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Oscillations: importance and challenges of combination of present and future experiments

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Oscillations: importance and challenges of combination of present and future experiments

Caveat – will focus on future long-baseline beam experiments and general concepts rather than details of current generation

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With thanks to L. Berns, N. Wardle and C. Wret

Overview

- Neutrino oscillations and experiments

- Why combine neutrino experiments?
  - Degeneracies
  - Precision
  - New Physics

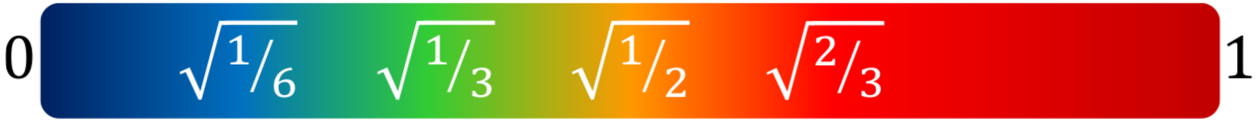
- How should we combine experiments?

Neutrinos oscillations

- Mixing of flavour and mass eigenstates

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

- Oscillation probability is function of neutrino energy, E, and propagation distance L

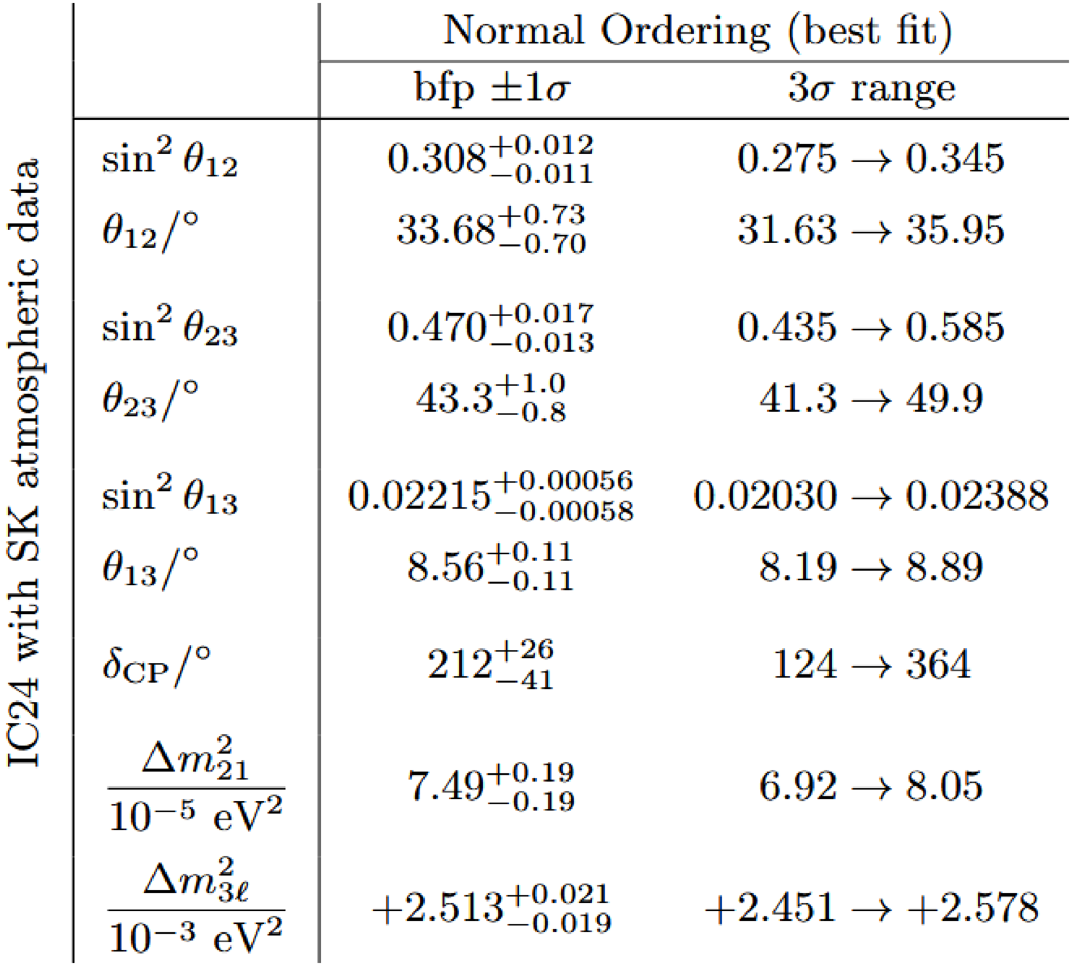


$$P_{\alpha\rightarrow\beta} = \left|\sum_i U^*_{\alpha i}\, U_{\beta i}\, e^{-i m_i^2 L/2E}\right|^2$$

[NuFit 6.0, JHEP 12 (2024) 216](#)

Current knowledge

- Impressive progress measuring oscillation parameters



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

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

[NuFit 6.0, JHEP 12 (2024) 216]

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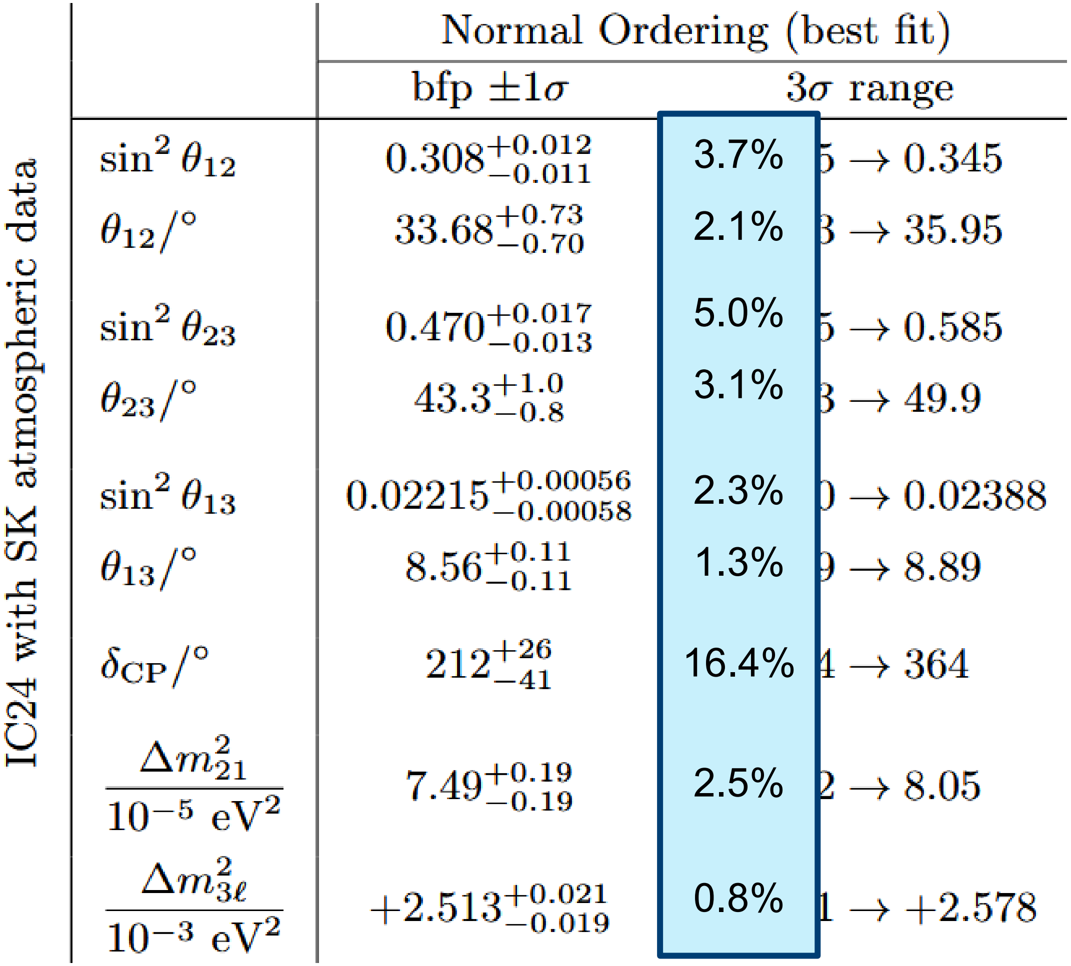
Current knowledge

- Impressive progress measuring oscillation parameters

- Open questions:
  - Octant of θ_{23}
  - Mass ordering
  - CP violation?
  - Value of δ_{CP}
  - Unitarity of PMNS
  - Other new physics?



		Normal Ordering (best fit)		
		bfp $\pm 1\sigma$		3σ range
IC24 with SK atmospheric data	$\sin^2\theta_{12}$	$0.308^{+0.012}_{-0.011}$	3.7%	$5 \to 0.345$
	$\theta_{12}/^\circ$	$33.68^{+0.73}_{-0.70}$	2.1%	$3 \to 35.95$
	$\sin^2\theta_{23}$	$0.470^{+0.017}_{-0.013}$	5.0%	$5 \to 0.585$
	$\theta_{23}/^\circ$	$43.3^{+1.0}_{-0.8}$	3.1%	$3 \to 49.9$
	$\sin^2\theta_{13}$	$0.02215^{+0.00056}_{-0.00058}$	2.3%	$0 \to 0.02388$
	$\theta_{13}/^\circ$	$8.56^{+0.11}_{-0.11}$	1.3%	$9 \to 8.89$
	$\delta_{\mathrm{CP}}/^\circ$	212^{+26}_{-41}	16.4%	$4 \to 364$
	$\dfrac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.49^{+0.19}_{-0.19}$	2.5%	$2 \to 8.05$
	$\dfrac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.513^{+0.021}_{-0.019}$	0.8%	$1 \to +2.578$

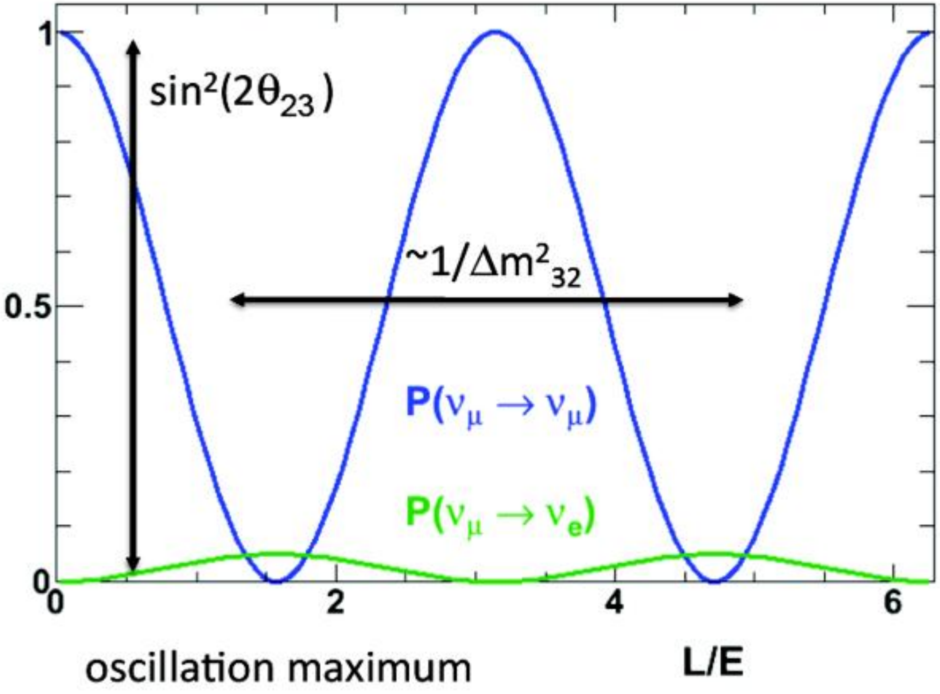
See also F. Capozzi et al., Phys. Rev. D 104, 8, 083031
P. F. de Salas et al., JHEP 02, 071 (2021)

Oscillation probabilities

- Leading order oscillation probabilities for ν_μ survival and ν_e appearance

$$\boxed{P(\nu_\mu \to \nu_\mu) \cong 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m_{32}^2 L}{4E}\right)}$$

$$\boxed{P(\nu_\mu \to \nu_e) \cong \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right)}$$



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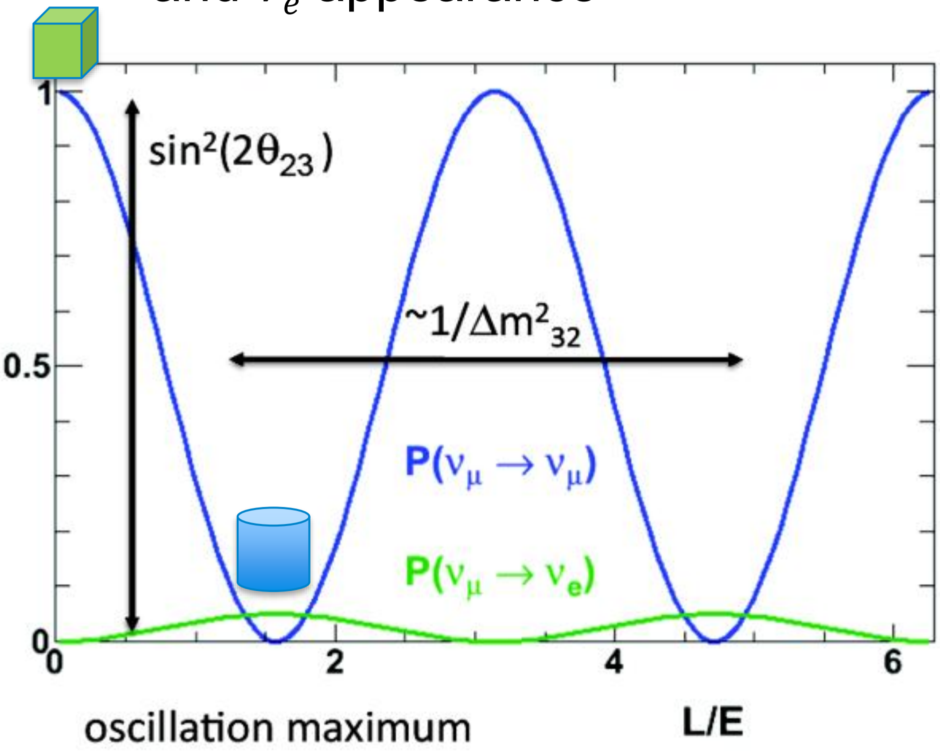
Oscillation probabilities

- Leading order oscillation probabilities for ν_μ survival and ν_e appearance

$$P(\nu_\mu \to \nu_\mu) \cong 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$$

$$P(\nu_\mu \to \nu_e) \cong \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$



- Place detectors at zero distance and at oscillation dip
- Measuring oscillation probability requires accurate reconstruction of neutrino species and energy

Sensitivity to unknown oscillation parameters

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) = {} & 4c_{13}^{2} s_{13}^{2} s_{23}^{2} \sin^2 \Delta_{31} && \boxed{\theta_{13}} \\
& + 8c_{13}^{2} s_{12} s_{13} s_{23} (c_{12} c_{23} \cos\delta - s_{12} s_{13} s_{23}) \cos\Delta_{32} \sin\Delta_{31} \sin\Delta_{21} && \boxed{\text{CPC}} \\
& - 8c_{13}^{2} c_{12} c_{23} s_{12} s_{13} s_{23} \sin\delta \sin\Delta_{32} \sin\Delta_{31} \sin\Delta_{21} && \boxed{\text{CPV}} \\
& + 4s_{12}^{2} c_{13}^{2} (c_{12}^{2} c_{23}^{2} + s_{12}^{2} s_{23}^{2} s_{13}^{2} - 2c_{12} c_{23} s_{12} s_{23} s_{13} \cos\delta) \sin^2 \Delta_{21} && \boxed{\text{Solar}}
\end{aligned}
$$

replace δ by –δ for $P(\overline{\nu_\mu} \to \overline{\nu_e})$

$c_{ij} = \cos\theta_{ij}, s_{ij} = \sin\theta_{ij}$

$$\Delta_{ij} = \Delta m_{ij}^2 \frac{L}{4E_\nu}$$

Sensitivity to unknown oscillation parameters

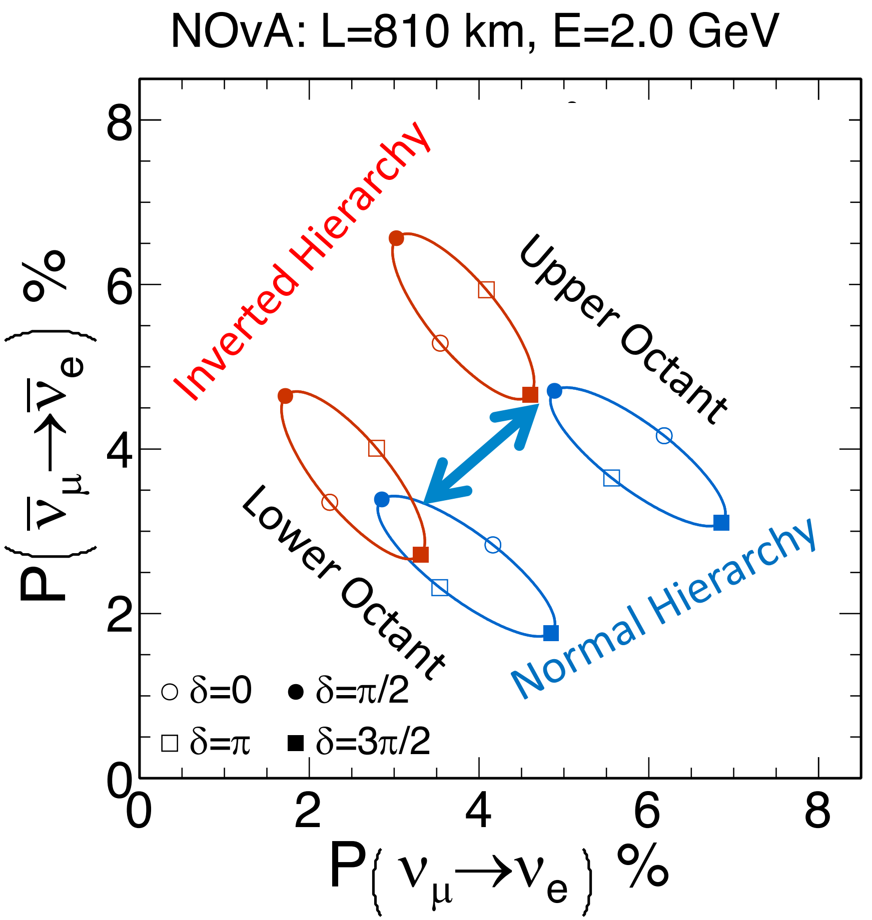


Image by A. Himmel / NOvA

Many experiments to enjoy (oscillation focus)

