ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

KM3NeT/Super-ORCA: Measuring the leptonic CP-phase with atmospheric neutrinos - a feasibility study

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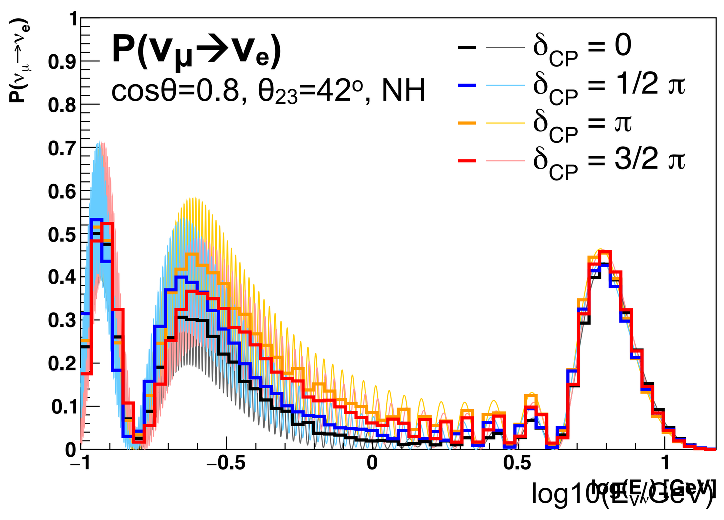
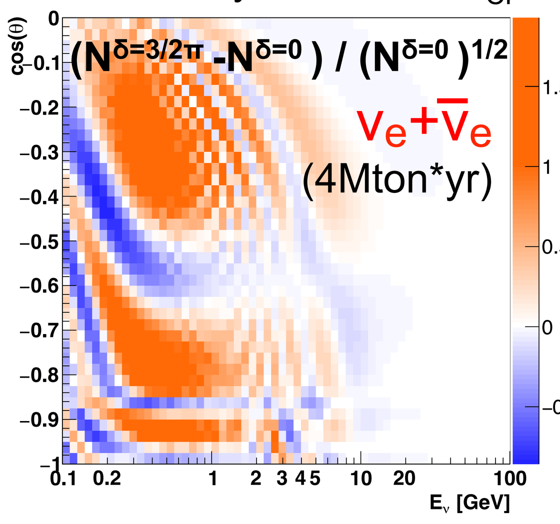
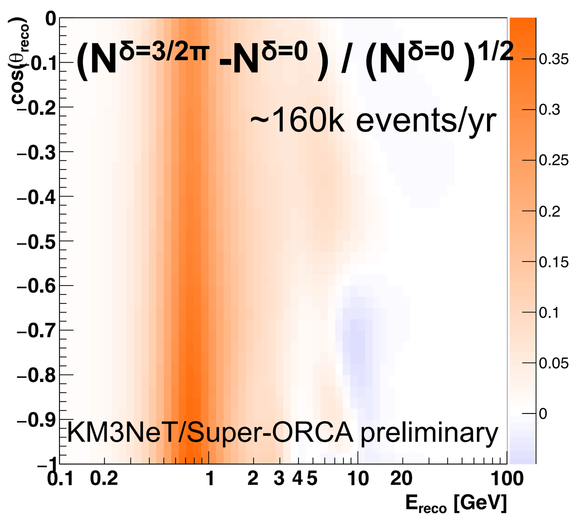
Measurement principle

All neutrino oscillation parameters of the 3ν framework are by now experimentally measured to a fair precision, expect for the neutrino mass hierarchy (NMH) and the Dirac CP-phase δ_{CP}. The latter is associated to a possible violation of the charge-parity (CP) symmetry in neutrino flavour mixing. Recent analyses of global data favour normal hierarchy (NH) over inverted hierarchy (IH) and $\delta_{CP} \approx 3/2\pi$, i.e. maximal CP violation [1].
Studying the oscillation pattern of atmospheric neutrinos below ~3GeV with a future multi-megaton Cherenkov detector may allow for a δ_{CP} measurement [2].

