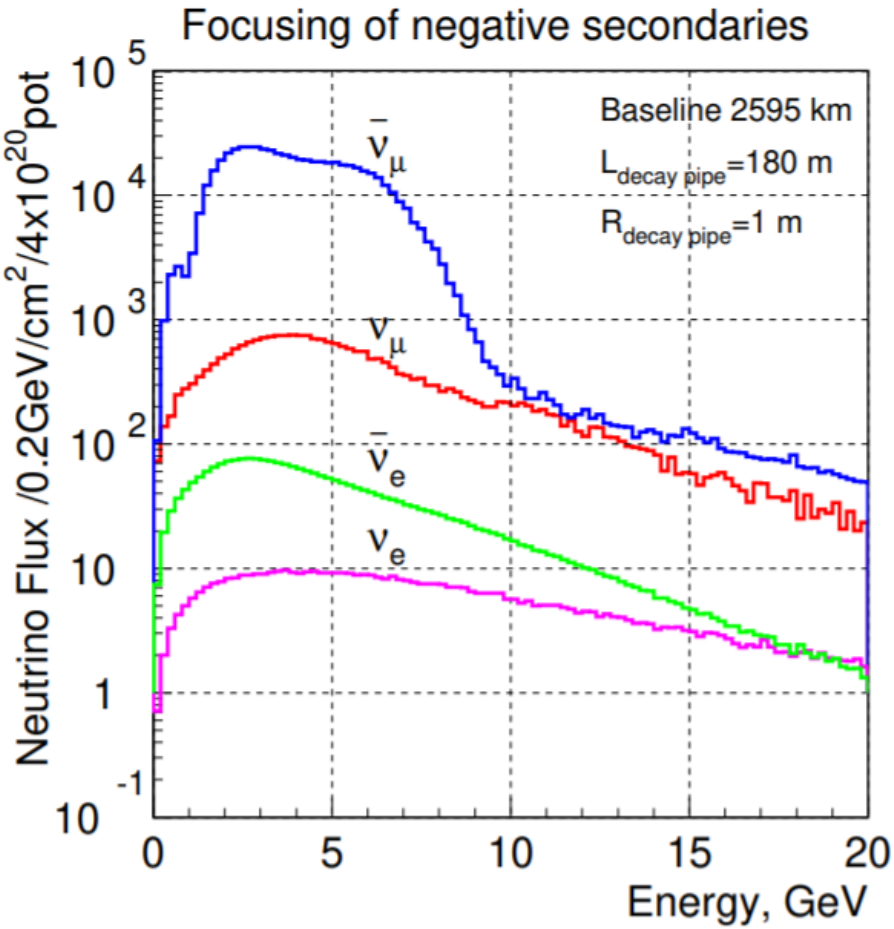
- high-granularity detector with water in a one or more of its parts, inspired by T2K and NOνA
- water tank with PMTs (possibly KM3NeT PMTs), inspired by T2HK
- multiple detectors with different techniques

Considered media:

- water
- water-based liquid scintillator
- heavy water
  - only in a part of the detector
  - for nuclear effect studies
  - for cross-section measurements on free p and n