HYPER K

DUNE
DEEP UNDERGROUND
NEUTRINO EXPERIMENT

SUPER K

NOvA

Daya Bay
θ_{13}

ICECUBE

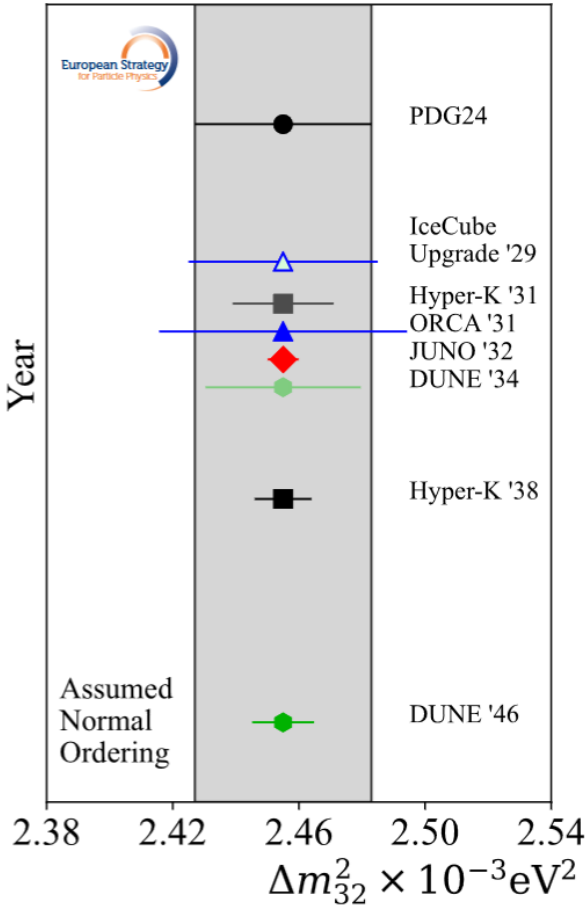
T2K

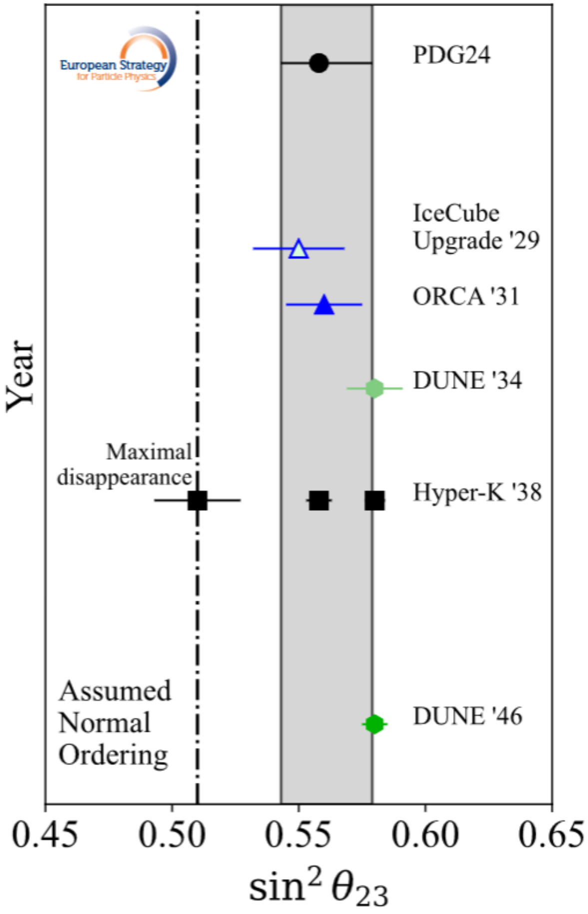
SNO

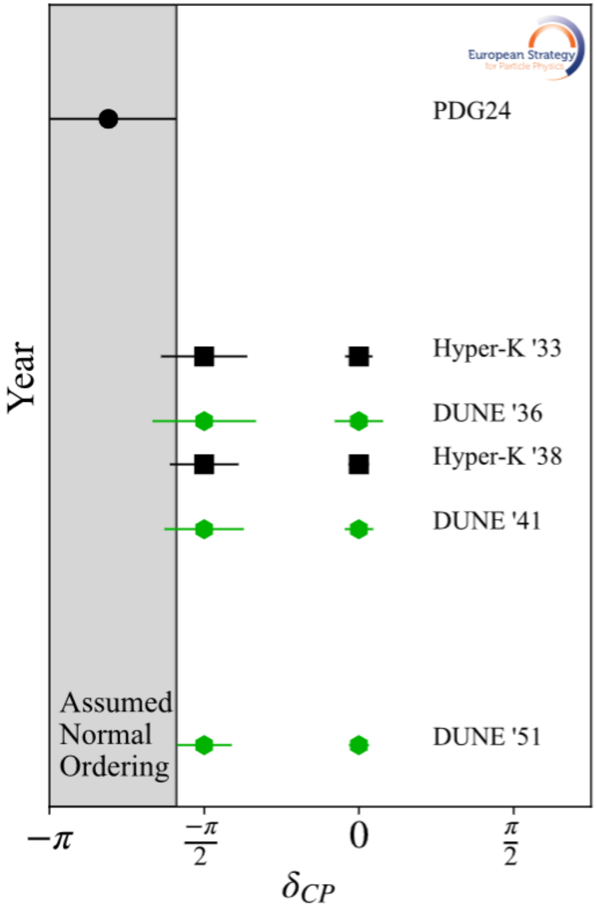
KamLAND
Kamioka Liquid scintillator Anti-Neutrino Detector

JUNO

Current and future status – atmospheric mixing



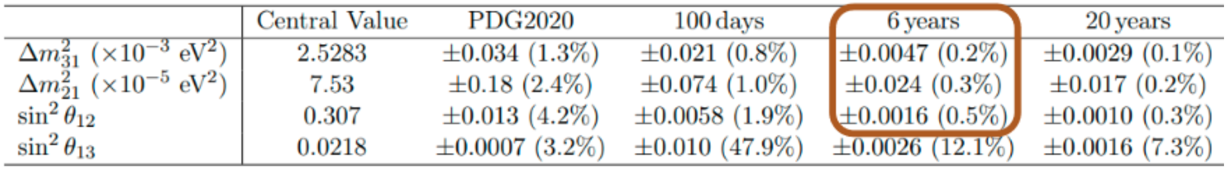




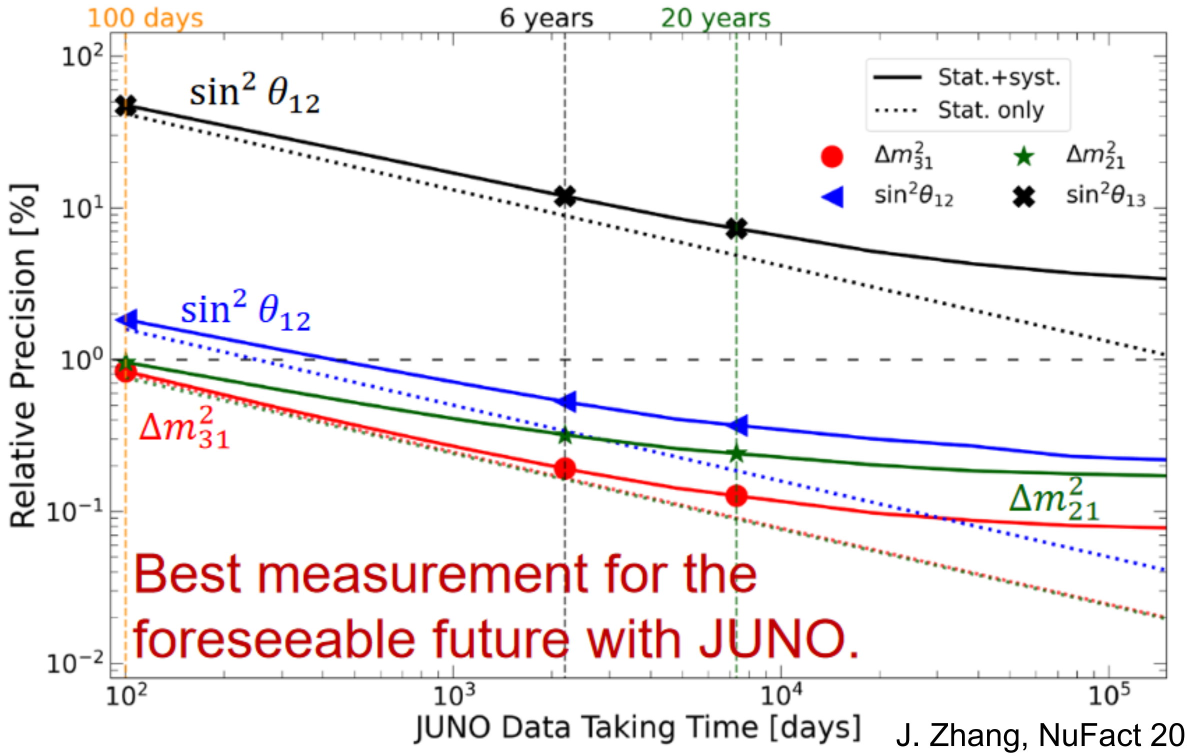
Current and future status – solar mixing

- Daya Bay/RENO lead precision on θ_{13}
    - DUNE and HK will provide modest improvement
- JUNO will provide $\Delta m^2{}_{21}$, $\Delta m^2{}_{31}$, and θ_{12}

Precision of $\sin^2\theta_{12}$, Δm^2_{21}, $|\Delta m^2_{31}|/|\Delta m^2_{32}|$ < 0.5% in 6 yrs



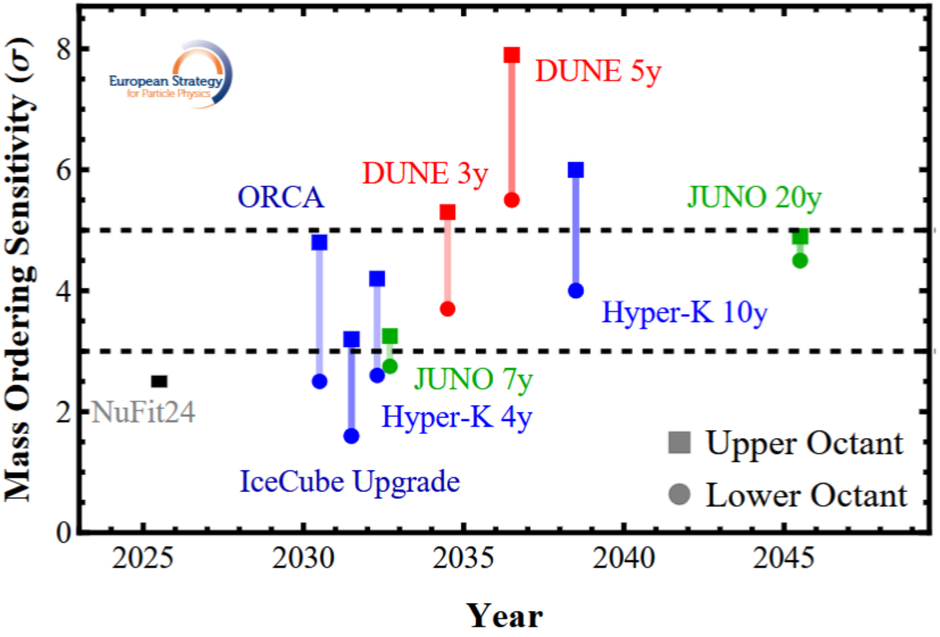
	Central Value	PDG2020	100 days	6 years	20 years
Δm^2_{31} ($\times 10^{-3}$ eV^2)	2.5283	±0.034 (1.3%)	±0.021 (0.8%)	±0.0047 (0.2%)	±0.0029 (0.1%)
Δm^2_{21} ($\times 10^{-5}$ eV^2)	7.53	±0.18 (2.4%)	±0.074 (1.0%)	±0.024 (0.3%)	±0.017 (0.2%)
$\sin^2\theta_{12}$	0.307	±0.013 (4.2%)	±0.0058 (1.9%)	±0.0016 (0.5%)	±0.0010 (0.3%)
$\sin^2\theta_{13}$	0.0218	±0.0007 (3.2%)	±0.010 (47.9%)	±0.0026 (12.1%)	±0.0016 (7.3%)

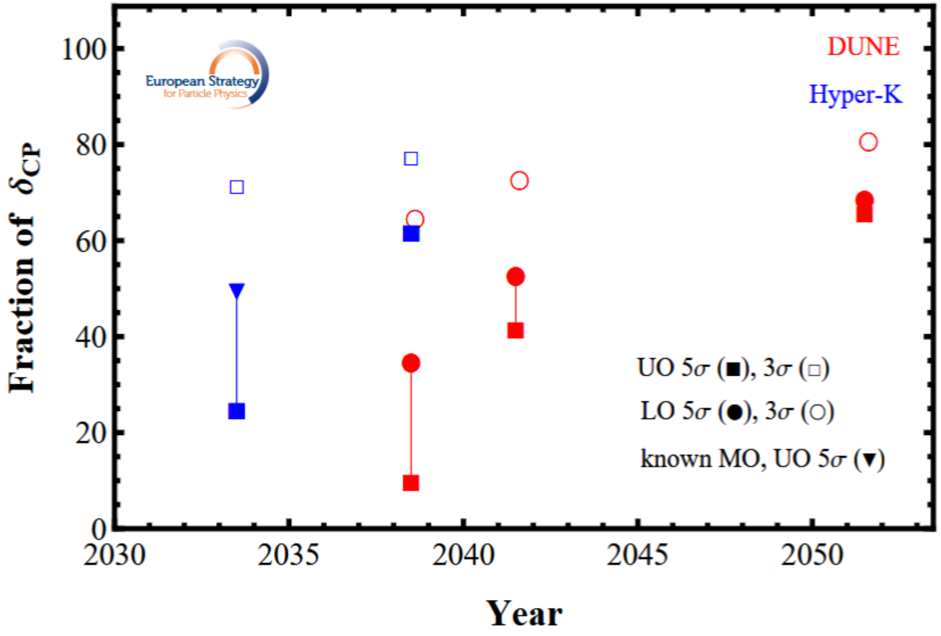


Best measurement for the foreseeable future with JUNO.

J. Zhang, NuFact 2022

Current and future status – CPV and MO





- Many experiments with mass ordering sensitivity, DUNE dominates by 2036
- Hyper-K and DUNE sensitive to CP violation

Why should we combine experiments?

EPJC, 83, No.782, (2023)

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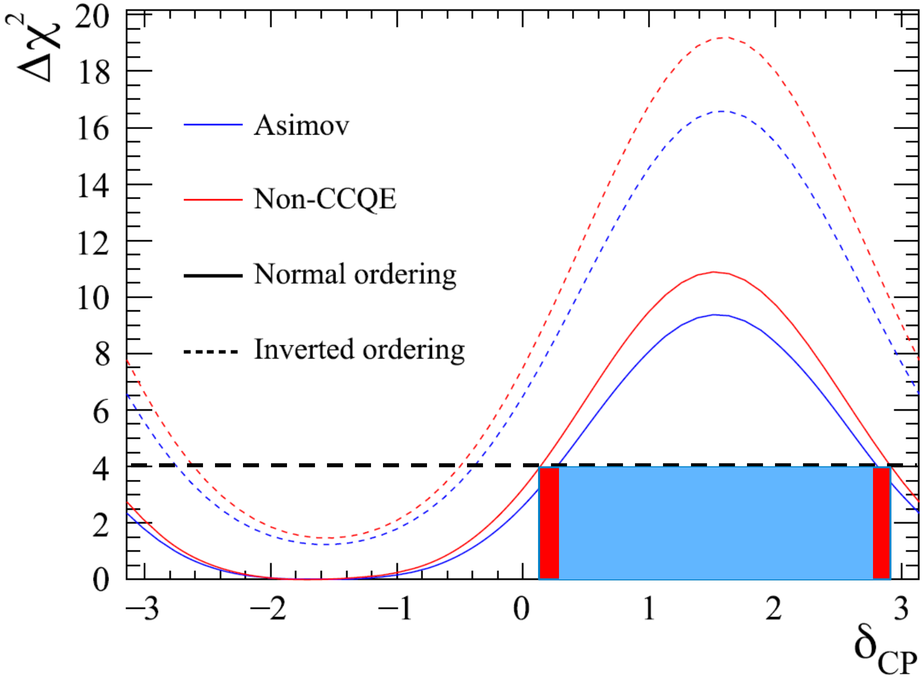
Why combine data? Improved robustness

- Neutrino interaction cross-section has significant uncertainty
  - Dominant systematic in oscillation measurements, even after near detector tuning
  - Multiple valid models exist that make different predictions

- T2K developed simulated data studies to quantitatively assign uncertainty due to model choice



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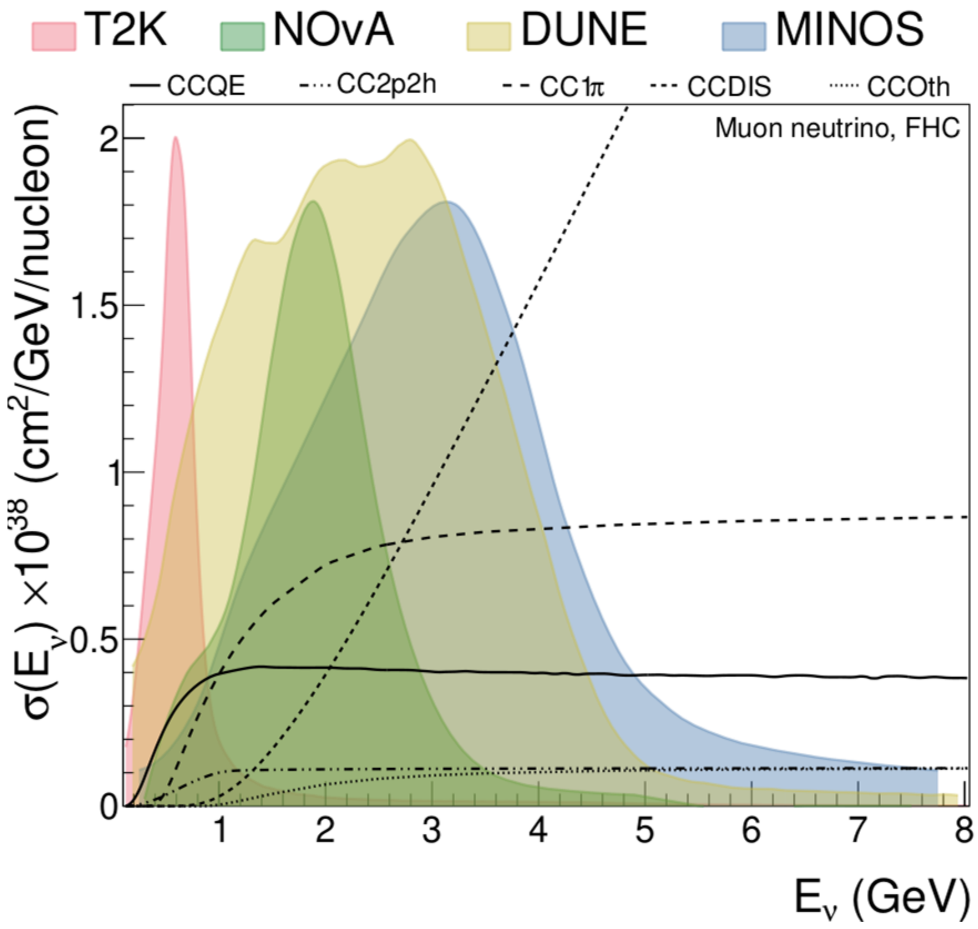
Why combine data? Improved robustness

