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Combining data from neutrino experiments: How and why should we do it?

Mark Scott
m.scott09@imperial.ac.uk

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Combining data from neutrino experiments:
How and why should we do it?

Caveat – will focus on neutrino oscillations and in particular future oscillation experiments and general concepts rather than details of current generation

Mark Scott
m.scott09@imperial.ac.uk

With thanks to N. Wardle and C. Wret

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Overview

- Neutrino oscillations, sources and experiments

- Why combine neutrino experiments?
  - Breaking degeneracies
  - Precision measurement
  - New Physics

- How should we combine experiments?
  - Methods of combining results
  - Combining likelihoods

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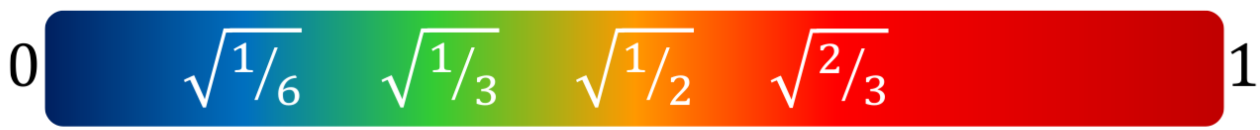
Neutrinos oscillations

- 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



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

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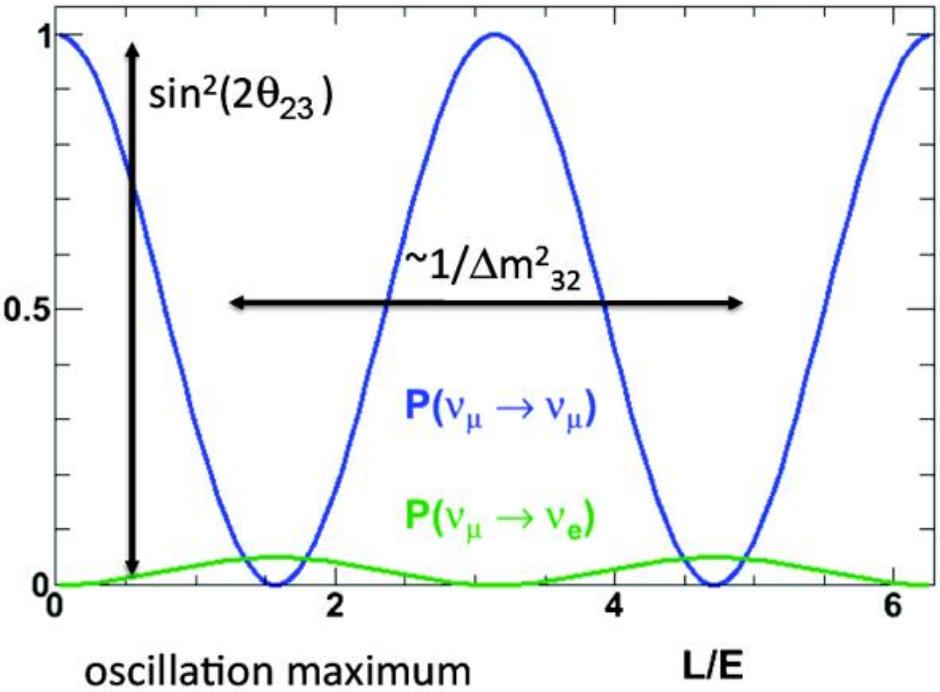
Oscillation probabilities

- Leading order oscillation probabilities for ν_μ survival and ν_e appearance

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

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



- Measuring oscillation probability requires **accurate** reconstruction of **neutrino energy!**

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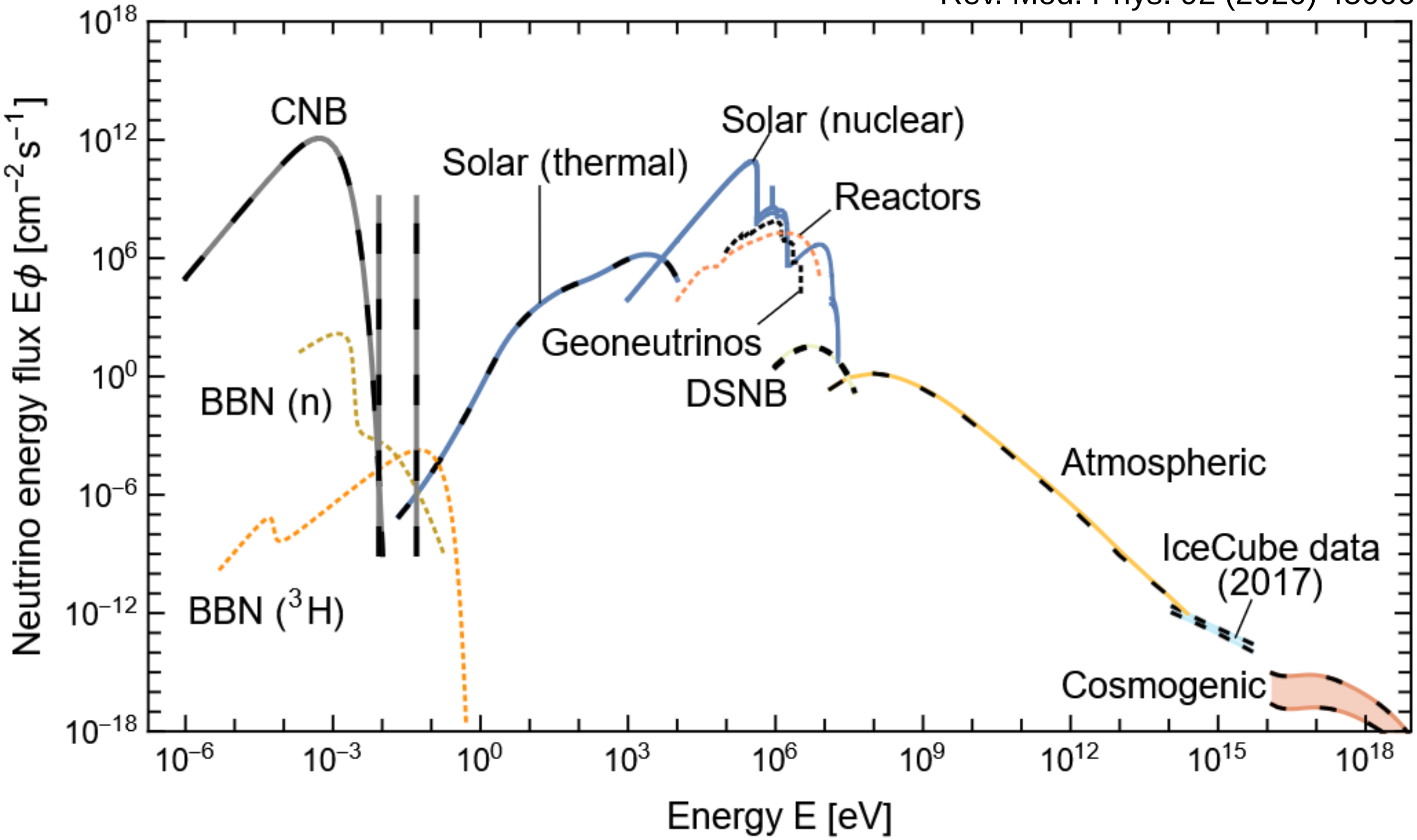
Neutrino sources

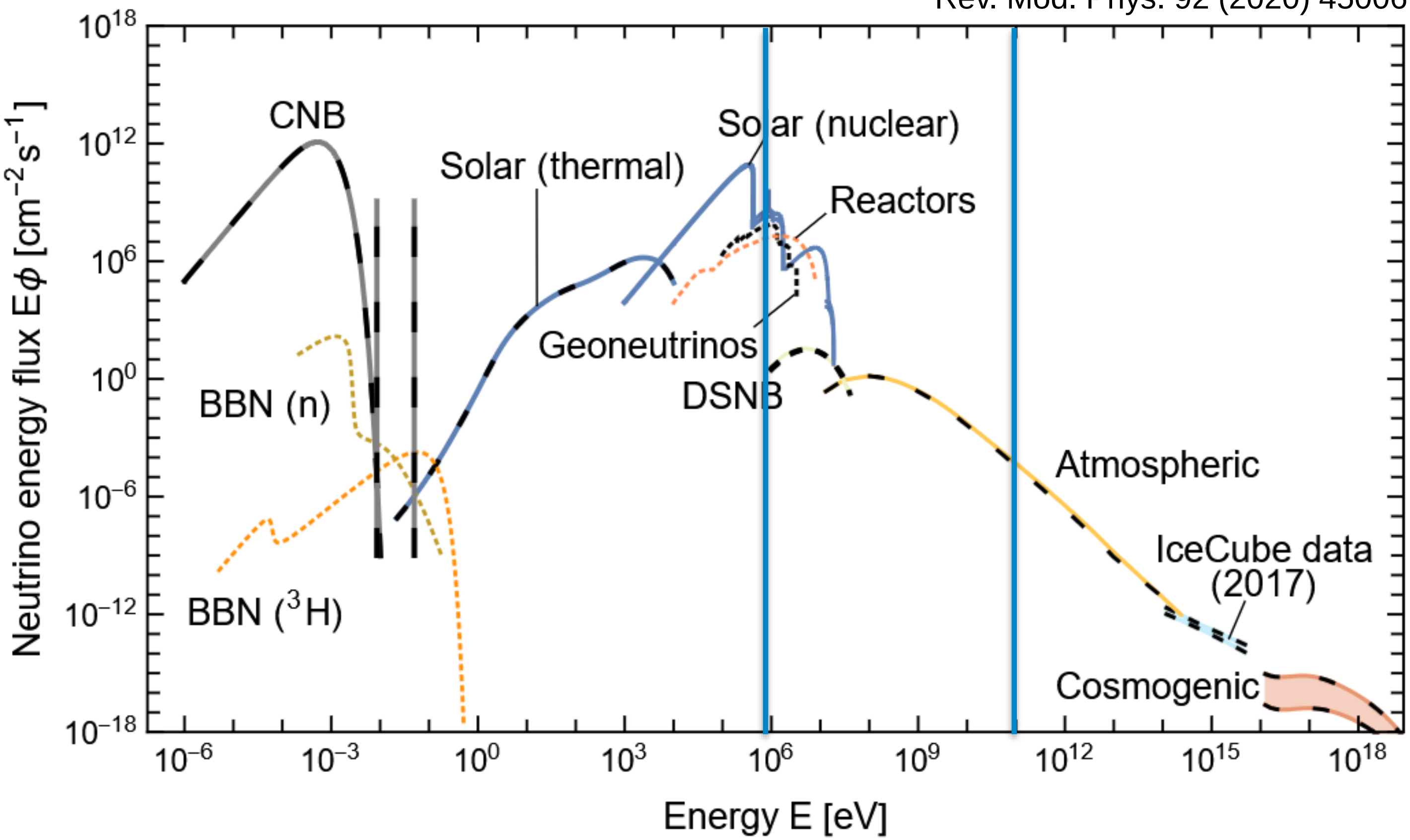
Rev. Mod. Phys. 92 (2020) 45006



- Many natural sources of neutrinos across huge energy range

Neutrino sources

Rev. Mod. Phys. 92 (2020) 45006



- Many natural sources of neutrinos across huge energy range

Many experiments to enjoy (oscillation focus)

HYPER K

DUNE
DEEP UNDERGROUND
NEUTRINO EXPERIMENT

ICECUBE

SUPER K

NOvA

Daya Bay
θ13

JUNO

T2K

SNO

Kam
LAND
Kamioka Liquid scintillator Anti-Neutrino Detector

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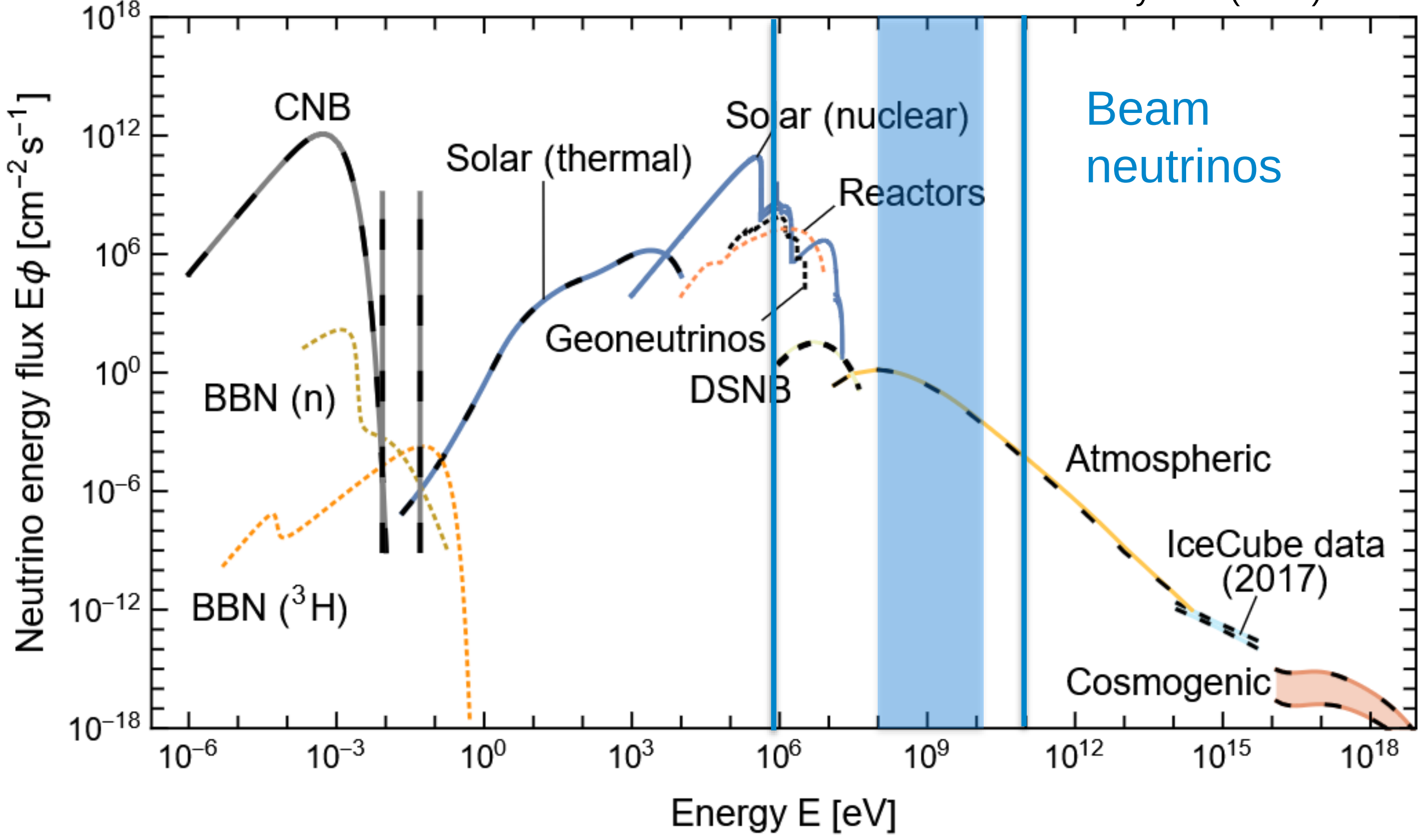
Neutrino sources