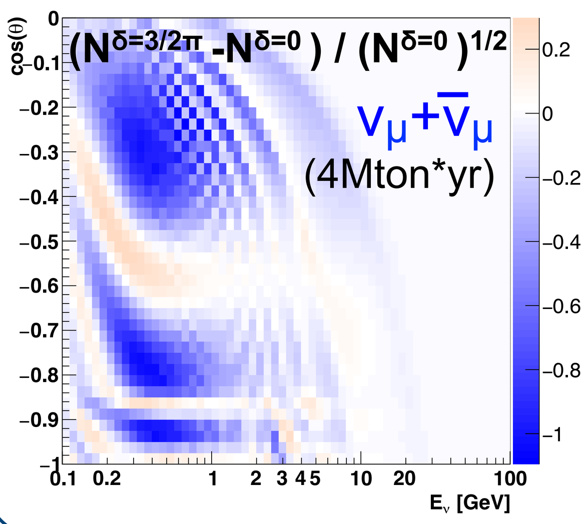




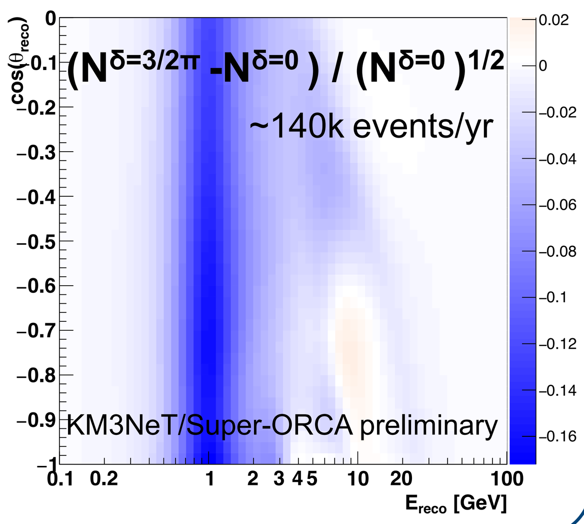
Distinctive pattern in neutrino energy E_ν and zenith angle θ_ν shows distinguishability.
δ_{CP}-effect remains after detector smearing.



detector response



Main challenges:
- δ_{CP} effect intrinsically small
- ν_e/ν_μ separation essential
- event-by-event fluctuations in neutrino interactions limiting E_ν and θ_ν resolution [3]



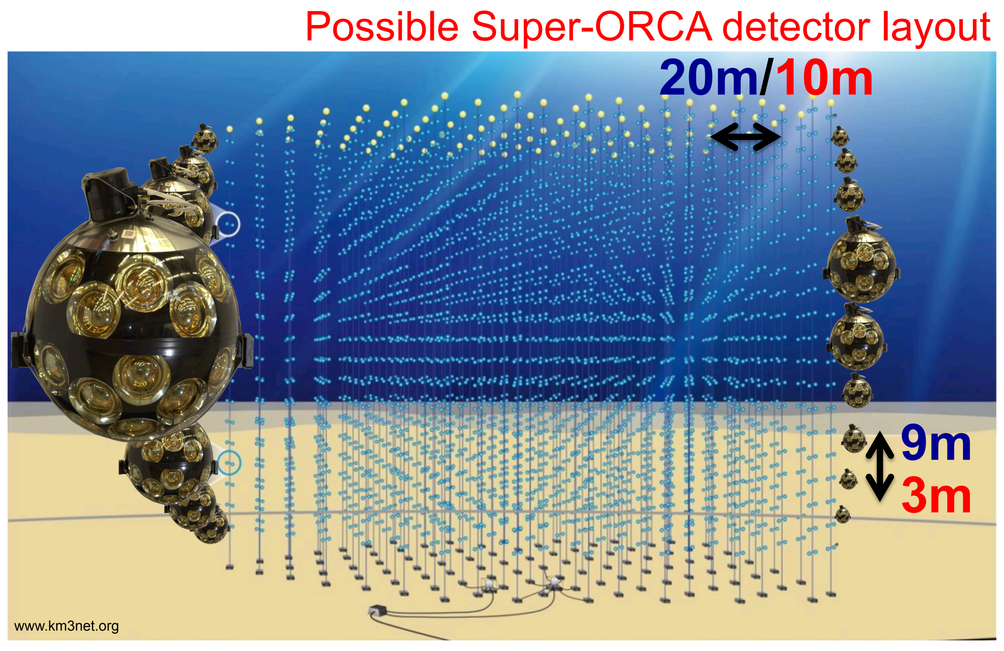
[1] arXiv:1804.09678
[2] JHEP 1505, 139 (2015)
[3] JHEP 05, 008 (2017)