- Significant overlap in energy between neutrino beams

- Different energies give different physics and interaction sensitivities

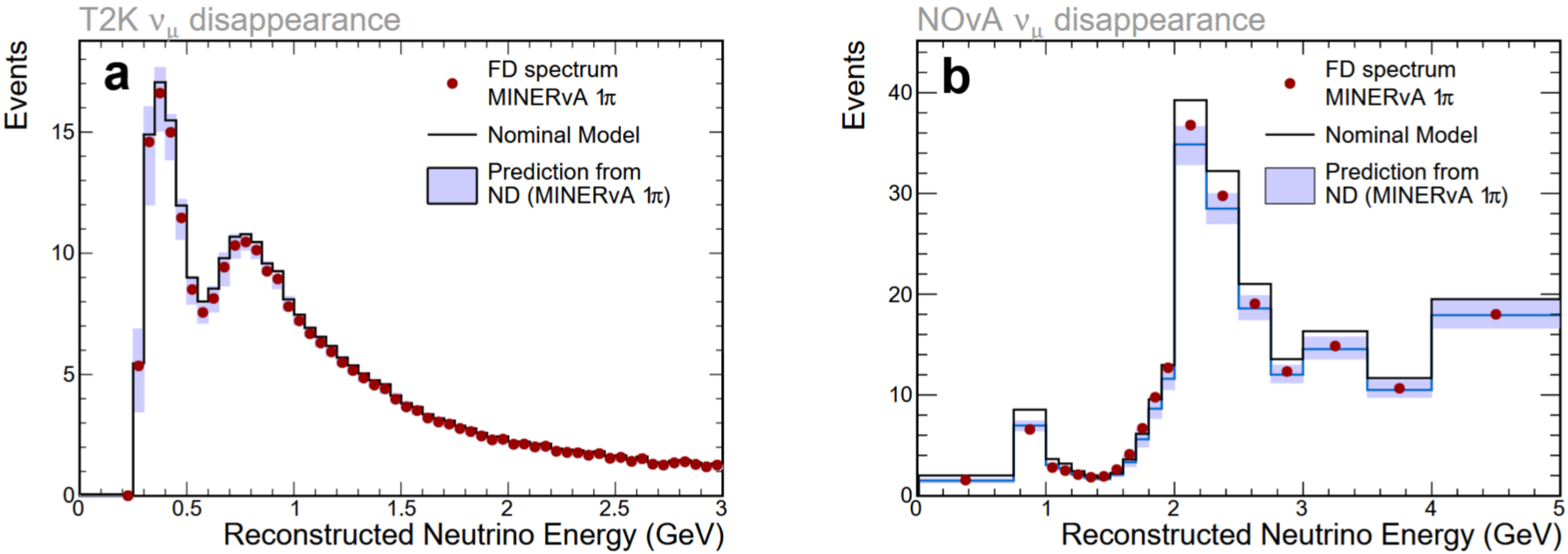


Plot courtesy C. Wret

Nature 646, 818-824 (2025)

Why combine data? Improved robustness

- T2K combined analysis with NOvA performed simulated data studies similar to those done by T2K
- Vary Q^2 suppression of CC1π cross-section –T2K shows event rate change in oscillation dip, while NOvA sees change in tails


T2K ν_μ disappearance

NOvA ν_μ disappearance

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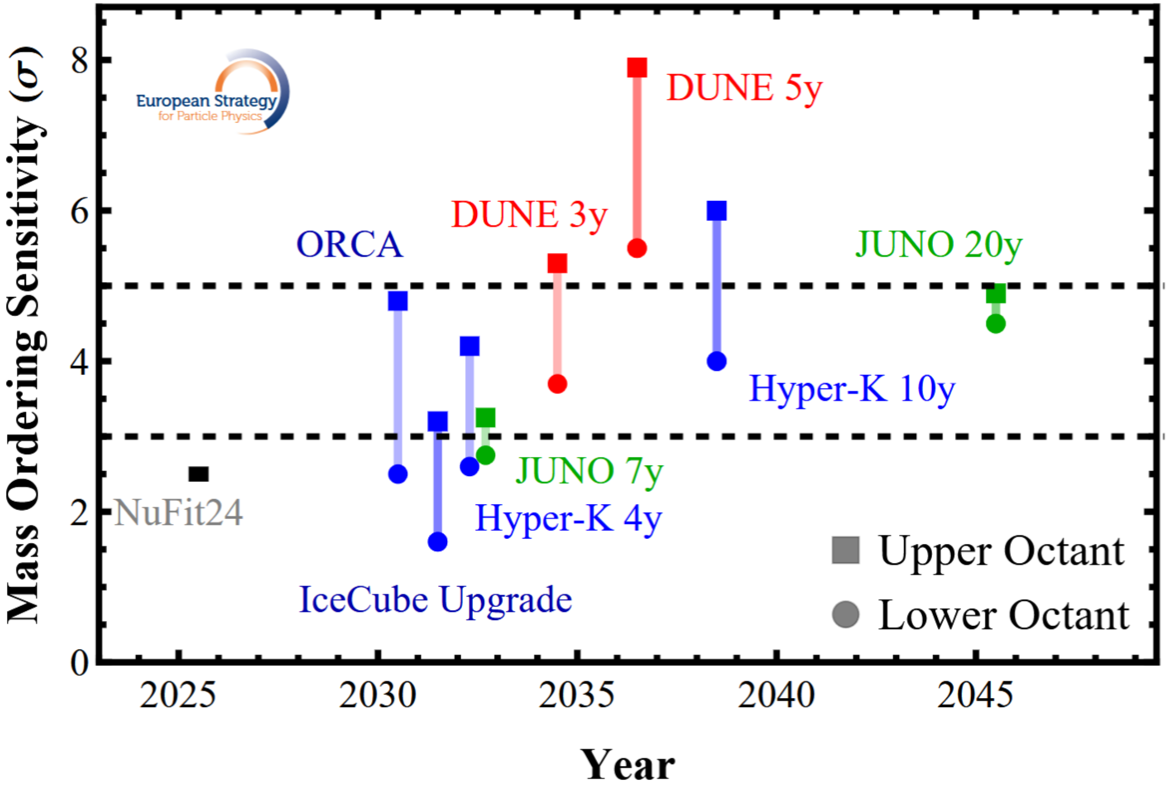
Why combine data? Faster discovery

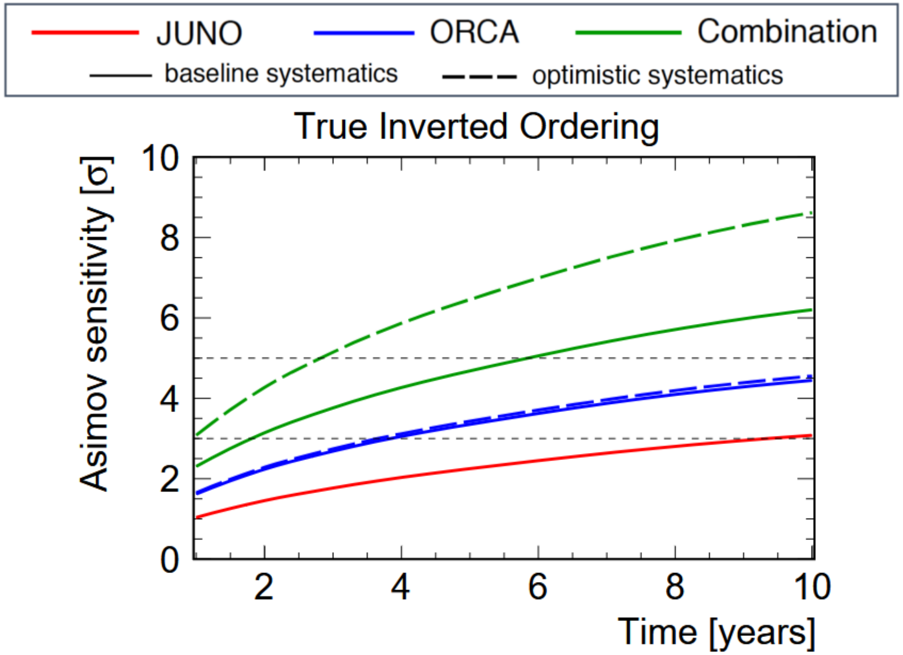
- Neutrino mass ordering will be known by 2036



CERN-ESU-2025-001

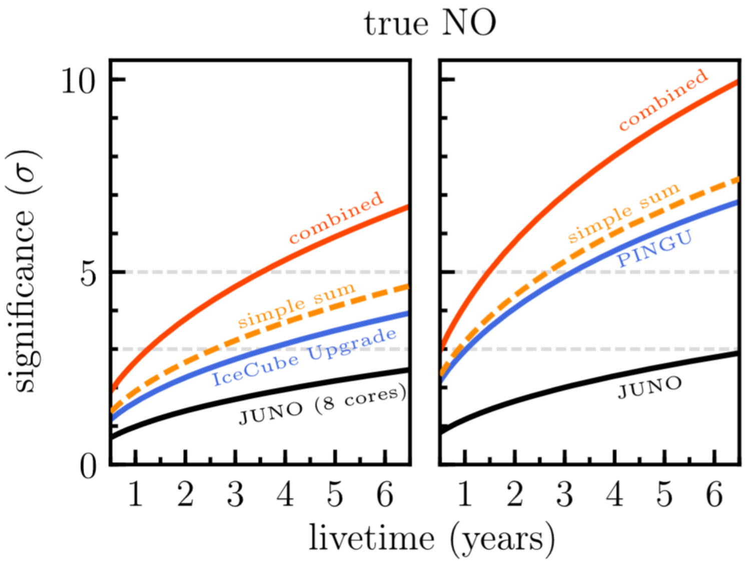
Why combine data? Faster discovery

- Neutrino mass ordering will be known ~~by 2036~~ before 2036!
- JUNO provides unique sensitivity to MO, independent of matter effect measurement



JHEP 03 (2022) 055

JUNO + IceCube



PRD 101, 032006 (2020)

Why combine data? Fast and robust discovery

- Reactor disappearance measures different mass splitting to long-baseline disappearance. To leading order:

$$\Delta m^2_{ee} = \Delta m^2_{31} \cos^2\theta_{12} + \Delta m^2_{32} \sin^2\theta_{12}$$

$$\Delta m^2_{\mu\mu} \approx \Delta m^2_{31} \sin^2\theta_{12} + \Delta m^2_{32} \cos^2\theta_{12} + \sin^2\theta_{13} \cos\delta_{CP}\, \Delta m^2_{21}$$

- Should see $|\Delta m^2_{ee}| > |\Delta m^2_{\mu\mu}|$ for NO, opposite for IO
  - Difference is at the ~couple of percent level

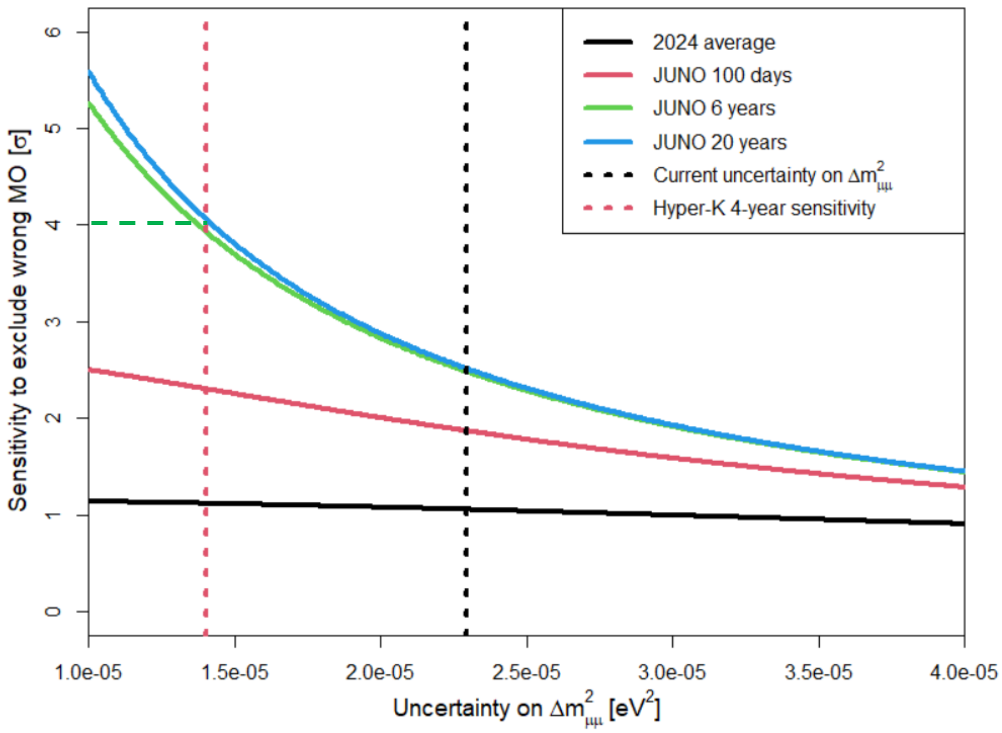
- JUNO provides ~0.3% uncertainty measurements of neutrino mass splitting
- Next-generation long-baseline experiments estimate <1% uncertainty

Courtesy of L. Berns,
Inspired by S. Parke and R. Funchal, Phys.Rev.D 111 (2025) 1, 013008

Why combine data? Fast and robust discovery

- Can calculate χ^2 between NO and IO assuming current best fit oscillation parameters, then show significance as a function of precision on $\Delta m^2_{\mu\mu}$

- Four years operation at HK gives 4σ MO significance in **disappearance** channel alone!
  - Adding appearance and atmospherics will give higher significance

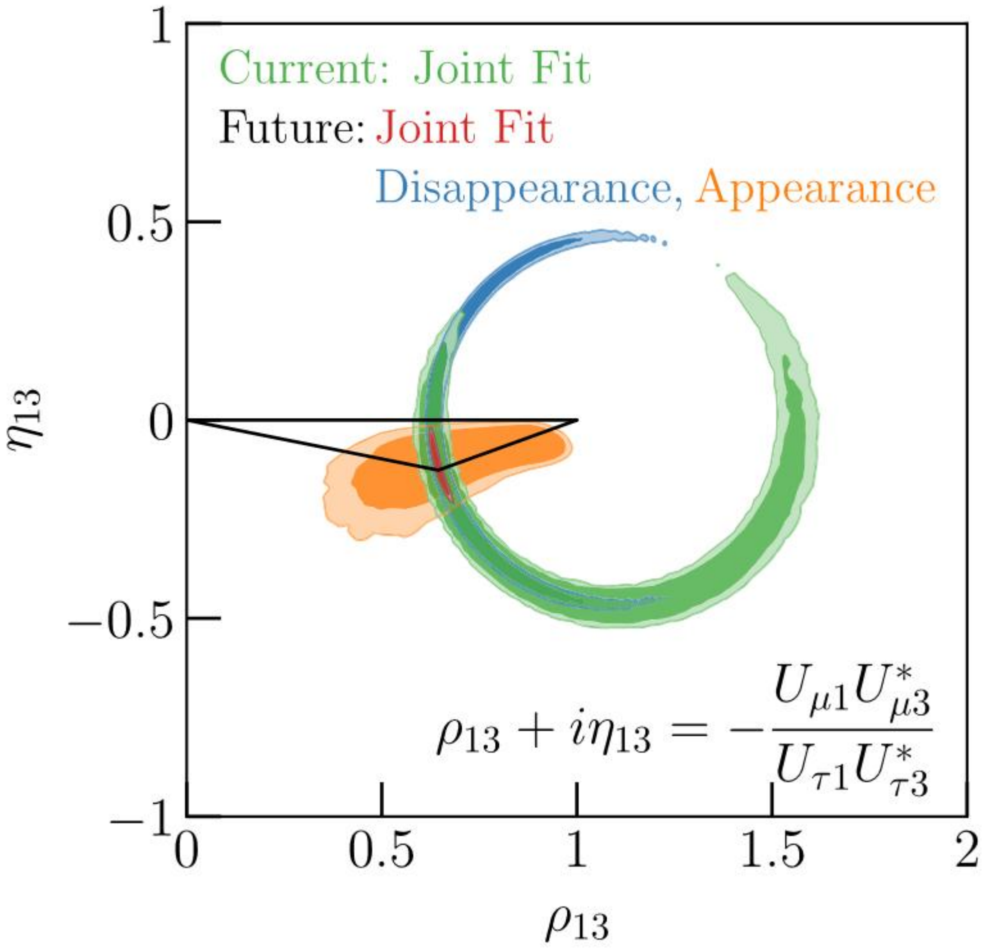


Courtesy of L. Berns,
Inspired by S. Parke and R. Funchal, Phys.Rev.D 111 (2025) 1, 013008

Why combine data? New Physics

- Many new physics models (Non-Standard Interactions, neutrino decay, sterile neutrinos etc.) would lead to apparent non-unitarity
  - Combining experiments (JUNO, IceCube, DUNE, HK) necessary to isolate individual PMNS elements
  - Test consistency between neutrino experiments

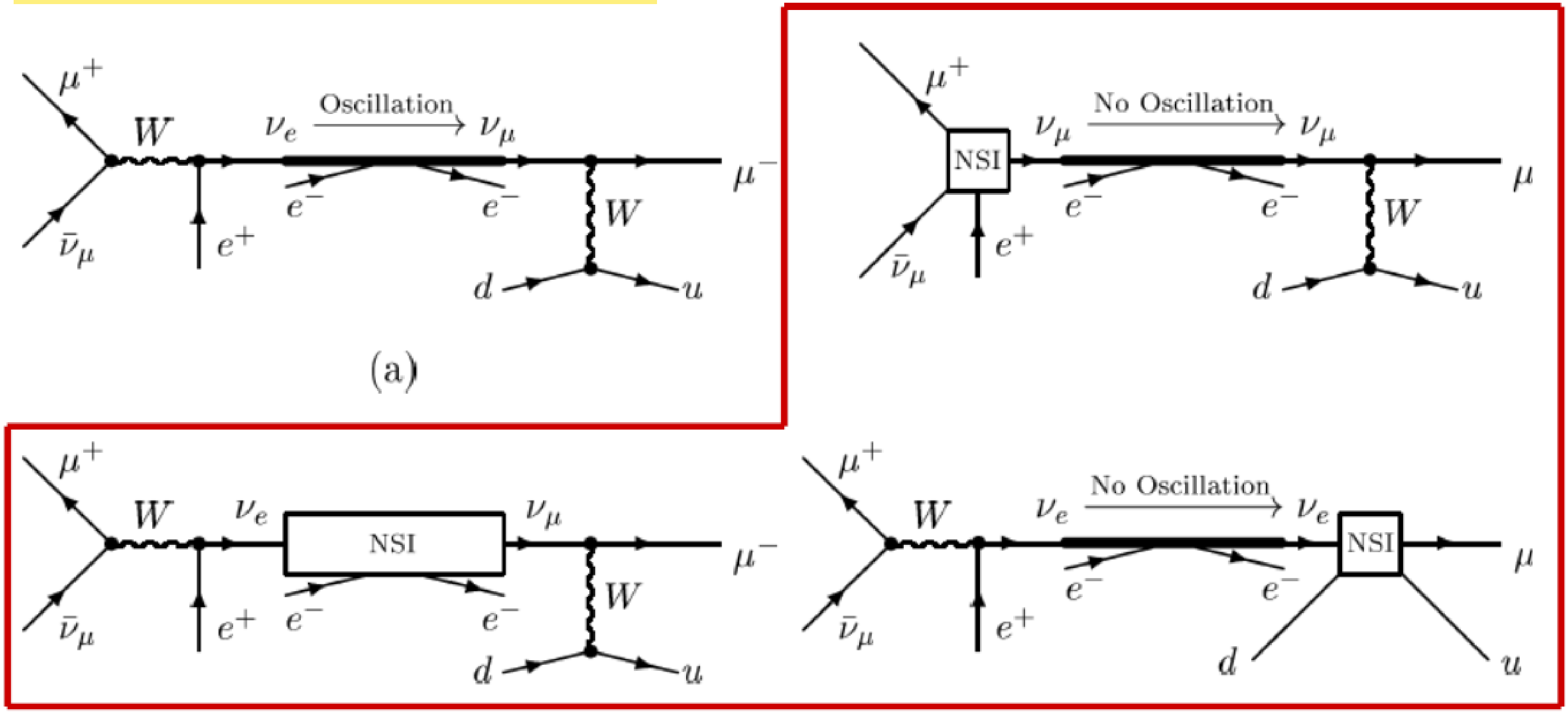
PHYS. REV. D 102, 115027 (2020)



