IMPERIAL

Neutrino Oscillation Physics

Mass Splittings, Mixing & CP violation

ESPPU Open Symposium | Venice | 23 June 2025

Mark Scott on behalf of the Neutrinos and Cosmic Messengers WG

23/06/2025

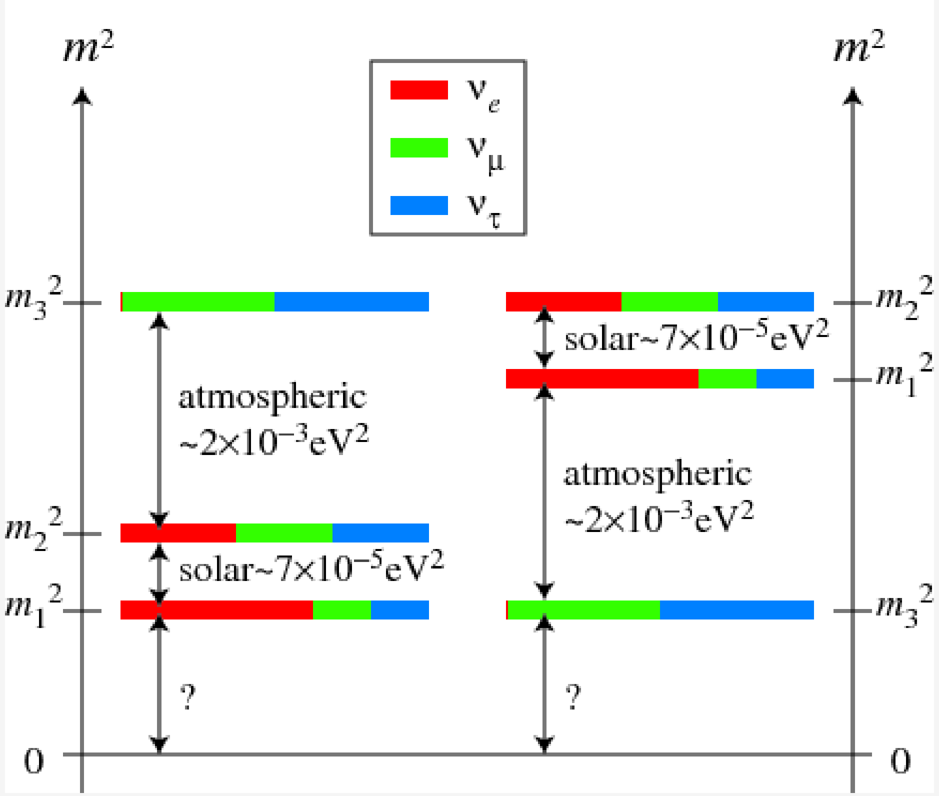
Neutrino Oscillation

Mass splittings and mixing

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- Mixing between neutrino mass and flavour eigenstates described by PMNS matrix
  - Large off-diagonal elements
  - Three mixing angles and one phase

- Three mass eigenstates gives two mass splittings
  - Mass ordering is unknown



Neutrino Oscillation
Mass splittings and mixing

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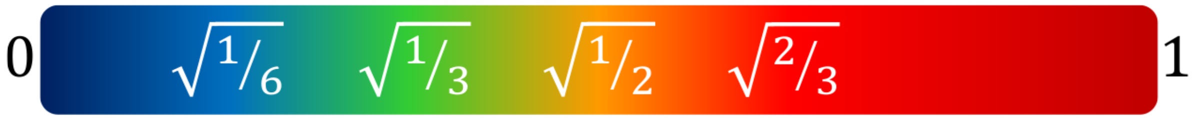

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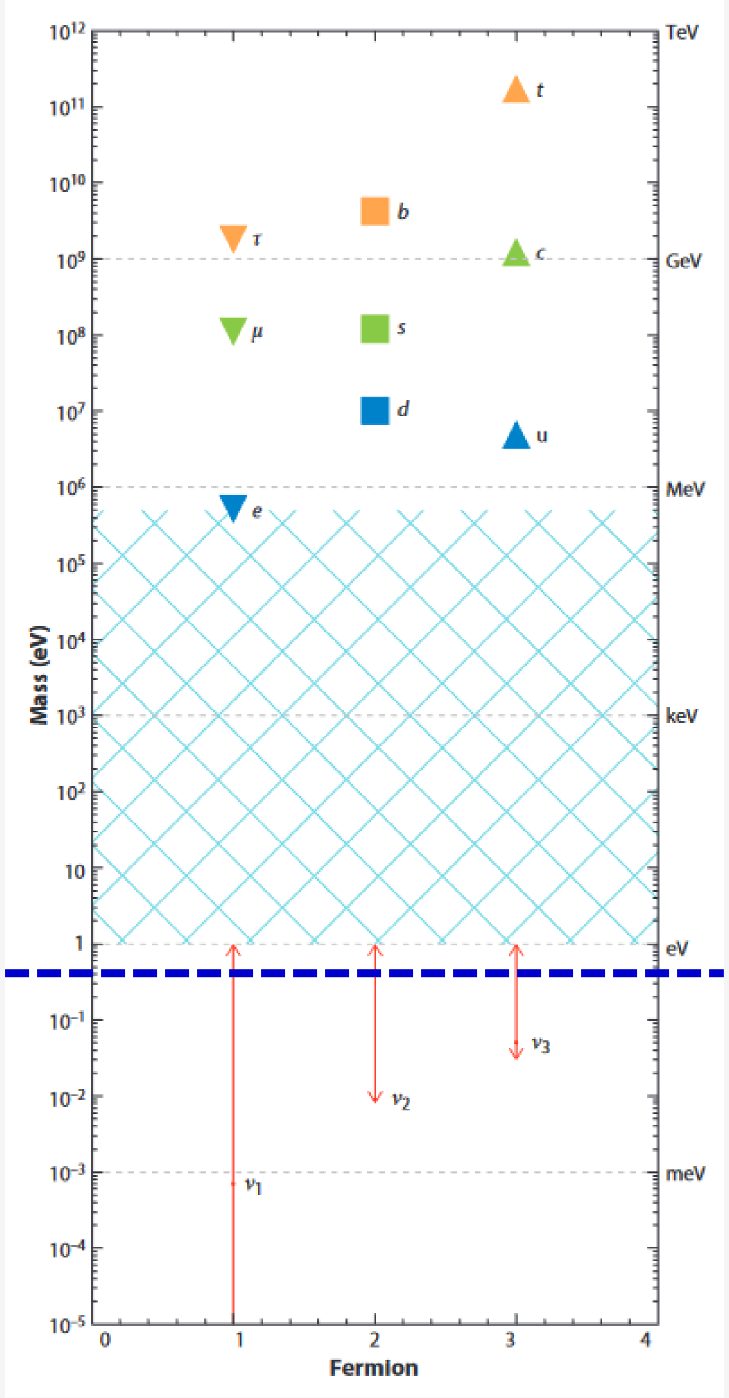

[A. Gouvea, Annu. Rev. Nucl. Part. Sci. 2016.66: 197-217]

Newer limits from multiple experiments

Neutrino Oscillation
Current knowledge

[NuFit 6.0, JHEP 12 (2024) 216]

- Impressive progress in measuring oscillation parameters

		Normal Ordering (best fit)	
		bfp $\pm 1\sigma$	3σ range
IC24 with SK atmospheric data	$\sin^2\theta_{12}$	$0.308^{+0.012}_{-0.011}$	$0.275 \to 0.345$
	$\theta_{12}/^\circ$	$33.68^{+0.73}_{-0.70}$	$31.63 \to 35.95$
	$\sin^2\theta_{23}$	$0.470^{+0.017}_{-0.013}$	$0.435 \to 0.585$
	$\theta_{23}/^\circ$	$43.3^{+1.0}_{-0.8}$	$41.3 \to 49.9$
	$\sin^2\theta_{13}$	$0.02215^{+0.00056}_{-0.00058}$	$0.02030 \to 0.02388$
	$\theta_{13}/^\circ$	$8.56^{+0.11}_{-0.11}$	$8.19 \to 8.89$
	$\delta_{CP}/^\circ$	212^{+26}_{-41}	$124 \to 364$
	$\dfrac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.49^{+0.19}_{-0.19}$	$6.92 \to 8.05$
	$\dfrac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.513^{+0.021}_{-0.019}$	$+2.451 \to +2.578$

See also F. Capozzi et al., Phys. Rev. D 104, 8, 083031
P. F. de Salas et al., JHEP 02, 071 (2021)

Neutrino Oscillation
Current knowledge

NuFit 6.0, JHEP 12 (2024) 216

- Impressive progress in measuring oscillation parameters
- Most parameters measured with few percent precision (note, have taken 1/6 of 3σ range as error for dCP and theta23)
- Open questions:
  - Octant of θ_{23}
  - Mass ordering
  - CP violation?
  - Value of δ_{CP}
  - Unitarity of PMNS
  - Other new physics?

IC24 with SK atmospheric data

	Normal Ordering (best fit)		
	bfp $\pm 1\sigma$		3σ range
$\sin^2\theta_{12}$	$0.308^{+0.012}_{-0.011}$	3.7%	$75 \to 0.345$
$\theta_{12}/^\circ$	$33.68^{+0.73}_{-0.70}$	2.1%	$63 \to 35.95$
$\sin^2\theta_{23}$	$0.470^{+0.017}_{-0.013}$	5.0%	$35 \to 0.585$
$\theta_{23}/^\circ$	$43.3^{+1.0}_{-0.8}$	3.1%	$.3 \to 49.9$
$\sin^2\theta_{13}$	$0.02215^{+0.00056}_{-0.00058}$	2.3%	$30 \to 0.02388$
$\theta_{13}/^\circ$	$8.56^{+0.11}_{-0.11}$	1.3%	$19 \to 8.89$
$\delta_{CP}/^\circ$	212^{+26}_{-41}	16.4%	$24 \to 364$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.49^{+0.19}_{-0.19}$	2.5%	$92 \to 8.05$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.513^{+0.021}_{-0.019}$	0.8%	$51 \to +2.578$

See also F. Capozzi et al., Phys. Rev. D 104, 8, 083031
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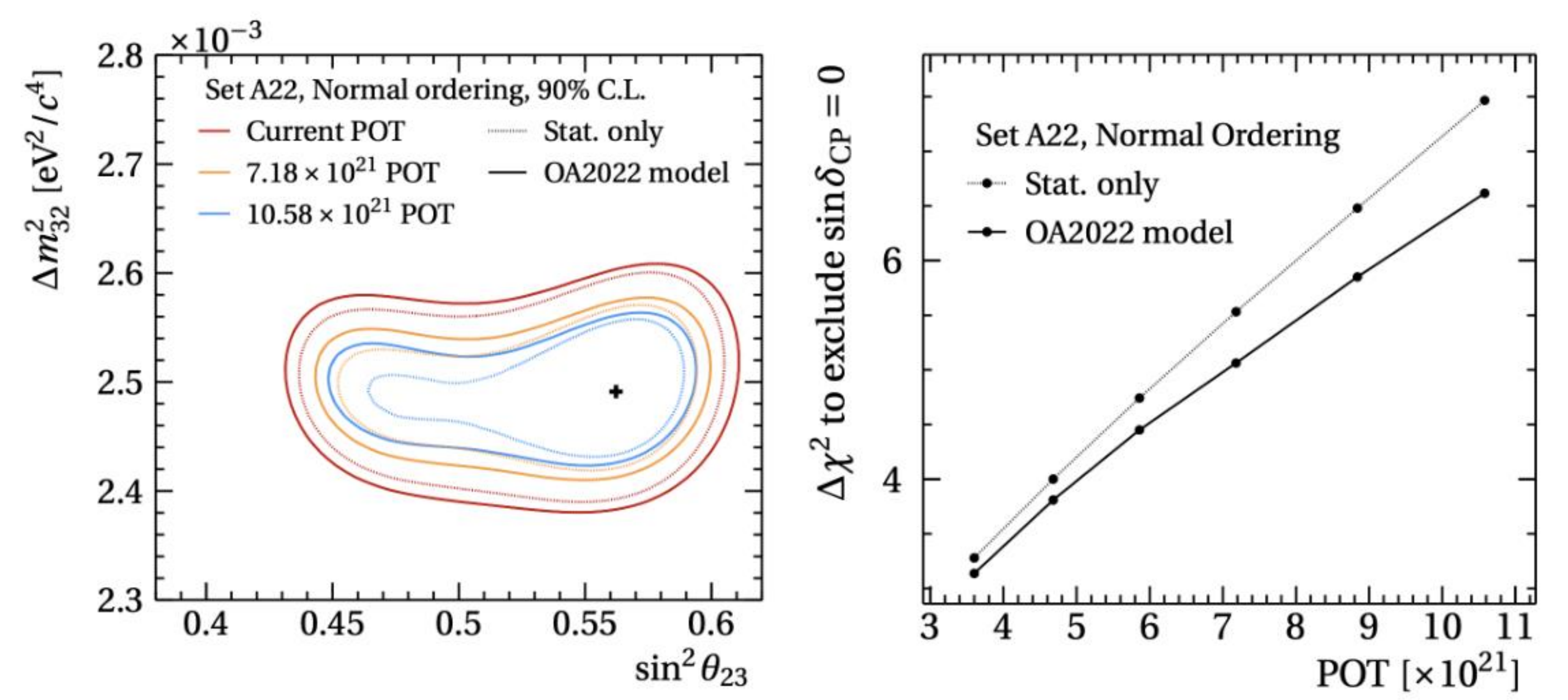
Long-baseline Oscillation

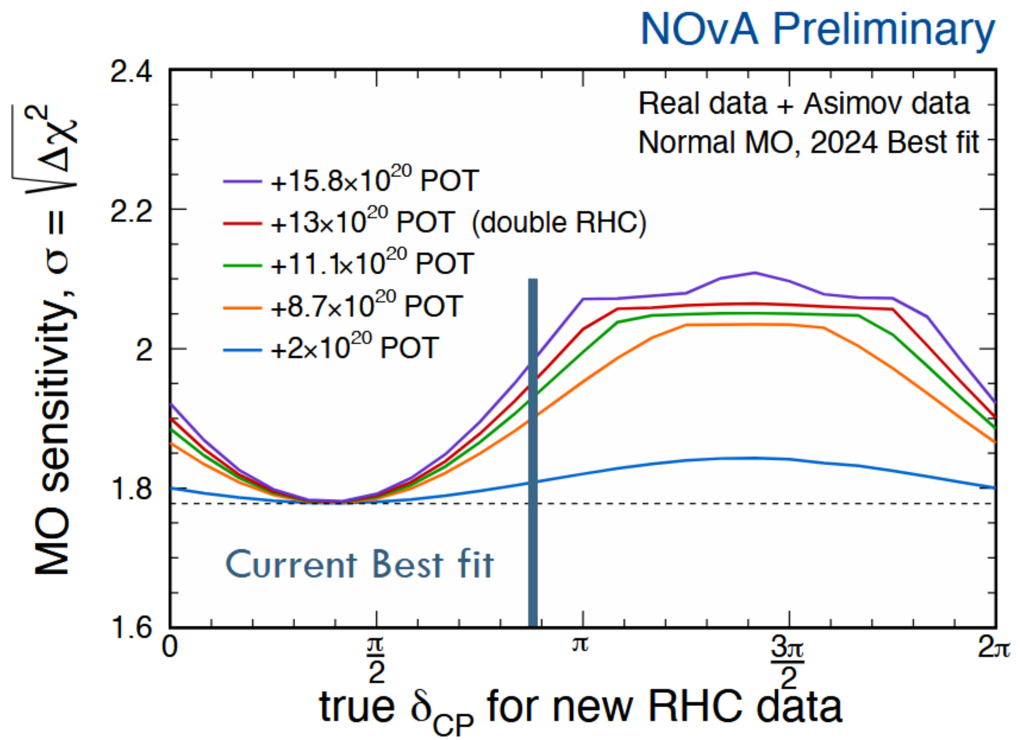
Current experiments



[#106 ESPPU]

- T2K and NOvA providing tightest constraint on Δm^2_{32} and $\sin^2\theta_{23}$
- Demonstrated sensitivity to MO and δ_{CP} at the $1-2\sigma$ level
- T2K sensitivity for increased exposure of 1×10^{22} POT, 99% median confidence limits on CPV ($\delta_{CP} = \frac{-\pi}{2}$)

Long-baseline Oscillation
Current experiments



P. Vahle, NOvA PAC '24

- T2K and NOvA providing tightest constraint on Δm^2_{32} and $\sin^2\theta_{23}$
- Demonstrated sensitivity to MO and δ_{CP} at the $1-2\sigma$ level
- T2K sensitivity for increased exposure of 1×10^{22} POT, 99% median confidence limits on CPV ($\delta_{CP}=\frac{-\pi}{2}$)
- NOvA (beam expected Fall 2026) sensitivity for increased anti-neutrino beam exposure, $\sim 2\sigma$ for MO

Neutrino Oscillation

Where are we going?