Rev. Mod. Phys. 92 (2020) 45006



- Neutrino beams and atmospheric neutrinos overlap

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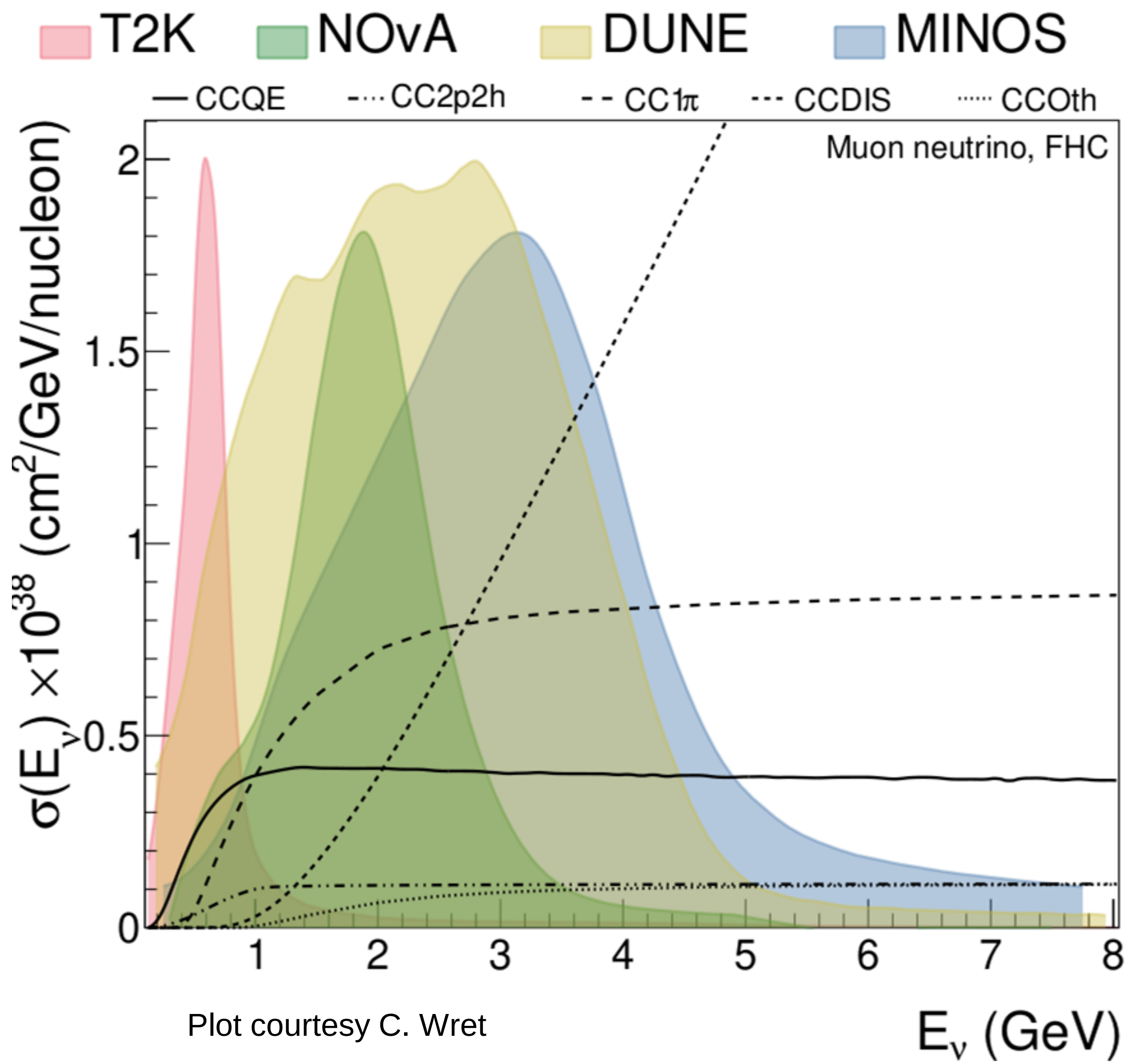
Neutrino beams

- Significant overlap in energy between neutrino beams
- Different energies give different physics and interaction sensitivities
  - Background for Hyper-K is signal in DUNE



Plot courtesy C. Wret

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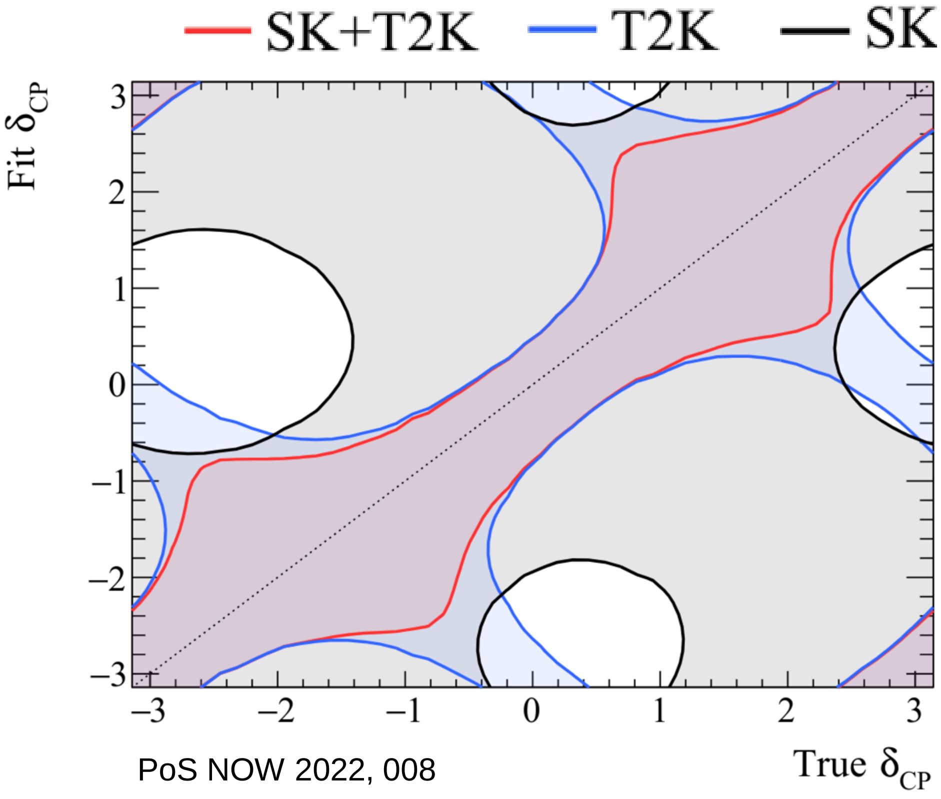
Why combine data? Breaking degeneracy

- 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

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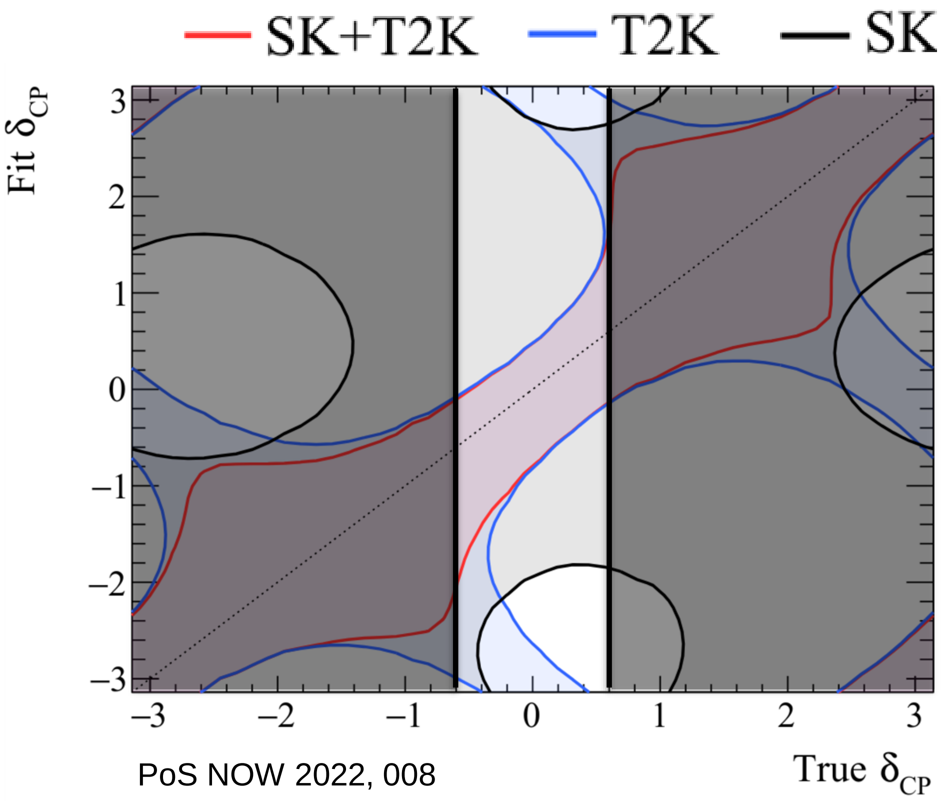
Why combine data? Breaking degeneracy

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



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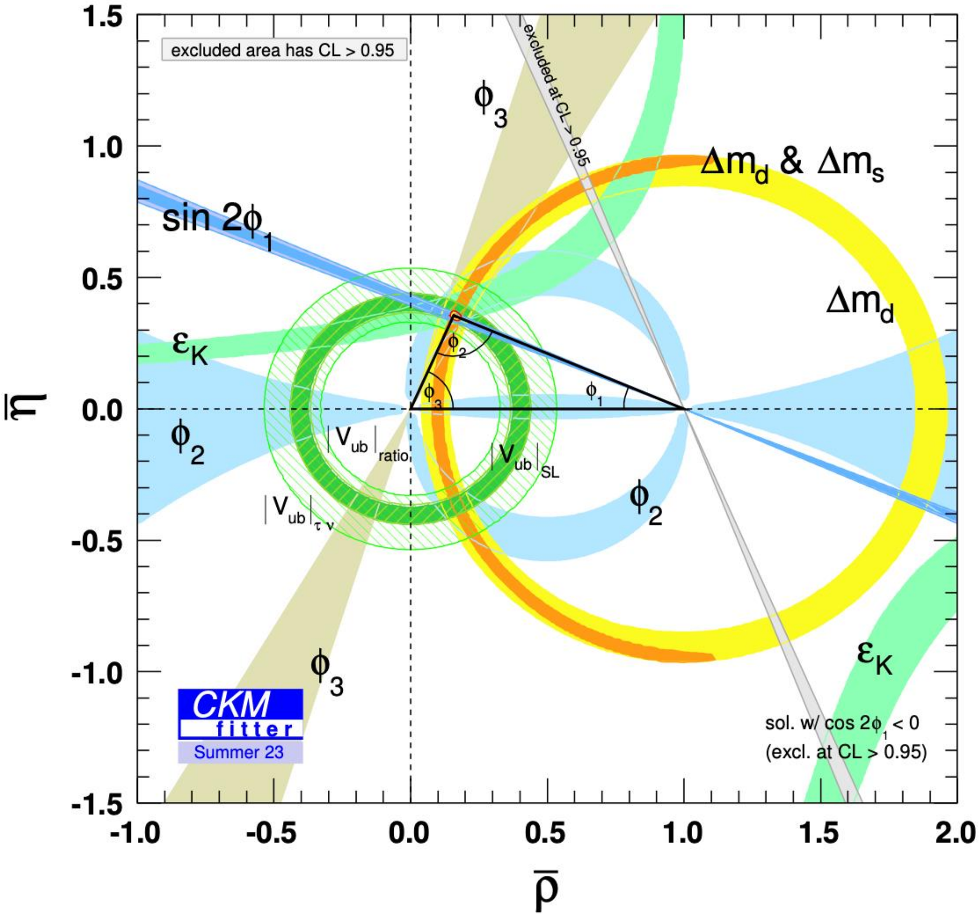
Why combine data? Precision measurements

- Non-unitarity not seen in quarks (yet)
- Would indicate new physics
  - Generic search (steriles, neutrino decay, NSIs etc.)
- Requires **over-constraint** of PMNS parameters

CKMFitter, CKM 2023 workshop



Unitarity measurements in PMNS

- Many contributions
  - Daya Bay
  - JUNO
  - SNO
  - Hyper-K / DUNE
  - DUNE / Hyper-K / IceCube

Experiment	Measured quantity with unitarity
Reactor SBL ($\overline{\nu}_e \to \overline{\nu}_e$)	$4\lvert U_{e3}\rvert^2\left(1-\lvert U_{e3}\rvert^2\right)=\sin^2 2\theta_{13}$
Reactor LBL ($\overline{\nu}_e \to \overline{\nu}_e$)	$4\lvert U_{e1}\rvert^2\lvert U_{e2}\rvert^2=\sin^2 2\theta_{12}\cos^4\theta_{13}$
SNO (ϕ_{CC}/ϕ_{NC} Ratio)	$\lvert U_{e2}\rvert^2=\cos^2\theta_{13}\sin^2\theta_{12}$
SK/T2K/MINOS ($\nu_\mu \to \nu_\mu$)	$4\lvert U_{\mu 3}\rvert^2\left(1-\lvert U_{\mu 3}\rvert^2\right)=4\cos^2\theta_{13}\sin^2\theta_{23}\left(1-\cos^2\theta_{13}\sin^2\theta_{23}\right)$
T2K/MINOS ($\nu_\mu \to \nu_e$)	$4\lvert U_{e3}\rvert^2\lvert U_{\mu 3}\rvert^2=\sin^2 2\theta_{13}\sin^2\theta_{23}$
SK/OPERA ($\nu_\mu \to \nu_\tau$)	$4\lvert U_{\mu 3}\rvert^2\lvert U_{\tau 3}\rvert^2=\sin^2 2\theta_{23}\cos^4\theta_{13}$