NSIs interfere with Oscillations

the “golden” oscillation channel

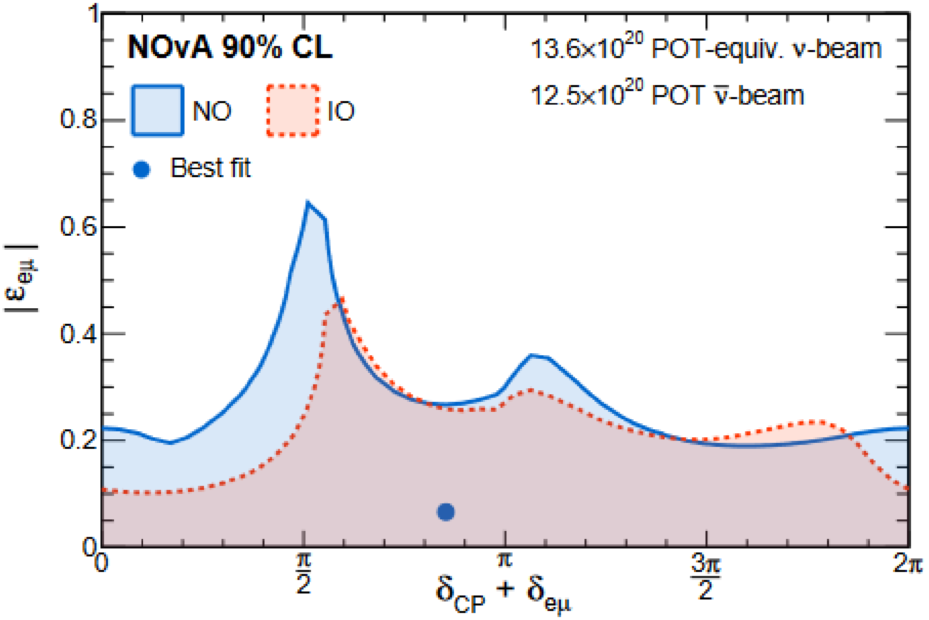
NSI contributions to the “golden” channel

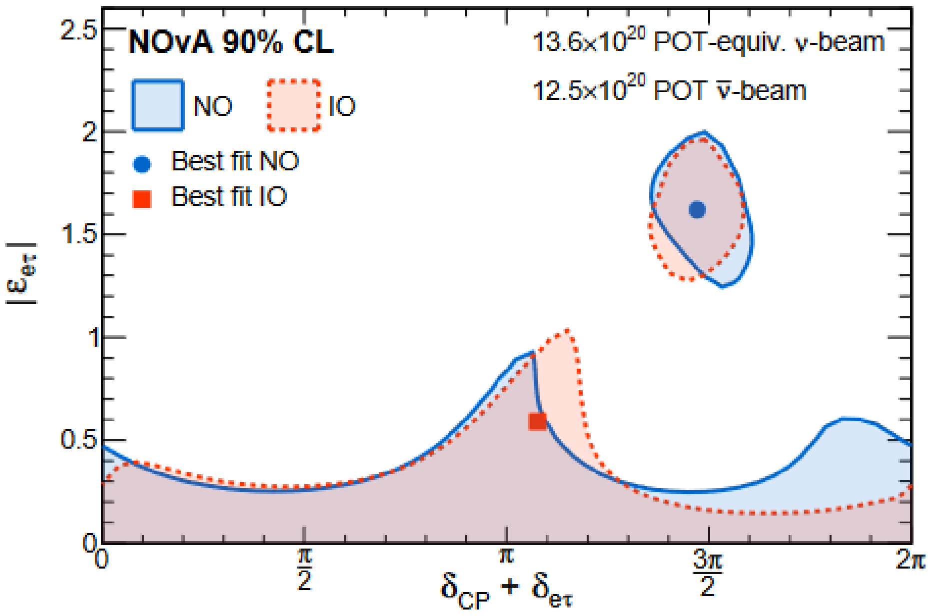


interference in oscillations $\sim\varepsilon$ ⟷ FCNC effects $\sim\varepsilon^2$

NOvA NSI results

- Analysis uses regular oscillation event samples
- Add new phases and mixing magnitudes for NSI in $e \rightarrow \mu$ and $e \rightarrow \tau$ oscillations

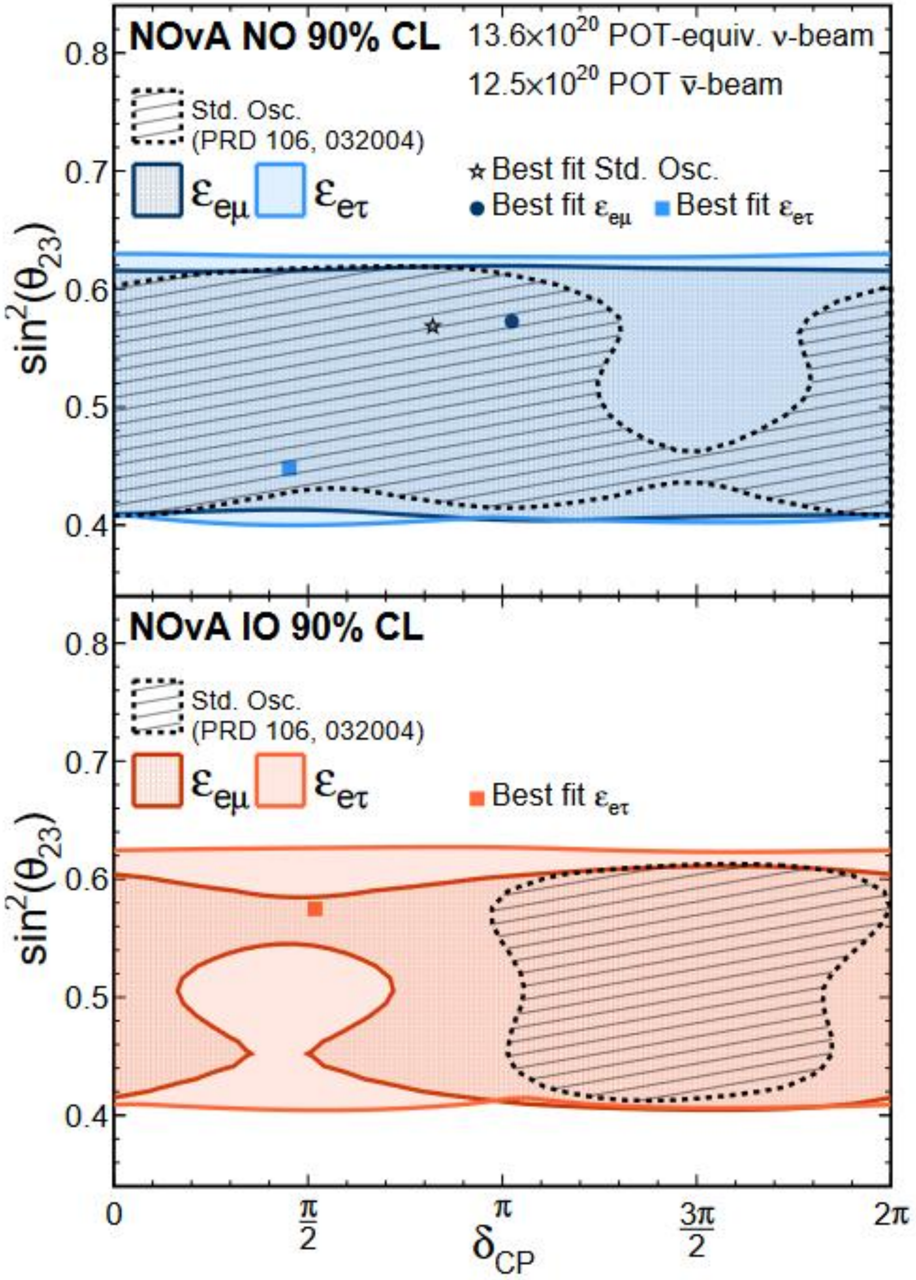




https://arxiv.org/abs/2403.07266

NOvA NSI results

- Impact on PMNS δ_{CP} and octant
- Including NSI removes almost all sensitivity to δ_{CP} and octant in standard PMNS matrix
  - Effects are degenerate!



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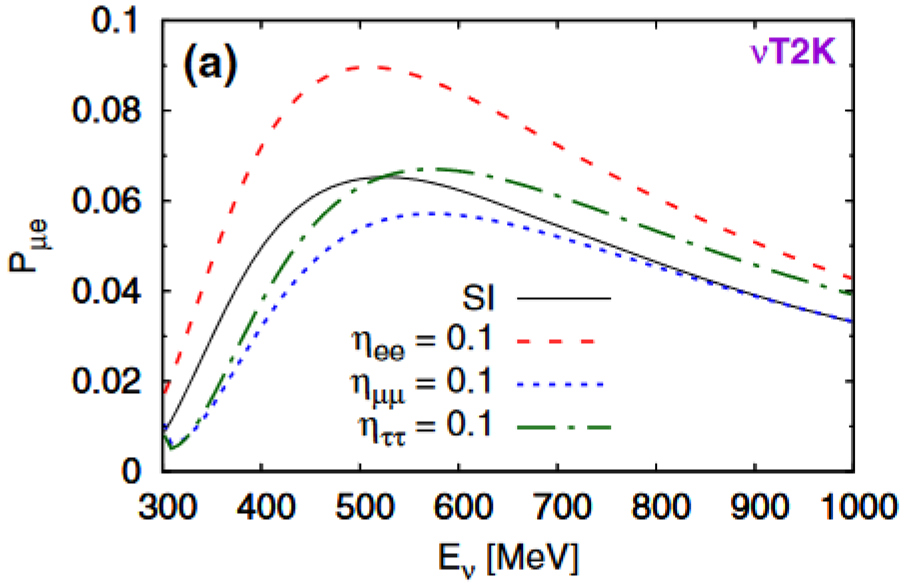
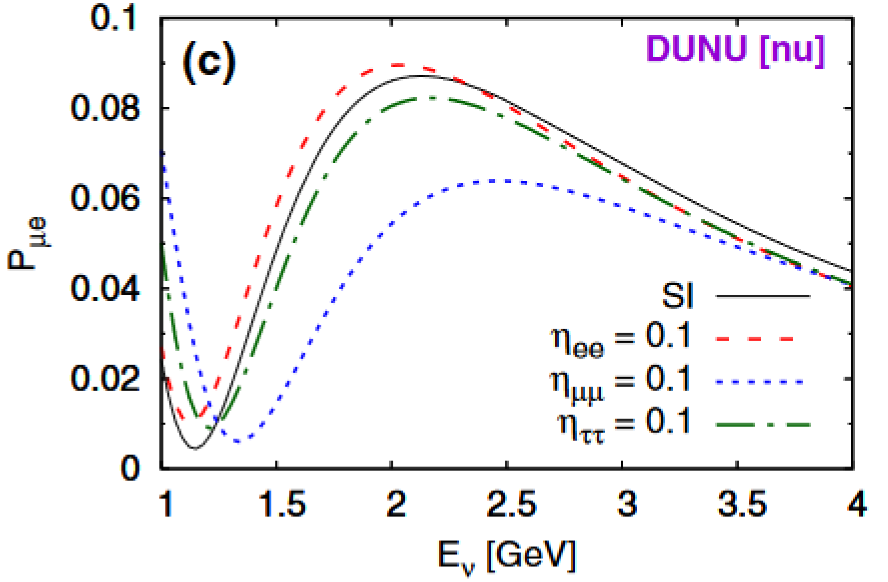
From PhysRevLett.122.211801

Multi-experiment NSI

- HK neutrinos travel 295km
- DUNE neutrinos travel 1300km

- See different NSI terms have different effects
  - Combining data from multiple experiments allows us to gain sensitivity
  - Break degeneracy with regular PMNS oscillations



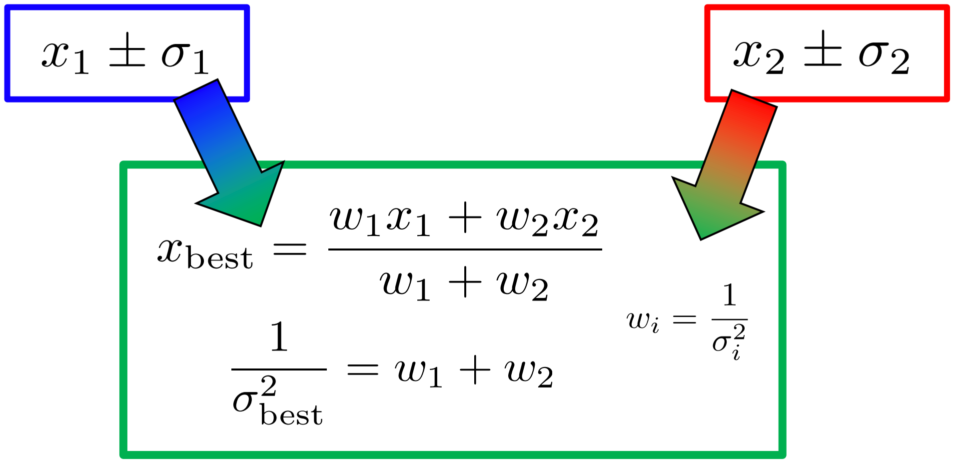


How should we combine experiments?

How to combine experimental results?

- Lots of existing expertise
  - LHC experiments
  - NuFit et al.
  - PDG
  - T2K + NOvA, T2K + Super-K

- Independent, Gaussian measurements with known correlations – relatively easy



$x_1 \pm \sigma_1$

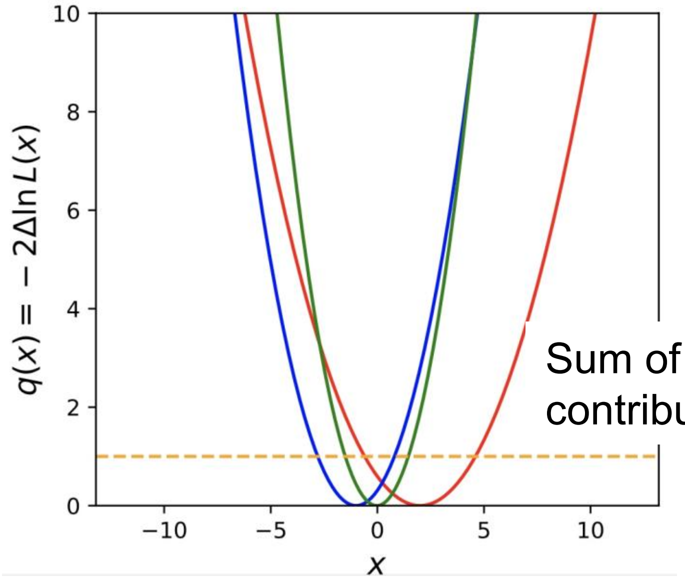
$x_2 \pm \sigma_2$

$$x_{\text{best}} = \frac{w_1 x_1 + w_2 x_2}{w_1 + w_2}$$

$$\frac{1}{\sigma^2_{\text{best}}} = w_1 + w_2$$

$$w_i = \frac{1}{\sigma_i^2}$$

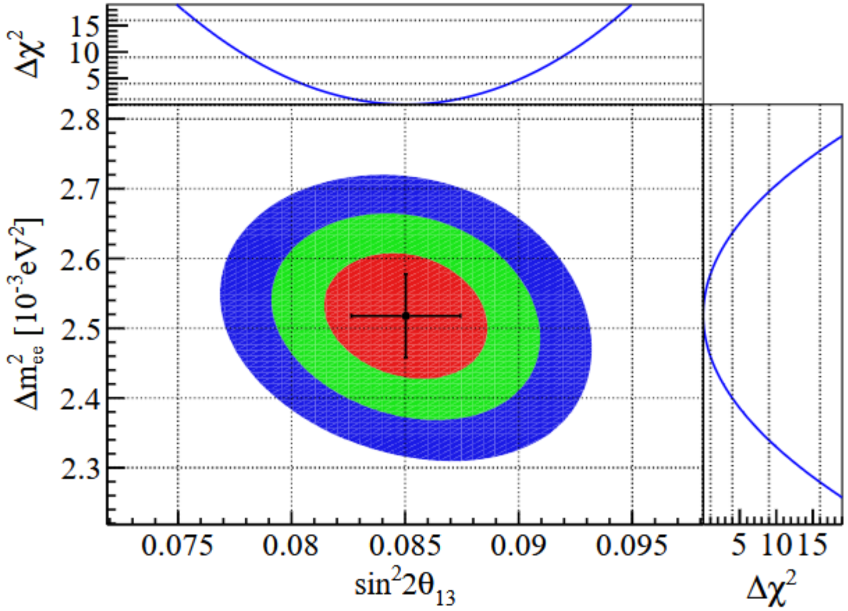
Courtesy N. Wardle



Sum of χ^2 contributions

Other methods of combination

- Publish χ^2 maps of the parameters of interest
  - Easy to combine experiments (just add maps)
  - Allows simple correlation of parameters between experiments
  - Can include multiple dimensions to get correlations within an experiment