Long-baseline experiments

- Hyper-Kamiokande
- DUNE

- Factor 20-100 more events than T2K/NOvA, limited by systematics
- Mass ordering and CP violation discovery potential

Solar/Reactor experiments

- JUNO
- SNO+

- Unprecedented precision on $\sin^2\theta_{12}$ and mass splittings
- Mass ordering sensitivity

Atmospheric neutrino experiments

- KM3NeT-ORCA
- IceCube Upgrade

- Megaton scale detectors
- Sensitive to $\sin^2\theta_{23}$, Δm^2_{32} and mass ordering

Proposed experiments

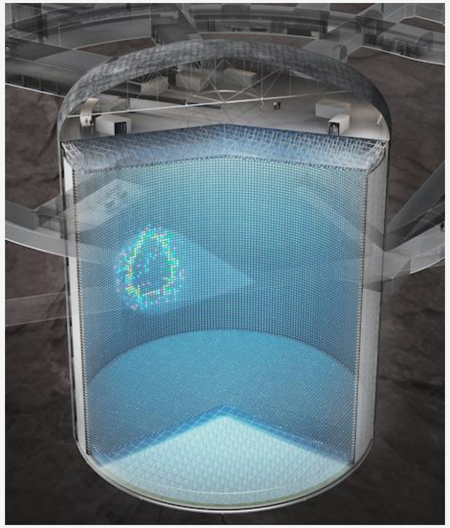
- ESSNuSB
- THEIA
- SuperCHOOZ

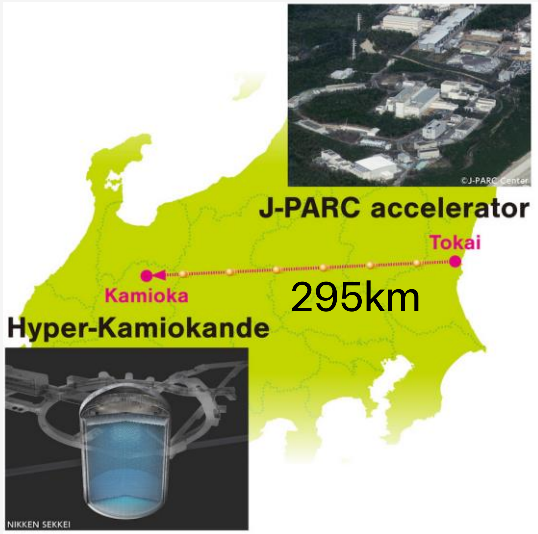
- Beam development and new technologies
- Long-baseline, solar and reactor sources
- Construction/operation would start after 2032

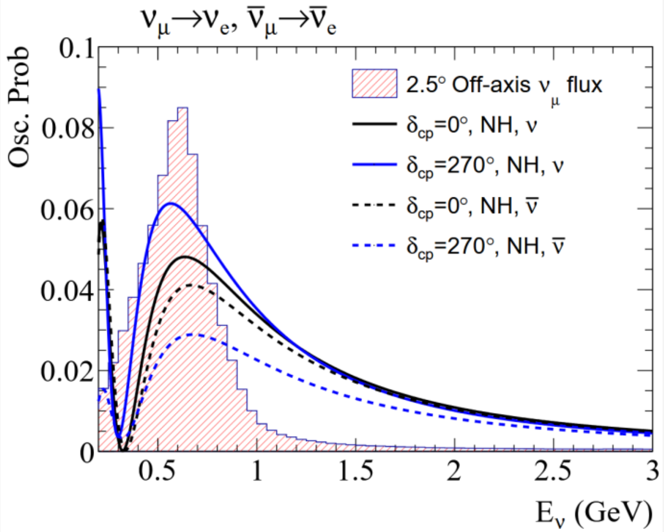
Neutrino Oscillation Experiments
Hyper-Kamiokande and DUNE

Hyper-Kamiokande

- 188 kt fiducial volume
- Water Cherenkov detector
- 295km baseline
- 0.6 GeV neutrino energy

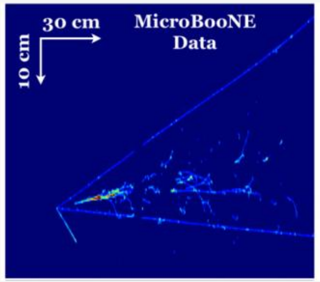


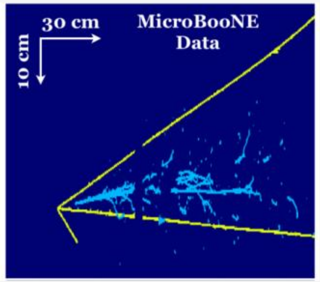


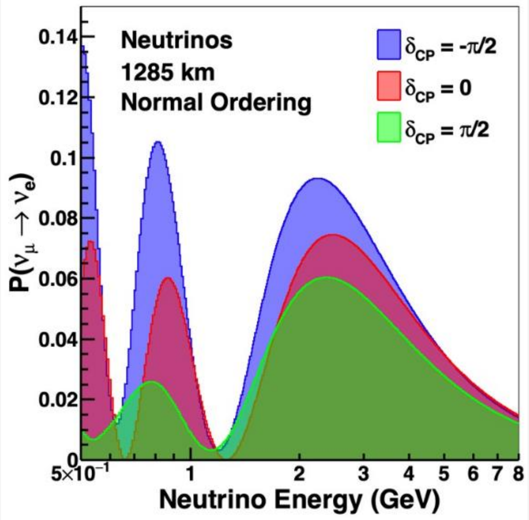


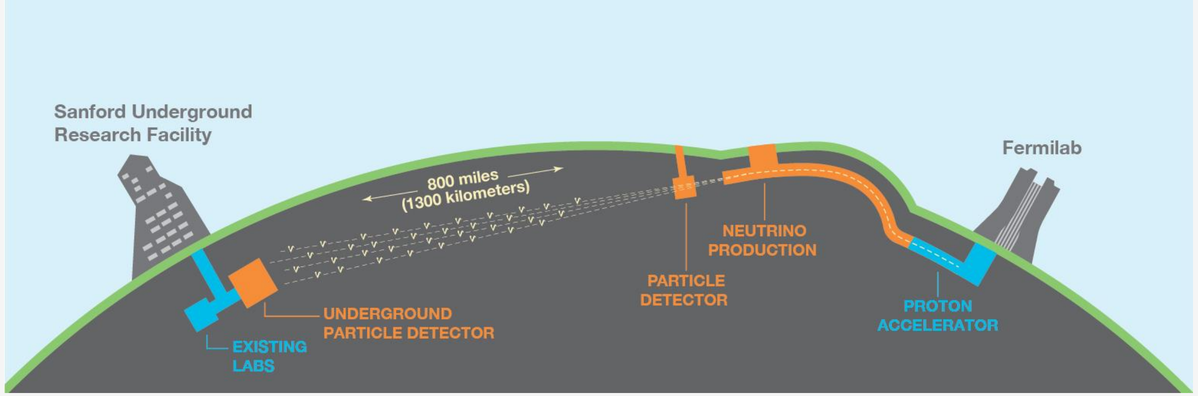
DUNE

- 20kt (Phase 1) + 20kt (Phase 2) fiducial volume
- Liquid Argon TPC
- 1300km baseline
- 2-3 GeV neutrino energy





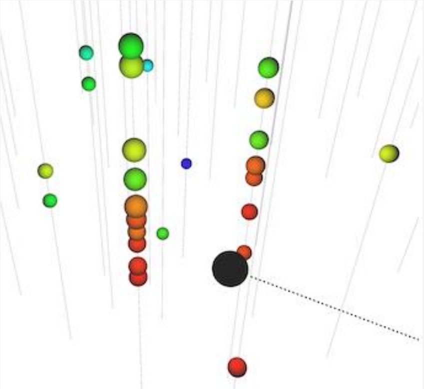


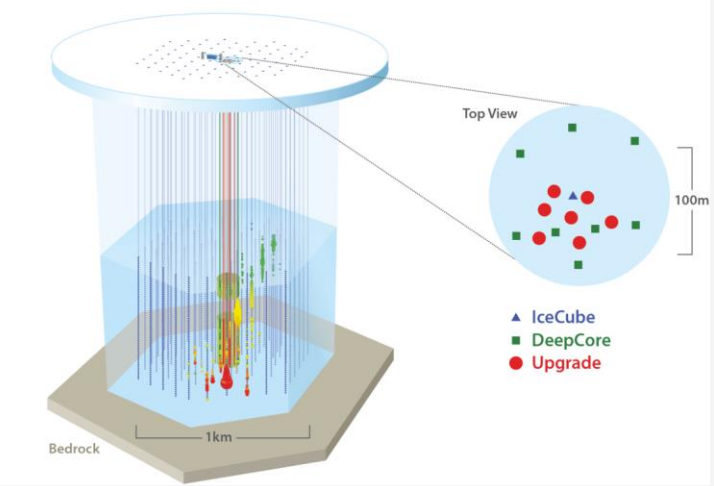


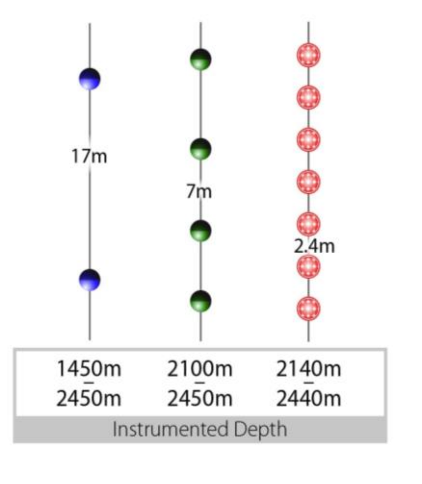
Neutrino Oscillation Experiments
IceCube and KM3NeT-ORCA

IceCube

- Mega-tonne scale Cherenkov detector at South Pole
- Atmospheric (and astrophysical) neutrinos
- Higher density DeepCore, with Upgrade being installed

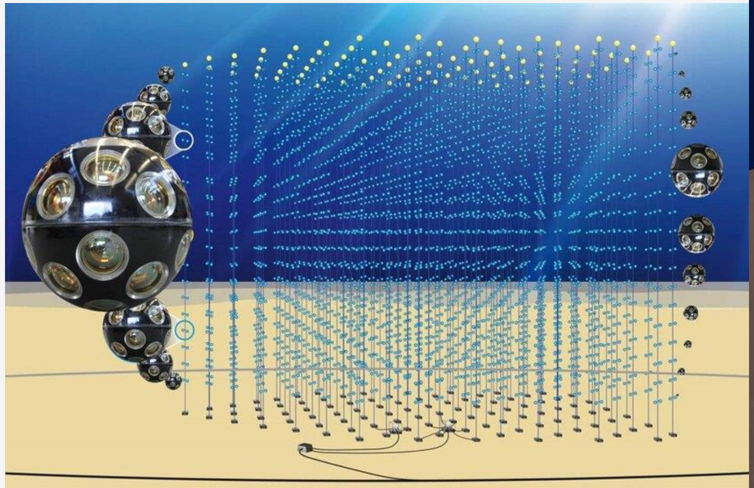


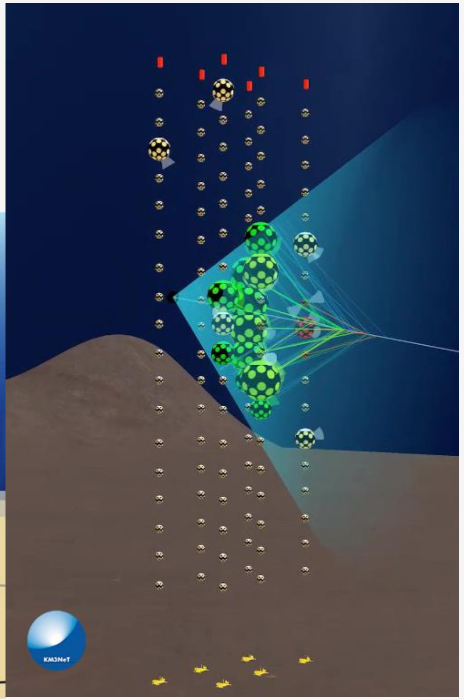




KM3NeT-ORCA

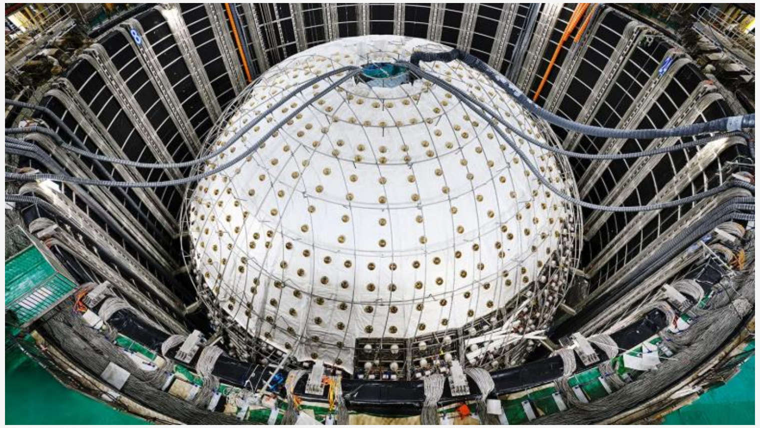
- Mega-tonne scale Cherenkov detector in Mediterranean Sea
- Atmospheric (and astrophysical) neutrinos
- 24 strings deployed

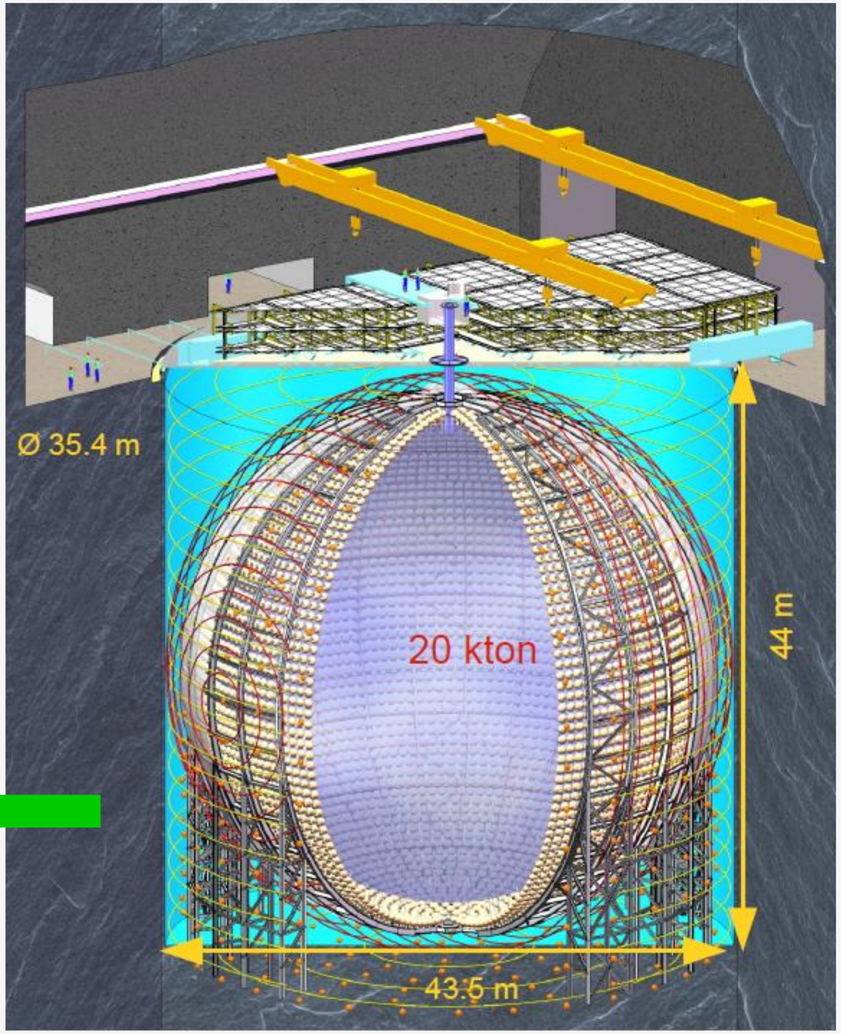




Neutrino Oscillation Experiments
JUNO

- 20 kt liquid scintillator detector
- 20” and 3” PMT systems
- Reactor anti-neutrinos, 50 km baseline
- Near detector, TAO, for precise reactor flux





Future experiment timeline

2025
- JUNO filling, first data soon

2026
- IceCube Upgrade completion
- Start of SNO+ Te Phase 1

2028
- Completion of Hyper-K, start of data collection
- Completion of DUNE far detector module 1, collection of atmospheric data