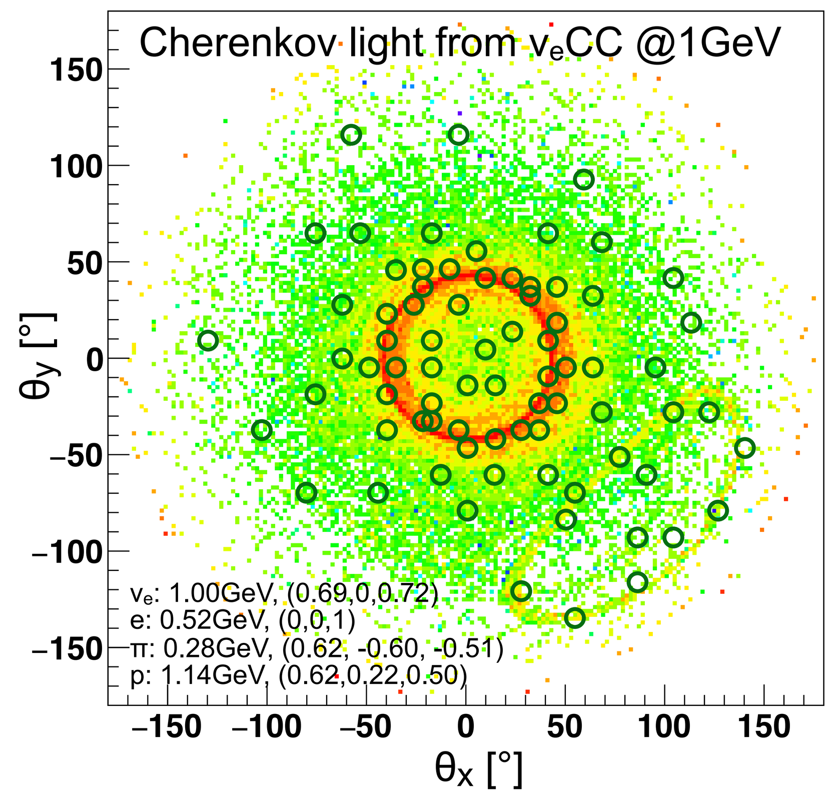
Detector

❖ **ORCA** [4]:
Underwater Cherenkov detector optimised for NMH determination:
- detection threshold: $E_\nu \approx 3$GeV
- instrumented mass: ~8Mton

Super-ORCA:
~10x more densely instrumented version of ORCA with lower detection threshold and improved event reconstruction capabilities