S. Parke, M. Ross-Lonergan, Phys. Rev. D 93, 113009 (2016)

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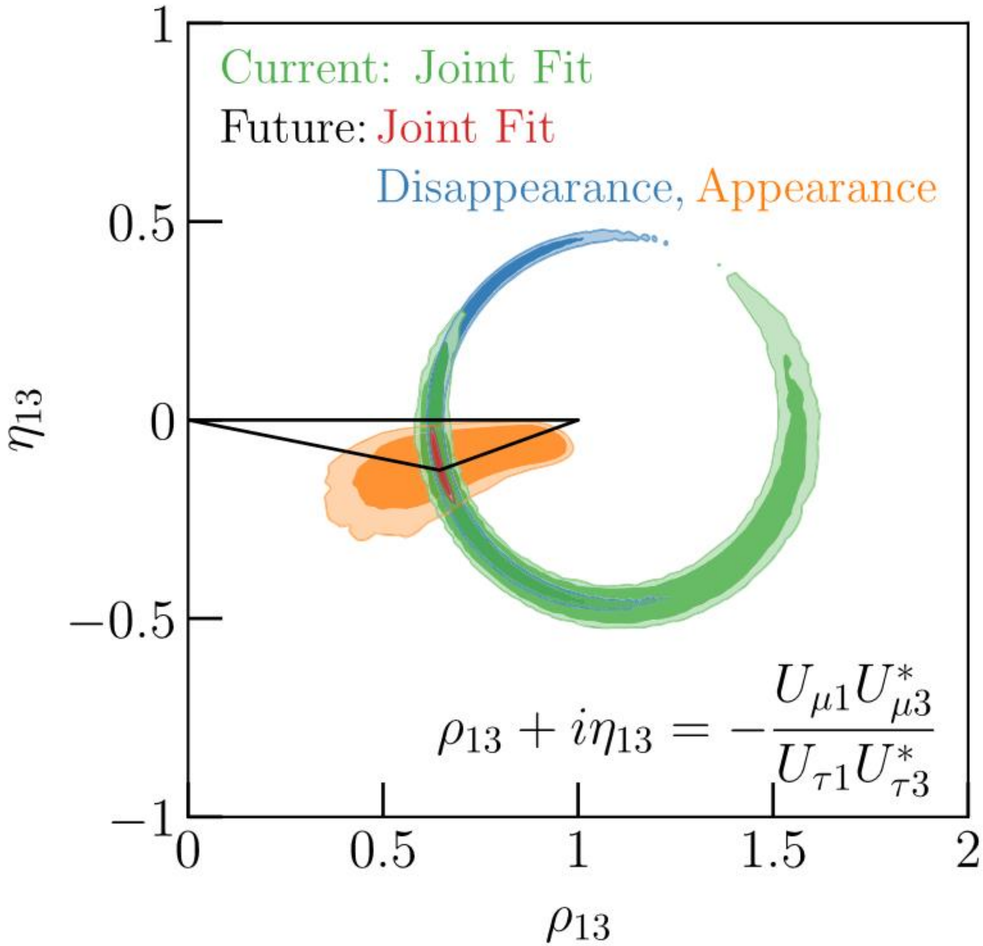
Unitarity measurements in data

- PMNS unitarity circa 2020
  - Combined experiments(JUNO, IceCube, DUNE, HK) gives greater precision
  - Necessary to isolate individual PMNS elements
- Also look at consistency of experiments
  - Compare θ_{13} measured by reactors and long-baseline neutrinos

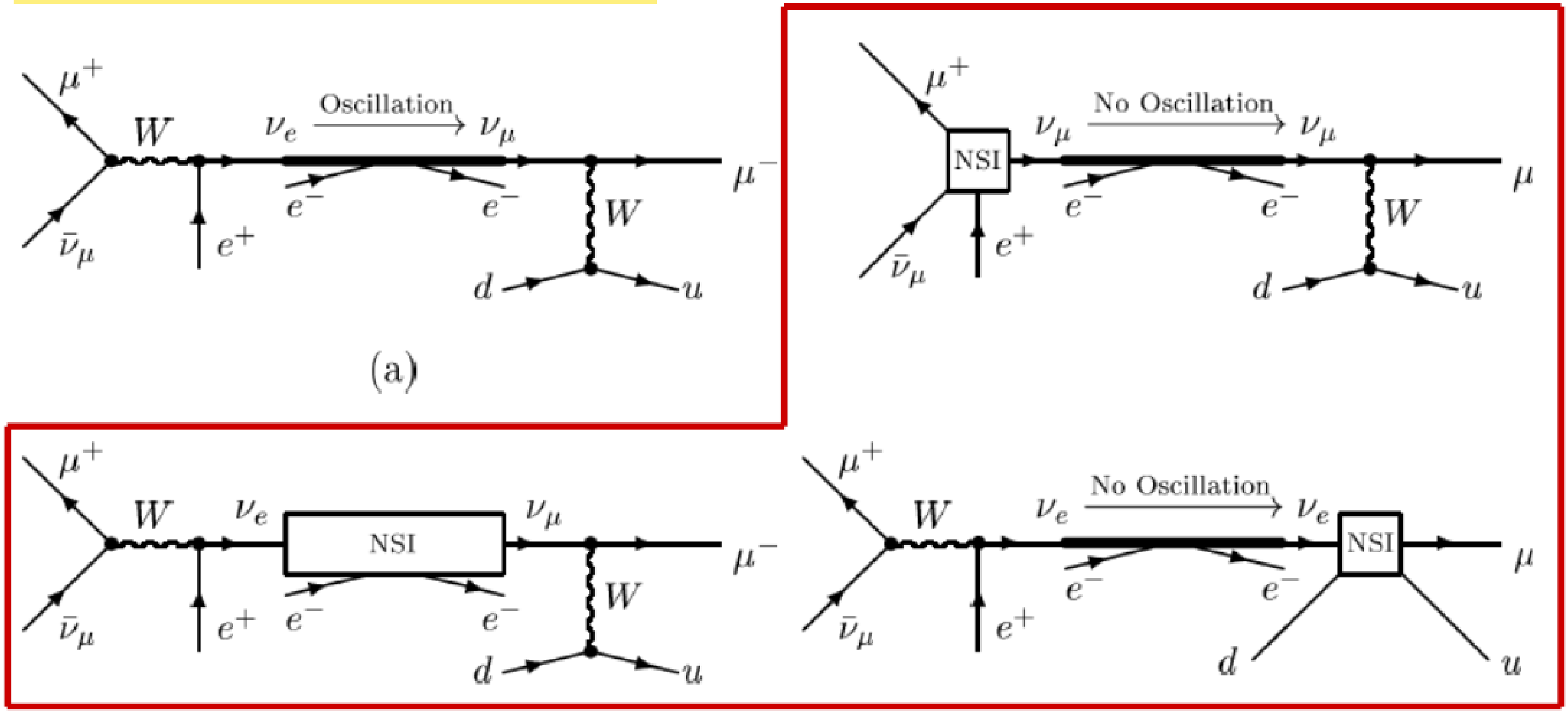
PHYS. REV. D 102, 115027 (2020)



NSIs interfere with Oscillations

the "golden" oscillation channel

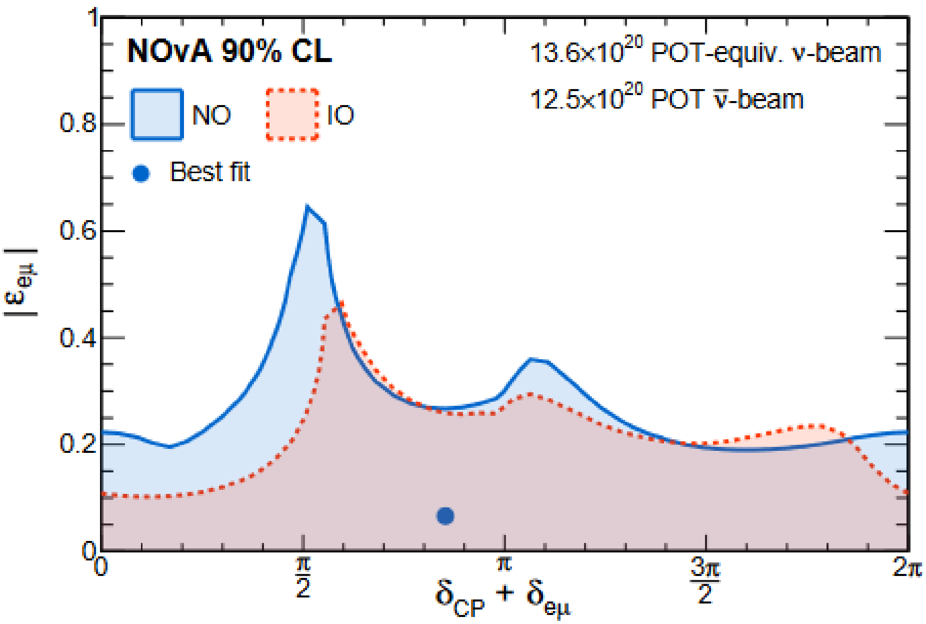
NSI contributions to the "golden" channel

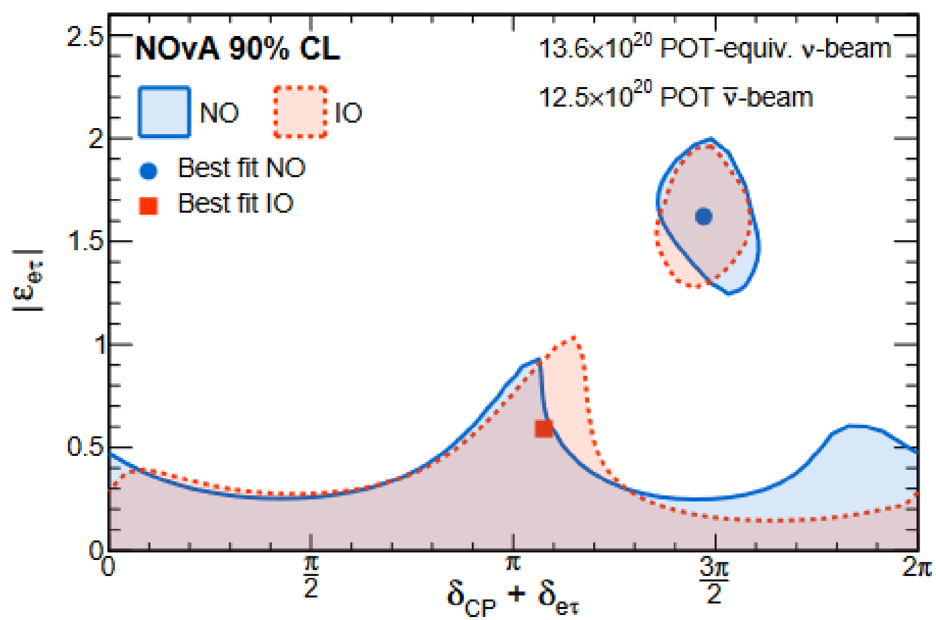


interference in oscillations ~ε ⇔ FCNC effects ~ε^2

NOvA NSI results

- Measuring disappearance of muon (anti)neutrinos and appearance of electron (anti)neutrinos
- Looking for phase and magnitude of NSI in $e \rightarrow \mu$ and $e \rightarrow \tau$





https://arxiv.org/abs/2403.07266

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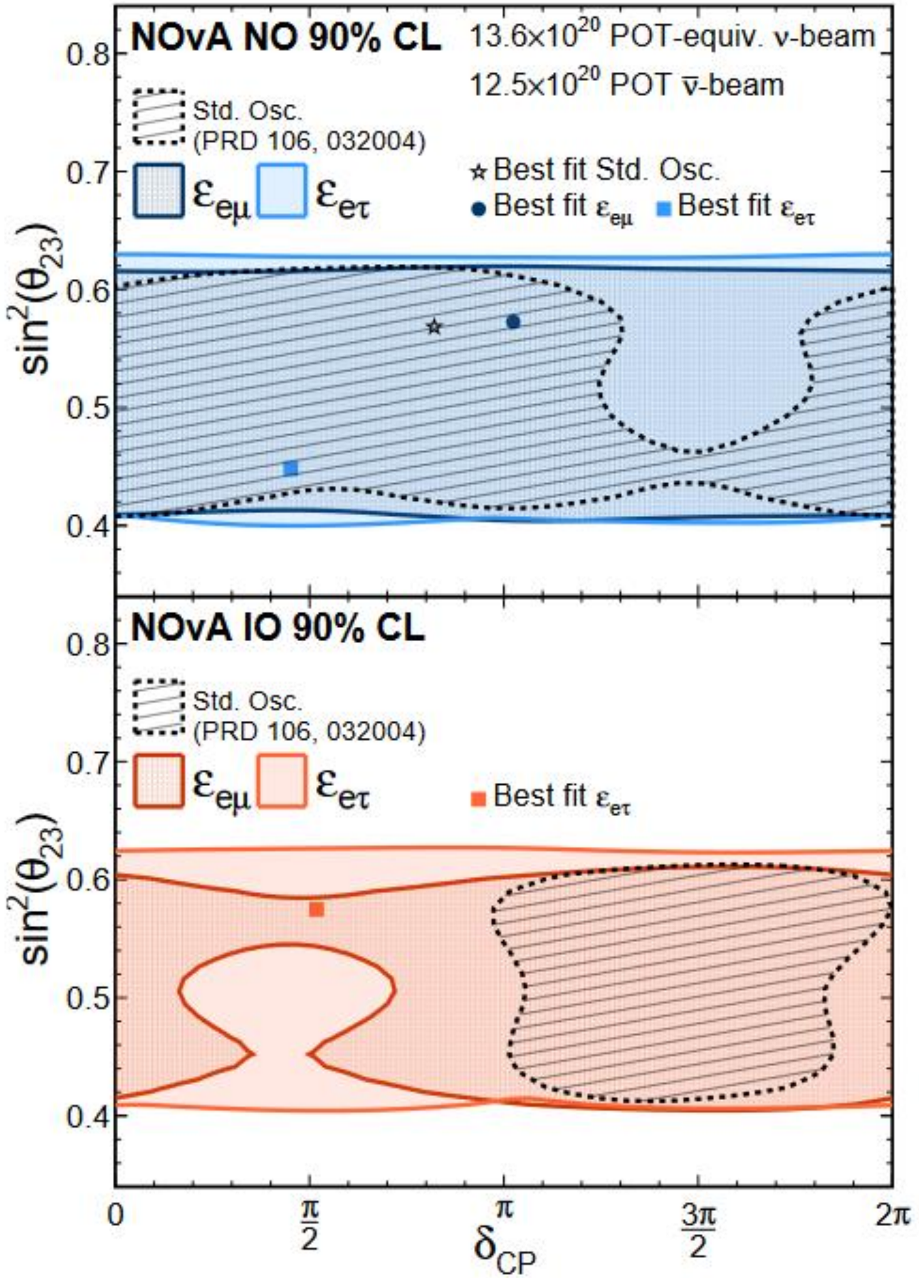
NOvA NSI results