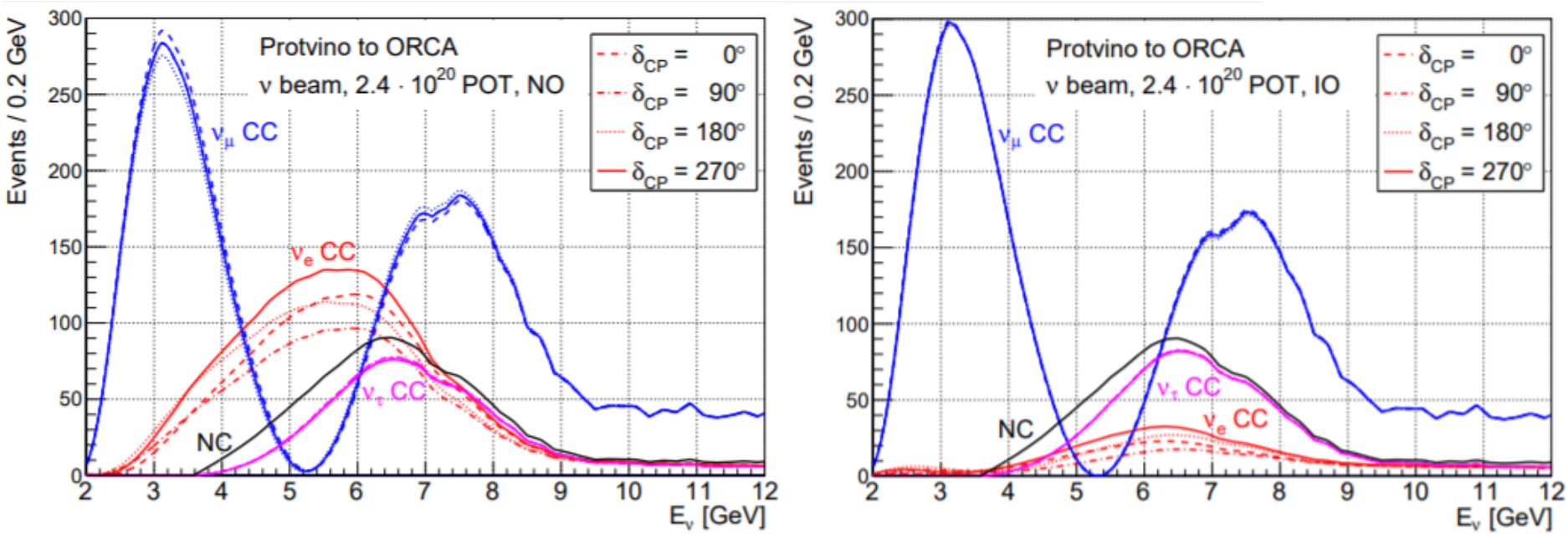
Protvino E_ν spectra for ν and $\bar{\nu}$ mode





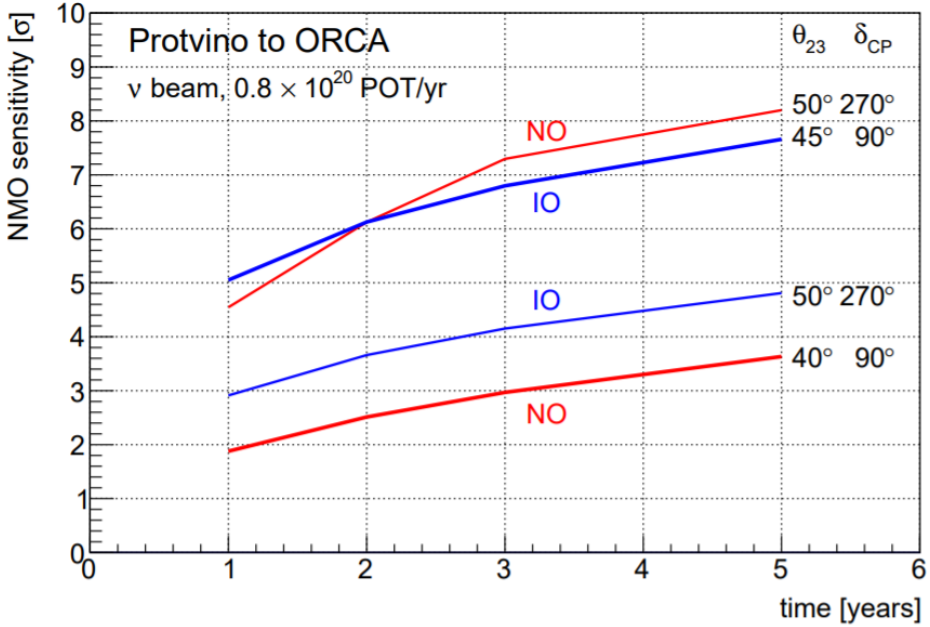
Absolute normalisation corresponds to 1 y with 450 kW beam or 5 y with 90 kW beam