Possible Super-ORCA detector layout





Simplifications for detector response of Super-ORCA

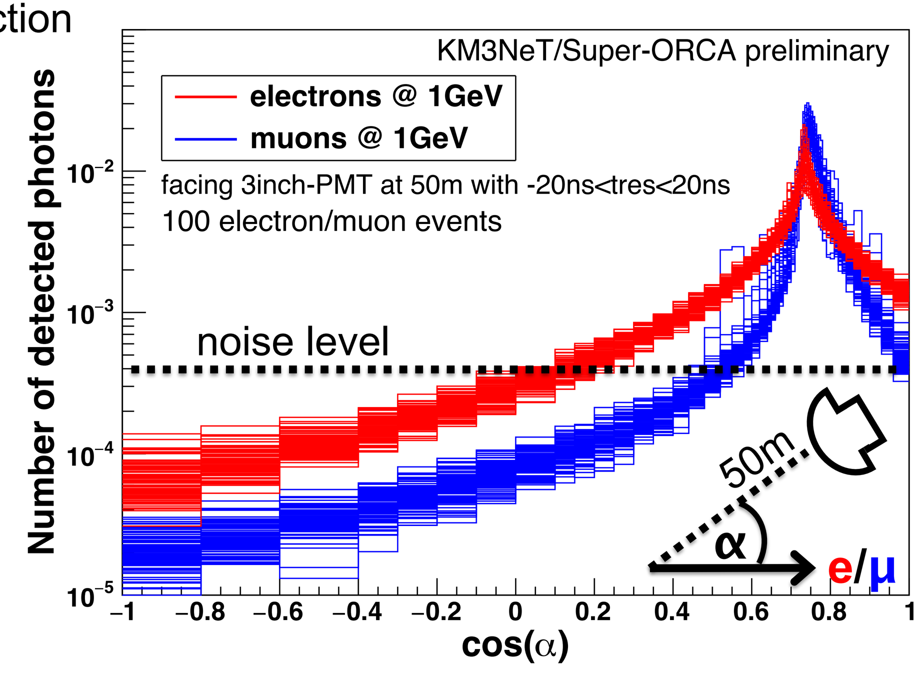
❖ Homogeneous instrumentation of infinitely small PMTs with isotropic orientations, i.e. no 'clumpiness' of PMTs
❖ Fully contained events, i.e. no edge effects
❖ Up-to-date model of optical water properties and background in deep sea
➔ Detector response estimate depends only on instrumentation density
➔ Here assumed: 115k 3'' PMT/Mton
For comparison: ~1% density of Super-K
➔ ~100 detected photons (o) per GeV

[4] J. Phys. G43, 084001 (2016)

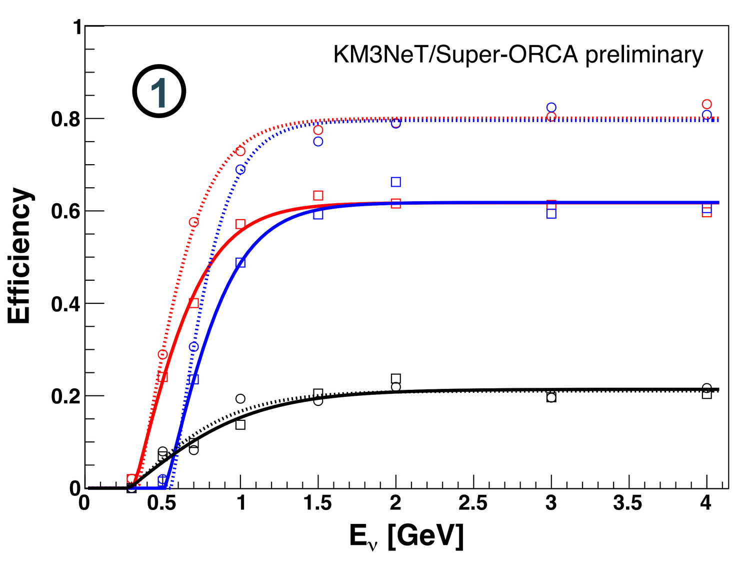
Event reconstruction performance

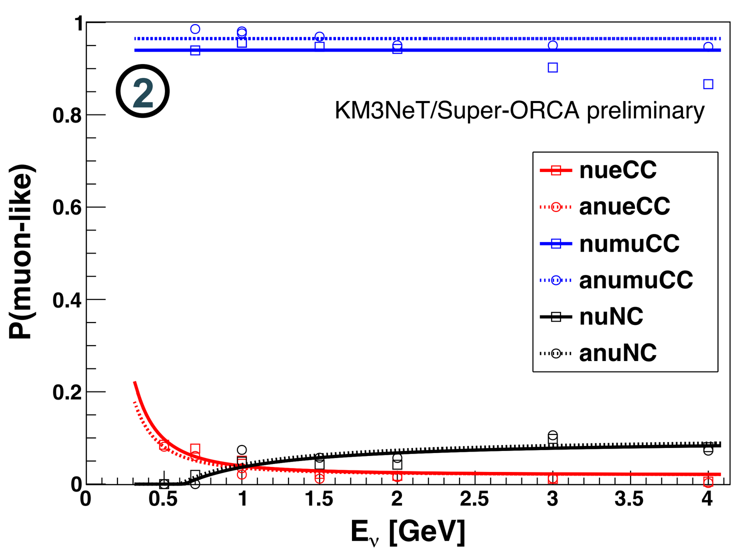
How does ν_e/ν_μ identification @ ~1GeV work?
❖ Mostly quasi-elastic charged current events with pure **e/μ** signatures and little hadronic activity
→ **e/μ** identification via angular profile of Cherenkov cone
→ prerequisite: precise **e/μ** direction reconstruction