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



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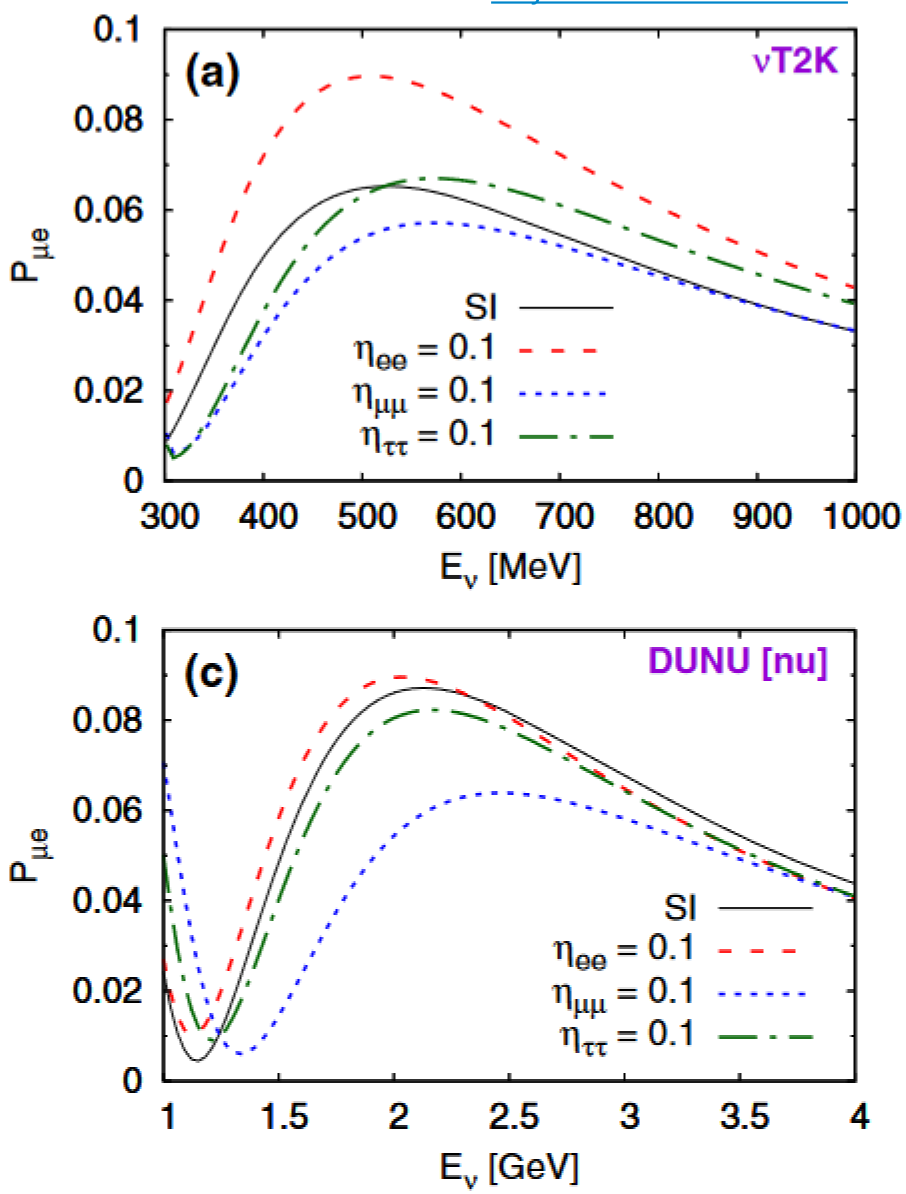
Multi-experiment NSI

- 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

From PhysRevLett.122.211801



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

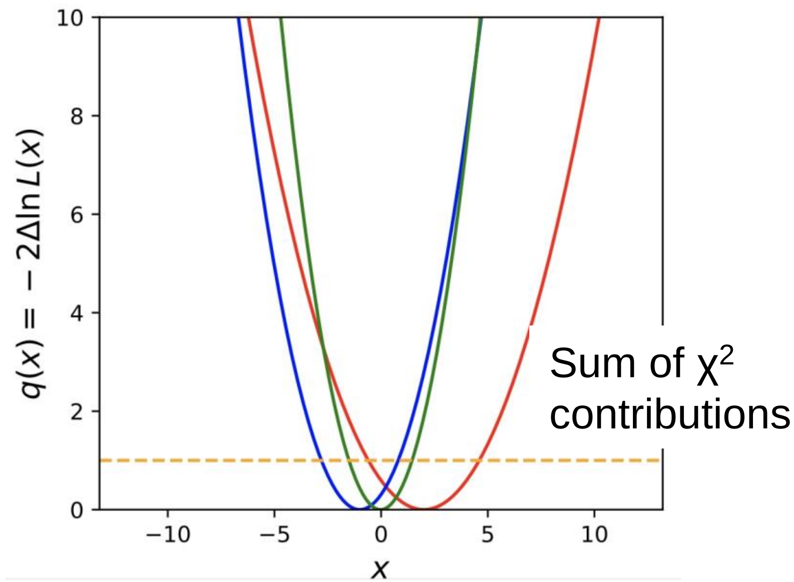
$$x_1 \pm \sigma_1$$

$$x_2 \pm \sigma_2$$

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

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

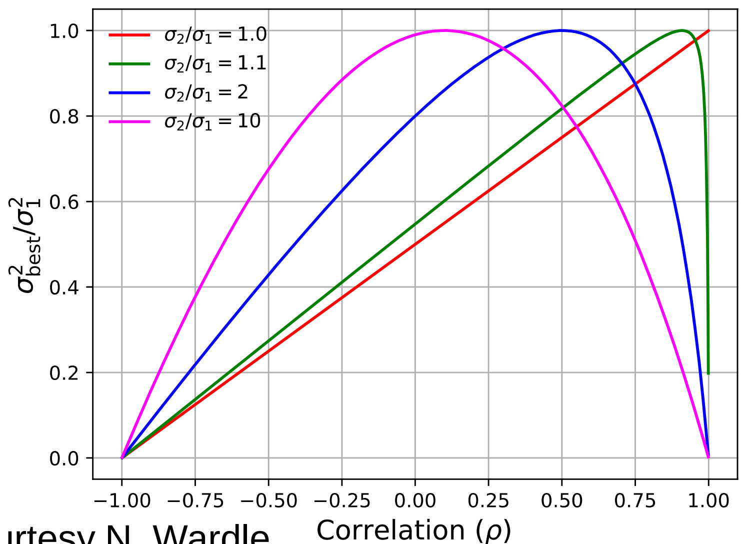
$$w_i = \frac{1}{\sigma_i^2}$$



Courtesy N. Wardle

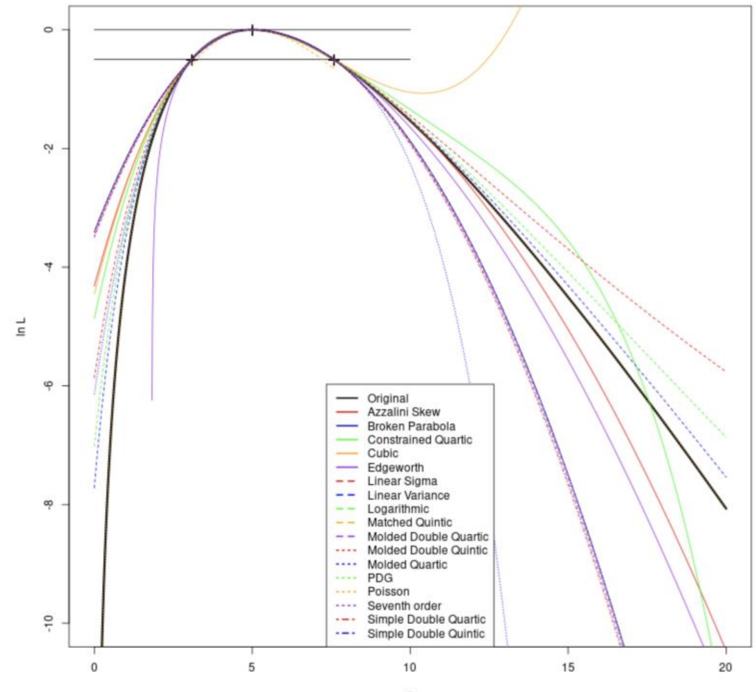
Potential issues

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



Courtesy N. Wardle

- Asymmetric errors
  - ln L from approx. of Poisson
  - OK at ~1 sigma, diverges past this
  - How do we interpret published value?



https://arxiv.org/abs/2411.15499

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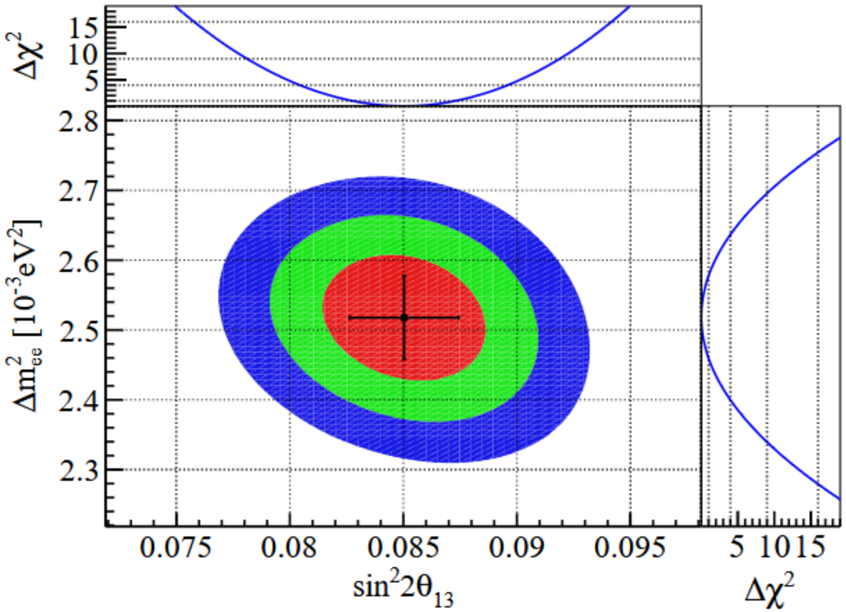
Other methods of combination

- 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

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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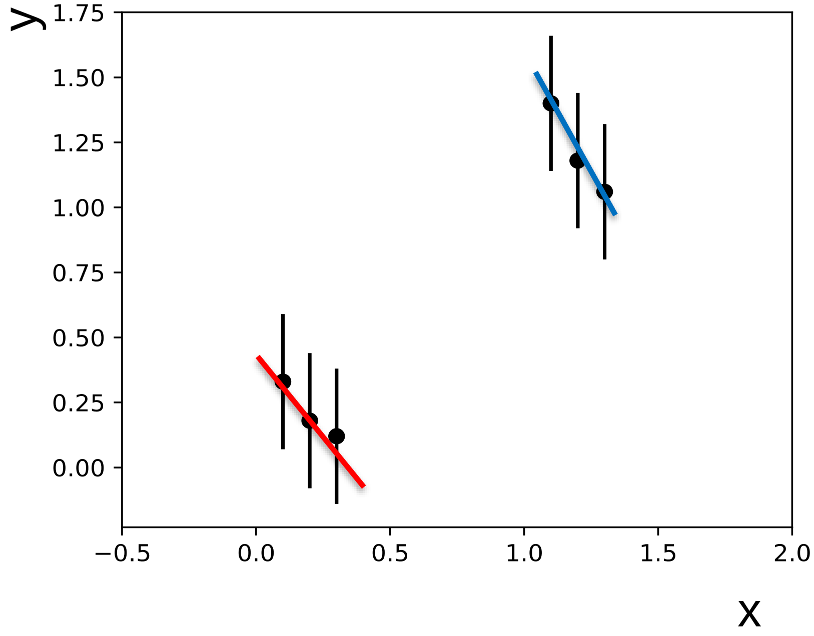
Warning about combining likelihoods

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



- Fit straight line to two data samples

$$y = mx + c$$

- Marginalise over parameter *c*
- Combine…

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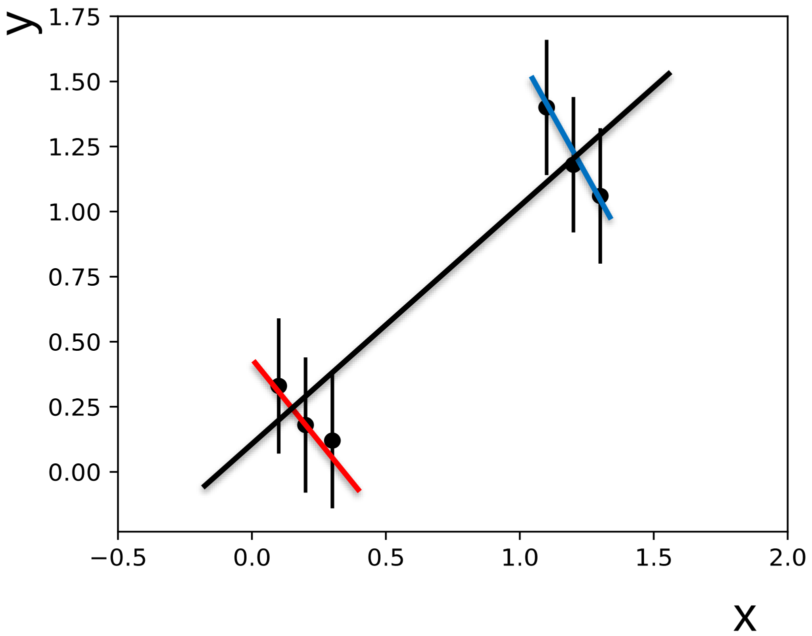
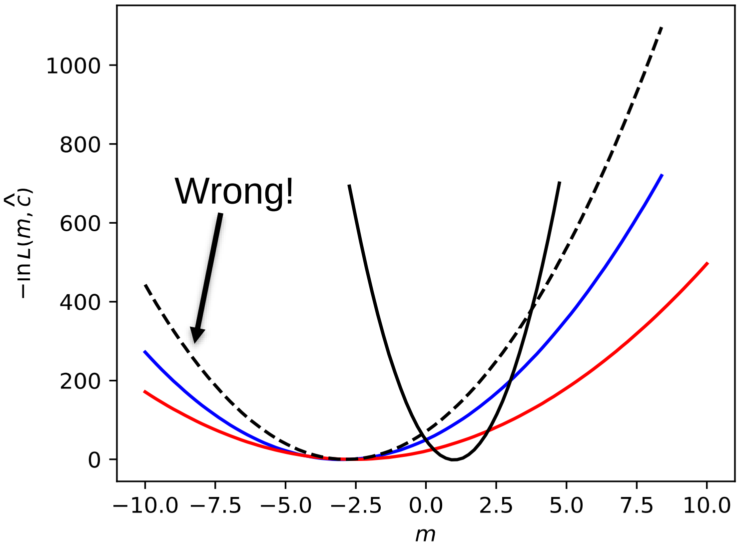
Warning about combining likelihoods

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





- Need to study correlations of data and models when combining
  - Demonstrate (in)compatibility of model with data at very least

Difficulties facing combined analyses

- Measurements from Daya-Bay, JUNO, Hyper-K, DUNE, IceCube-Upgrade, KM3NeT, P-ONE etc. will be systematics limited
  - Cannot rely on statistical combination of results

- To date community has struggled to produce a neutrino interaction model that can correctly predict event rates at a different experiment / neutrino source
  - Scaling of interaction cross section across energies, nuclear targets difficult
  - Removing effects of detector from measurements also tricky
  - Does parameter A in HK’s model mean the same as parameter A’ in the model used by DUNE?