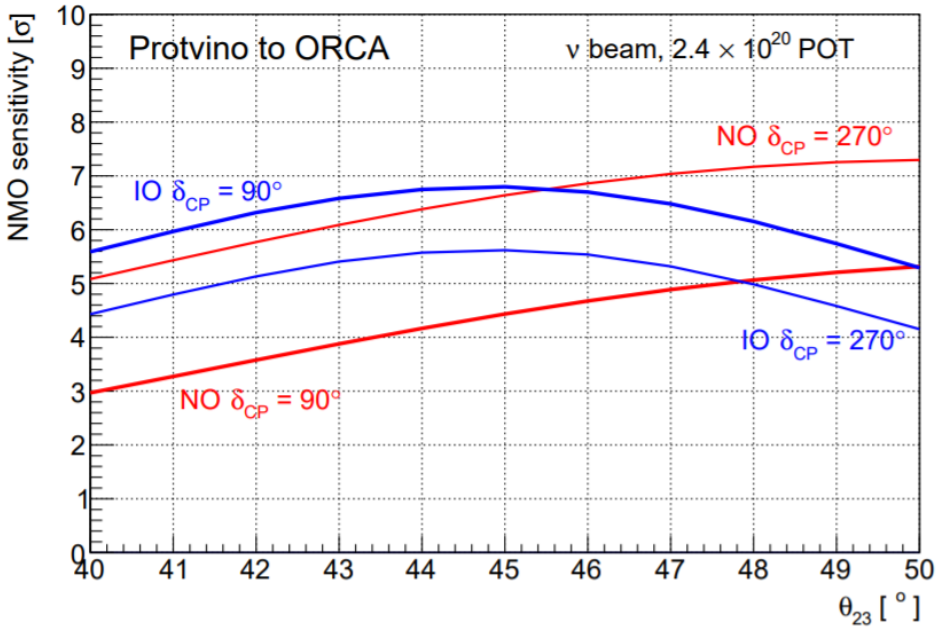
P2O spectra for NO and IO



Plots for 3 y with the 90 kW beam

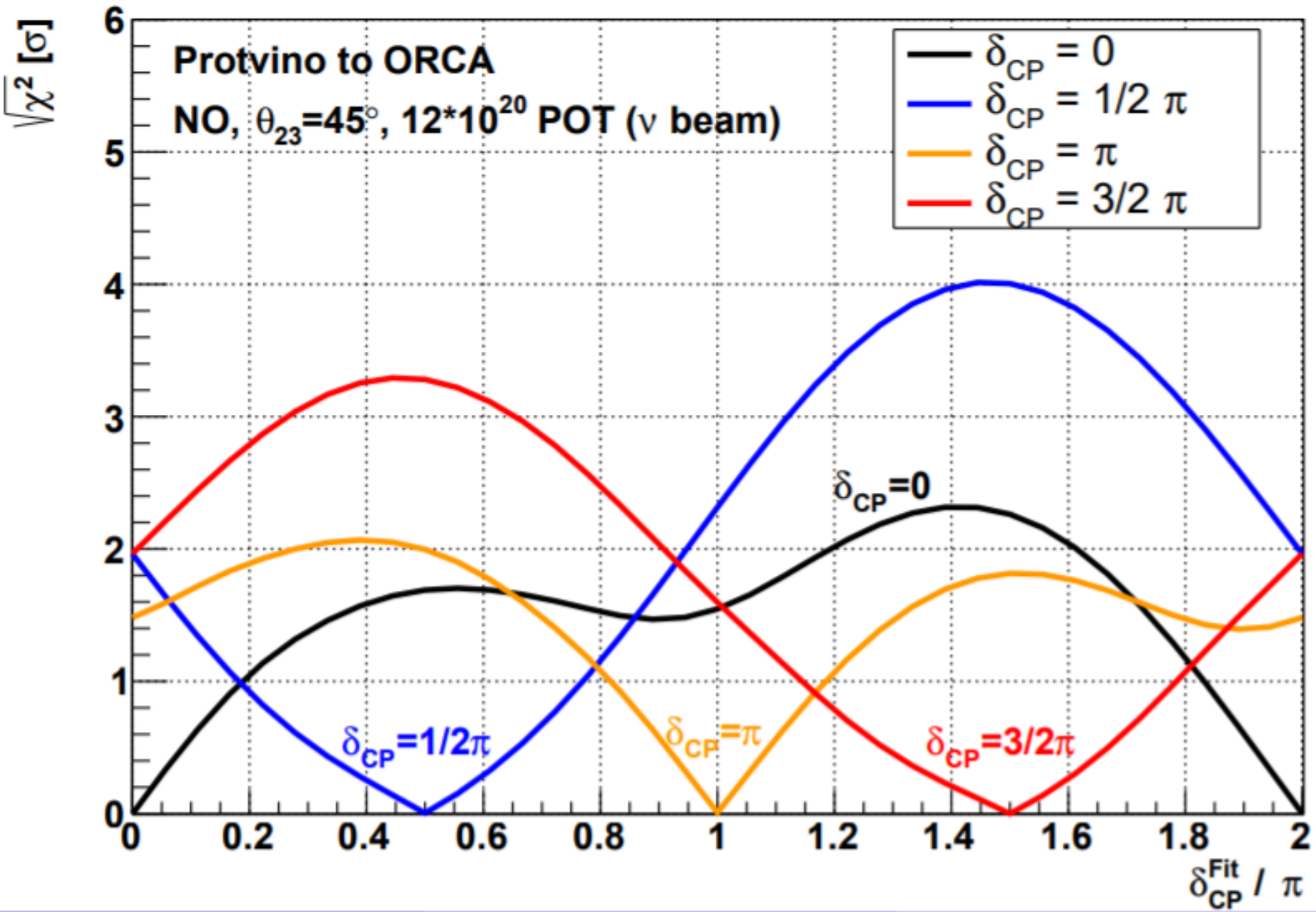
P2O sensitivity to the NMO