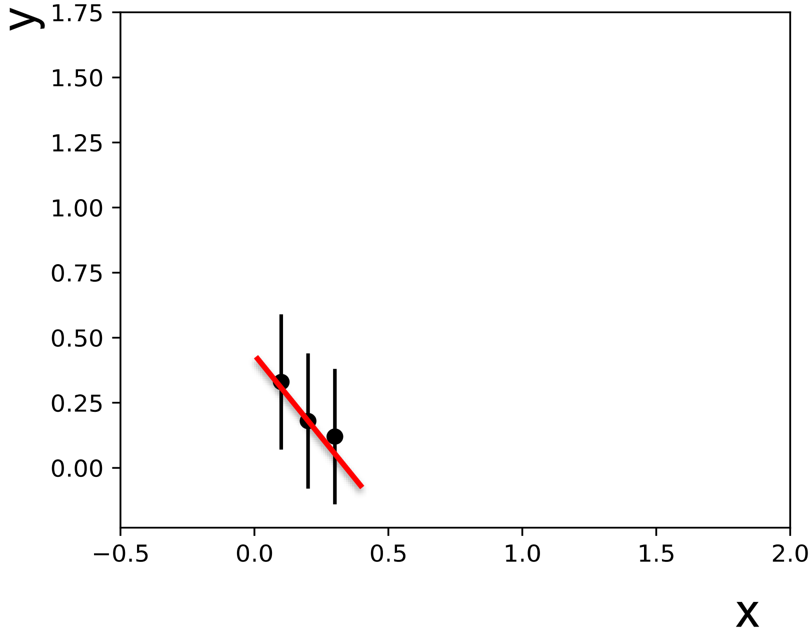


https://arxiv.org/abs/2309.05989

- In future might need high-dimensionality surfaces at high significance
  - >3σ for CPV discovery?
- Disjoint likelihoods, such as mass-ordering hypotheses, pose difficulties

Warning about combining likelihoods

- Experiments marginalise/profile nuisance parameters – combining these reduced likelihoods not always correct



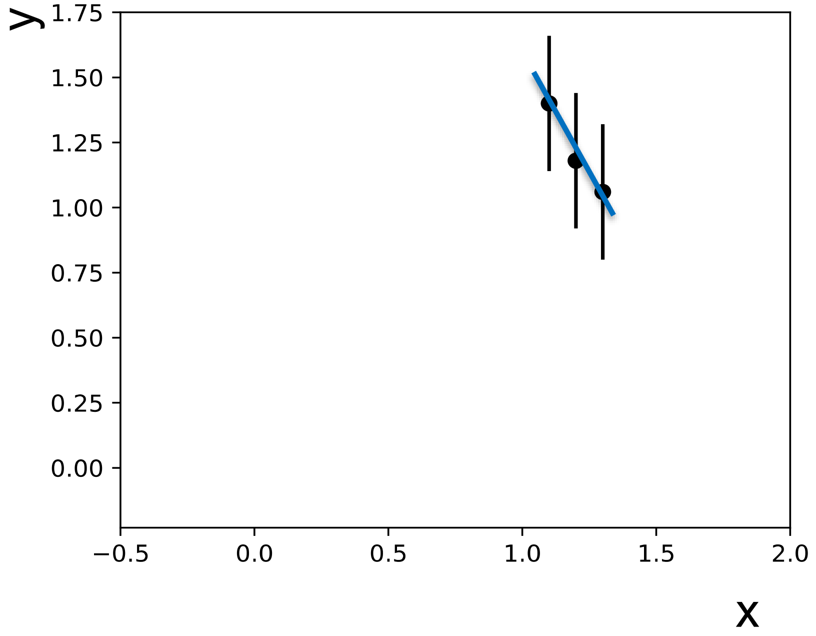
- Experiment 1 fits straight line to some data

$$y = mx + c$$

- Marginalise over parameter *c* and extract *m*

Warning about combining likelihoods

- Experiments marginalise/profile nuisance parameters – combining these reduced likelihoods not always correct



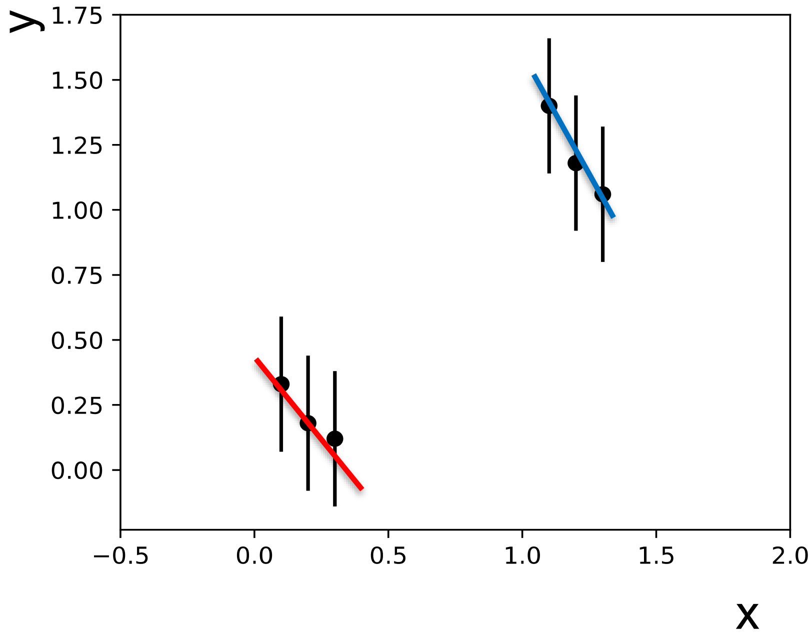
- Experiment 2 fits straight line to some data

$$y = mx + c$$

- Marginalise over parameter *c* and extract *m*

Warning about combining likelihoods

- Experiments marginalise/profile nuisance parameters – combining these reduced likelihoods not always correct



- Fit straight line to data

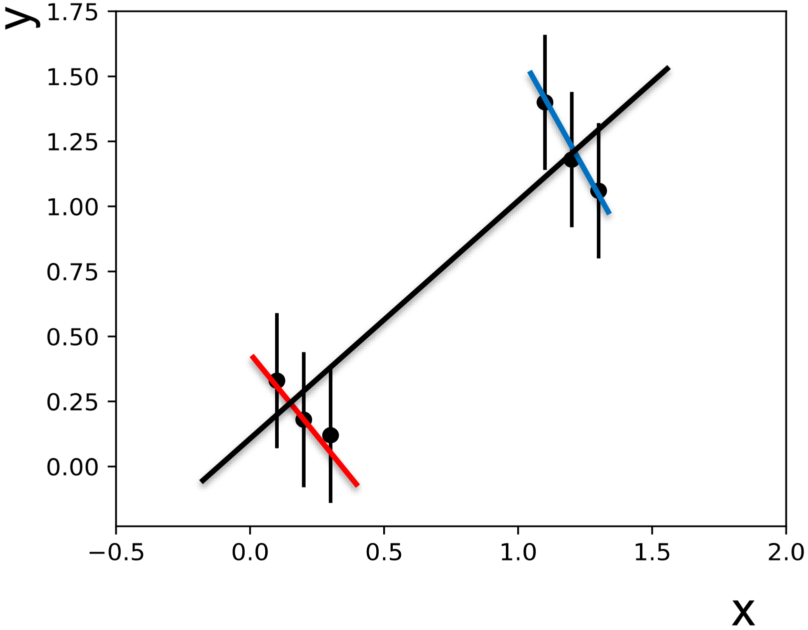
$$y = mx + c$$

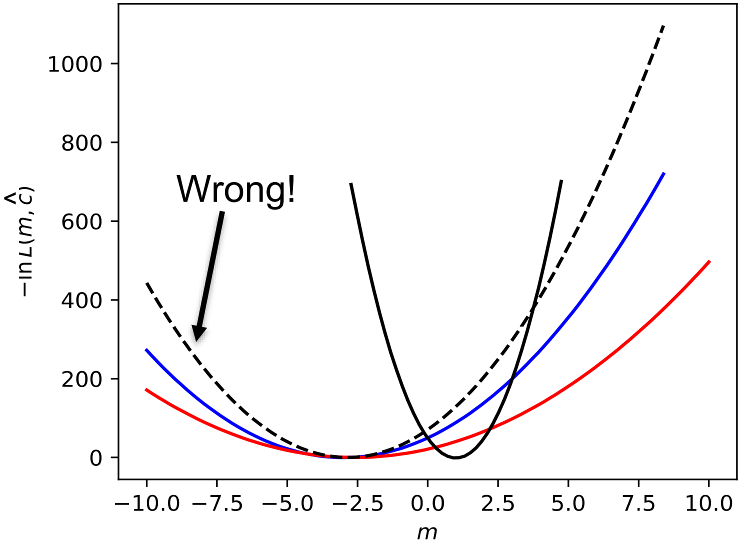
- Marginalise over parameter *c*
- What happens when we combine…

Example from L. Lyons

Warning about combining likelihoods

- Experiments marginalise/profile nuisance parameters – combining these reduced likelihoods not always correct





- T2K marginalizes over ~230 nuisance parameters, about half of which are shared by NOvA…

Summary

- Many benefits to combining neutrino data, and many ways to perform this combination
  - Simple methods likely not correct for high statistics neutrino data!
  - Direct combination of likelihoods preferred, but must understand correlations of both nuisance and signal parameters

- Beam experiments tune neutrino flux and interaction cross section models to near detector data
  - Need to “combine” near detector analyses as well
  - Multiple detectors in shared neutrino beam ~ideal to study this
  - nuSCOPE@CERN

- **Multi-experiment analyses take a long time to perform (4-8 years based on LHC and T2K+NOvA) so must start planning earlier rather than later!**

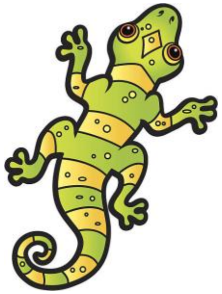
Thank you!

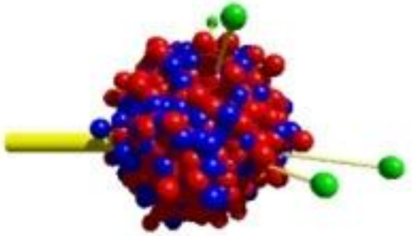
Neutrino event generators

- Currently five (that I know) main event generators:

NuWro
Wrocław Neutrino Event Generator

Genie
UNIVERSAL NEUTRINO GENERATOR
& GLOBAL FIT





- Three are regularly used by experiments
- Include different interaction models, and different assumptions about implementation – predicted event rates not always directly comparable
- Common I/O format being developed
  - **NuHEPMC**
  - Essential for future combined analysis

Combining experiments directly

- Next generation of experiments aim for **precision** neutrino physics
  - **Require** combining data from multiple experiments
    - JUNO measures mass ordering, mass splittings and θ_{12} very precisely
    - Daya Bay gives θ_{13} very precisely, but same reactor as JUNO, therefore correlated systematics

- Ideally, combine likelihoods from experiments directly and **make likelihoods publicly available for future use**
  - Full information available to analysis
  - Energy reconstruction performed by experiment simulation
    - Can correctly predict reconstructed neutrino energy distribution for any value of oscillation parameters
    - Get **L/E** correct!

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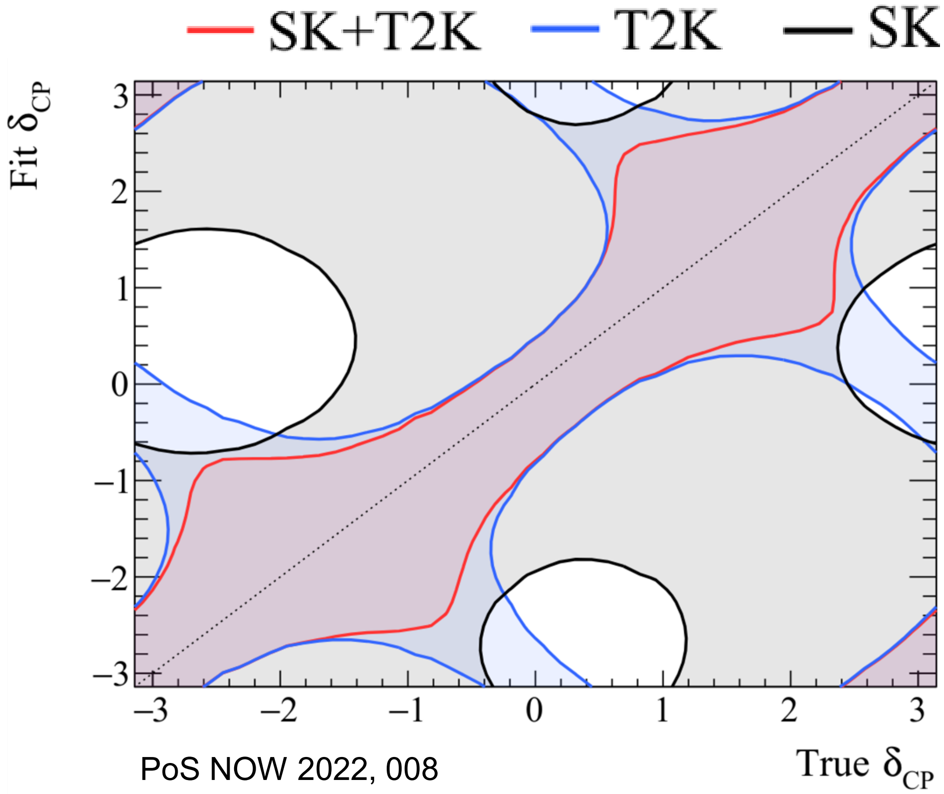
Why combine data? Breaking degeneracy

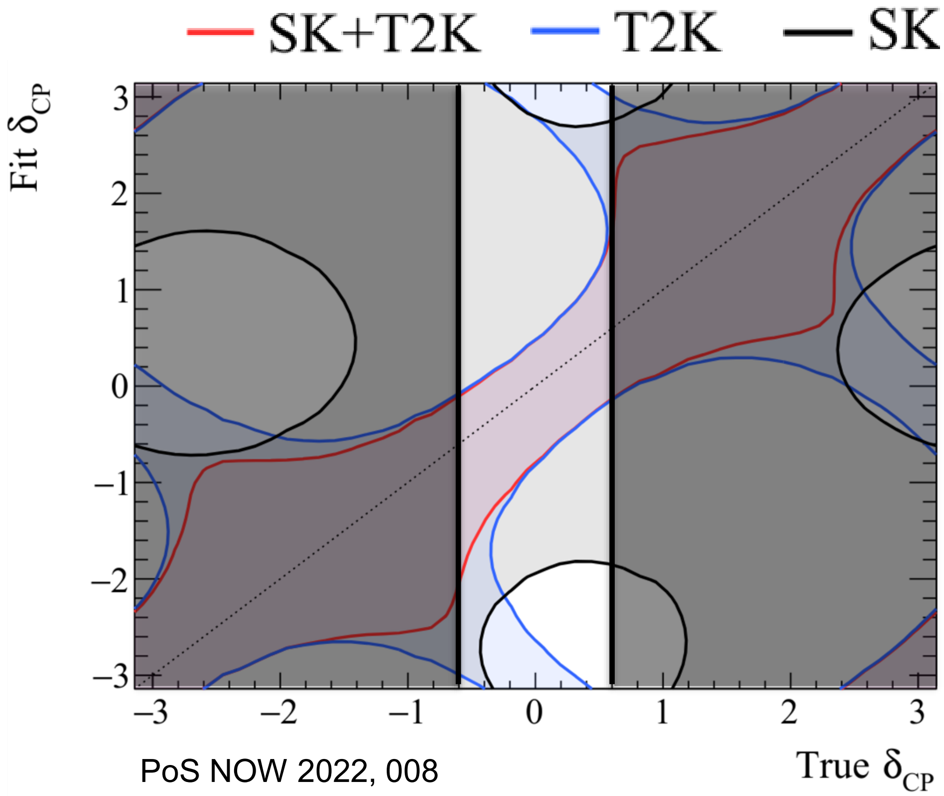
- Example from T2K + Super-K sensitivity studies
  - T2K uses neutrino beam
  - SK uses atmospheric neutrinos
- T2K measures δ_{CP} more precisely than **Super-K**



PoS NOW 2022, 008

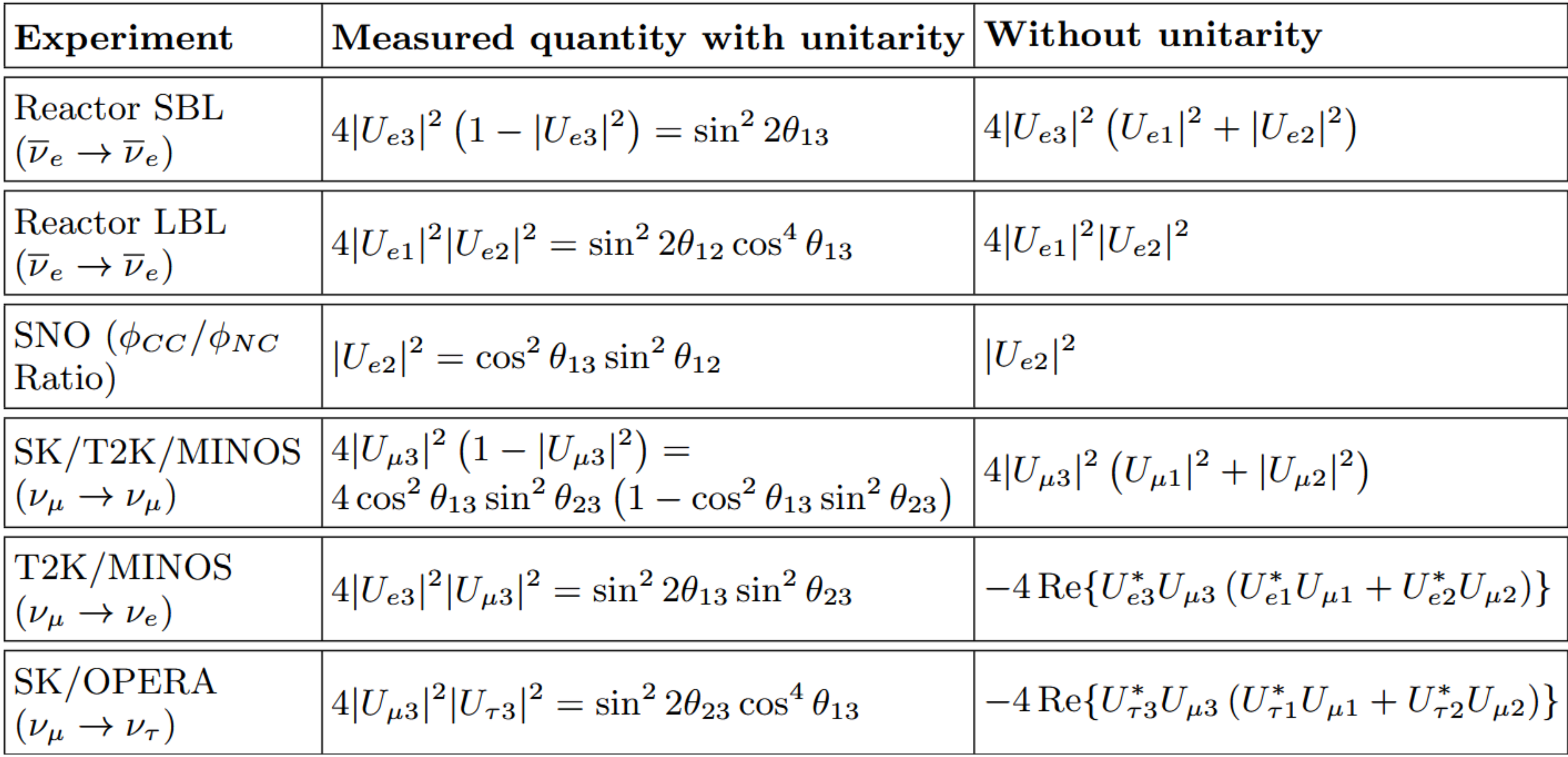
Why combine data? Breaking degeneracy

- Example from T2K + Super-K sensitivity studies
  - T2K uses neutrino beam
  - SK uses atmospheric neutrinos
- T2K measures δ_{CP} more precisely than **Super-K**
- Combined result breaks degeneracy seen by T2K around CP conserving values