- Beam experiments tune neutrino flux and interaction cross section models to near detector data
  - Need to “combine” near detector analyses as well

Neutrino event generators

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

- 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

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Overcoming difficulties

- Start talking about them!
  - Help experiments develop analyses with ease of combination in mind
  - Help with sociological side of combined analyses
  - Support development of common formats (NuHEPMC etc.)

- Start doing it now!
  - T2K + NOvA and T2K + SK demonstrate how to do this
  - Discover (and address) potential issues for future experiments

- Potential to have joint facilities in future!
  - NA61/SHINE for next gen experiments
  - Neutrino beamline at CERN (NuSTORM, EnuBET etc.) with argon, scintillator, water Cherenkov detectors

Summary

- Many ways to combine experiment results
  - Simple methods not easy for (high statistics) neutrino data!
  - Direct combination of likelihoods preferred

- Must understand correlations of both nuisance and signal parameters across reactor, atmospheric, solar and beam neutrinos

- Compatibility of event rate model across experiments likely a key issue
  - Must be able to compare near detector data between experiments
  - Unified event generator I/O, common analysis tools
  - Multiple detectors in shared neutrino beam ~ideal to study this

- **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!**

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Thank you!

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Electron (anti)neutrino appearance

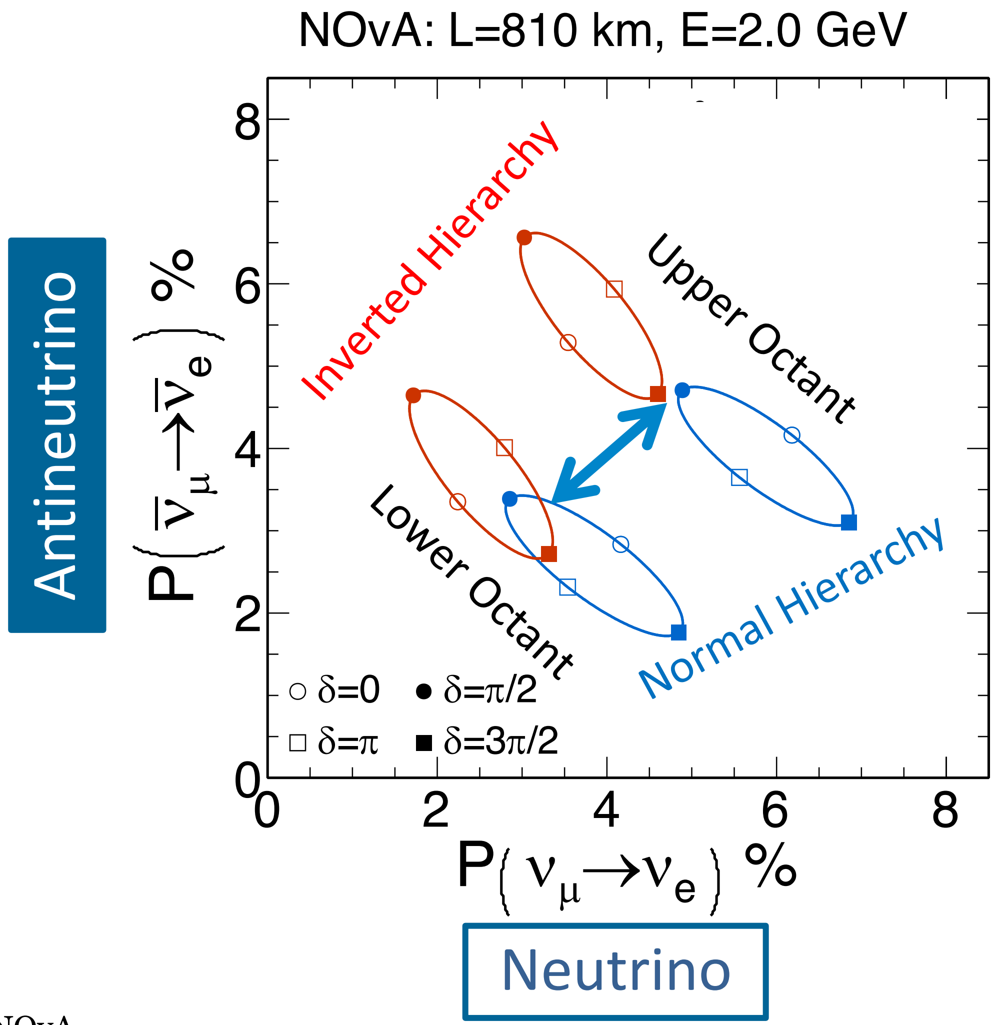

Image by A. Himmel / NOvA

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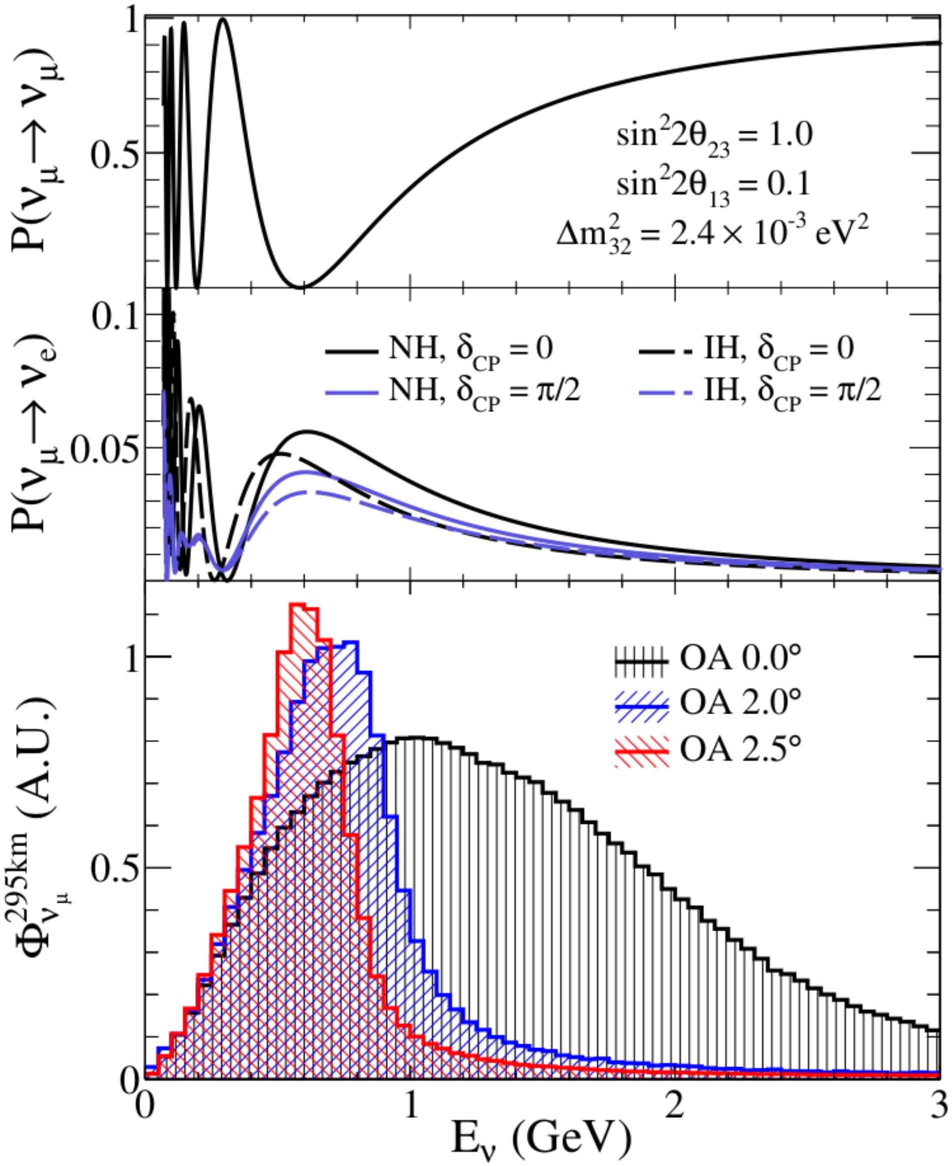
T2K Off-axis beam

- 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



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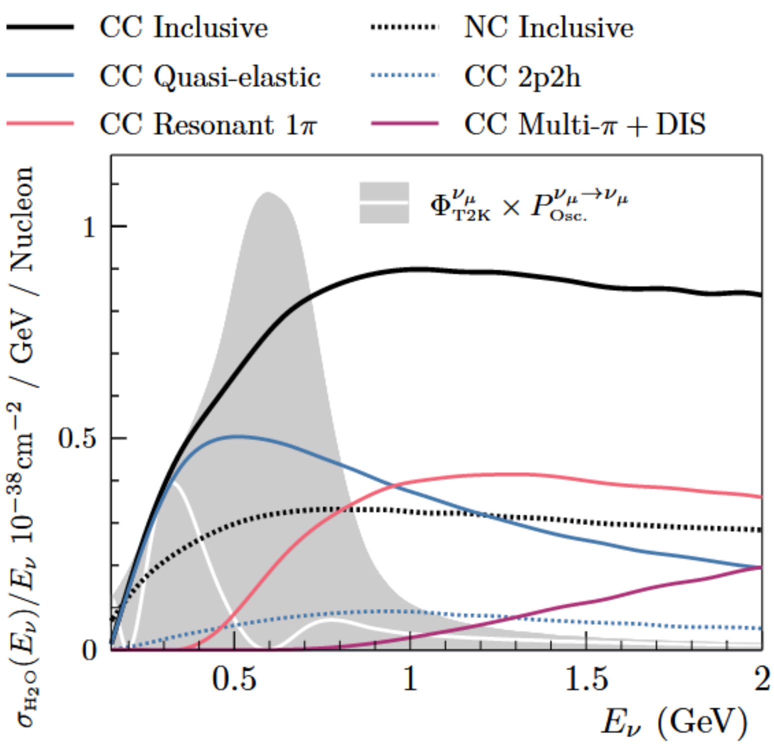
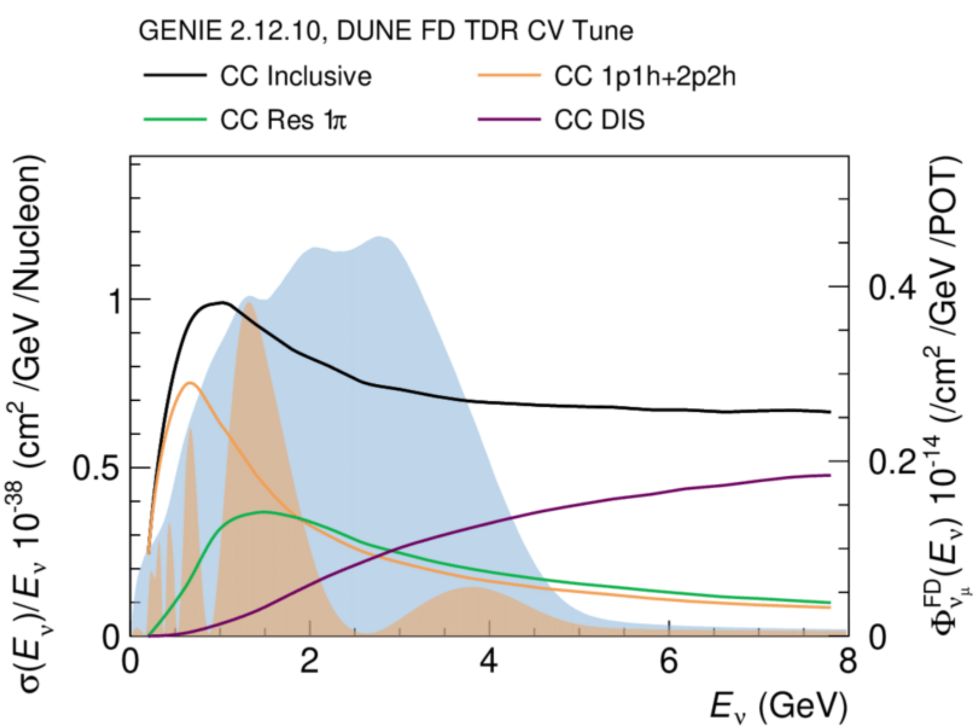
Flux and Cross-section at T2K and DUNE

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





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T2K systematic errors (2020)