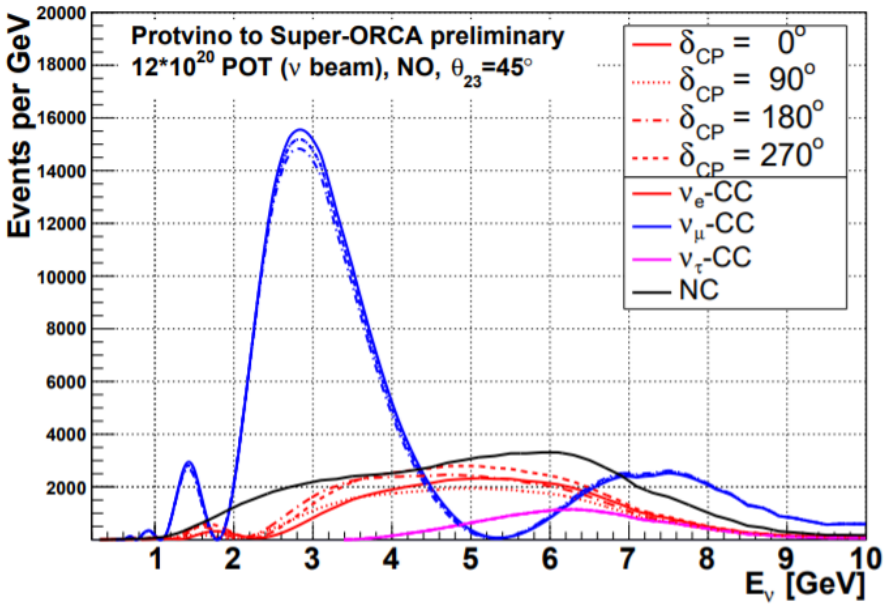
Plots for the 90 kW beam

P2O sensitivity to δ_{CP}

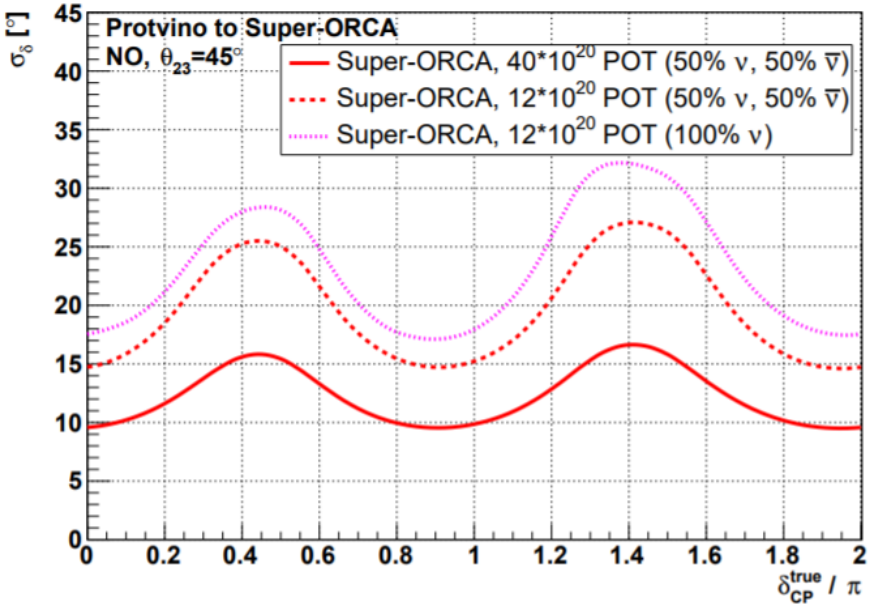


P2(S-)O expected performance

E distribution at Super-ORCA