PoS NOW 2022, 008

Unitarity measurements in PMNS



Experiment	**Measured quantity with unitarity**	**Without unitarity**
Reactor SBL $(\overline{\nu}_e \to \overline{\nu}_e)$	$4\lvert U_{e3}\rvert^2 \left(1 - \lvert U_{e3}\rvert^2\right) = \sin^2 2\theta_{13}$	$4\lvert U_{e3}\rvert^2 \left(\lvert U_{e1}\rvert^2 + \lvert U_{e2}\rvert^2\right)$
Reactor LBL $(\overline{\nu}_e \to \overline{\nu}_e)$	$4\lvert U_{e1}\rvert^2 \lvert U_{e2}\rvert^2 = \sin^2 2\theta_{12} \cos^4 \theta_{13}$	$4\lvert U_{e1}\rvert^2 \lvert U_{e2}\rvert^2$
SNO $(\phi_{CC}/\phi_{NC}$ Ratio)	$\lvert U_{e2}\rvert^2 = \cos^2 \theta_{13} \sin^2 \theta_{12}$	$\lvert U_{e2}\rvert^2$
SK/T2K/MINOS $(\nu_\mu \to \nu_\mu)$	$4\lvert U_{\mu 3}\rvert^2 \left(1 - \lvert U_{\mu 3}\rvert^2\right) =$ $4 \cos^2 \theta_{13} \sin^2 \theta_{23} \left(1 - \cos^2 \theta_{13} \sin^2 \theta_{23}\right)$	$4\lvert U_{\mu 3}\rvert^2 \left(\lvert U_{\mu 1}\rvert^2 + \lvert U_{\mu 2}\rvert^2\right)$
T2K/MINOS $(\nu_\mu \to \nu_e)$	$4\lvert U_{e3}\rvert^2 \lvert U_{\mu 3}\rvert^2 = \sin^2 2\theta_{13} \sin^2 \theta_{23}$	$-4\,\mathrm{Re}\{U_{e3}^* U_{\mu 3} \left(U_{e1}^* U_{\mu 1} + U_{e2}^* U_{\mu 2}\right)\}$
SK/OPERA $(\nu_\mu \to \nu_\tau)$	$4\lvert U_{\mu 3}\rvert^2 \lvert U_{\tau 3}\rvert^2 = \sin^2 2\theta_{23} \cos^4 \theta_{13}$	$-4\,\mathrm{Re}\{U_{\tau 3}^* U_{\mu 3} \left(U_{\tau 1}^* U_{\mu 1} + U_{\tau 2}^* U_{\mu 2}\right)\}$

S. Parke, M. Ross-Lonergan, https://arxiv.org/abs/1508.05095

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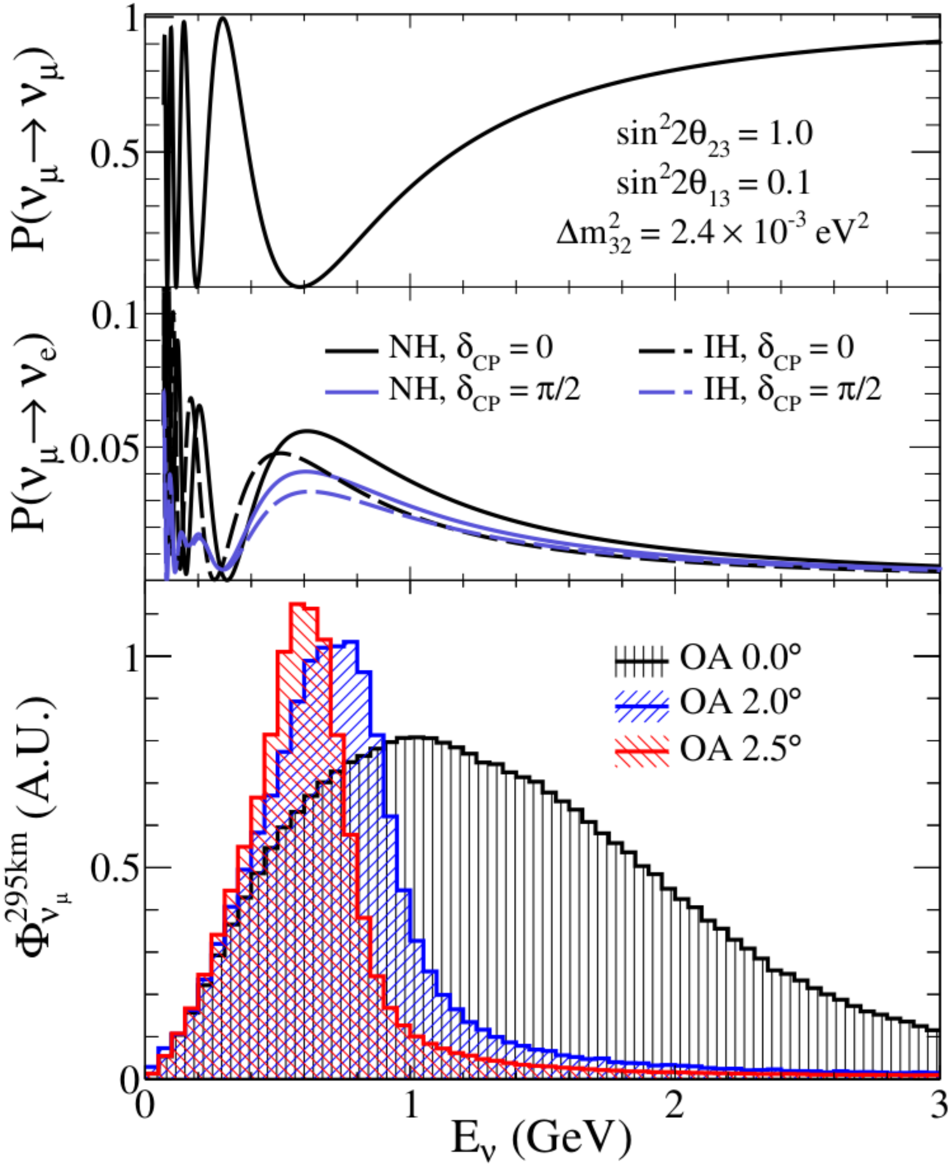
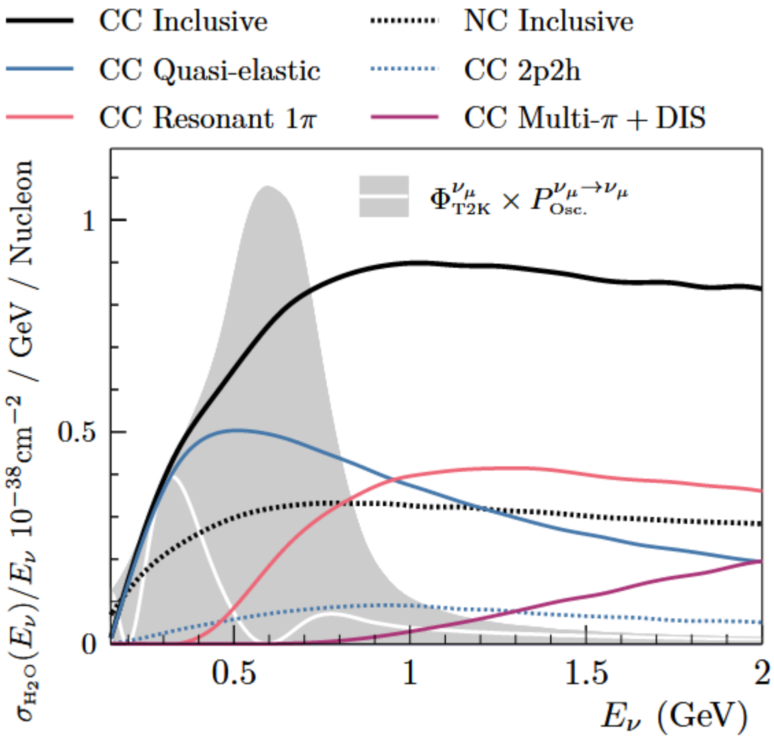
T2K Off-axis beam

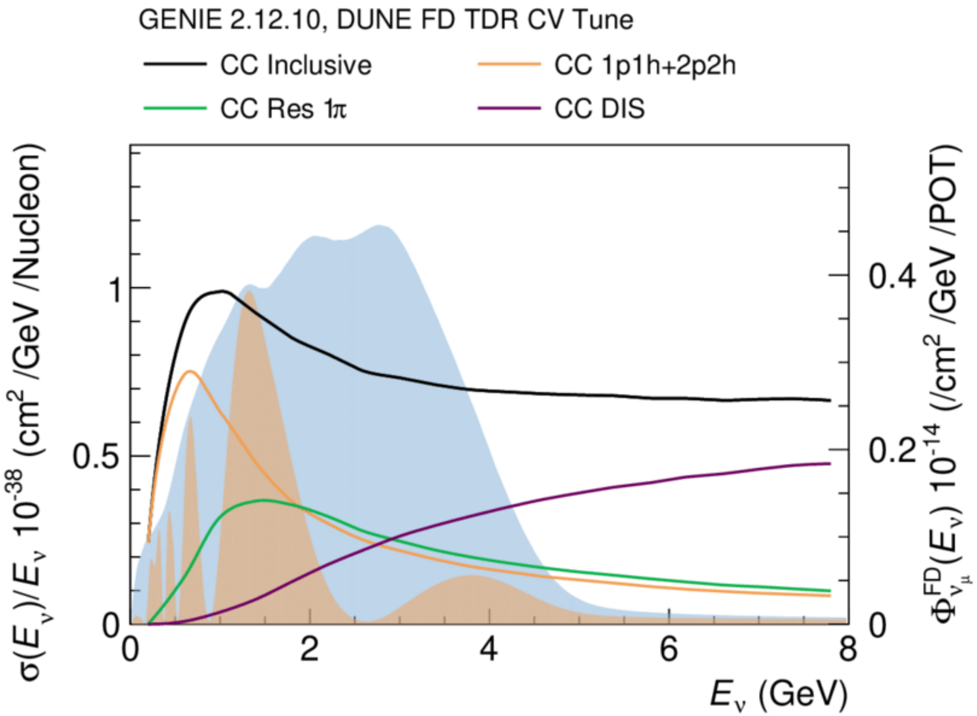
- Two-body pion decay
  - Angle and energy of neutrino directly linked
- Moving off axis:
  - Lower peak energy
  - Smaller high energy tail
  - Less energy spread
- T2K is at 2.5° off-axis



Flux and Cross-section at T2K and DUNE

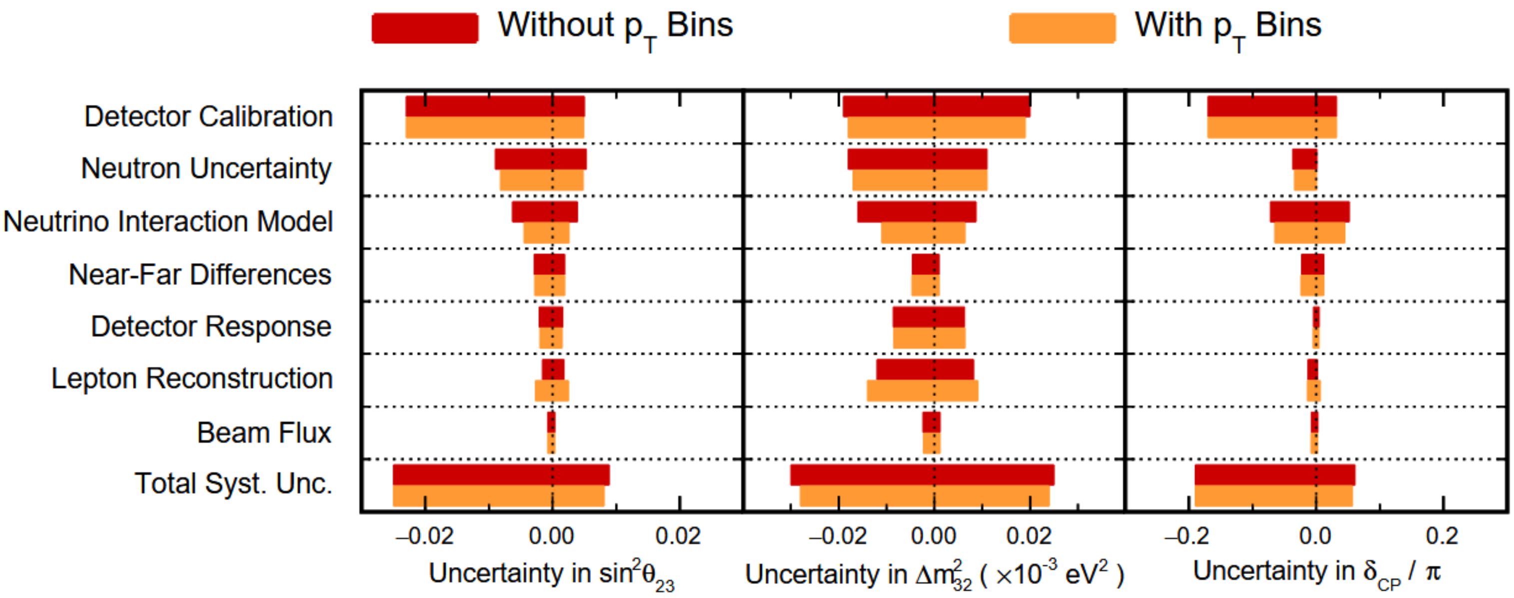
- T2K: CCQE + resonant pion production
- DUNE: CCQE + resonant pion + DIS
  - Oscillation suppresses higher energy flux





A note on NOvA

https://arxiv.org/pdf/2108.08219.pdf

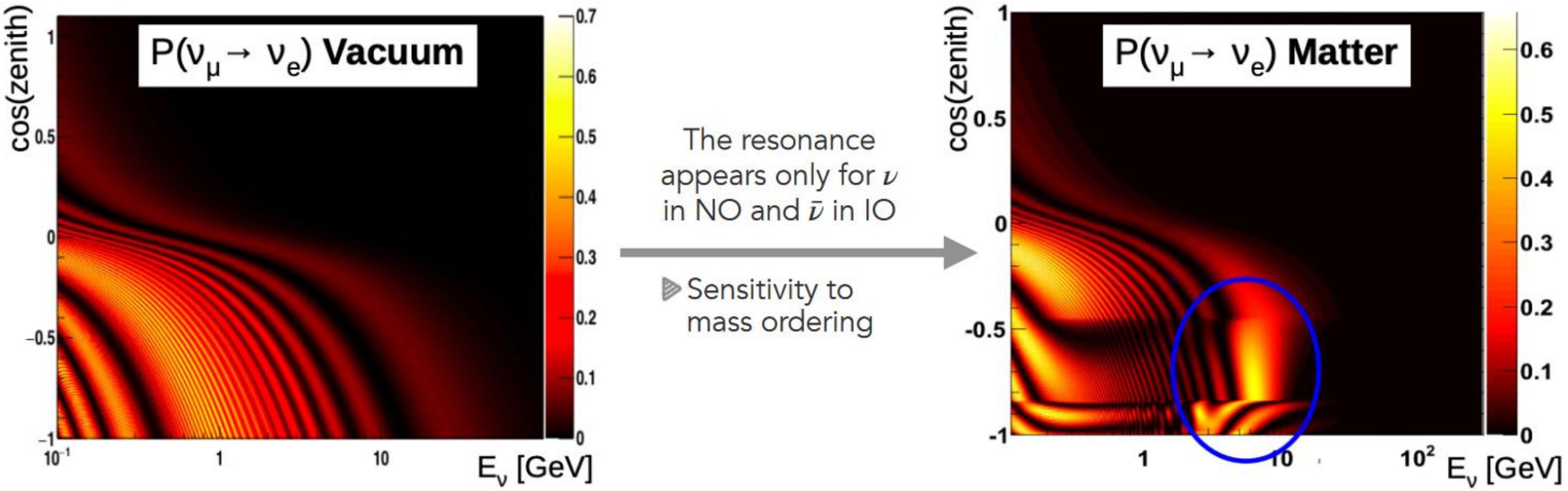


- Functionally identical near and far detector
- Neutrino interaction model and beam flux uncertainties significantly reduced
- Detector response/reconstruction more important

Atmospheric neutrino oscillation

Atmospheric neutrino oscillation probability (normal ordering)

from C. Bronner @ PANE 2018



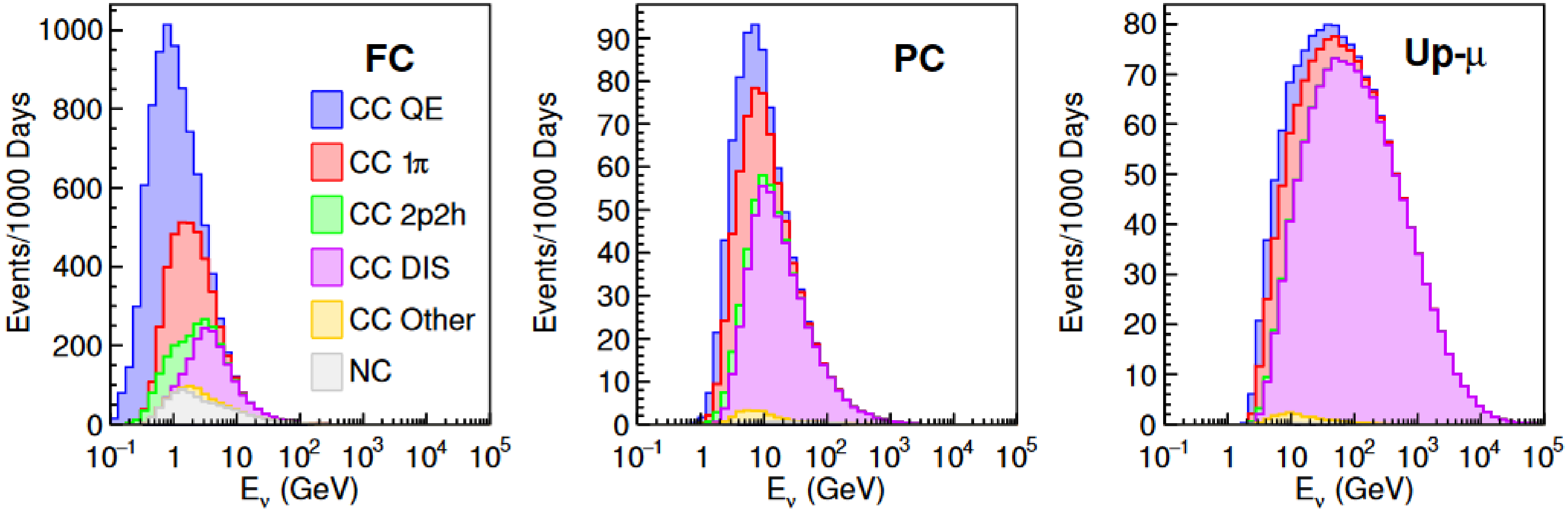
The resonance appears only for ν in NO and $\bar{\nu}$ in IO