	One-ring μ		One-ring e			
Error source	FHC	RHC	FHC	RHC	FHC 1 d.e.	FHC/RHC
Flux and (ND unconstrained)	14.3	11.8	15.1	12.2	12.0	1.2
cross section (ND constrained)	3.3	2.9	3.2	3.1	4.1	2.7
SK detector	2.4	2.0	2.8	3.8	13.2	1.5
SK FSI + SI + PN	2.2	2.0	3.0	2.3	11.4	1.6
Nucleon removal energy	2.4	1.7	7.1	3.7	3.0	3.6
$\sigma(\nu_e)/\sigma(\bar{\nu}_e)$	0.0	0.0	2.6	1.5	2.6	3.0
NC1γ	0.0	0.0	1.1	2.6	0.3	1.5
NC other	0.3	0.3	0.2	0.3	1.0	0.2
$\sin^2\theta_{23}$ and Δm^2_{21}	0.0	0.0	0.5	0.3	0.5	2.0
$\sin^2\theta_{13}$ PDG2018	0.0	0.0	2.6	2.4	2.6	1.1
All systematics	5.1	4.5	8.8	7.1	18.4	6.0

PhysRevD.103.112008

- Final column is “CP-violating” systematic error
  - Nucleon removal energy fixed in later analysis
  - ND constrained rate error can be reduced
  - Electron neutrino cross-section more difficult to reduce – target for next gen
  - Disappearance parameters also a leading error term

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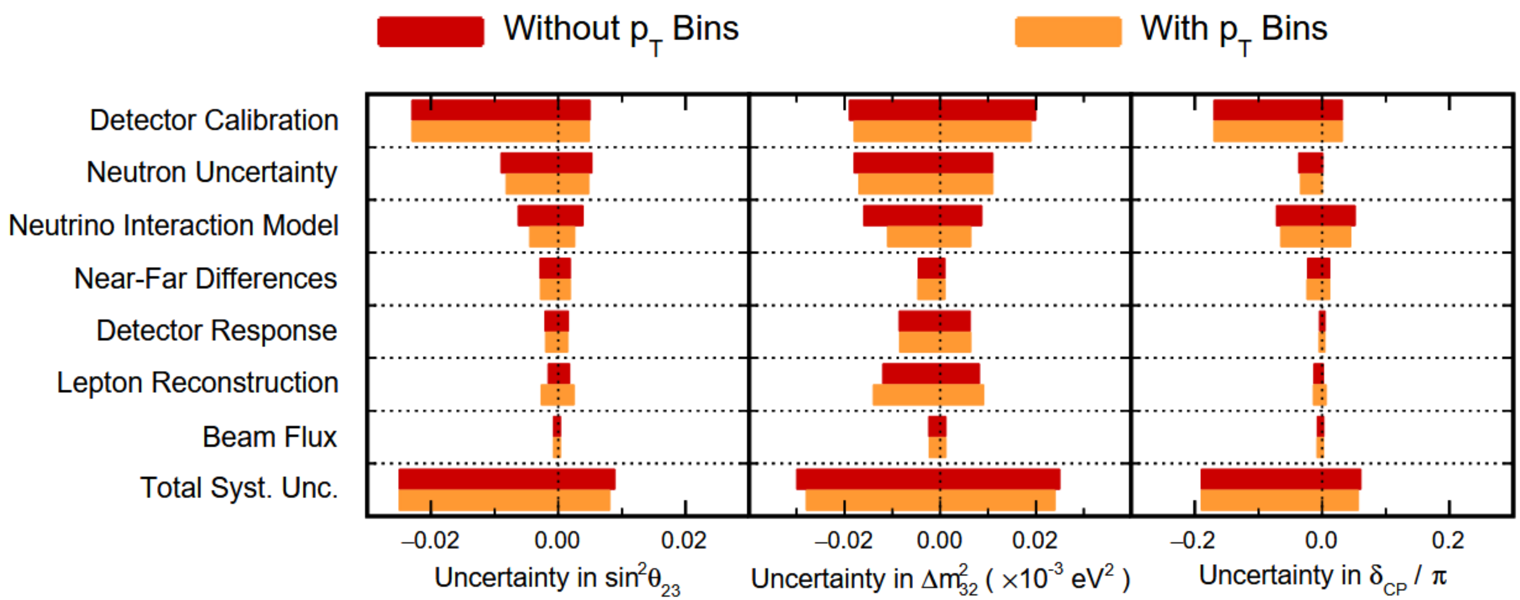
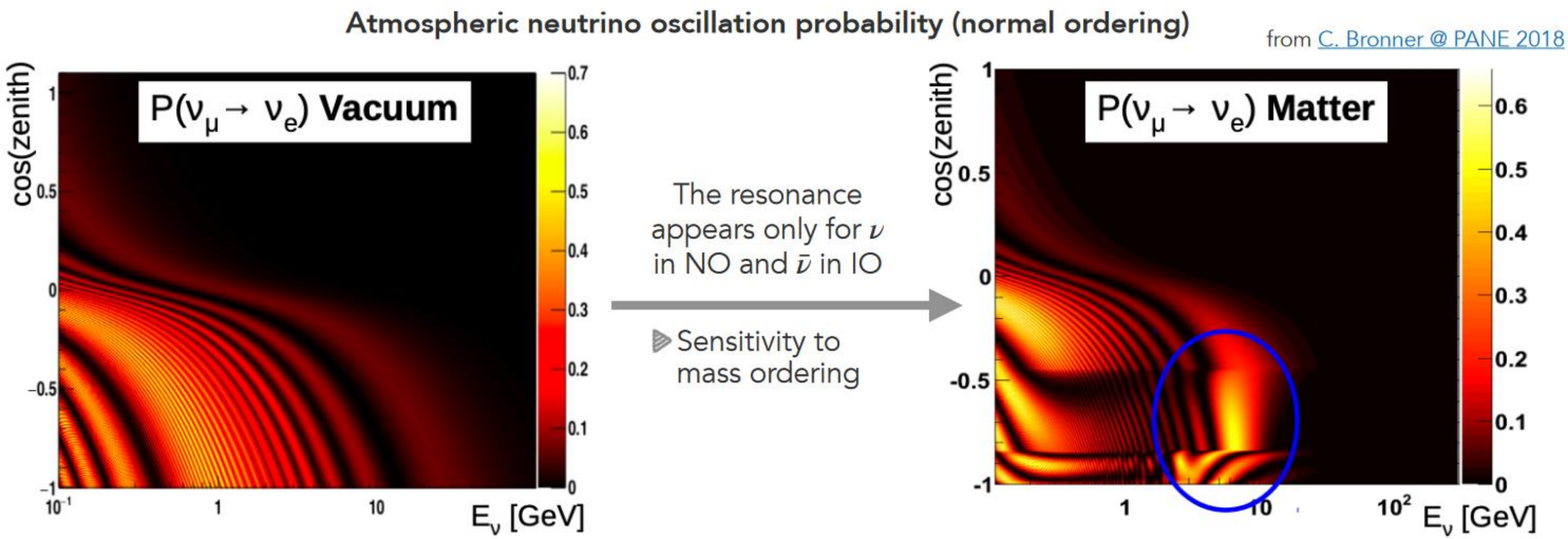
A note on NOvA

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



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

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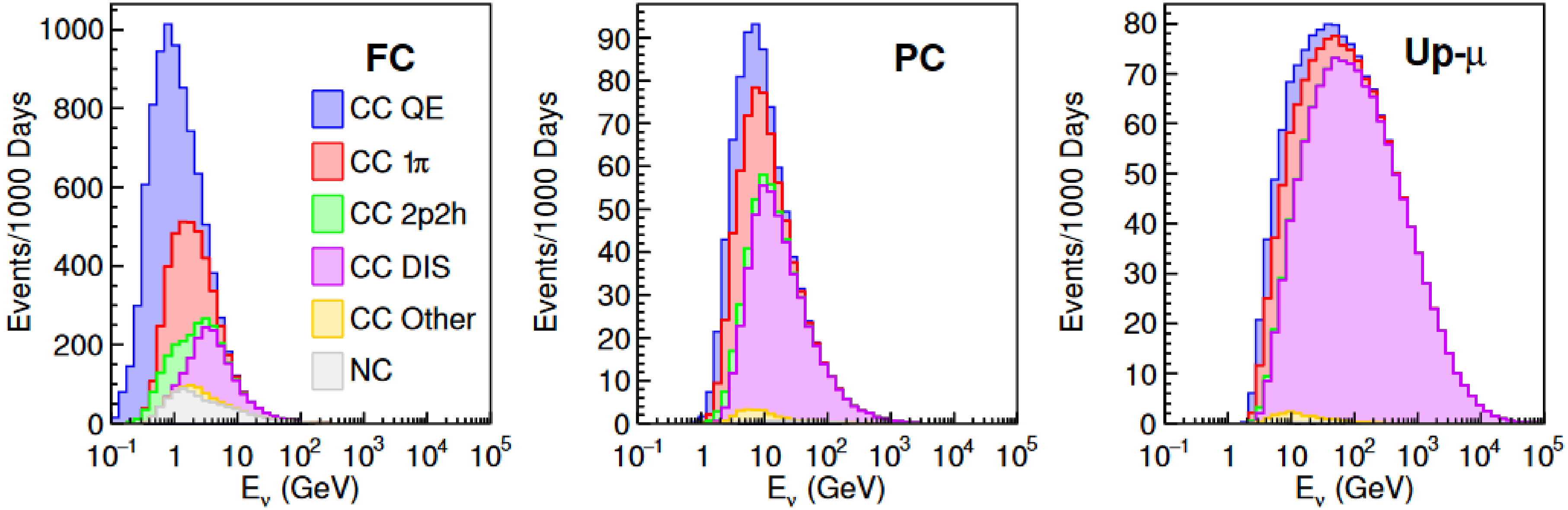
Atmospheric neutrinos – SK samples

T. Wester, PhD thesis



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

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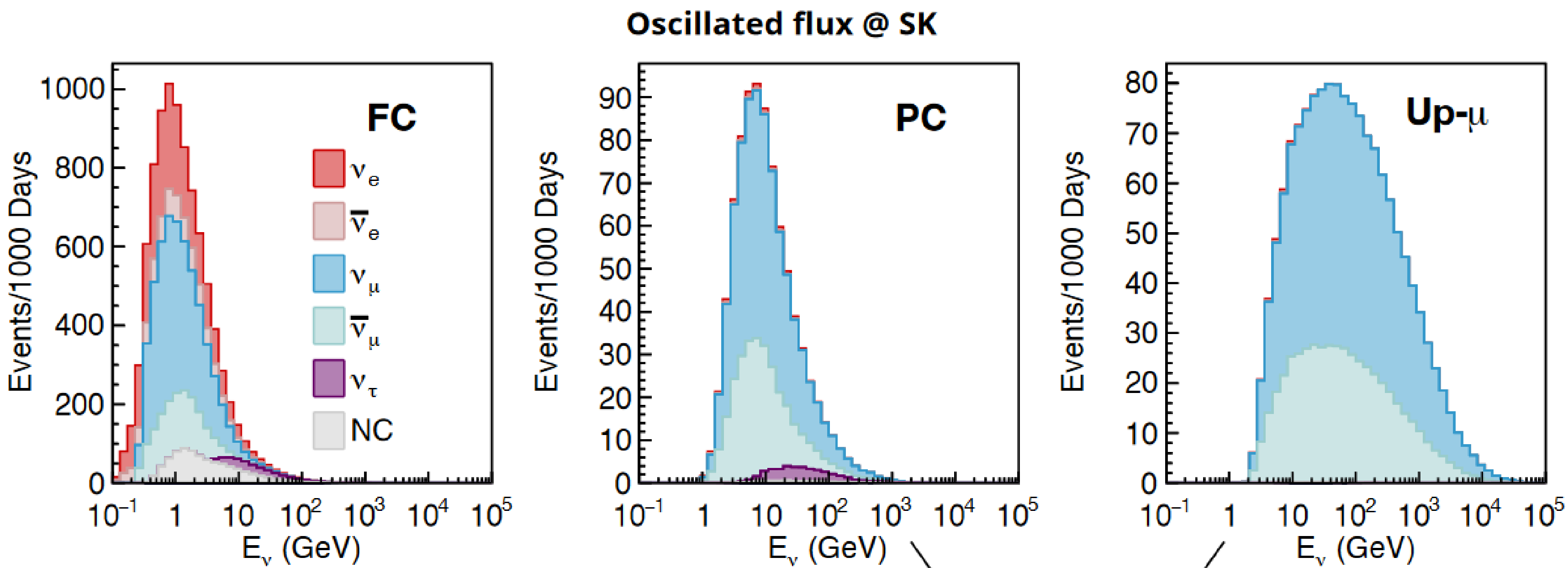
Atmospheric neutrinos – SK samples

T. Wester, NNN2023



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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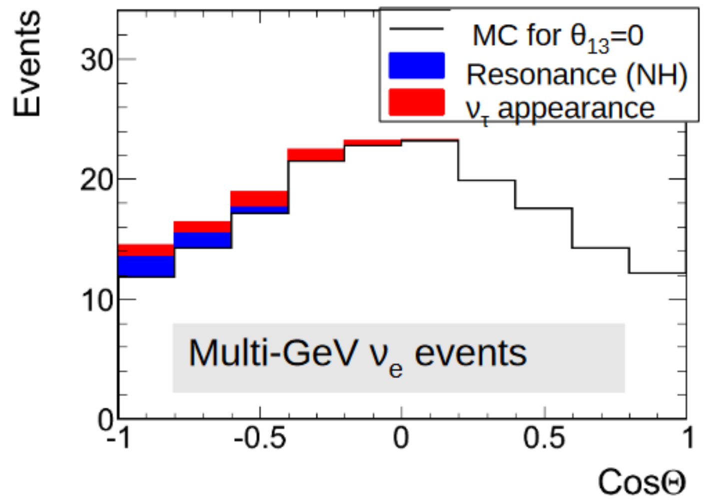
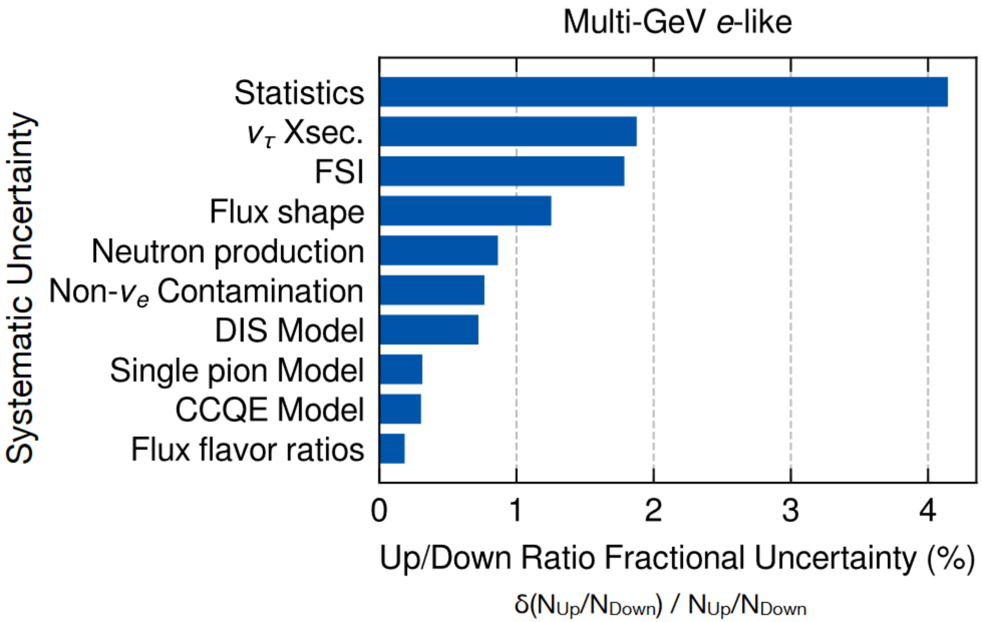
Atmospheric neutrinos – SK systematics