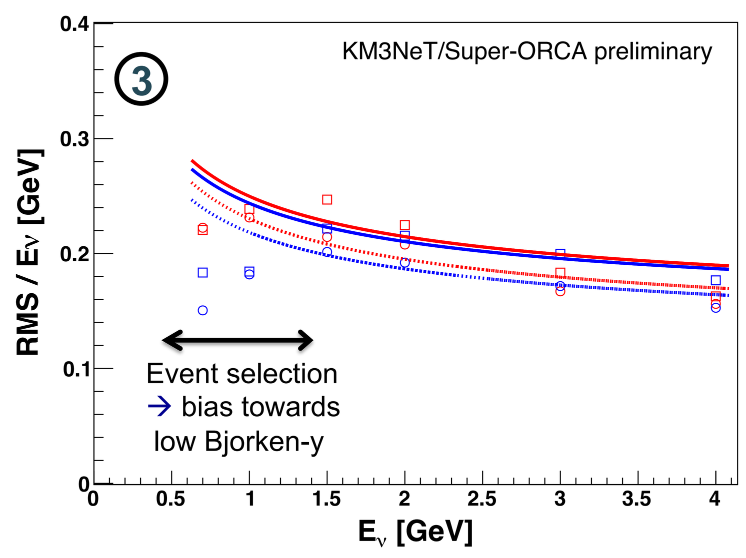
❖ Large photon scattering length in seawater
→ angular profile of emitted light well conserved over large distances
→ large lever arm for direction reconstruction
→ Cherenkov light signal above noise for distances up to more than 100m

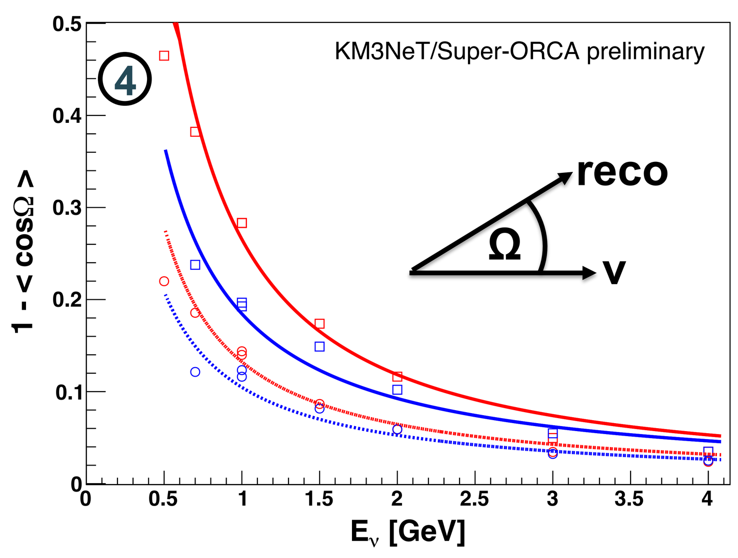


Reconstruction strategy:
❖ Full likelihood reconstruction assuming: **e/μ** + isotropic light from hadronic shower
❖ Simple event selection based on reconstruction output → high-purity ν_e/ν_μ samples
❖ Main separation power: likelihood of **e** and **μ** hypothesis