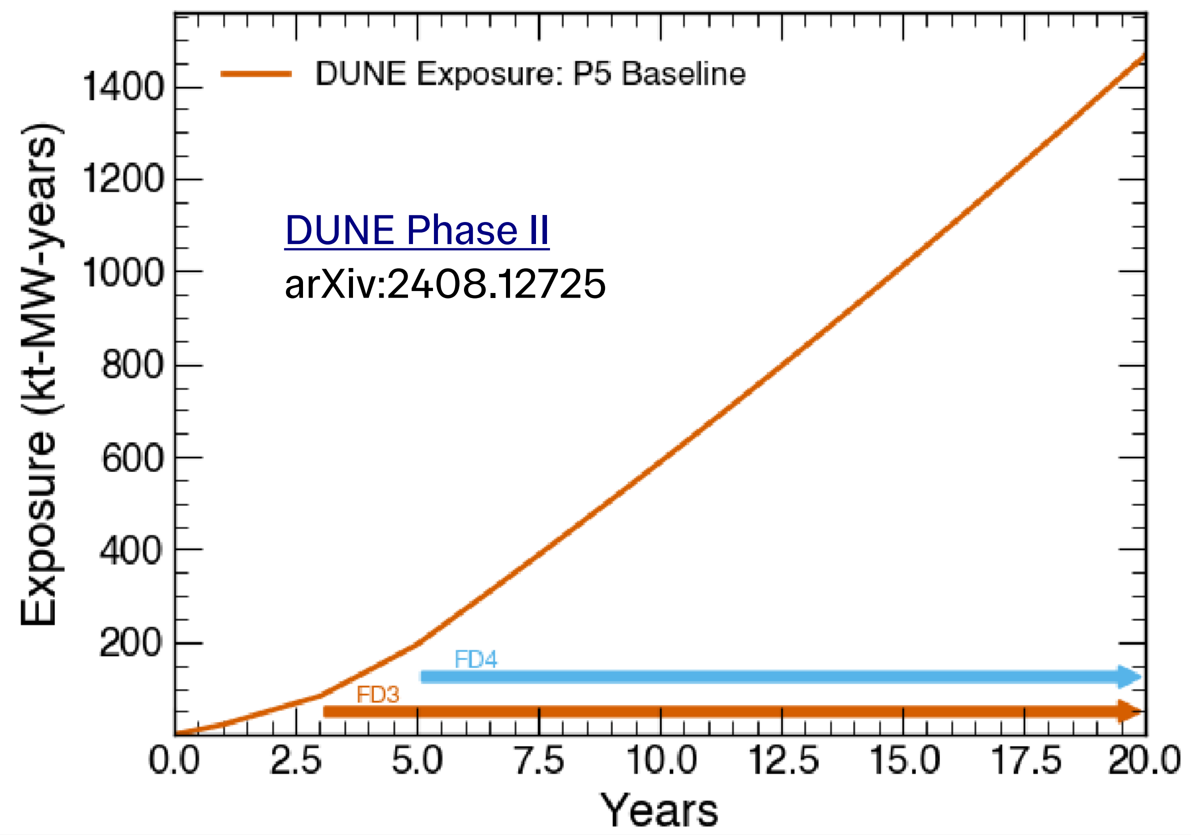
2030
- Completion of KM3NeT-ORCA
- Completion of DUNE far detector module 2

2031
- DUNE Phase I beam data collection

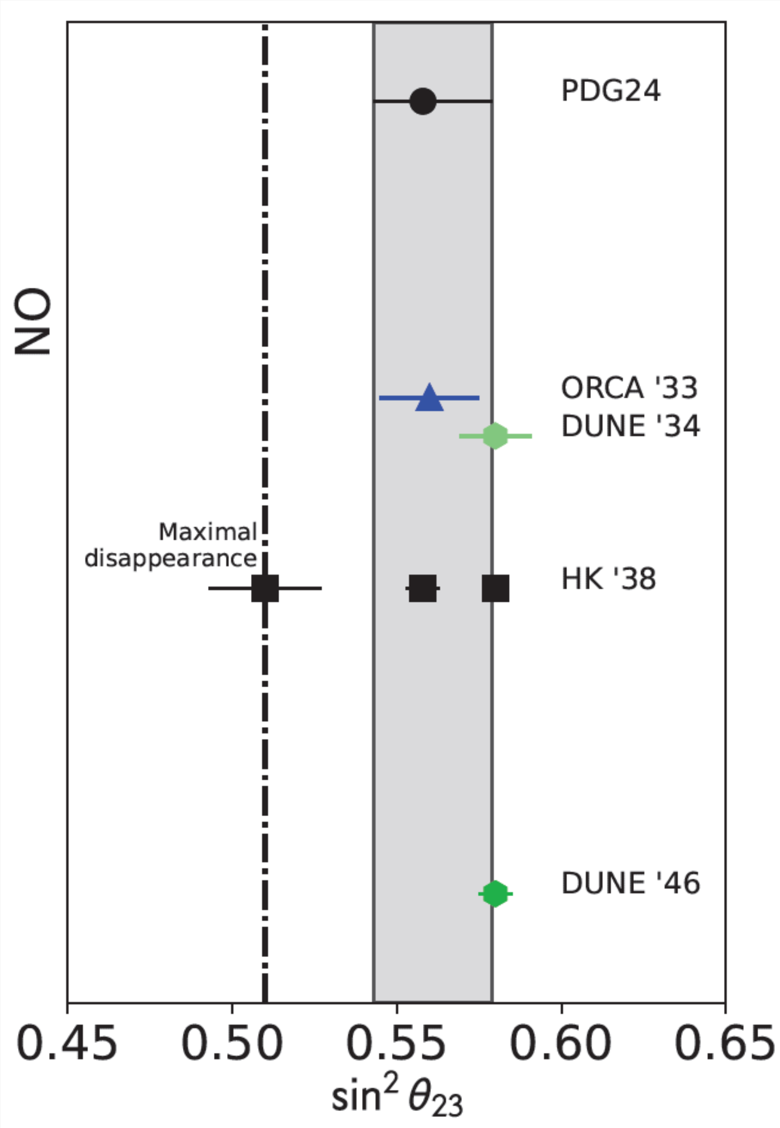
2034+
- DUNE Phase II
- Proposed future experiments

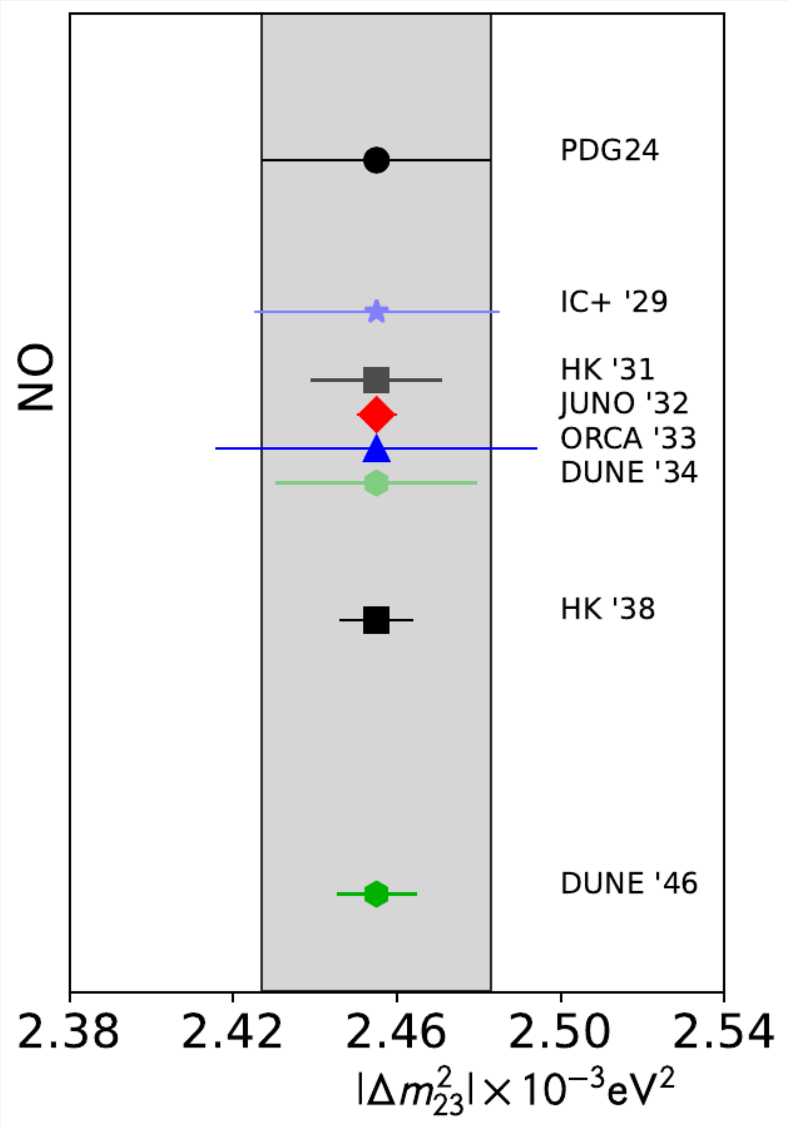
DUNE Phasing and Exposure

- DUNE Phase 1 consists of:
  - 10kt Far Detector Module 1, 10kt Far Detector Module 2, both liquid argon
  - Suite of near detectors, inc. liquid argon detector
  - 1.2 MW neutrino beam
- DUNE Phase 2 consists of:
  - Far Detector Modules 3 and 4, assumed to be 10kt each of liquid argon in sensitivity studies
  - More Capable Near Detector (MCND), assumed to be gaseous argon TPC
  - Beam power upgraded to 2.3MW
- DUNE performance submitted as a function of kt-MW-years exposure, plot on right converts to year since beam start (nominally 2031)



Future precision on $\sin^2\theta_{23}$ and Δm^2_{32}



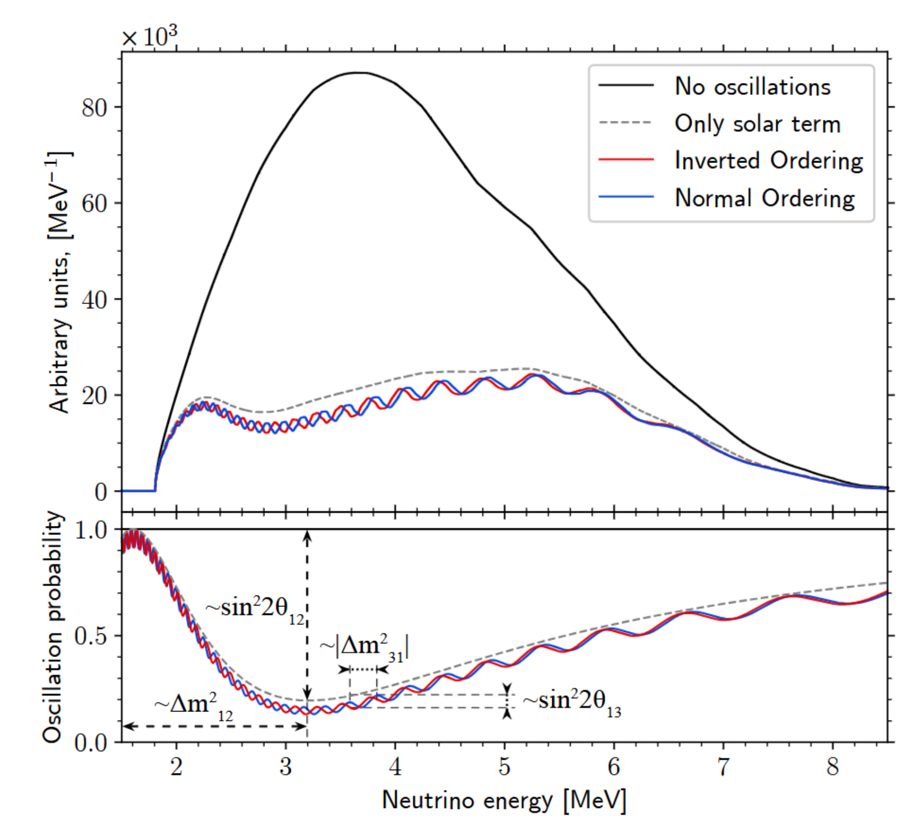


- For long-baseline experiments precision on $\sin^2\theta_{23}$ depends on true value
  - Hyper-K illustrates this on left
- Both DUNE and HK can achieve comparable precision on disappearance parameters
  - Best precision on $\sin^2\theta_{23}$
- JUNO provides best precision on Δm^2_{3l}
- Multiple experiments with different systematics

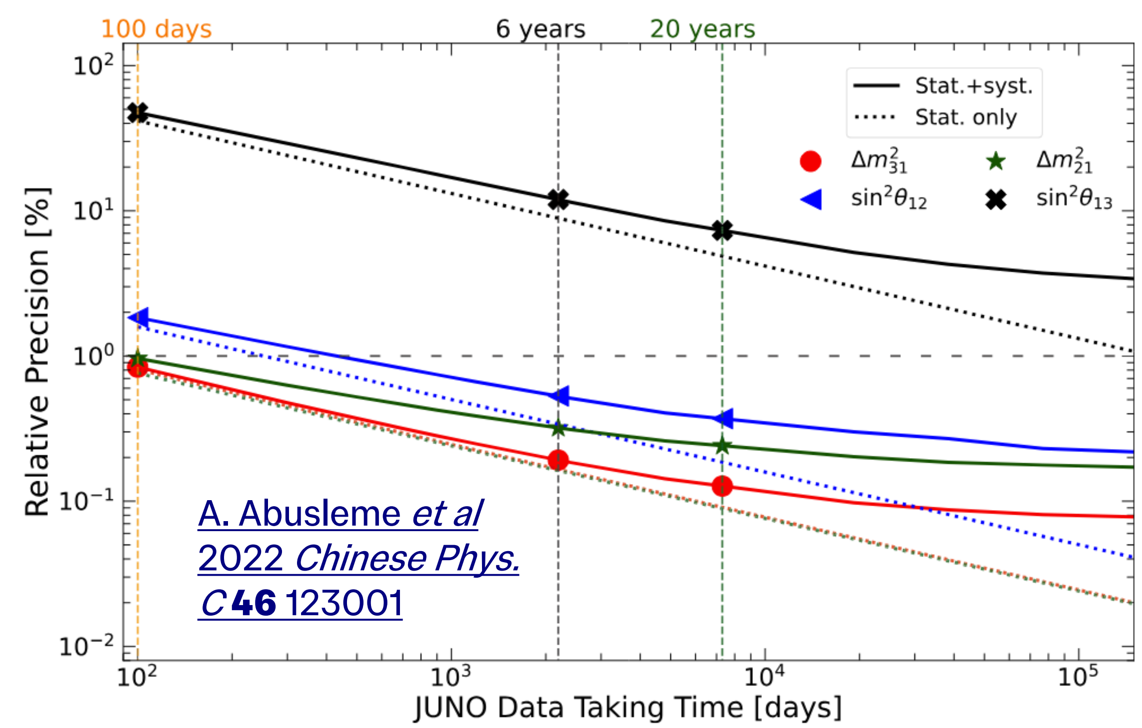
Precision measurements from JUNO

- Plan to measure fast oscillation on top of larger oscillation
  - Relies on precise energy calibration

[#36 ESPPU]