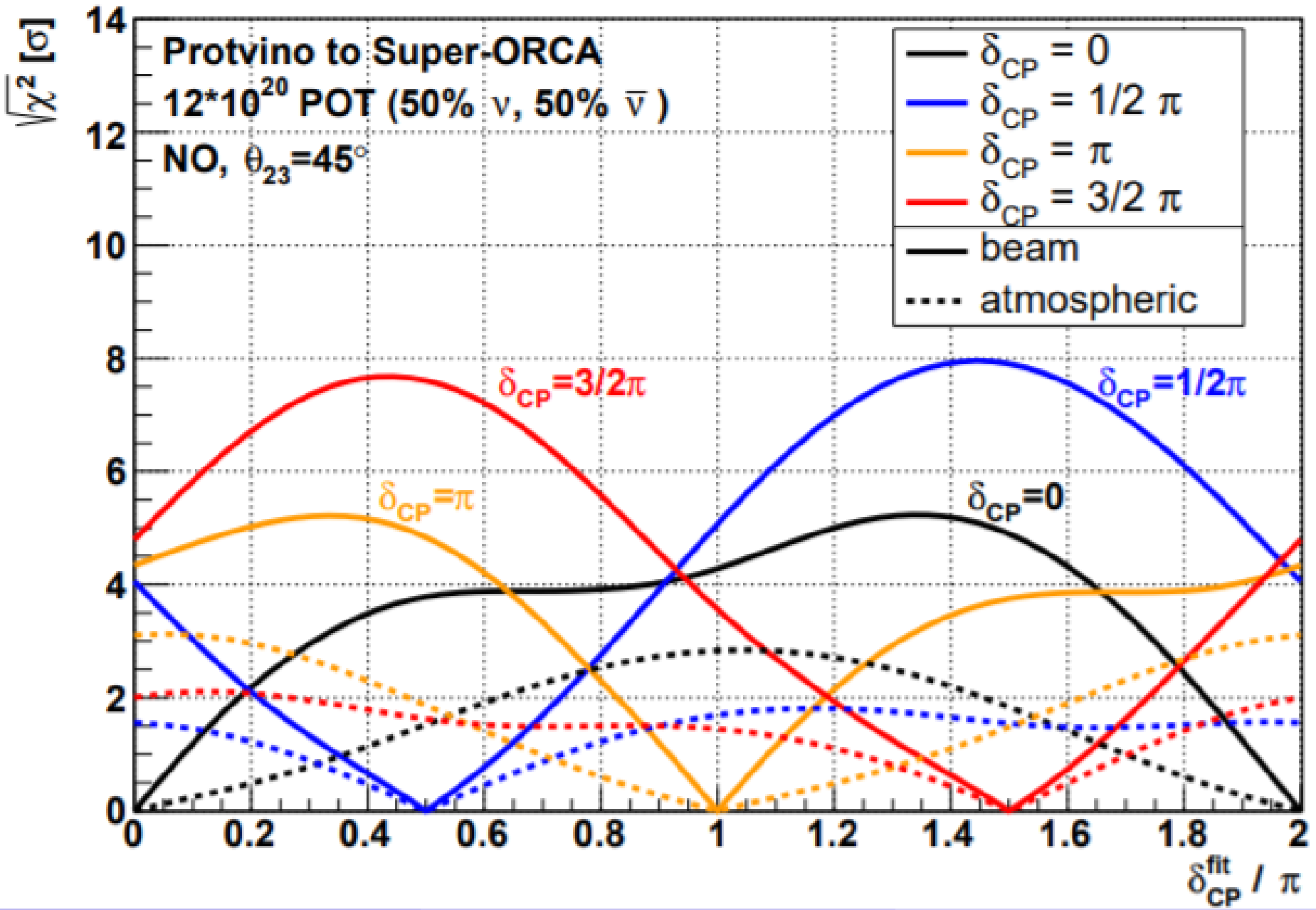


1σ-resolution on δ_{CP}



Plots for 3 y with the 450 kW beam

P2(S-)O sensitivity to δ_{CP}



P2O sensitivity to δ_{CP}: ORCA vs Super-ORCA