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



T. Wester, NNN2023

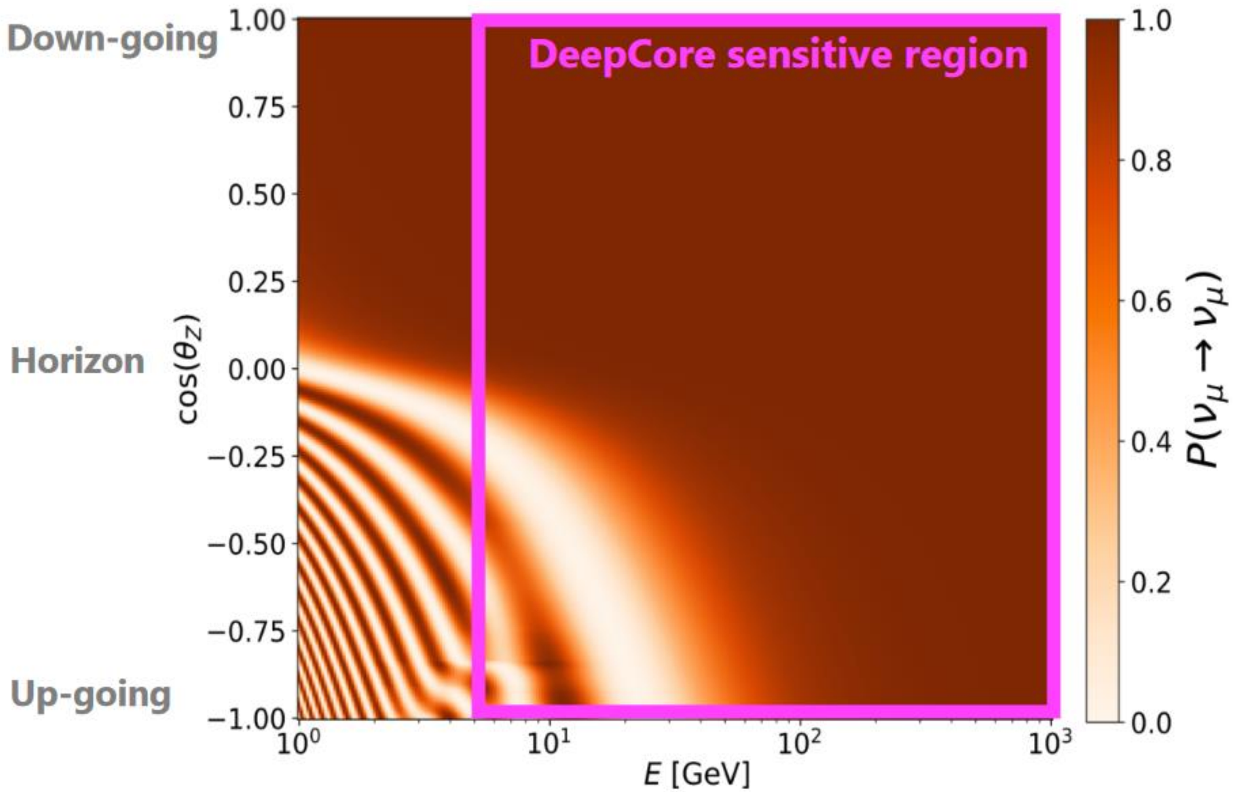


- Mass ordering sensitivity from upward-going, multi-GeV electron-like samples
- Tau cross-section uncertainty dominant systematic
  - Hyper-Kamiokande will have statistical error <2%

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

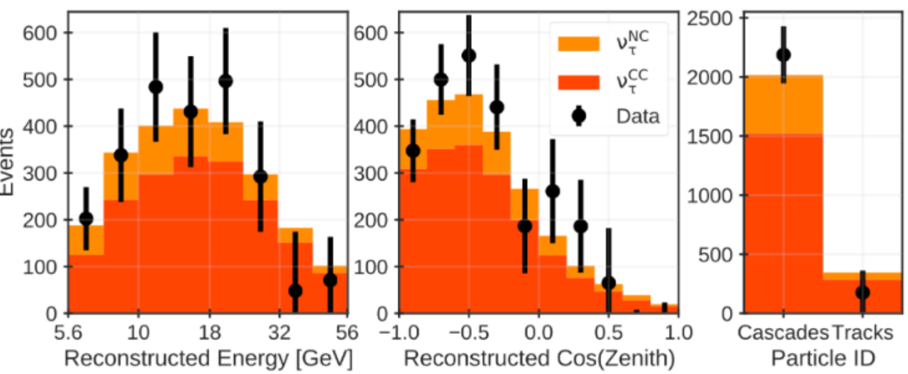
T. Stuttard, NuFact 2019



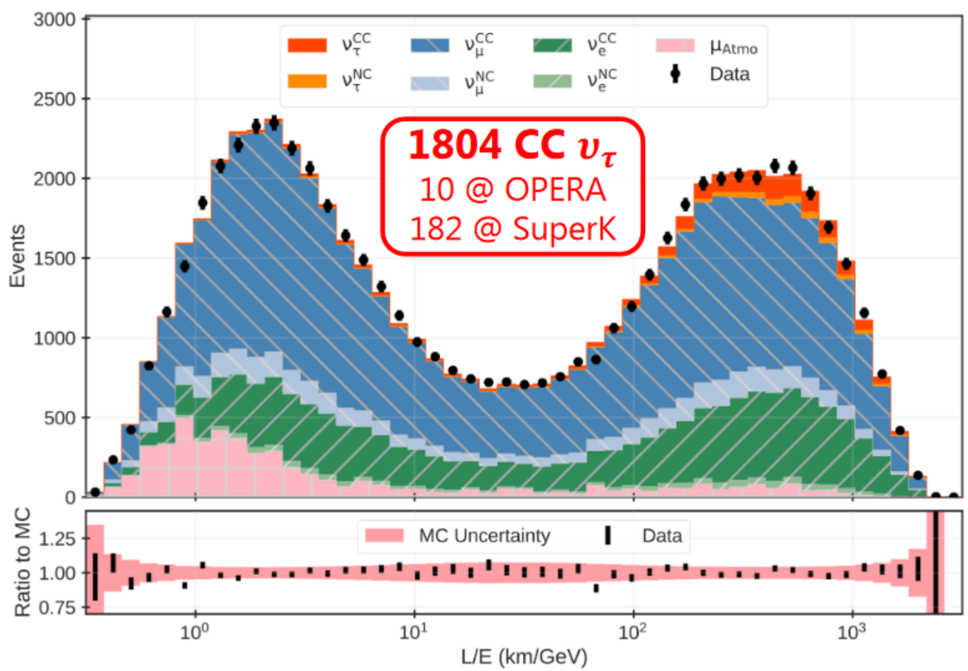
Tau appearance at IceCube

- Largest tau neutrino sample to date (more recent results have focused on measurement of oscillation parameters)
- IceCube-Gen2 – completion in 2032, ~same as DUNE

T. Stuttard, NuFact 2019



Data fit in [energy, cos(zenith), PID] space
Searching for 3D distortions (shape-only)



Tau neutrino cross-section

- As seen before, cross-section has significant uncertainty
- Very few (none?) tau neutrino cross-section measurements exist at 10 - 100GeV that do not assume PMNS unitarity
  - Wrong energy for terrestrial oscillations
  - Hard to produce

- Measurements exist from atmospheric neutrinos (IceCube, SK) and OPERA
  - Must assume unitarity to measure cross-section

    Or

  - Assume lepton universality and large systematic error if testing non-unitarity

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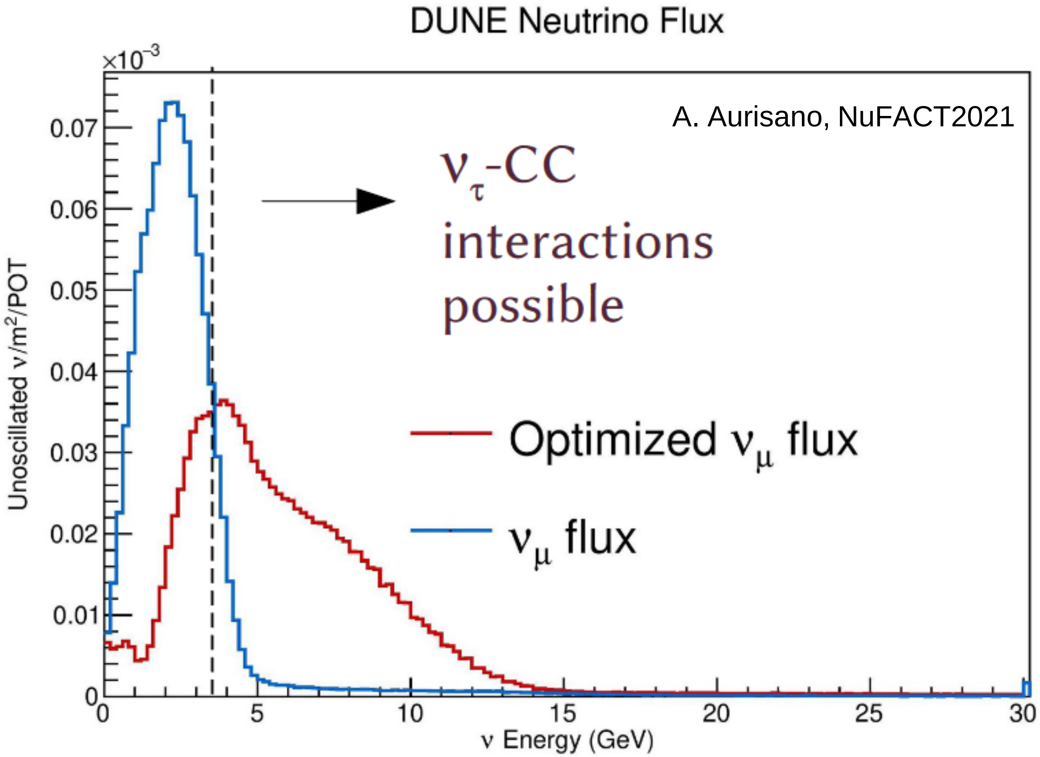
DUNE for Tau neutrino appearance

- DUNE neutrino beam has tail to higher energies
- Could operate in “Tau optimized mode”
  - Predict 800 tau appearance events per year
- Same issue with IceCube
  - Tau cross-section assumed from lepton universality
  - Large uncertainty
- Can flux shape information help?



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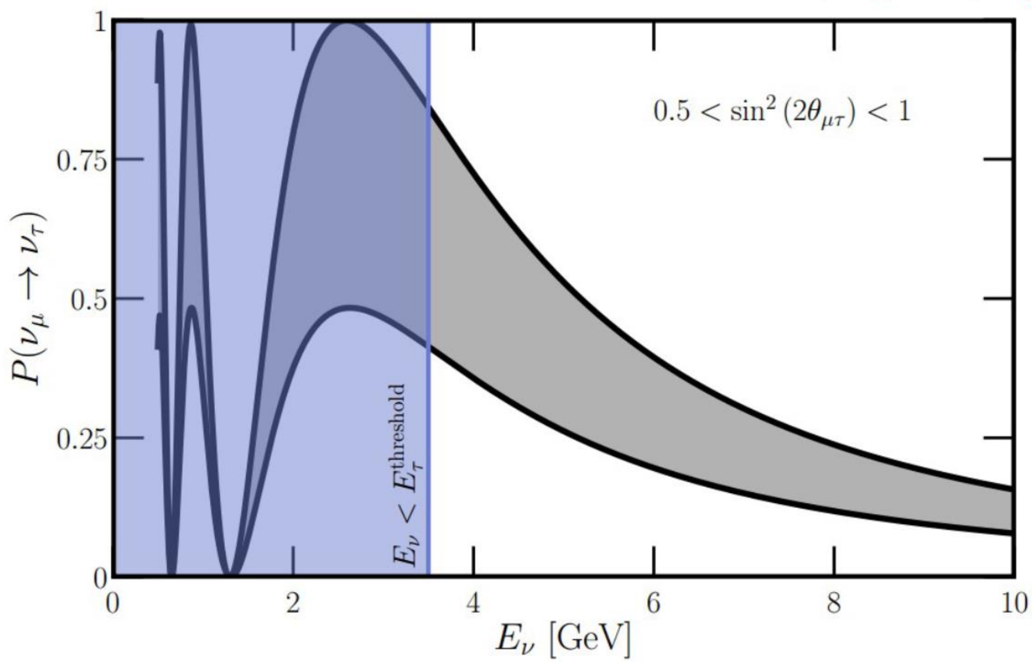
DUNE for Tau neutrino appearance

- Additional difficulty in that tau threshold is above oscillation maximum
  - Makes measurement of oscillation parameters ambiguous, since $\sin^2\theta_{\mu\tau}$ alters shape as well as normalisation

de Gouvea, Kelly, Stenico, Pasquini, PRD 100, 016004 (2019)