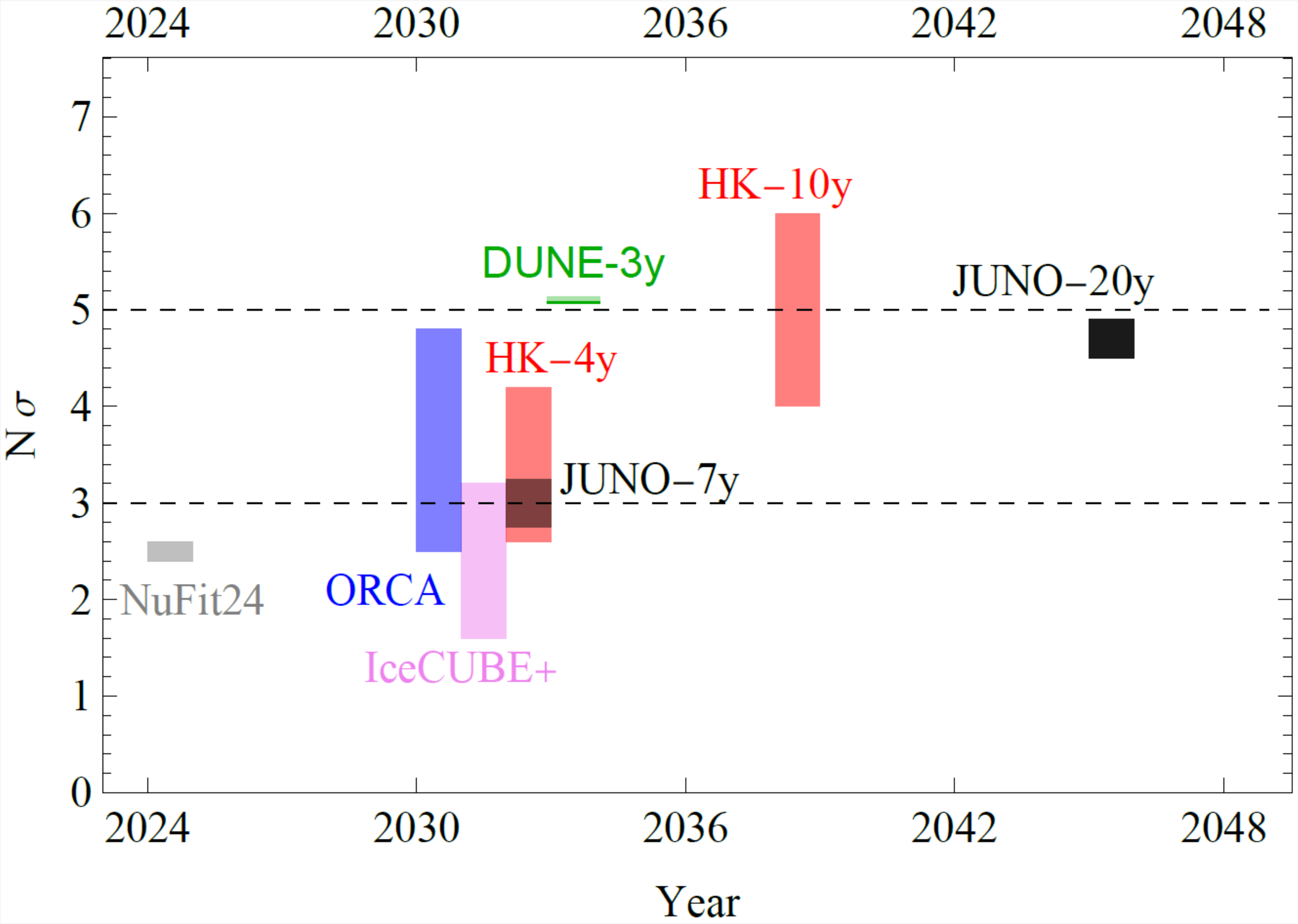


- After 6 years predict:
  - 0.2% precision on Δm^2_{31}
  - 0.3% precision on Δm^2_{21}
  - 0.5% precision on $\sin^2\theta_{12}$



[A. Abusleme *et al* 2022 *Chinese Phys. C* **46** 123001]

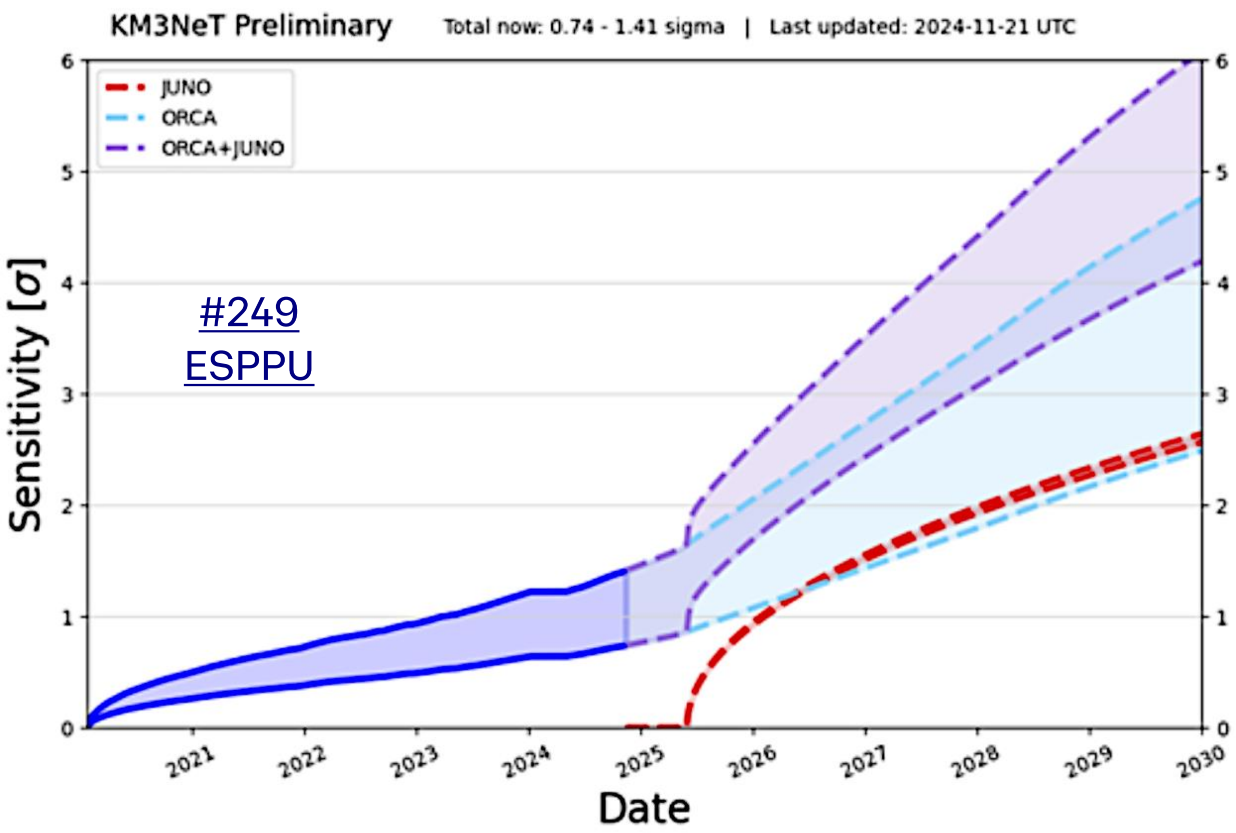
Future determination of mass ordering

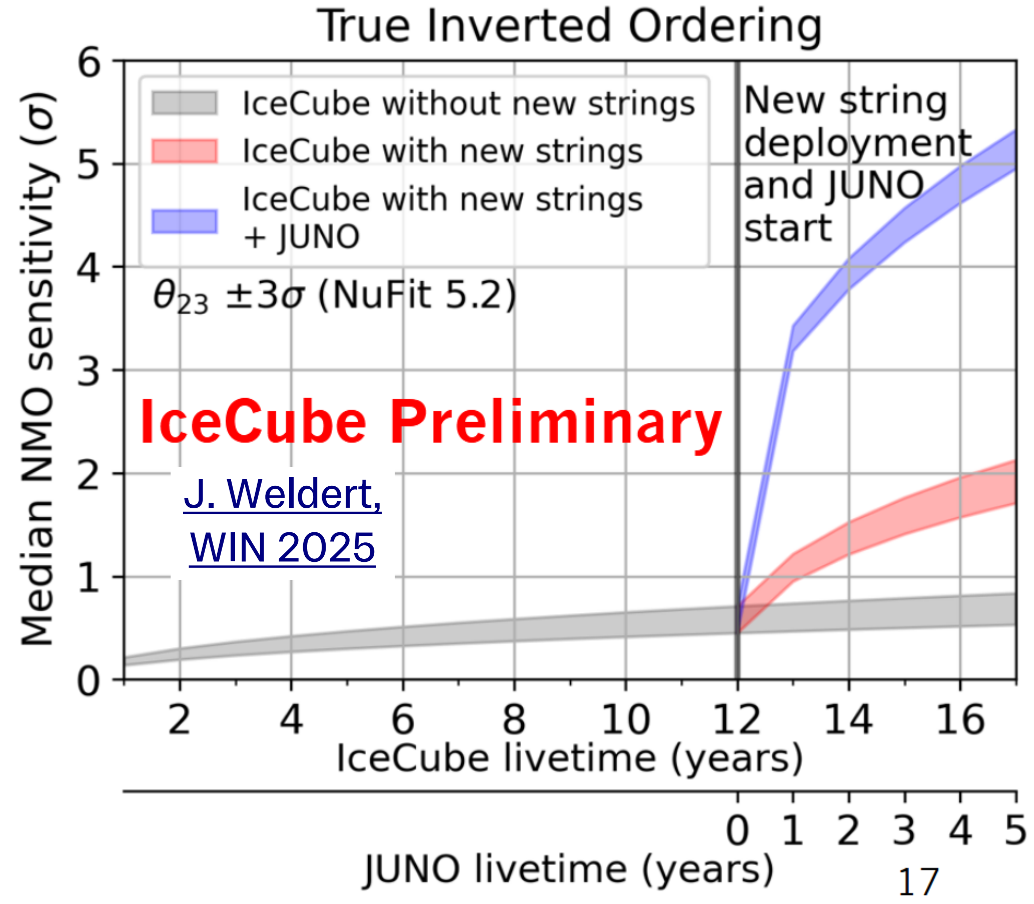


- Experiment sensitivity versus time, width from uncertainty on other oscillation parameters
  - Primarily $\sin^2\theta_{23}$
- Early 2030s:
  - Many experiments with 3σ sensitivity
  - Multiple neutrino sources and methods to determine MO
- DUNE has 5σ sensitivity shortly after beam starts
  - Assumes $\sin^2\theta_{23} = 0.58$, expect less sensitivity for smaller values

Mass ordering
Combinations with JUNO

- Many experiments with $\sim 3\sigma$ MO sensitivity expect results in early 2030
- Combination of long-baseline experiments with JUNO provides significant enhancement, up to 5σ

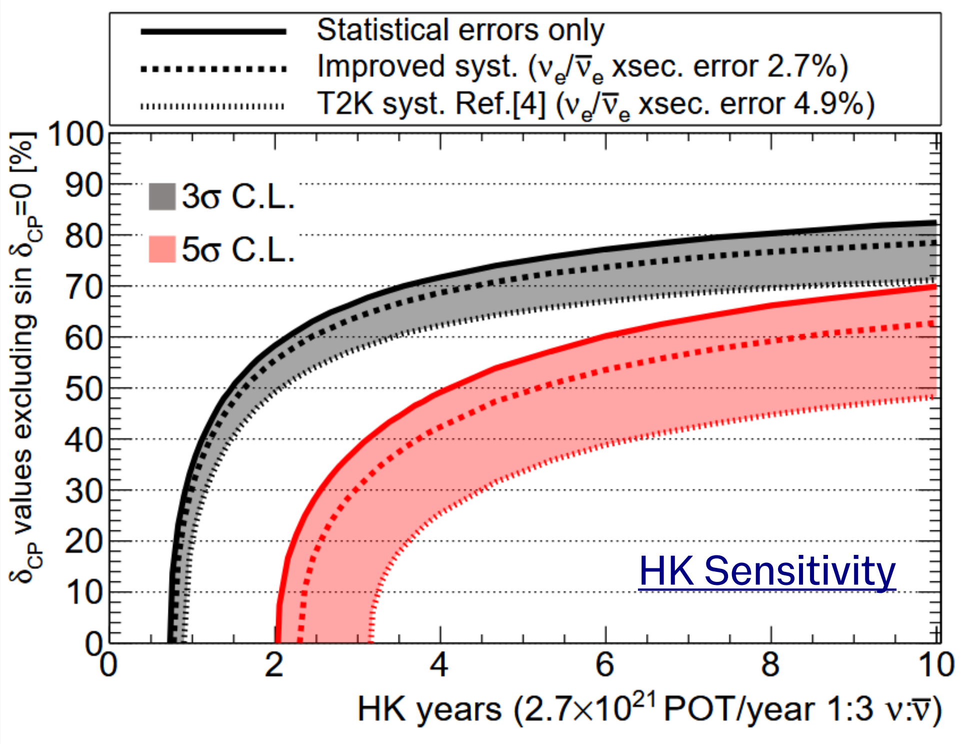




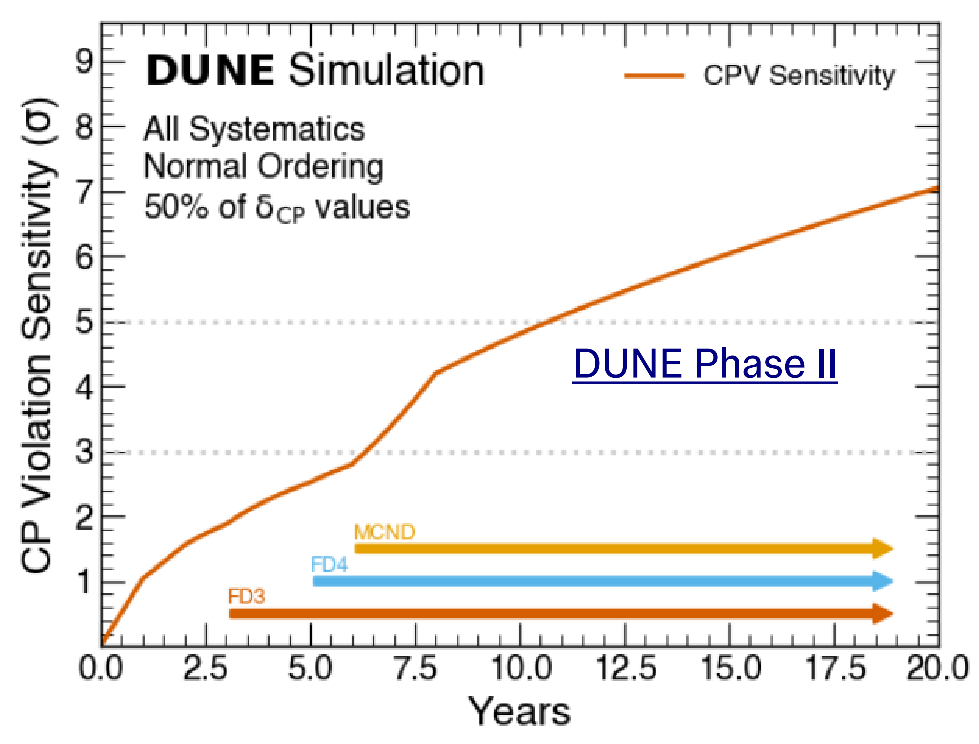
CP Violation sensitivity

Hyper-K and DUNE

- Hyper-K expects 5σ CPV sensitivity for 50% of values of δ_{CP} after ~5 years beam exposure
- 75% of values at 3σ after ~7 years



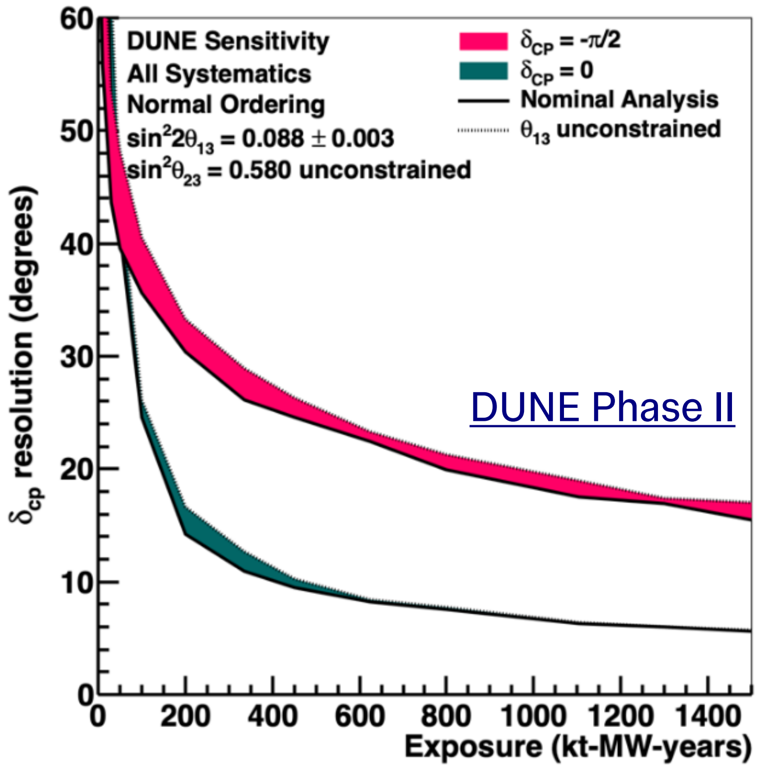
- DUNE expects 5σ CPV sensitivity for 50% of values of δ_{CP} with 600 kt-MW-years exposure (~10 years)
- 75% of values at 3σ with 1000 kt-MW-years (~14 years)