▷ Sensitivity to mass ordering

- Earth mass introduces resonance in upward-going electron neutrino appearance sample
- Provides sensitivity to neutrino mass ordering

Atmospheric neutrinos – SK samples

T. Wester, PhD thesis

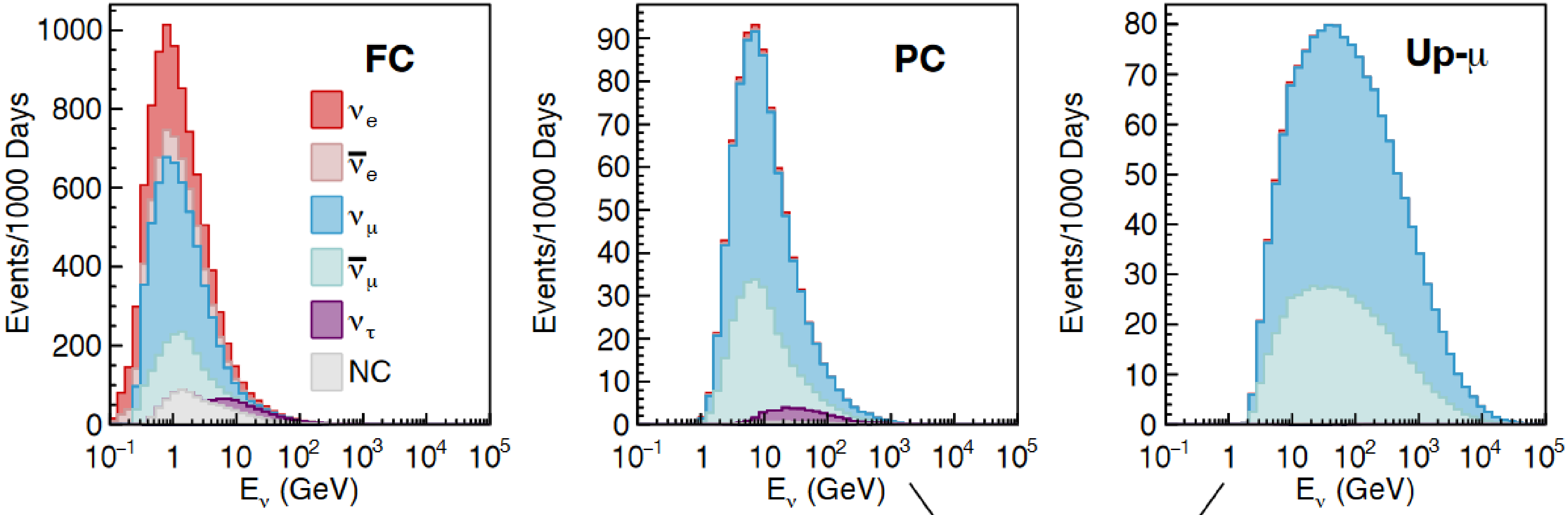


- Samples of “fully-contained”, “partially contained” and “upward-going muon” events
- PC and Up-mu are dominated by DIS events

Atmospheric neutrinos – SK samples

T. Wester, NNN2023

Oscillated flux @ SK



MeV - GeV, all flavors

Mass ordering, θ_{23} octant, δ_{CP}

GeV+, almost all ν_μ, missing energy

Constrain $\sin^2 2\theta_{23}$, Δm^2_{32}

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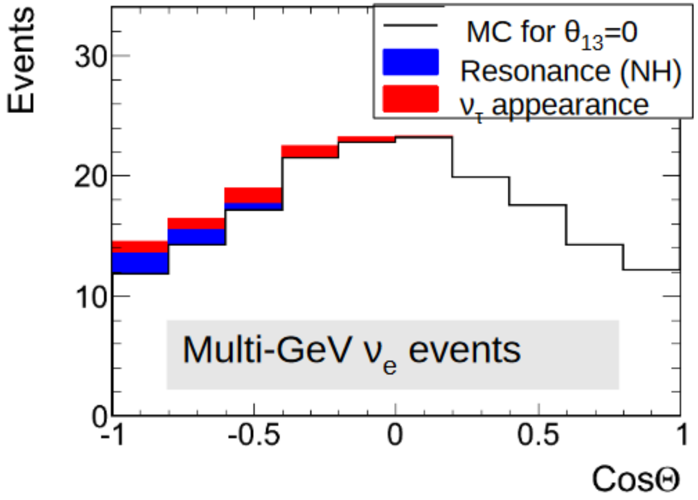
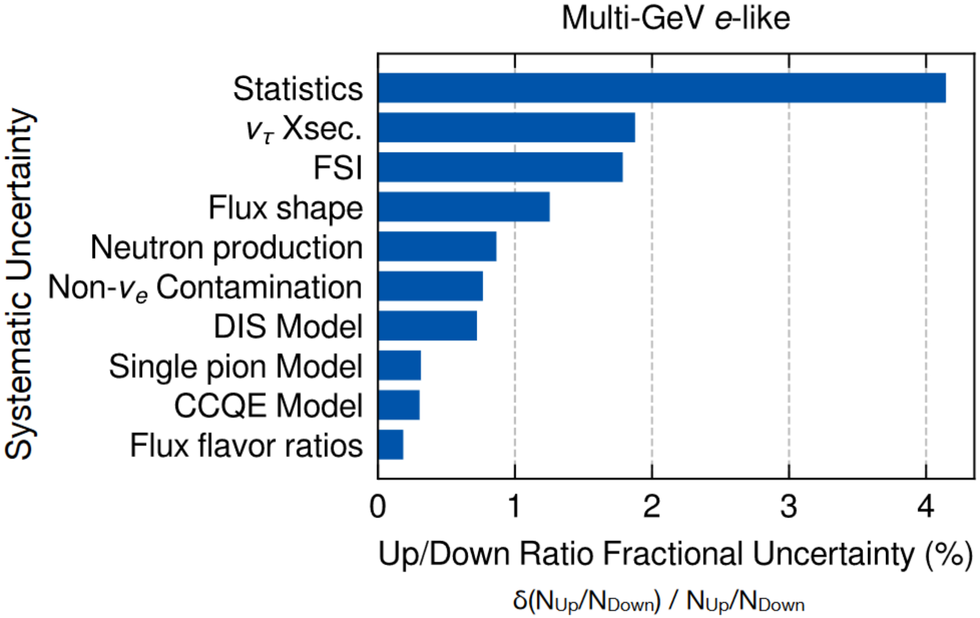
Atmospheric neutrinos – SK systematics

C. Bronner, https://indico-sk.icrr.u-tokyo.ac.jp/event/5223/



T. Wester, NNN2023

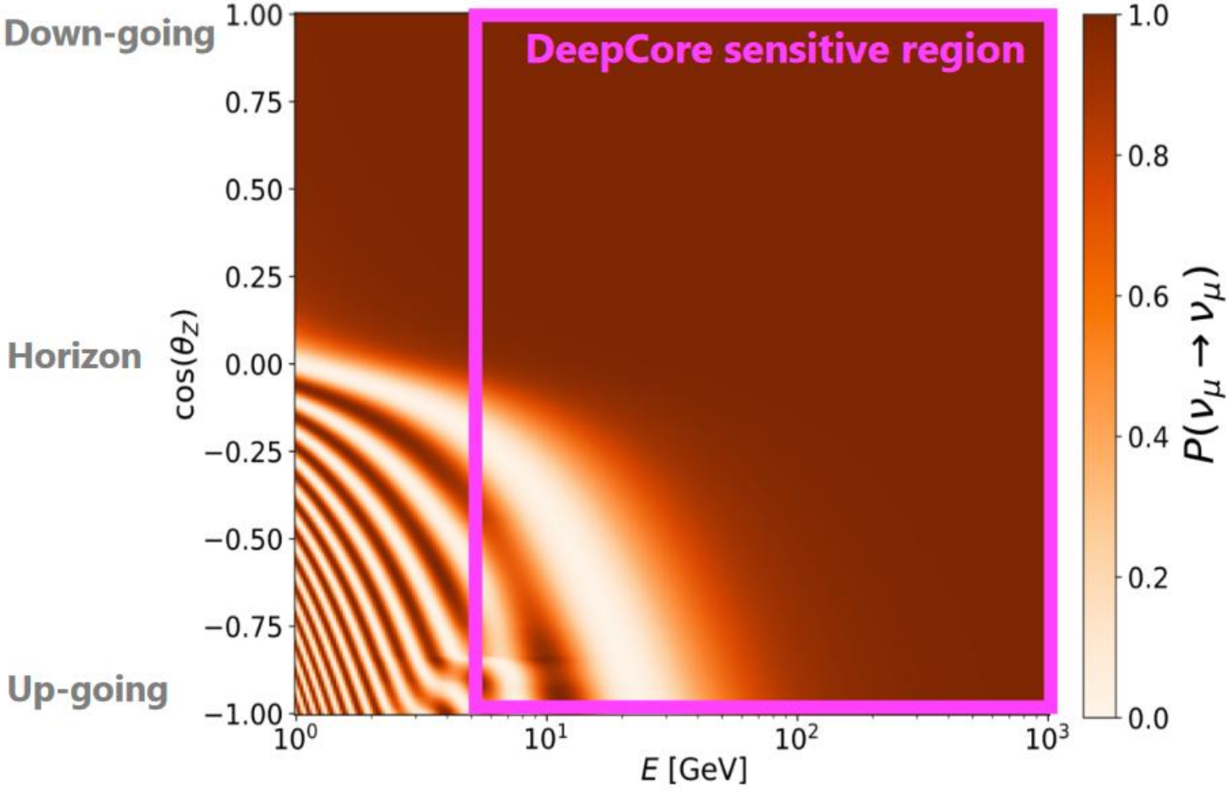


- Mass ordering sensitivity from upward-going, multi-GeV electron-like samples
- Tau cross-section uncertainty dominant systematic
  - Hyper-Kamiokande will have statistical error <2%

Neutrino oscillation at IceCube

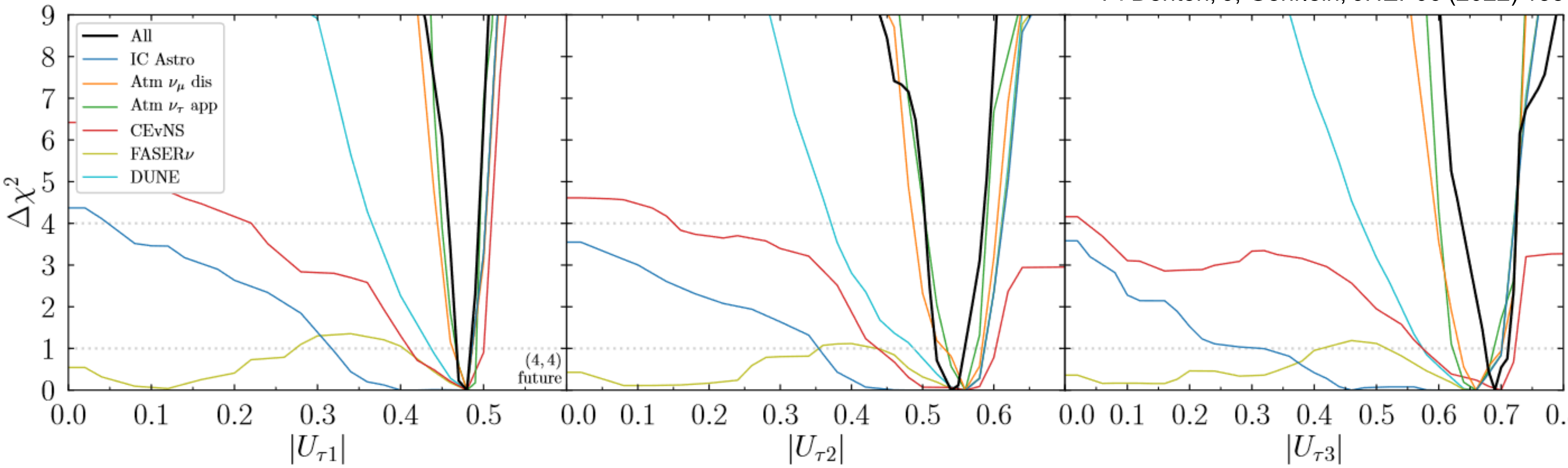
- Largest particle detector in existence (1Mt)
- Limited at low energy threshold ~ 10GeV
  - Reduced to 1GeV with Upgrade
- Above threshold of tau production – can measure tau appearance

T. Stuttard, NuFact 2019



Future limits on PMNS unitarity

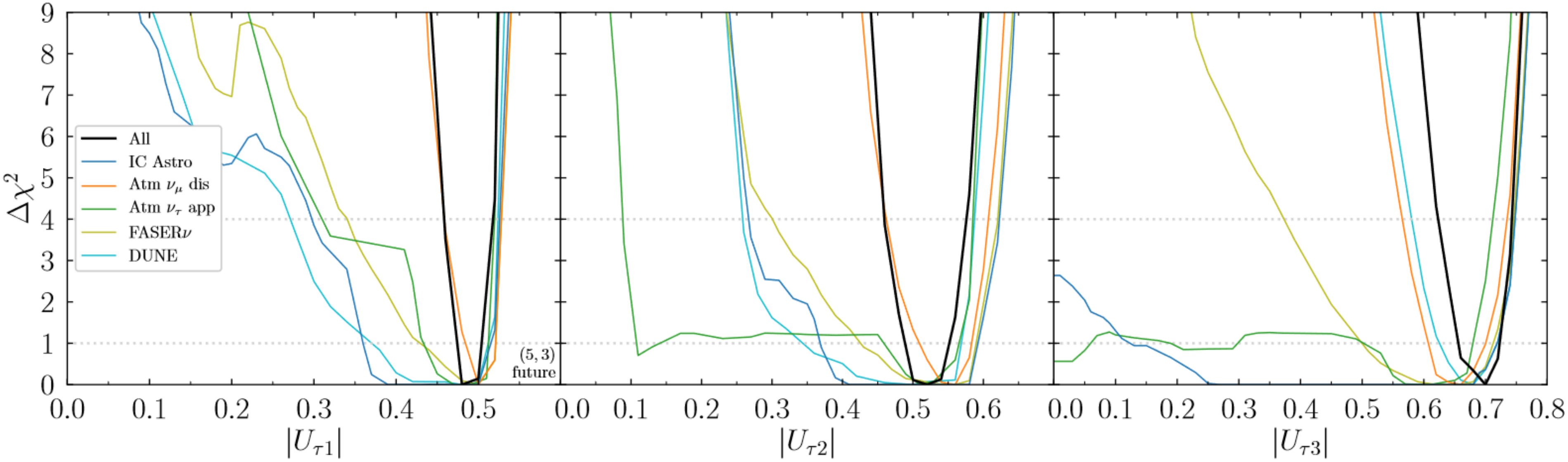
P. Denton, J, Gehrlein, JHEP06 (2022) 135



- Depends on the assumptions used in analysis
  - Here assuming 4 x 4 matrix, with the new state accessible
- Atmospheric neutrinos provide largest constraint on 3rd row of PMNS matrix

Future limits on PMNS unitarity

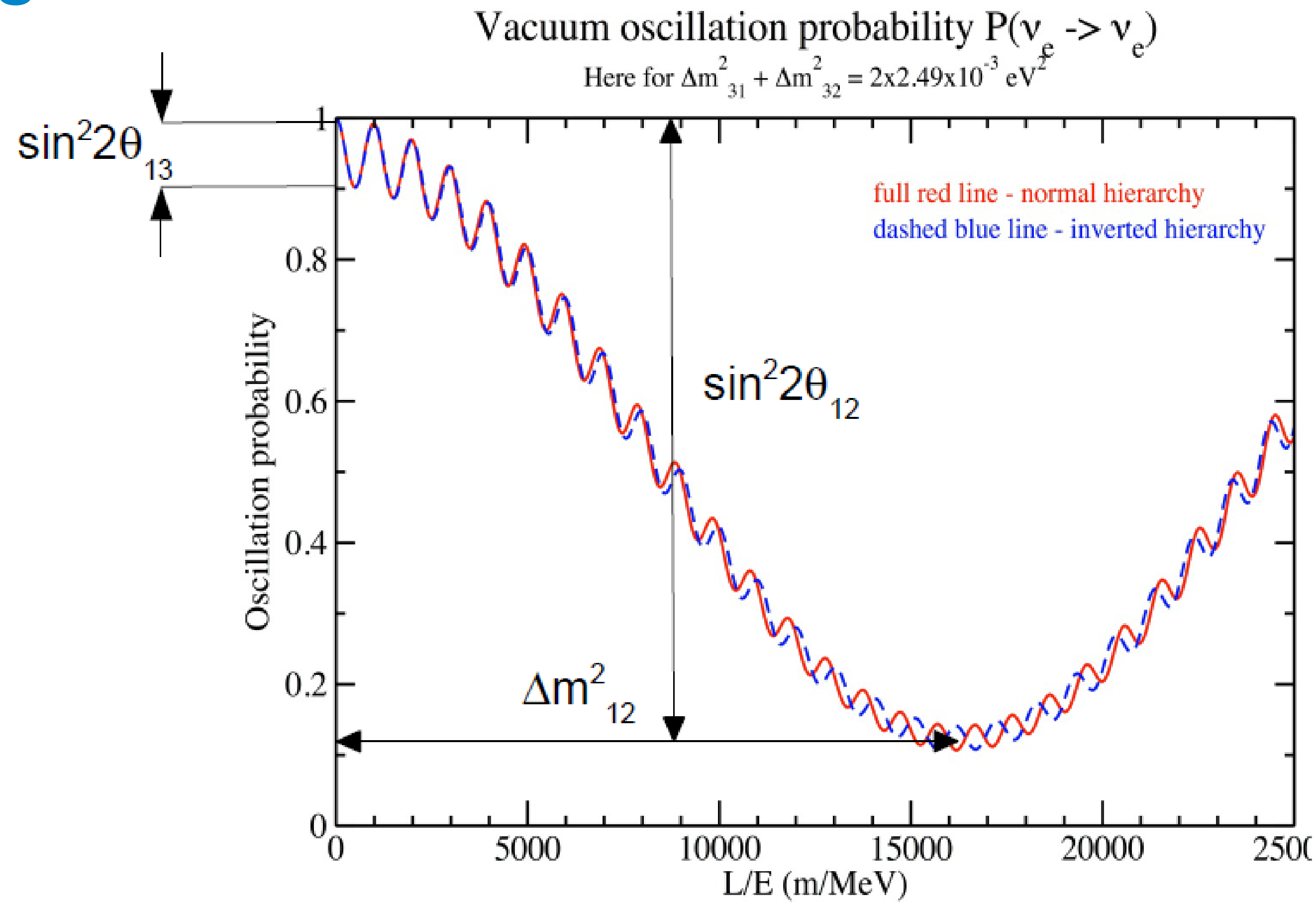
P. Denton, J, Gehrlein, JHEP06 (2022) 135