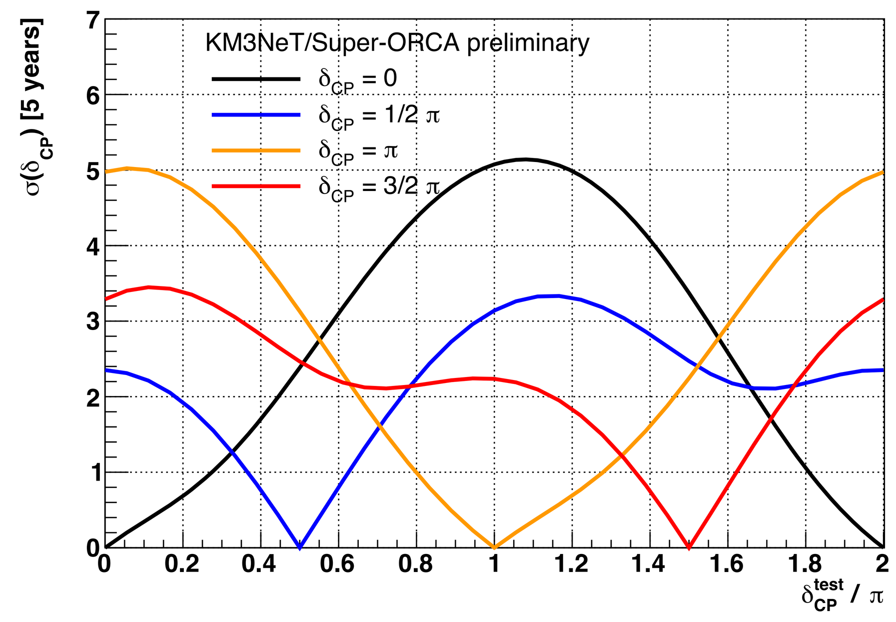
① Event selection efficiency: ~0.8/0.6/0.2 for $\bar{\nu}$CC/νCC/NC events
② Event classification purity : ~95%
③ Neutrino energy resolution: ~20% (dominated by intrinsic light yield fluctuations)
④ Neutrino direction resolution dominated by intrinsic ν-lepton scattering angle

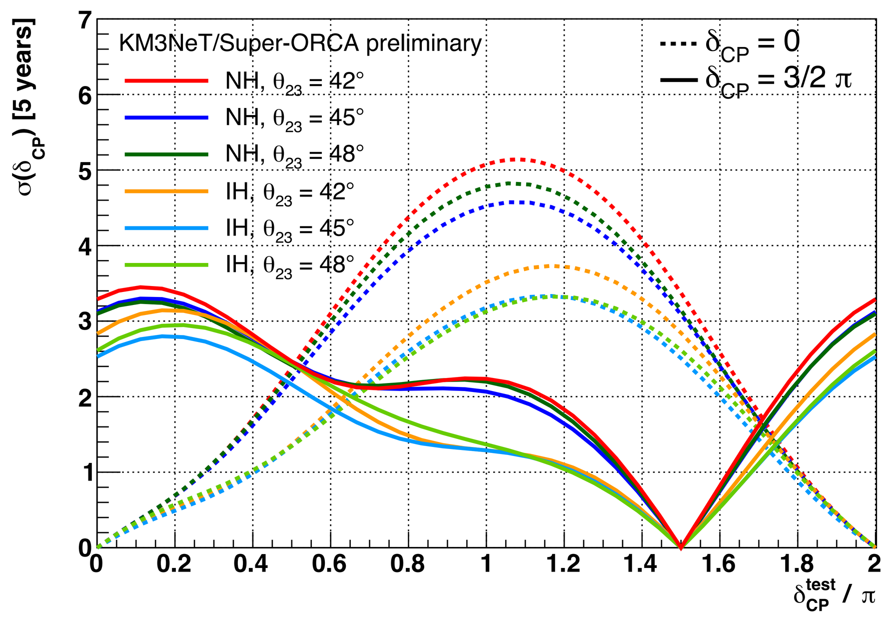
Sensitivity to δ_{CP}

❖ 'Asimov dataset' approach with χ^2 minimisation assuming a test δ_{CP}^{test} value and simultaneously fitting the parameters in table below
❖ $\Delta\chi^2$ gives sensitivity to reject δ_{CP}^{test}:

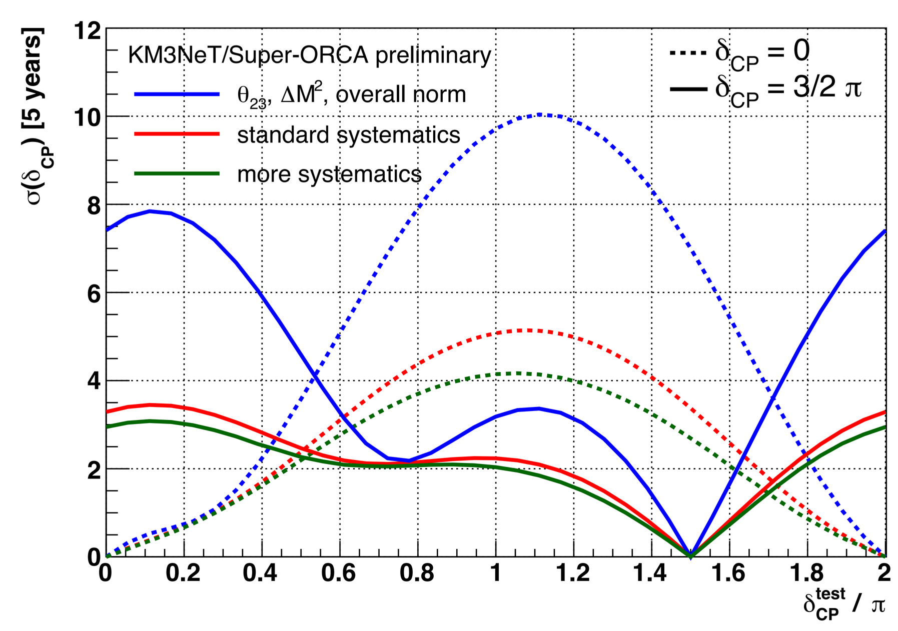
$$\Delta\chi^2 = \sum_i \frac{(\mu_i^{\delta=true} - \mu_i^{\delta=test})^2}{\mu_i^{\delta=true}}$$

N_i: expected number of events in i-th bin of reconstructed quantities (E_ν, θ_ν, e/μ)
❖ Results expressed in terms of standard deviations $\sigma=\sqrt{\Delta\chi^2}$ after 5 years of operation with 4 Mton fiducial volume





❖Maximal distinguishability between δ_{CP}=0 and δ_{CP}=π with 5σ
❖ 60% (70%) of δ_{CP} values disfavoured with ≥2σ for true δ_{CP}=0, π (δ_{CP}=π/2, 3/2π)
❖ 1σ uncertainty range: 25% (13%) of δ_{CP} values for δ_{CP}=0, π (δ_{CP}=π/2, 3/2π)
❖ Weak dependence on θ_{23}
❖IH needs larger exposure than NH for comparable significance
❖Most relevant systematics: $\bar{\nu}/\nu$, e/μ and NC/CC skews



parameter	*true* [5]	*prior*
θ_{23} [°]	42	-
θ_{13} [°]	8.8	fixed
θ_{12} [°]	33.7	fixed
ΔM^2 [10^{-3} eV^2]	2.43	-
Δm^2 [10^{-5} eV^2]	7.54	fixed
mass ordering	NO	fixed
overall norm	1	-
CC/NC skew	1	-
$\bar{\nu}/\nu$ skew	0	-
μ/e skew	0	-
spectral index tilt	0	-
up/hor skew $\propto \cos\theta$	0	-
up/hor skew $\propto \cos^2\theta$	0	-
energy scale overall	1	0.03
Escale $\nu/\bar{\nu}$ skew	0	0.03
Escale $\overset{(-)}{\nu}_e/\overset{(-)}{\nu}_\mu$ skew	0	0.03
Escale $\overset{(-)}{\nu}_{e,\mu}/\overset{(-)}{\nu}_\tau$ skew	0	0.05
Escale CC/NC skew	0	0.05
Escale up/hor skew	0	0.03

[5] Phys. Rev. D89, 093018

CAVEATS: Sensitivities on this poster are based on idealised & simplified detector response estimates and do NOT make use of the full KM3NeT detector simulation chain.
Uncertainties from neutrino interactions (cross sections & kinematics) are NOT fully included.

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