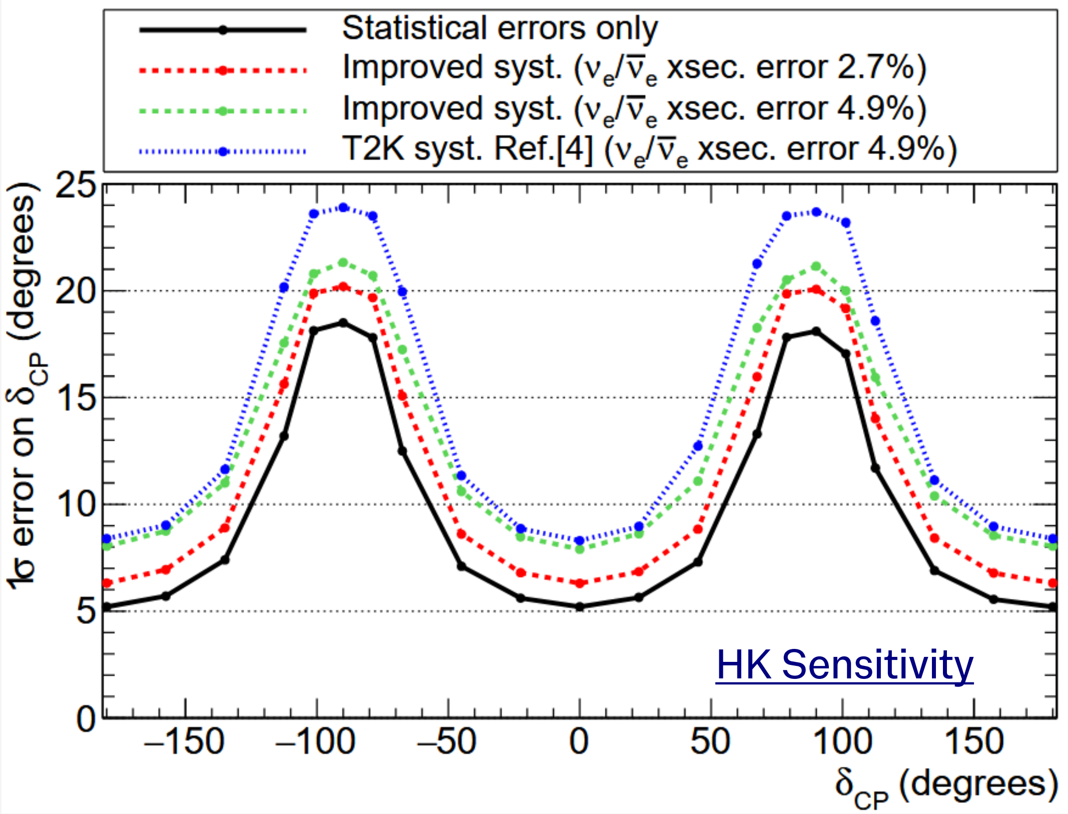
Precision on δ_{CP}

Hyper-K and DUNE

- Performance of both experiments similar
  - Approximately 6° if $\sin(\delta_{CP}) = 0$
  - If $\delta_{CP} = \pm\pi/2$ DUNE achieves ~19° with 1000-kt-MW-years while Hyper-K achieves ~20° after 10 years



[DUNE Phase II]



[HK Sensitivity]

Over-constraining PMNS parameters

Combining experiments

S. Ellis et al, PHYS. REV. D 102, 115027 (2020)

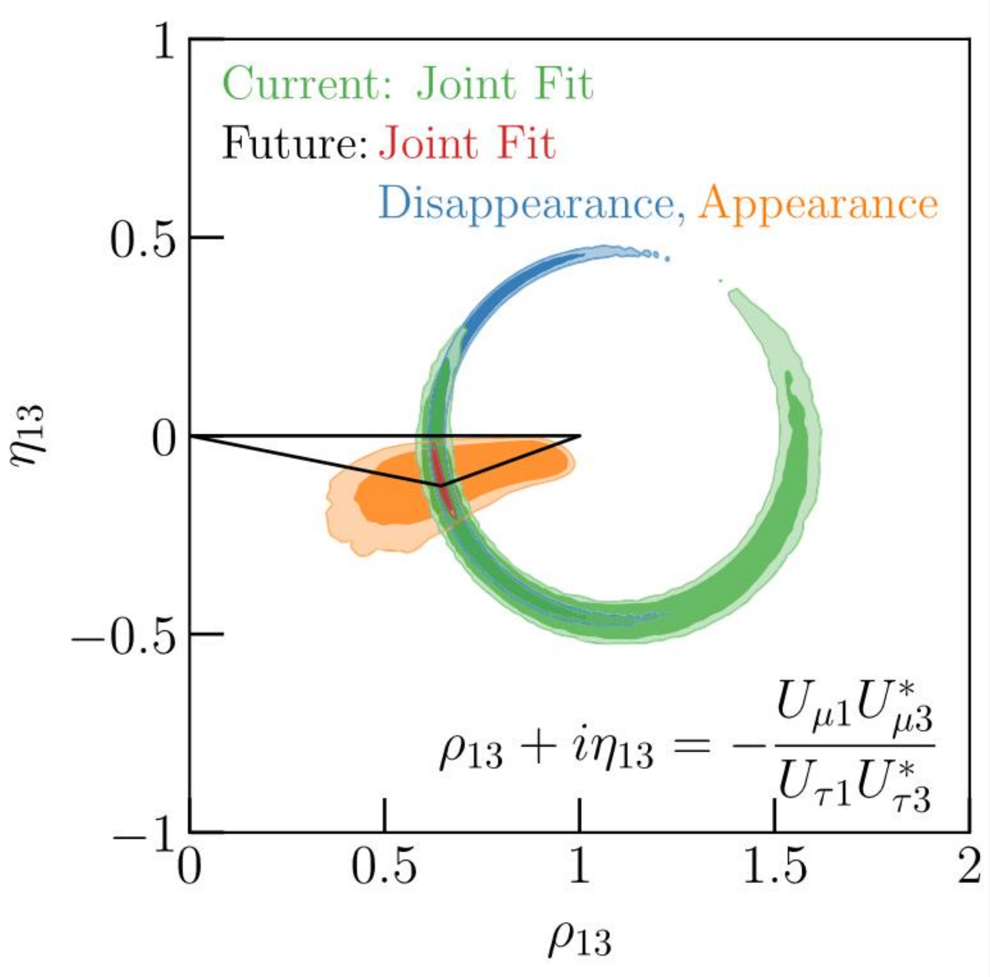
Majority of measurements today assume PMNS is unitary

- Current data (green) do not really constrain unitarity
- Combining future experiments (JUNO, IceCube, DUNE and HK on right) provides significantly greater power
- Study consistency of PMNS parameters between experiments
  - HK and DUNE will approach reactor precision on $\sin^2\theta_{13}$

This is a generic search for new physics

- BSM covered in more detail in talk by J. Kopp
- Requires detailed understanding of experiment uncertainties and correlations between experiments

Multiple experiments will provide robust determination of CPV, MO and PMNS parameters



Neutrino Oscillation
Systematic Uncertainties

Complex and detailed topic – cannot address in 30-minute talk, but critical for future experiments to achieve their design goals

JUNO

- 3%/√E energy resolution needed for MO determination and (perhaps) atmospheric mass splitting, solar mixing parameter and mass splitting are independent of this

IceCube/KM3NeT-ORCA

- Atmospheric neutrino flux has relatively large uncertainties, but largely cancel in ratio of up/down, electron/muon, neutrino/antineutrino
- Neutrino interaction cross section important for precise mixing parameter and mass splitting
- Detector systematics are also challenging

Hyper-Kamiokande/DUNE

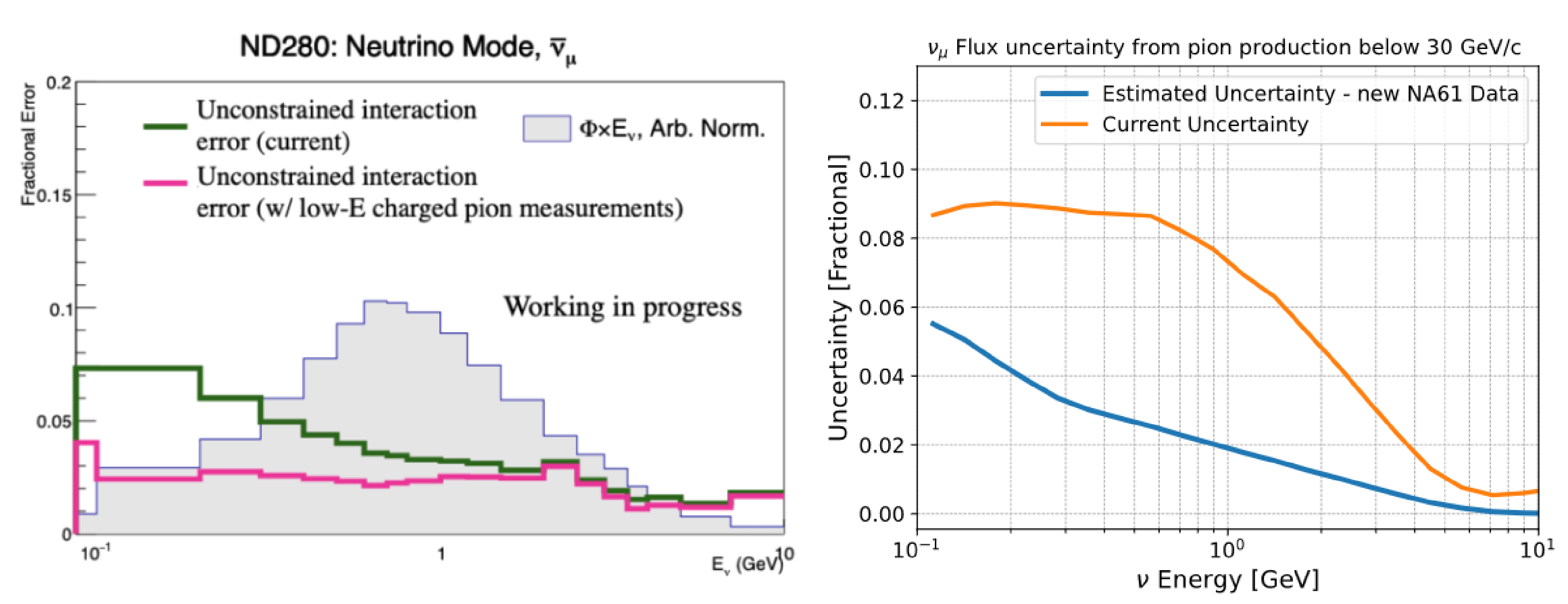
- Need near detectors, in-situ and external measurements to control neutrino flux and cross section
- Detector systematics assumed to be well controlled, will be challenging

Neutrino Flux Prediction
NA61/SHINE Experiment

- Plays an essential role in constraining neutrino flux uncertainties coming from unknown hadron production cross sections – **strong support from community** seen in ESPPU submissions
- Propose to continue measurements after CERN Long Shutdown 3

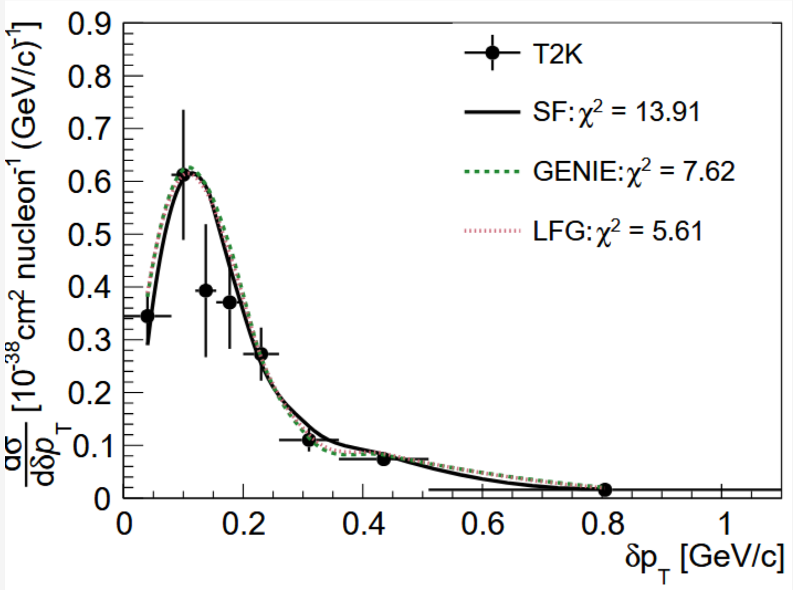
#238 ESPPU

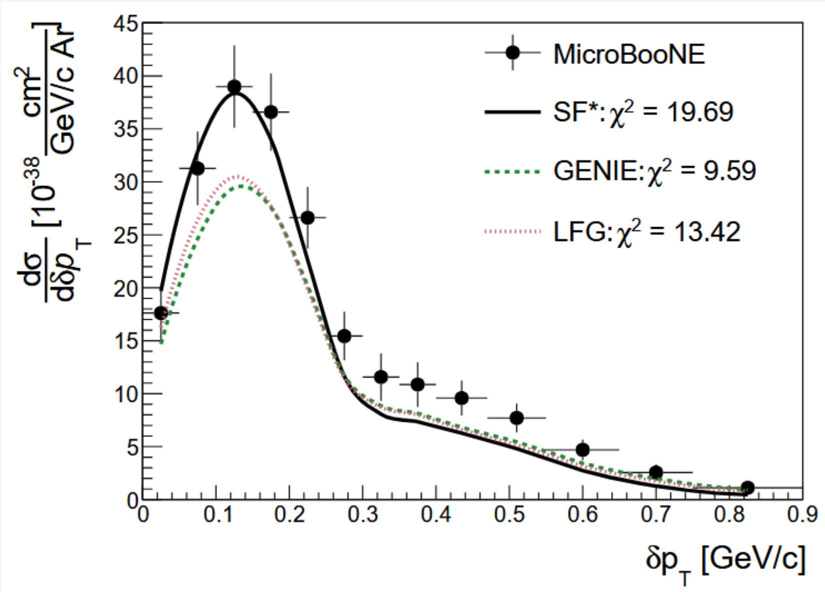
  - LBNF and T2K/HK replica targets
  - Low energy protons on nitrogen to constrain atmospheric flux
  - Mesons and protons on aluminium, water, iron and other targets
    - Understand secondary interactions in neutrino beam lines

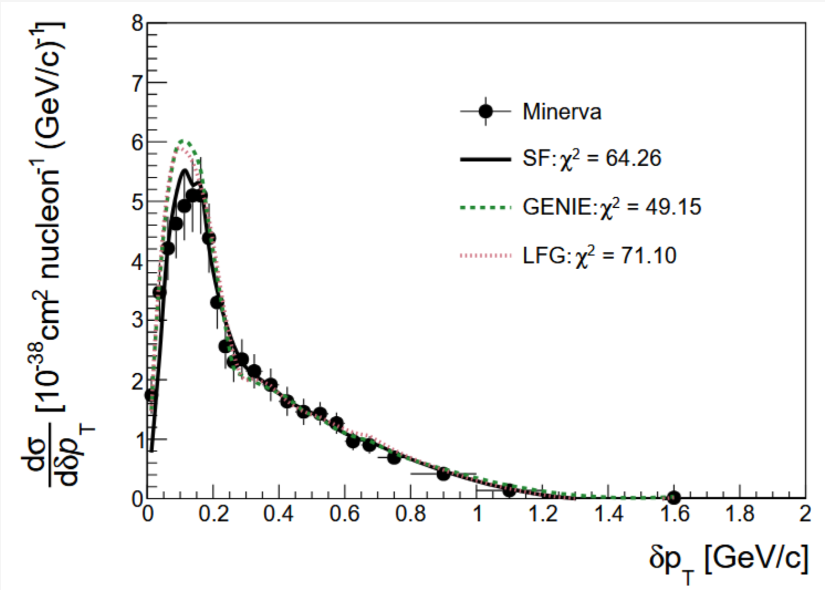


Neutrino cross sections in long-baseline experiments
Neutrino scattering ~1 GeV

- At GeV-scale neutrino event generators must model both interaction of neutrino with a nucleon and the impact of the surrounding nucleus on this process
  - Final state interactions, collective nuclear excitations, hadron-quark transition, low-W hadronization…
- Models do reasonably well for quasi-elastic interactions