- Alternative assumes two inaccessible mass states
- Atmospheric muon neutrino disappearance and DUNE tau neutrino appearance now provide biggest constraint

JUNO physics

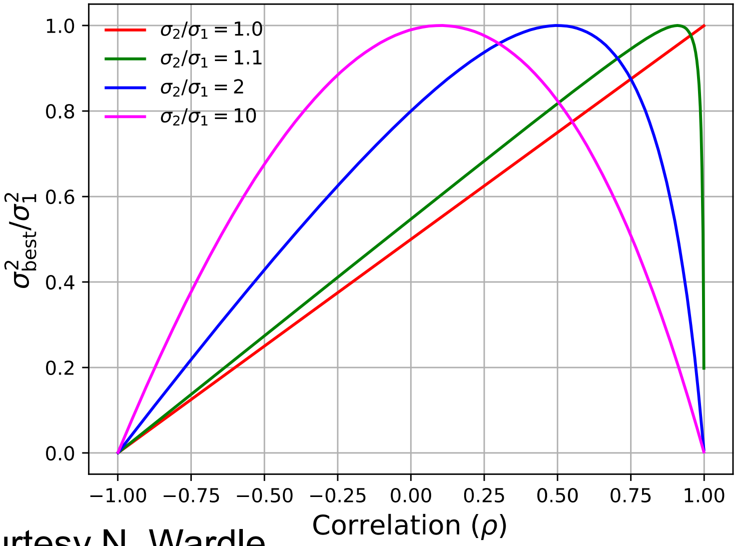
- Precision reactor neutrino measurements
  - Flux
  - Spectrum
- Determination of mass ordering
- Precise determination of θ_{12} and Δm^2_{12}
- Supernovae ν, geo-ν, solar ν, sterile ν…



B. Wonsak, Neutrino 2018

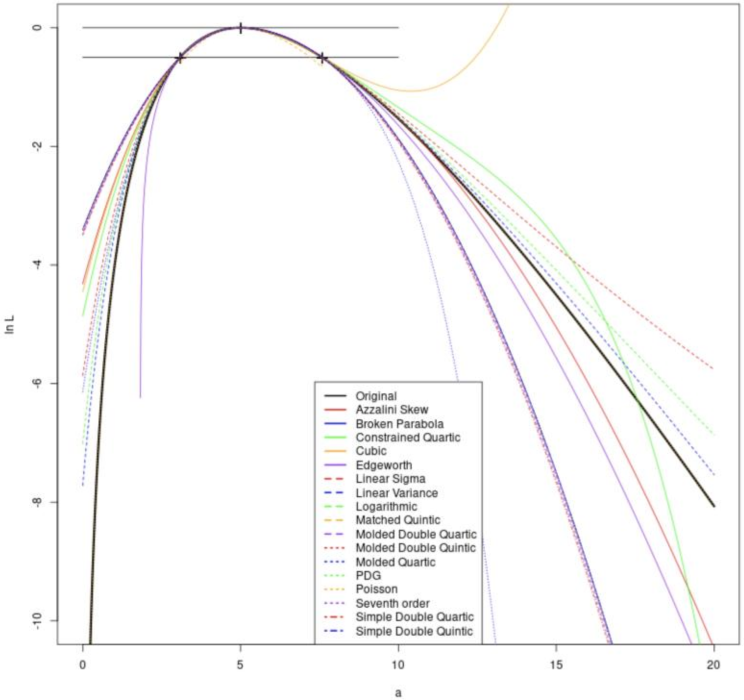
Potential issues

- Unknown correlations
  - Y-axis is ~error on combined result
  - Most conservative assumption not necessarily given by fully (un)correlated uncertainties



Courtesy N. Wardle

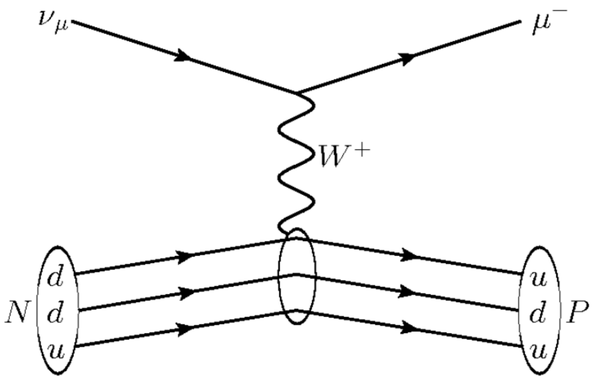
- Non-Gaussian errors
  - OK to assume Gaussian up to ~1 sigma, could diverge past this
  - How do we interpret published value?



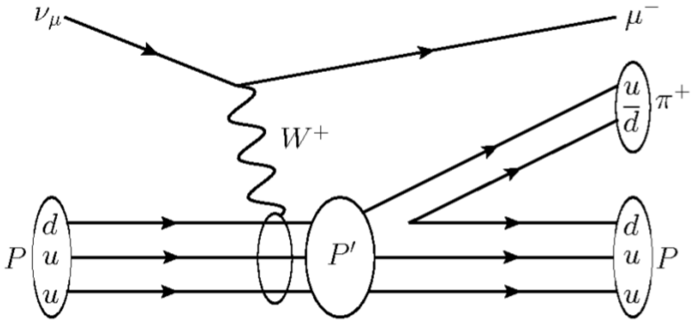
https://arxiv.org/abs/2411.15499

Neutrino interactions

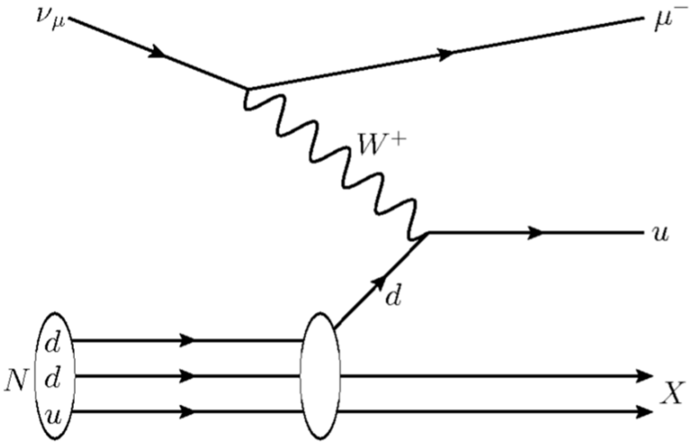
- Three principal types of neutrino interaction
- Occur as both charged current (CC) and neutral current processes



Quasi-elastic (CCQE)

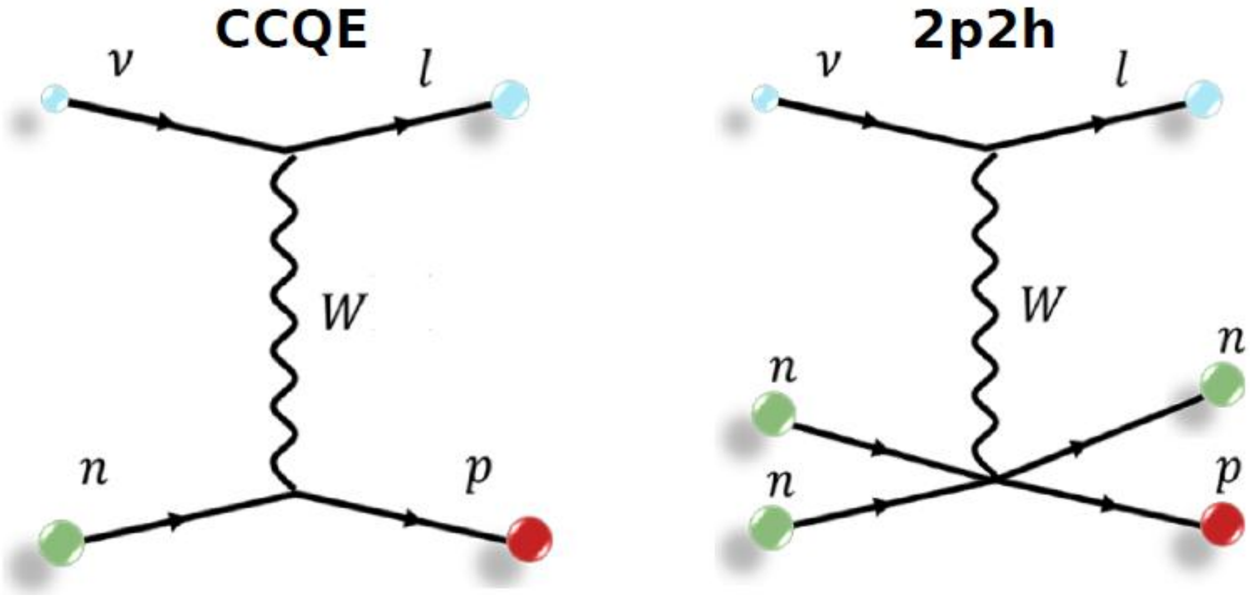


Single pion production



Deep inelastic scattering / Multi-pion production

Example energy bias – 2p2h interactions



- Similar to CCQE
- Neutrino interacts with correlated pair of nucleons – invisible to detector

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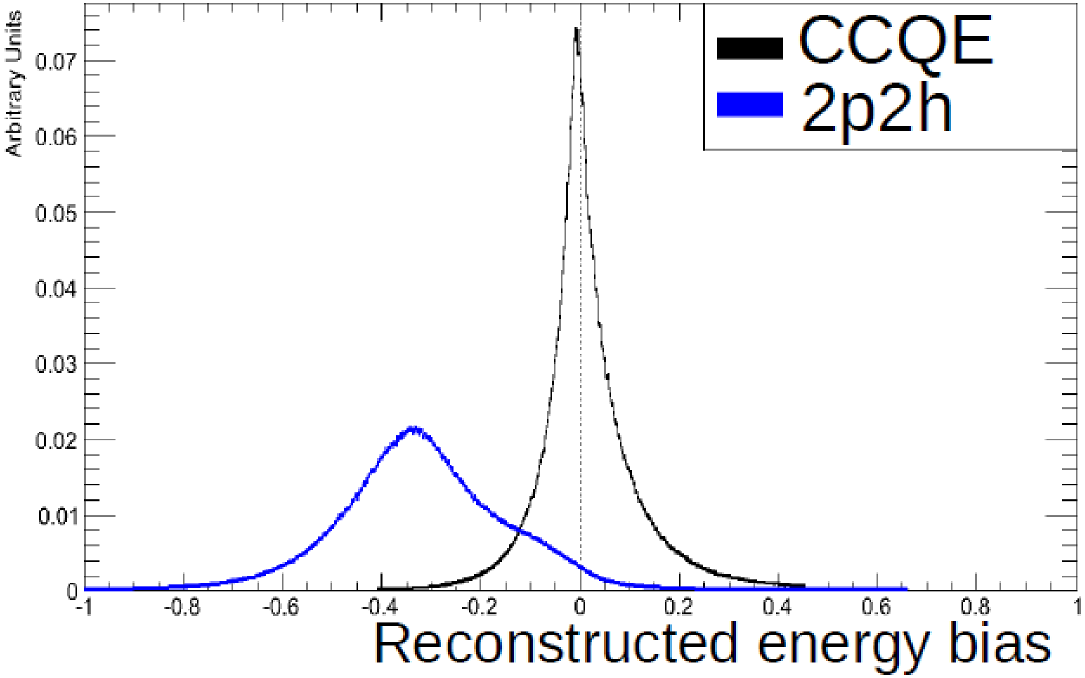
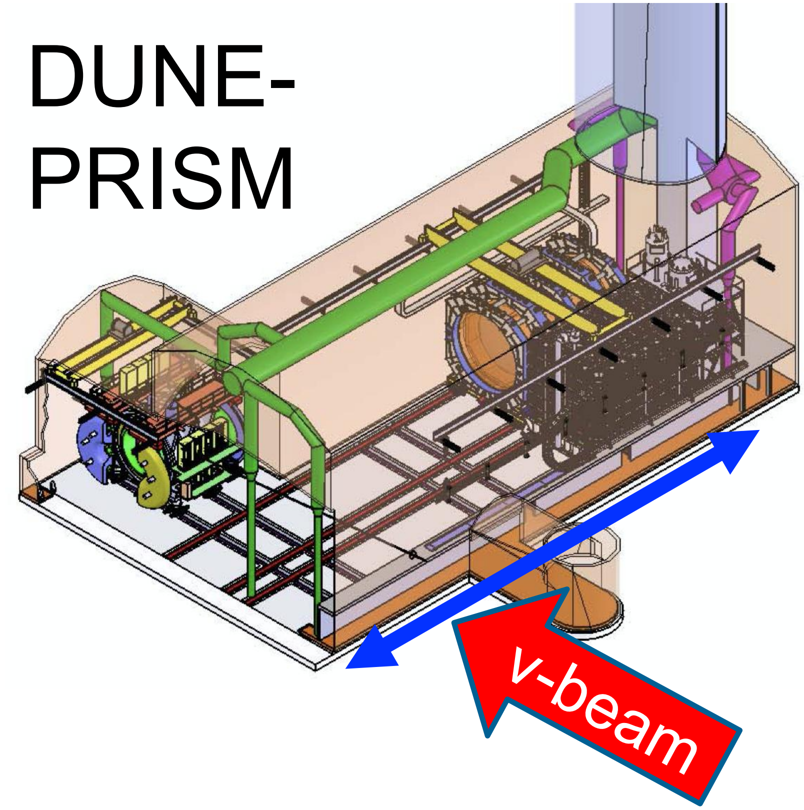
Example energy bias – 2p2h interactions

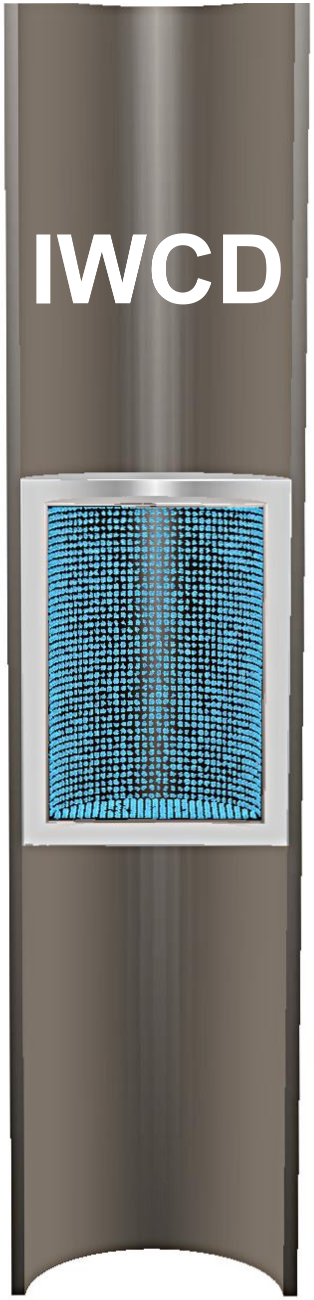


- Reconstructed neutrino energy is biased, leads to bias in oscillation parameters
- Requires improved experimental measurements or theoretical models

DUNE-PRISM and IWCD



- Near / intermediated detectors for DUNE / HK
- Span a range of angles off the centre of the neutrino beam
  - DUNE-PRISM – horizontal, ~35m
  - IWCD – vertical, ~50m



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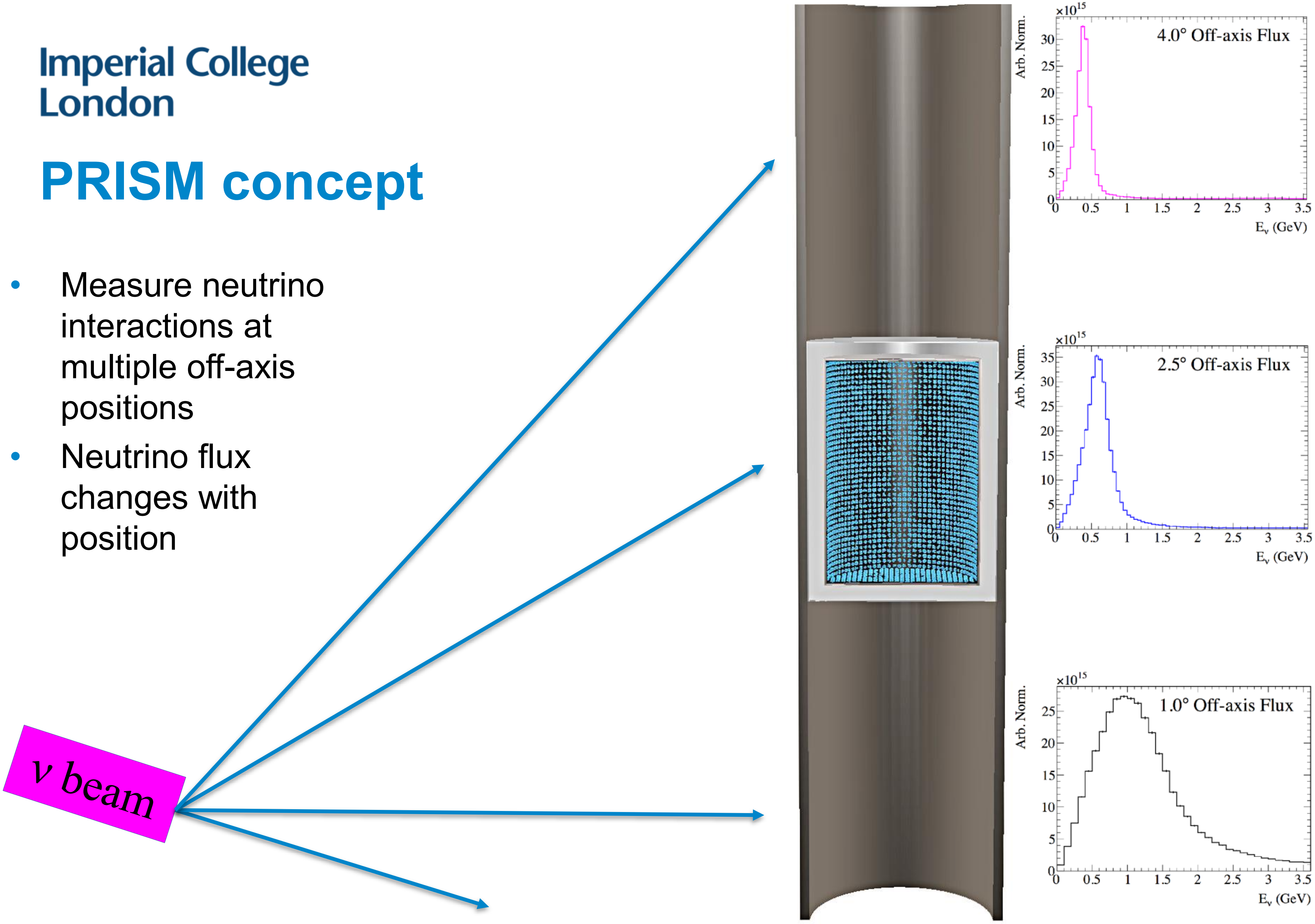
PRISM concept

- Measure neutrino interactions at multiple off-axis positions
- Neutrino flux changes with position



PRISM concept

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