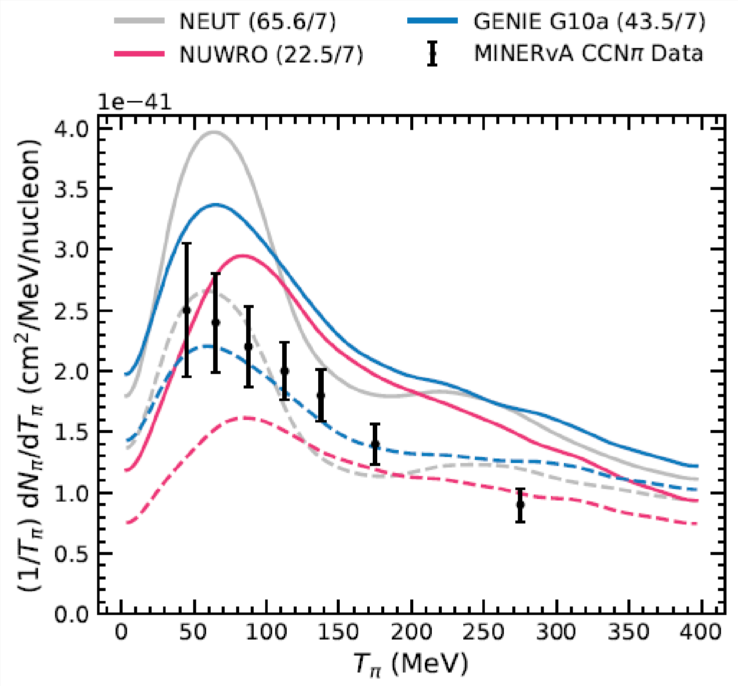




W. Filali et al, [Phys. Rev. D **111**, 032009]

Neutrino cross sections in Long-baseline Experiments
Neutrino scattering ~1 GeV

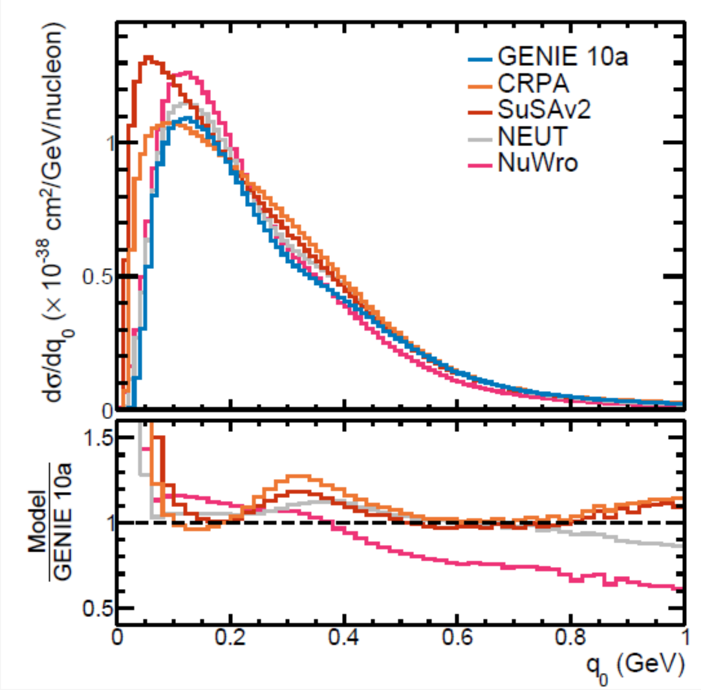
- At GeV-scale neutrino event generators must model both interaction of neutrino with a nucleon and the impact of the surrounding nucleus on this process
  - Final state interactions, collective nuclear excitations, hadron-quark transition, low-W hadronization…
- Models struggle to describe other data samples well (one example below)



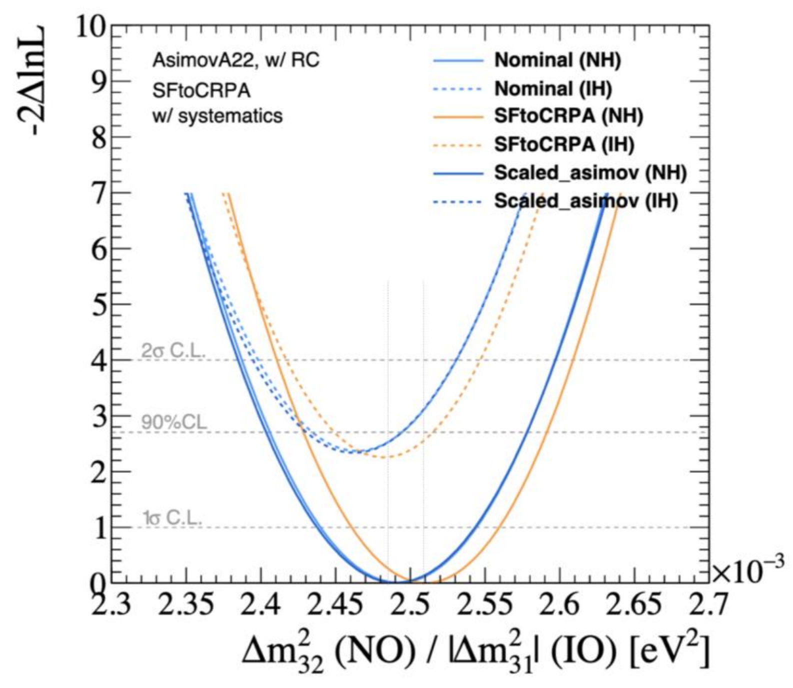
- T2K experiment developing interaction model and uncertainties for neutrinos with energies from 0.3 - 2 GeV for Carbon and Oxygen targets
  - Hyper-K benefits from this
- DUNE uses argon target, beam neutrino energy mainly above 1 GeV
  - No existing data on argon in this energy range
  - Some data from SBN program at lower energy

Neutrino cross sections in long-baseline experiments
Impact on oscillation physics – T2K

- Neutrino event generator cross section predictions differ by 50% at low energy transfer (right)
- T2K study:
  - Fit simulated data from CRPA model at near and far detector,
  - Extract oscillation parameters
  - Compare to expected value from nominal sensitivity fit



L. Munteanu, NuINT 2024



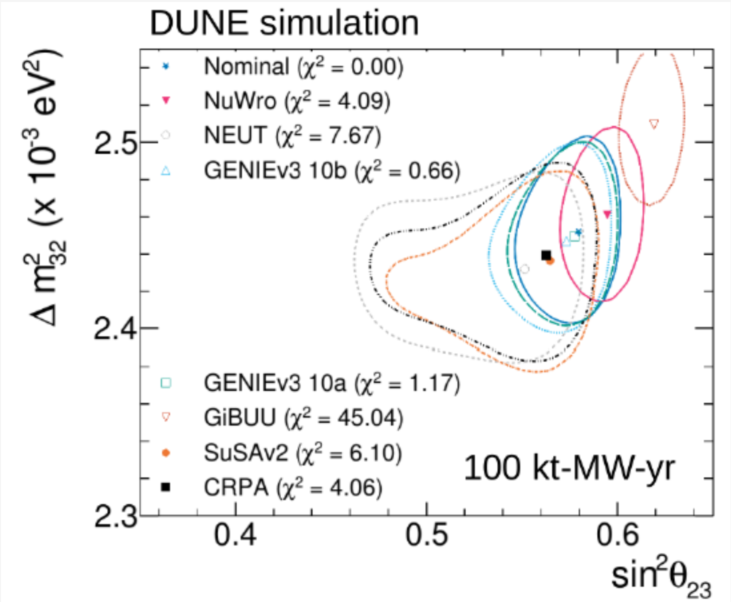
- Observed shift in best-fit value of Δm^2_{32}
  - Shift as large as total systematic error on Δm^2_{32}
  - Added as additional error

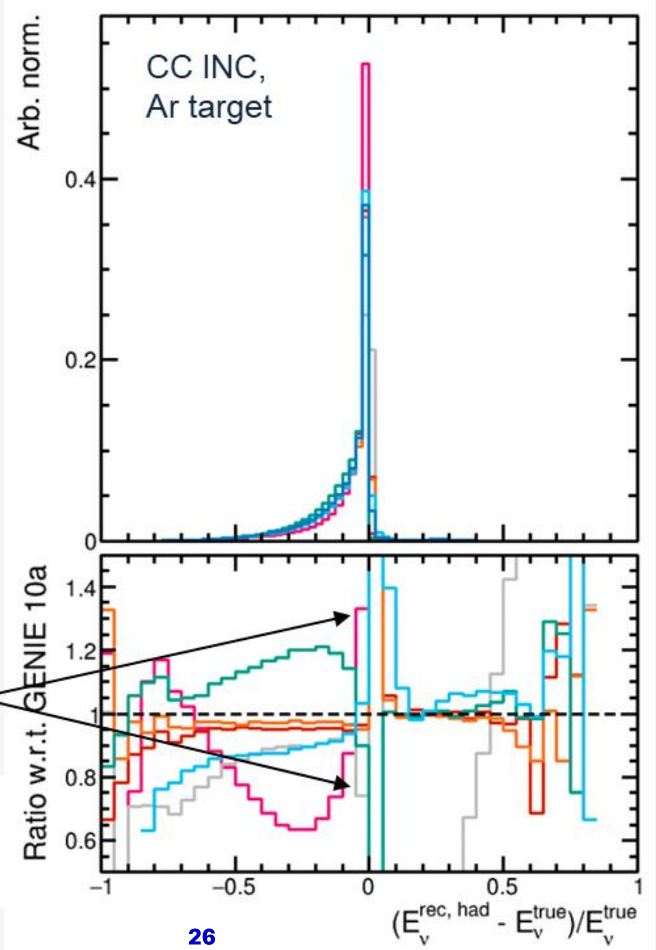
Neutrino cross sections in Long-baseline Experiments

Impact on oscillation physics - DUNE

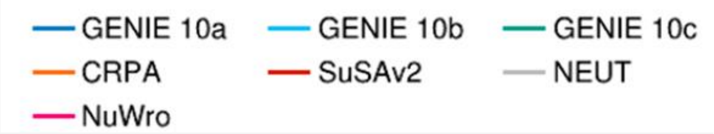
[Workshop on Neutrino Event Generators]

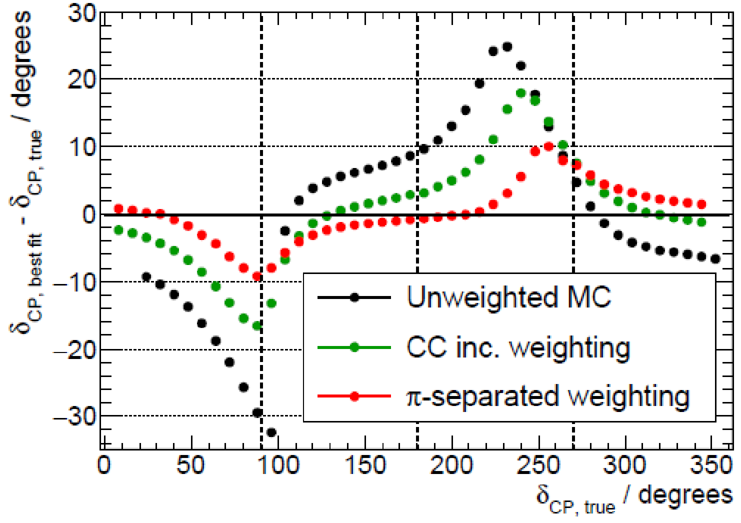
- DUNE has wide-band beam at higher energy
  - Modelling of neutrino energy v. important
  - Need to measure hadronic part of neutrino interaction as well as leptonic
  - Mis-modelling the amount of energy that is not detected can have significant impact





Proportion of E_ν reconstructed within 10% of the true E_ν differs by more than 20%





[DUNE ND CDR]

Neutrino cross sections measurements

Current and upcoming experiments

Many experiments with significant European involvement are currently collecting data, or plan to start soon – almost all have collected data on a variety of targets with both neutrinos and antineutrinos

T2K Near Detectors - #106 ESPPU

- Carbon and oxygen target, 0.6 GeV peak neutrino energy
- ND280 Upgrade (NP07) currently collecting data, new upgrade proposed for mid-2030s (ND++)

MINERvA - #149 ESPPU

- Many target nuclei from He to Pb, not argon
- Energies from 1 – 10 GeV, driver of model development

Short Baseline Neutrino Programme

- ICARUS (NP01, #226 ESPPU), MicroBooNE, SBND
- Millions of events with large (>40k) number of electron neutrinos
- Argon target, peak energy 0.8 GeV
  - ICARUS also plans to measure NuMI beam at higher neutrino energies

Neutrino cross sections measurements
Possibilities at CERN

CERN support for neutrino physics recognised as critical to success of oscillation program

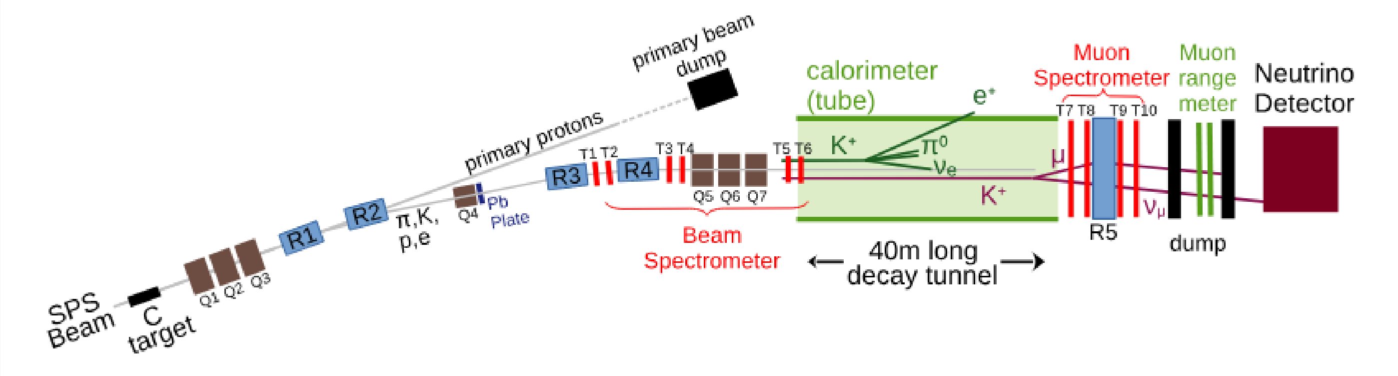
Broad interest in potential neutrino facilities at CERN

nuScope (formerly SBN@CERN) - [#101 ESPPU]

- Combination of ENUBET (NP06) instrumented decay region and NuTAG fast tracking to reconstruct kinematics of neutrino production from hadron decays
- 1% uncertainty on neutrino fluxes, measure "true" neutrino energy with 1% error for tagged events
- Technology under development, but most already demonstrated
- Proton requirement compatible with SHiP, 1.4×10^{19} POT over 4 – 7 years

Requires large (500 tonne, ~1 ProtoDUNE), capable detector

- O(1M) muon neutrino events
- ~80% tagging efficiency if timing performance (0.04ns beamline, 0.3ns for interaction in detector) achieved

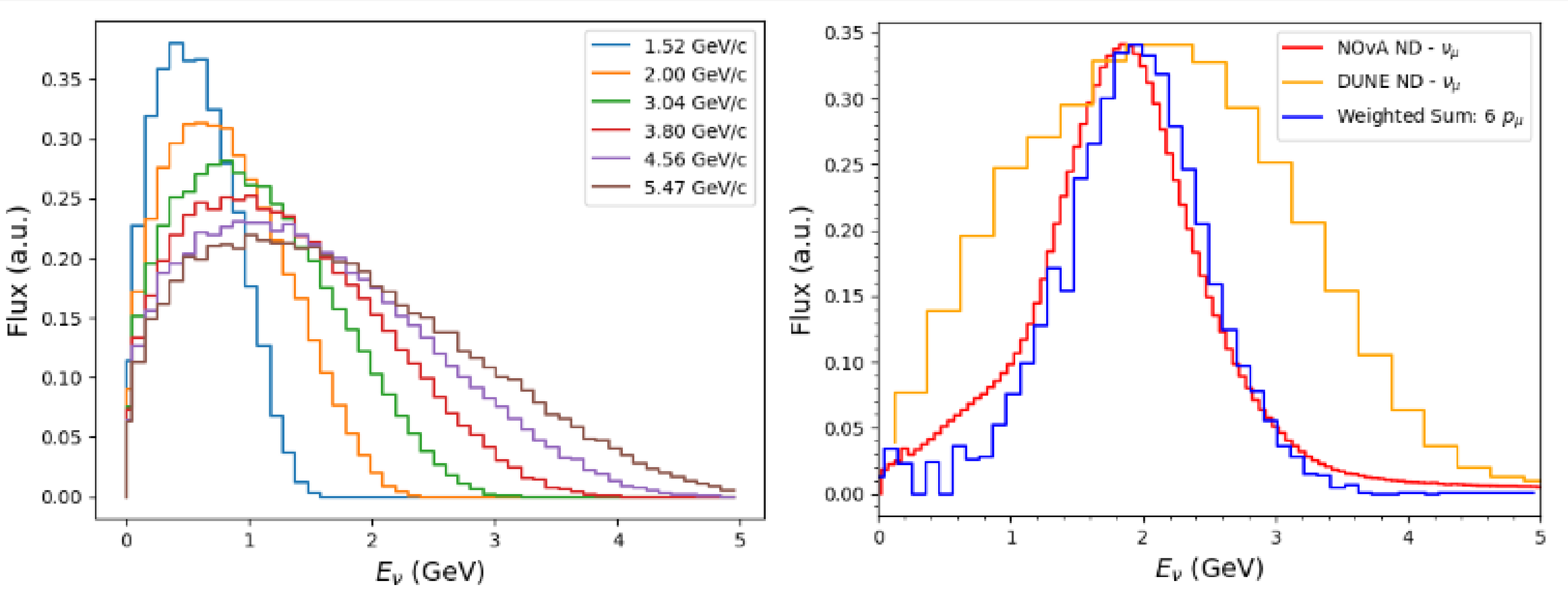


Neutrino cross sections measurements
Possibilities at CERN

Muon beams provide large electron neutrino fluxes, can provide both neutrinos and antineutrinos and the neutrino beam can be well characterised by measuring the muons

NuSTORM - #200 ESPPU

- Target station, pion transfer line, then muon storage ring
- Neutrinos from both muons and initial pions
- Possible to form bespoke fluxes



Neutrinos from high brightness muon beams - #251 ESPPU

- Looking at neutrino physics from first stage of muon collider at CERN
- Target station, cooling followed by initial stages of LINAC to 1.5 GeV/c (or higher for DUNE)
- Requires development of muon cooling

Neutrino cross sections measurements

Possibilities at CERN summary

Table shows areas to compare each proposal – non-exhaustive

- Electron neutrino cross section – limiting systematic for Hyper-K CPV sensitivity, significant for δ_{CP} precision and octant sensitivity
- Neutrino – vs – antineutrino cross section – limiting systematic for Hyper-K CPV sensitivity
- Neutrino energy – knowledge of neutrino energy and relation to reconstructed variables limiting systematic for precision measurements and CPV at DUNE

	nuSTORM	nuScope	Muon beam
$\sigma\ \nu_e/\nu_\mu$	✚	✚	✚
$\sigma\ \bar{\nu}/\nu$	✚	Under study	✚
E_ν	−	✚	−
Readiness	✚	✚	✖
Muon collider R&D	✚	✖	✚

- All can measure ν_e flux with 1% uncertainty
- Muon beams have well known $\bar{\nu}$ flux
- nuScope tagging, muons have tunable beam
- High brightness muon beam requires cooling R&D
- Muon beams develop technology for muon collider

Neutrino oscillation ecosystem

All experimental submissions highlight the importance of European support – both at CERN and elsewhere

All highlighted the benefit from the Neutrino Platform, and request **recognition and support for the Neutrino Platform**

- Played key role in T2K Near Detector Upgrade (NP07), BabyMIND (NP05)
- Hosted Proto-DUNEs (NP02, NP04)
- Direct participation in T2K and DUNE
- Hyper-K electronics testing (NP08)
- Many others

A number of submissions highlighted the benefit from both the CERN neutrino experimental and theoretical groups:

- CERN (and Europe) is in a unique with large contributions to Hyper-K and DUNE, as well as JUNO, KM3NeT and IceCube
- **Opportunity to be a nexus for cross-experiment work**, driving future discovery

Neutrino oscillation, mixing and mass splitting

Summary

Field is starting to measure mixing parameters and mass splittings with %-level precision

Many new experiments under construction or starting to collect data

- Expect MO to be known at 3σ by 2030, confirmed at 5σ by DUNE in 2034
- Discovery of CP violation possible by 2031, but Nature may not be kind, and it could be much harder
- Sub-% precision on most oscillation parameters by late 2030s – limited by systematics

Strong support in Europe for wide programme of experiments

- Hyper-K, DUNE, JUNO, KM3NeT-ORCA, IceCube, SNO+, ESSNuSB, SuperCHOOZ , NA61
  - CERN Neutrino Platform
- Neutrino beams at CERN can reach <1% precision on flux and cross sections
- Opportunity for cross-experiment research hub in Europe

IMPERIAL

Thank you

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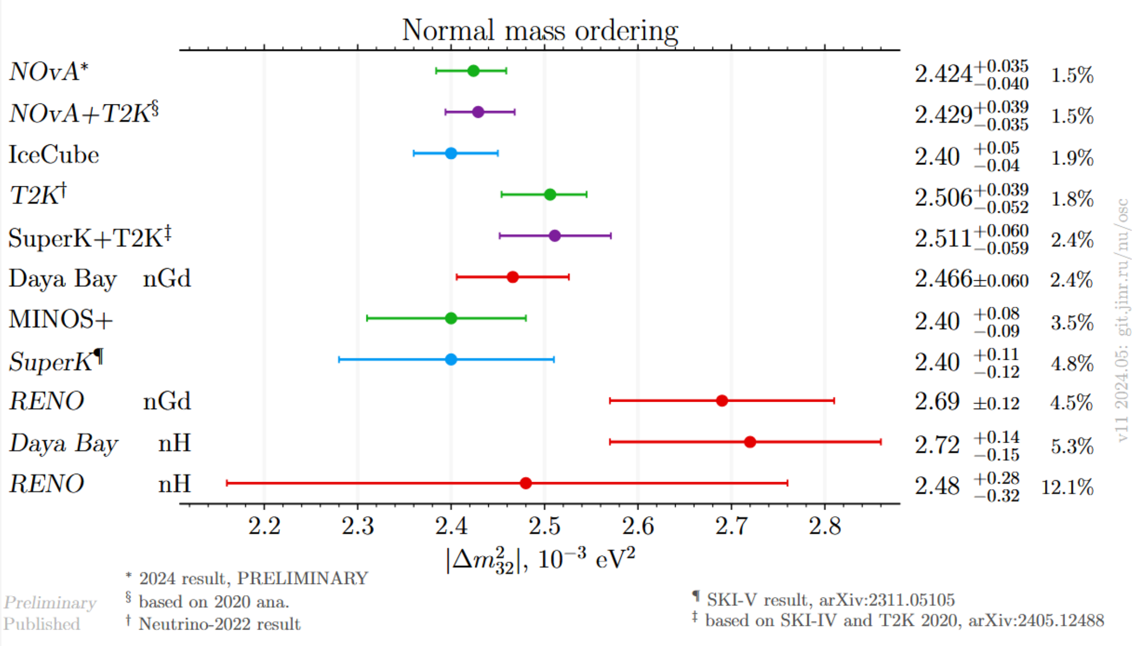
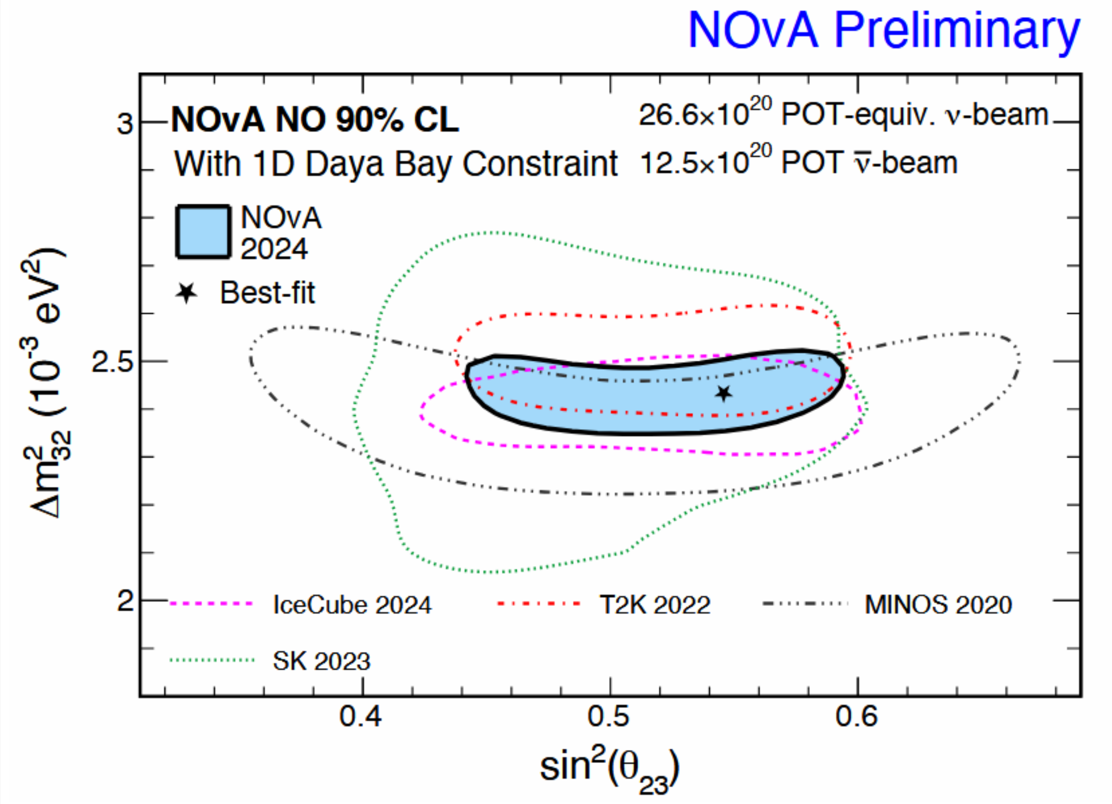
- NOvA: P. Vahle, NOvA PAC ’24
- DUNE: #118 ESPPU, arXiv:2408.12725, arXiv:2103.13910, C. Wilkinson, Workshop on Neutrino Event Generators
- JUNO: #36 ESPPU, arXiv:2405.18008, A. Abusleme *et al* 2022 *Chinese Phys. C* **46** 123001
- KM3NeT-ORCA: #249 ESPPU,
- Hyper-K: #238 ESPPU, arXiv:2505.15019
- NuFit 6.0, JHEP 12 (2024) 216
- IceCube: #236 ESPPU, J. Weldert, WIN 2025
- MINERvA - #149 ESPPU
- ICARUS - #226 ESPPU
- Neutrinos from high brightness muon beams - #251 ESPPU
- NuSTORM - #200 ESPPU
- nuScope (formerly SBN@CERN) - #101 ESPPU
- W. Filali et al, Phys. Rev. D **111**, 032009
- S. Ellis et al, PHYS. REV. D 102, 115027 (2020)

Long-baseline Oscillation
Current experiments

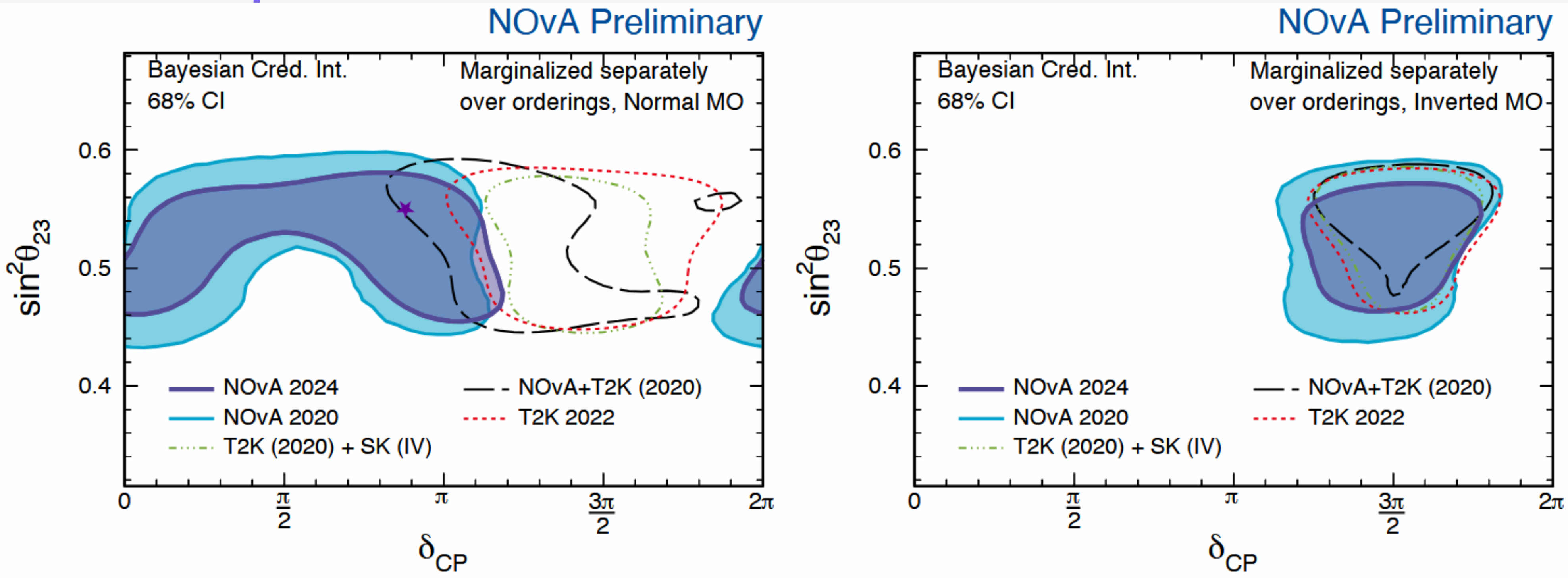




P. Vahle, NOvA PAC '24

- T2K and NOvA providing tightest constraint on Δm^2_{32} and $\sin^2\theta_{23}$

Long-baseline Oscillation
Current experiments



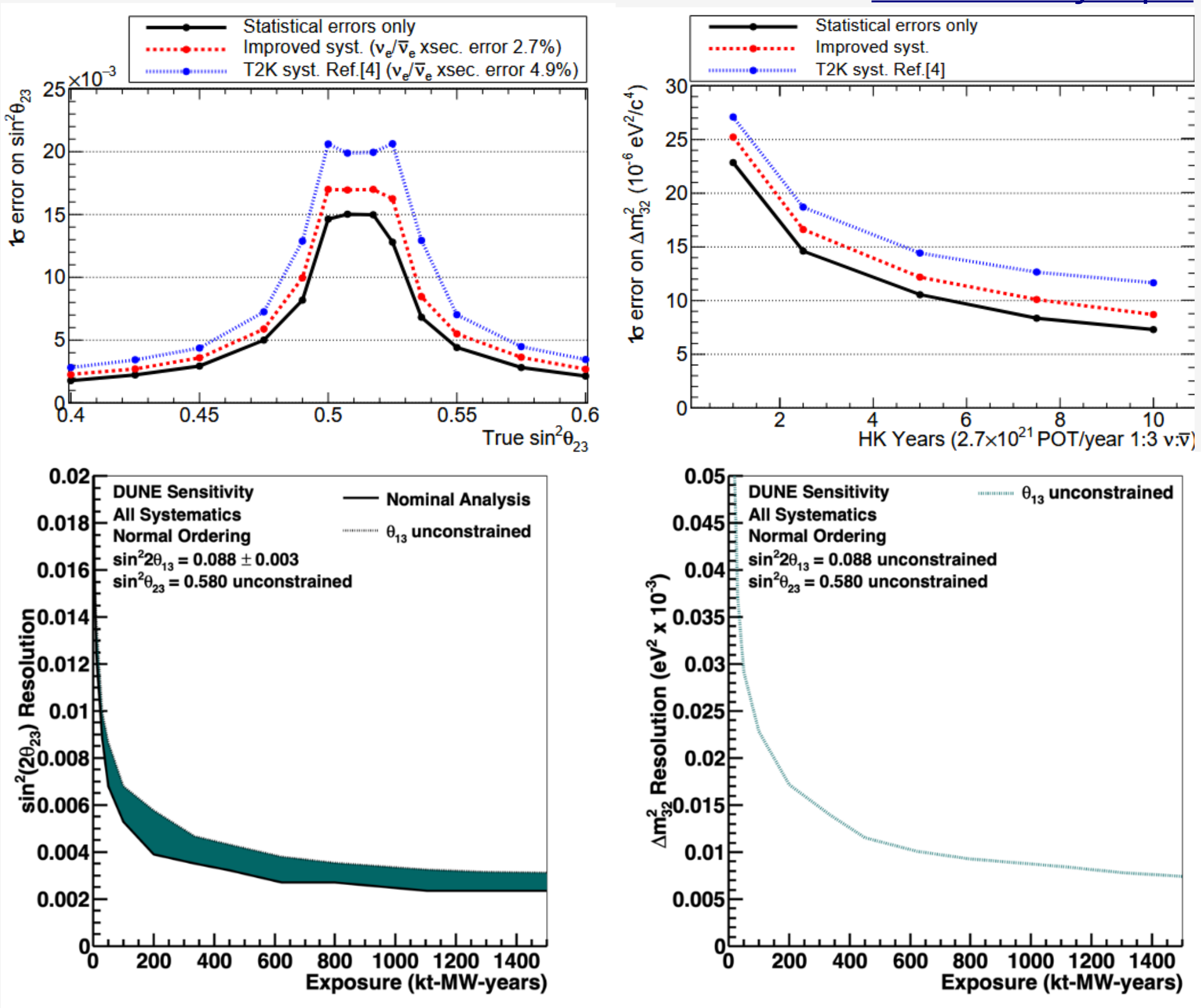
P. Vahle, NOvA PAC '24

- T2K and NOvA providing tightest constraint on Δm^2_{32} and $\sin^2\theta_{23}$
- Demonstrated sensitivity to MO and δ_{CP} at the $1-2\sigma$ level

Precision on $\sin^2\theta_{23}$ and Δm^2_{32}
Hyper-K and DUNE

[HK Sensitivity Paper]

- Precision on $\sin^2\theta_{23}$ depends on true value
  - Both DUNE and HK can achieve better than 4×10^{-3} precision for $\sin^2\theta_{23} = 0.58$ (current precision $\sim 2 \times 10^{-2}$)
- Precision on Δm^2_{3l}
  - DUNE: 1% - 0.4% with 100 – 1000 kt-MW-years exposure
  - HK: 1% - 0.4% with 1 – 10 years exposure
  - Current precision 1.5%



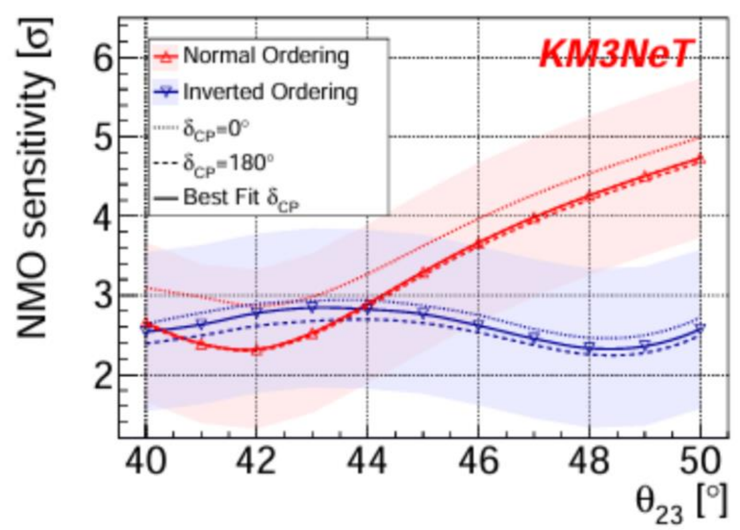
[DUNE TDR]

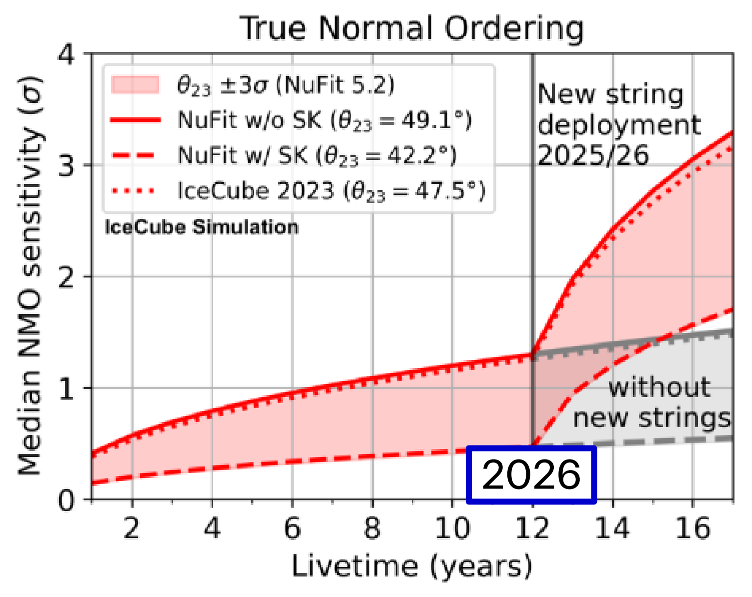
Precision on $\sin^2\theta_{23}$ and Δm^2_{32}

IceCube and ORCA

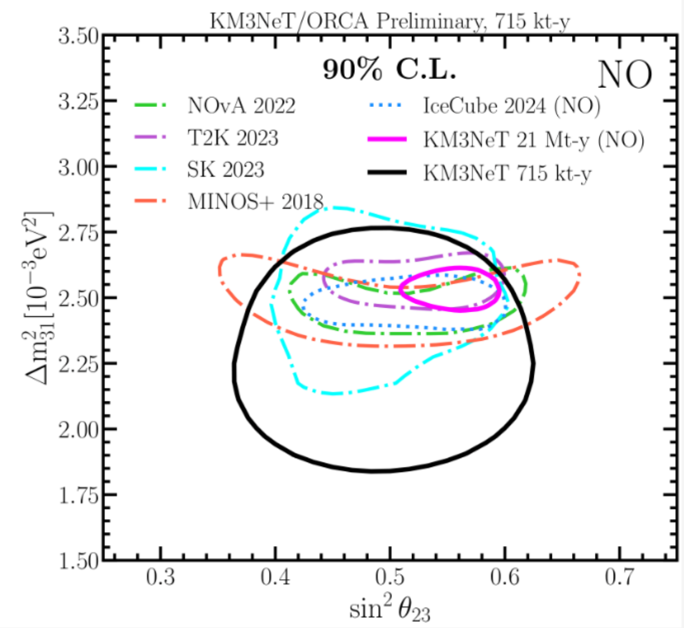
- Both IceCube and KM3NeT-ORCA expect to achieve $3-5\sigma$ MO sensitivity around 2033
  - Depends on value of $\sin^2\theta_{23}$

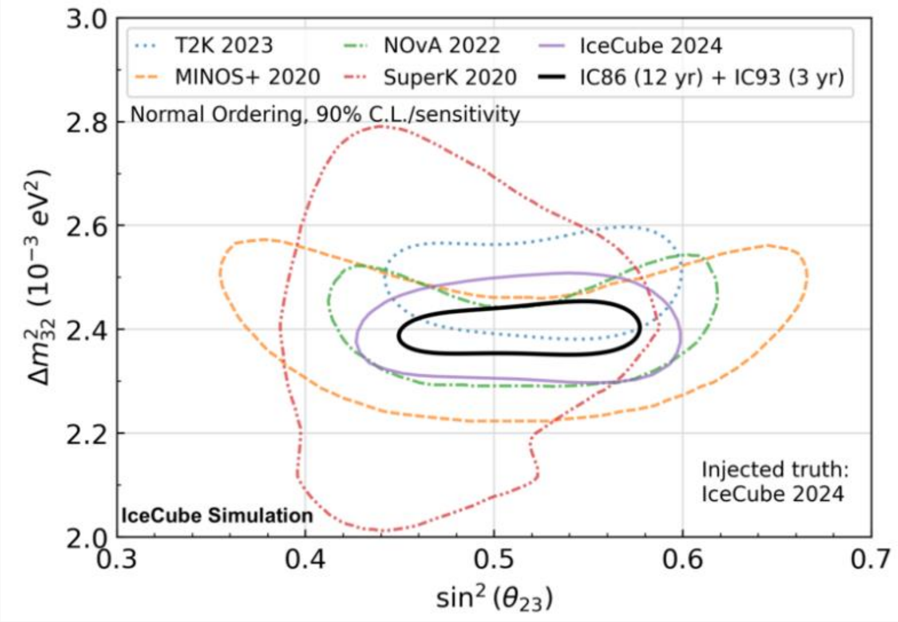
- Good precision on $\sin^2\theta_{23}$ and Δm^2_{3l} achievable
  - Better than current limits by small factor
  - Less precise than DUNE, Hyper-K and JUNO (Δm^2_{3l})





IceCube
ESPPU
Contrib.

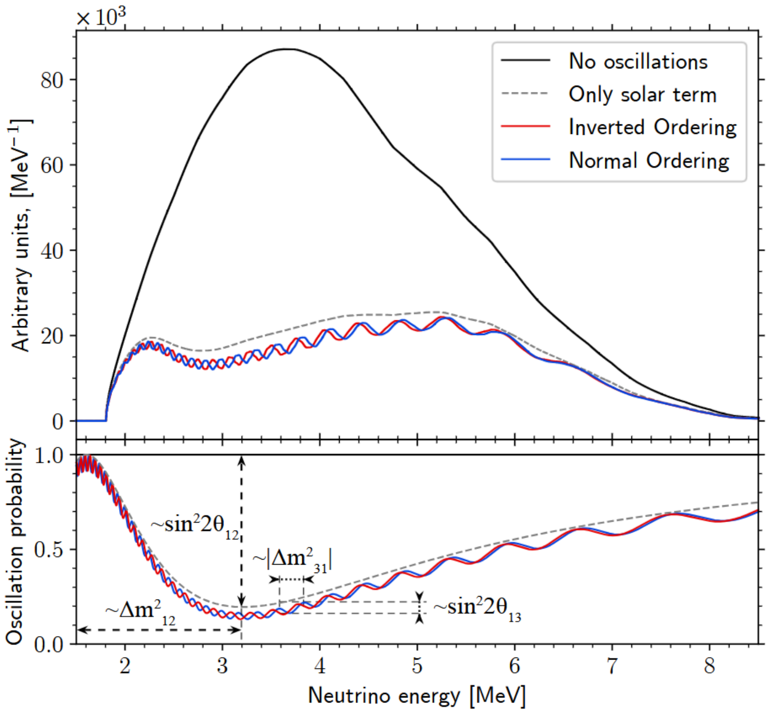




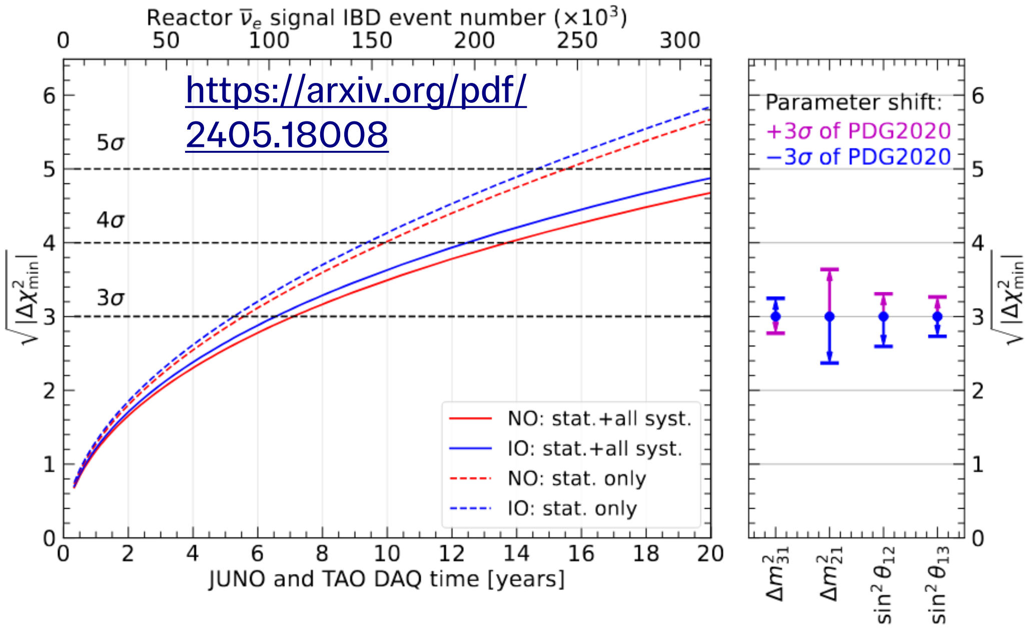
KM3NeT
ESPPU
Contrib.

Measurements from JUNO

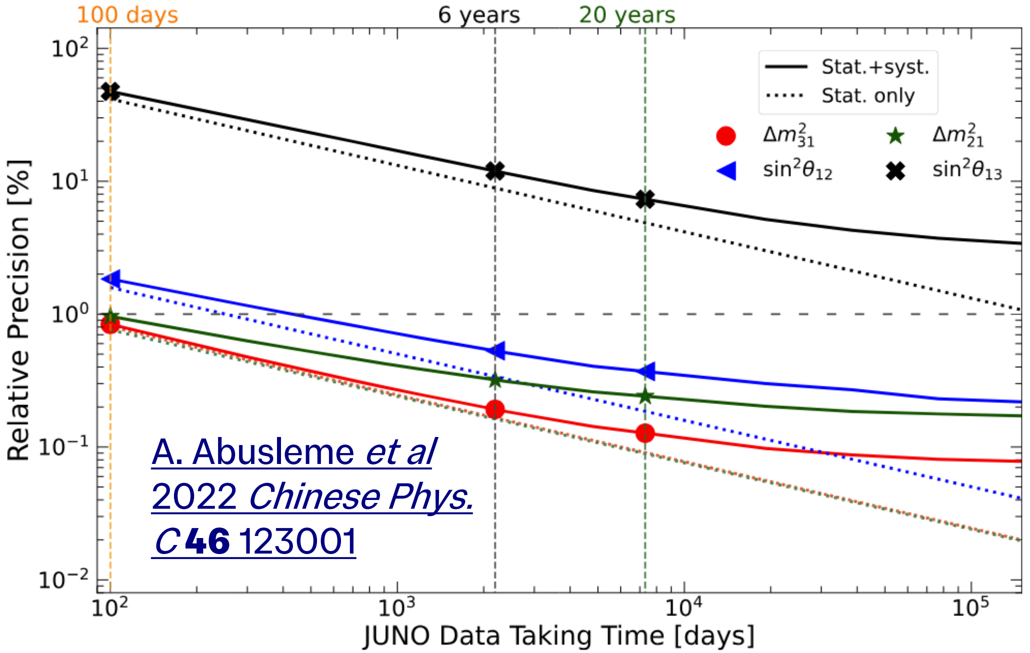
- Plan to measure fast oscillation on top of larger oscillation
  - Relies on precise energy calibration
- Predict $3-5\sigma$ sensitivity to MO after 7 – 20 years operation
- After 6 years predict:
  - 0.2% precision on Δm^2_{31}
  - 0.3% precision on Δm^2_{21}
  - 0.5% precision on $\sin^2\theta_{12}$



JUNO ESPPU Contrib.



https://arxiv.org/pdf/2405.18008

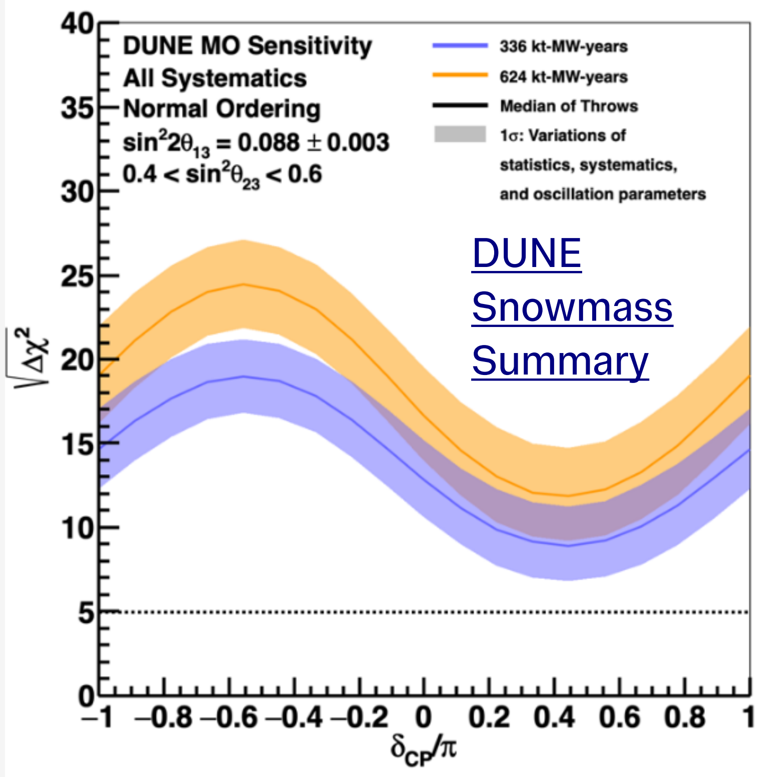


A. Abusleme *et al* 2022 *Chinese Phys. C* **46** 123001

Mass Ordering

Hyper-K and DUNE

- DUNE expects 5σ MO sensitivity for all values of δ_{CP} with 70 kt-MW-years exposure (~3 years of Phase I)



- Hyper-K expects $4 - 6\sigma$ MO sensitivity after 10 years exposure, combining beam and atmospheric neutrinos