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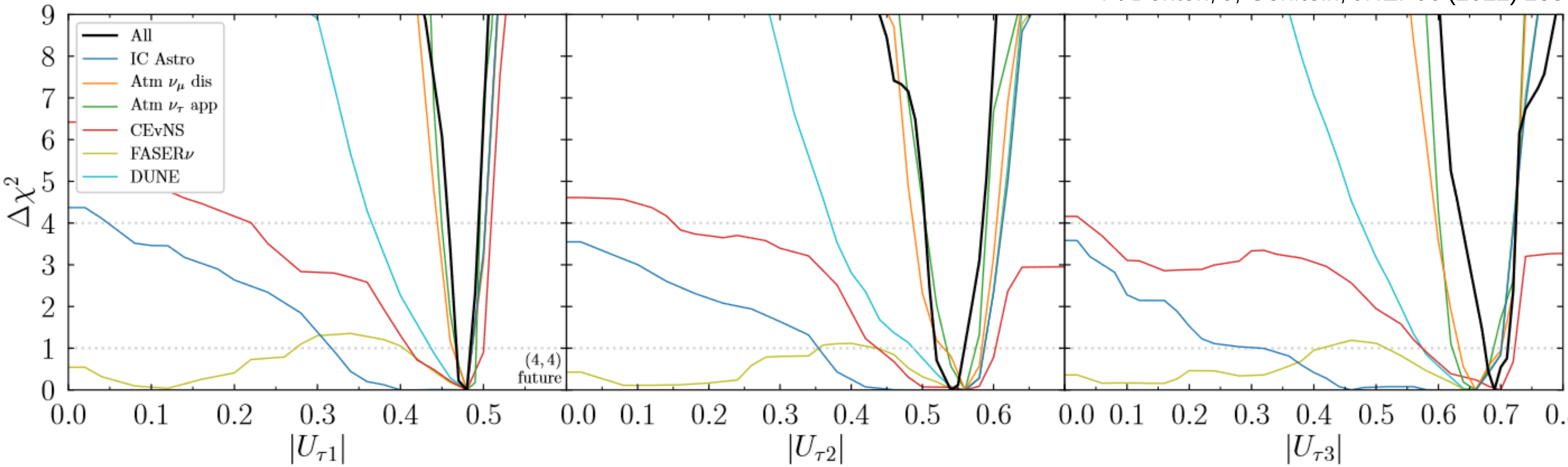
Future limits on PMNS unitarity

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

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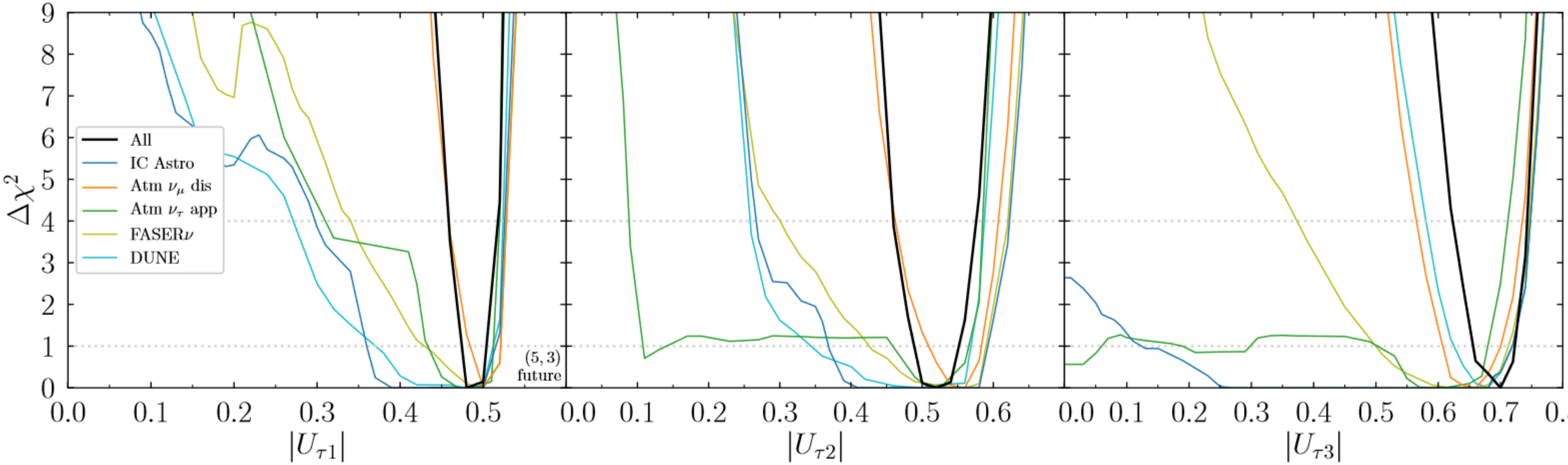
Future limits on PMNS unitarity

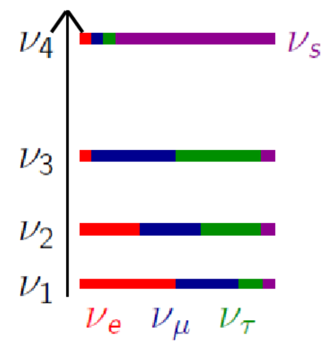
P. Denton, J, Gehrlein, JHEP06 (2022) 135



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

Sterile neutrinos

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



- Right-handed neutrino needed for mass generation
- May explain other experimental anomalies
- “3+1” model (above) is most studied

Sterile oscillations

3-flavour oscillation formula in blue

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2 \Delta_{31} + 2\sin^2 2\theta_{23} \sin^2 \theta_{24} \sin^2 \Delta_{31} - \sin^2 2\theta_{24} \sin^2 \Delta_{41}$$

and

$$1 - P(\nu_\mu \rightarrow \nu_s) \approx 1 - \cos^4 \theta_{14} \cos^2 \theta_{34} \sin^2 2\theta_{24} \sin^2 \Delta_{41} - \sin^2 \theta_{34} \sin^2 2\theta_{23} \sin^2 \Delta_{31} + \frac{1}{2} \sin \delta_{24} \sin \theta_{24} \sin 2\theta_{23} \sin \Delta_{31}$$

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

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Sterile oscillations

3-flavour oscillation formula in blue

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2 \Delta_{31}$$
$$+2 \sin^2 2\theta_{23} \sin^2 \theta_{24} \sin^2 \Delta_{31}$$
$$- \sin^2 2\theta_{24} \sin^2 \Delta_{41}$$

and

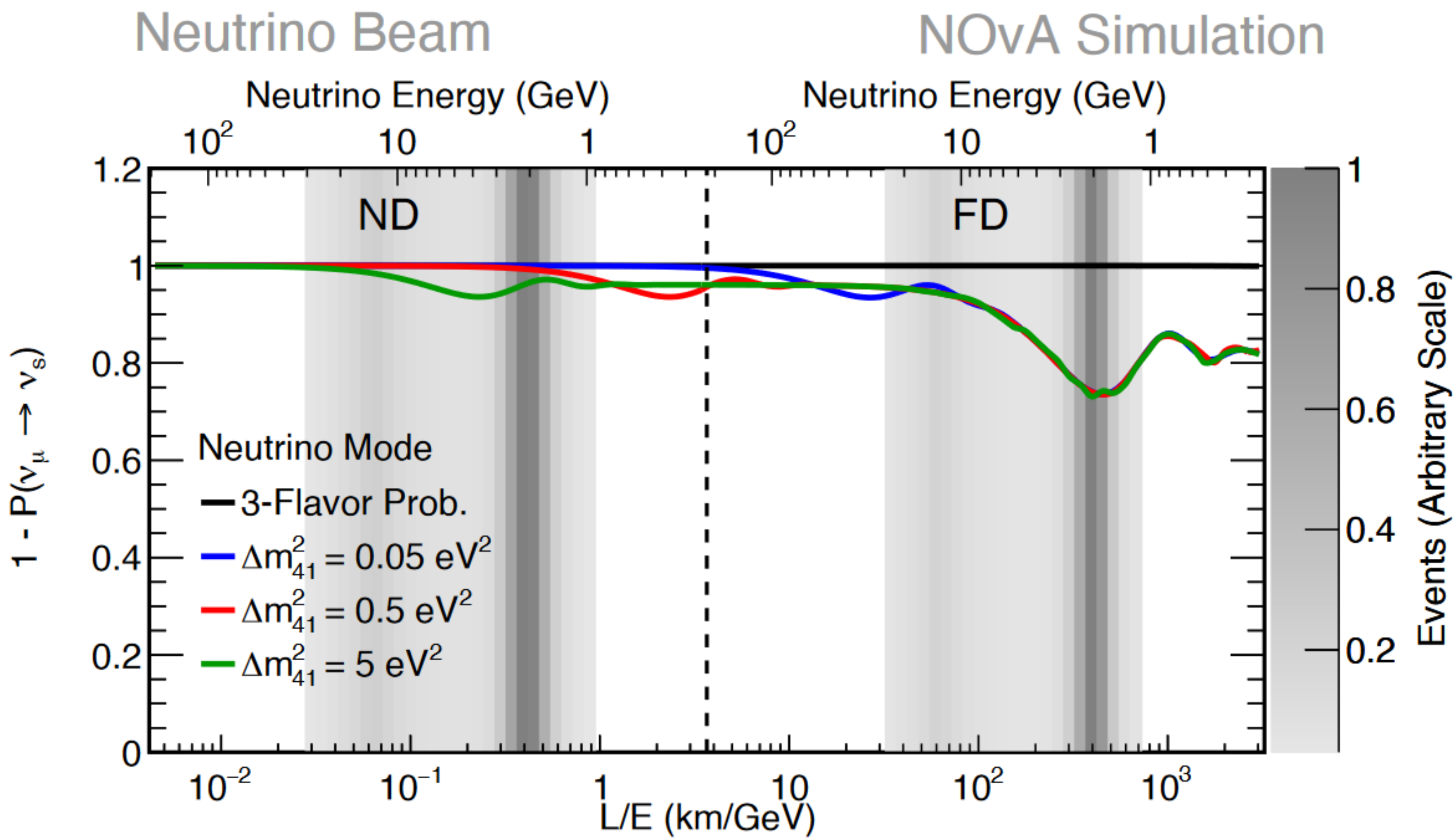
$$1 - P(\nu_\mu \to \nu_s) \approx 1 - \cos^4 \theta_{14} \cos^2 \theta_{34} \sin^2 2\theta_{24} \sin^2 \Delta_{41}$$
$$- \sin^2 \theta_{34} \sin^2 2\theta_{23} \sin^2 \Delta_{31}$$
$$+ \frac{1}{2} \sin \delta_{24} \sin \theta_{24} \sin 2\theta_{23} \sin \Delta_{31}$$

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

New parameters in red

Sterile oscillations

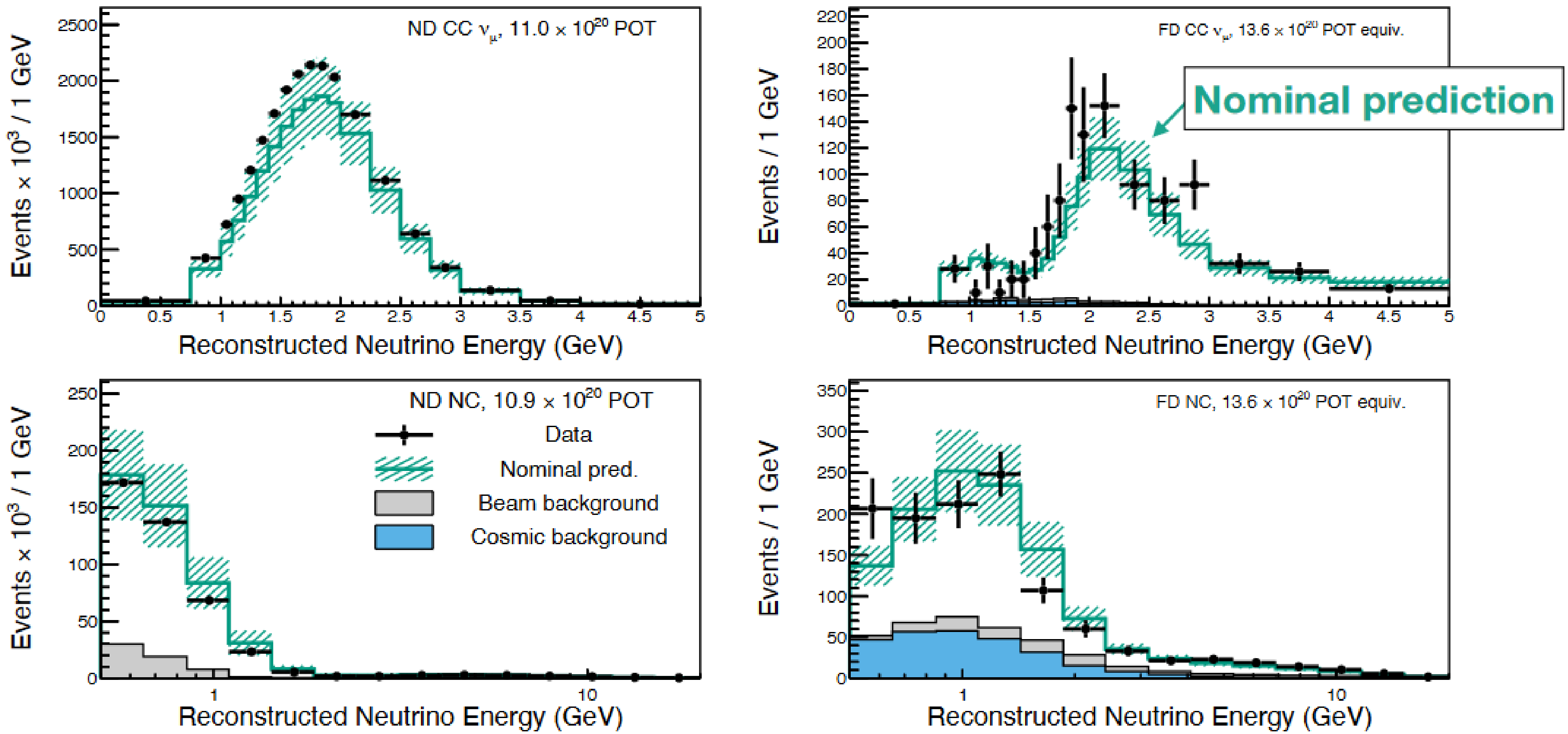
All results from: BSM neutrino oscillations at NOvA, V Hewes, NuFact 2022



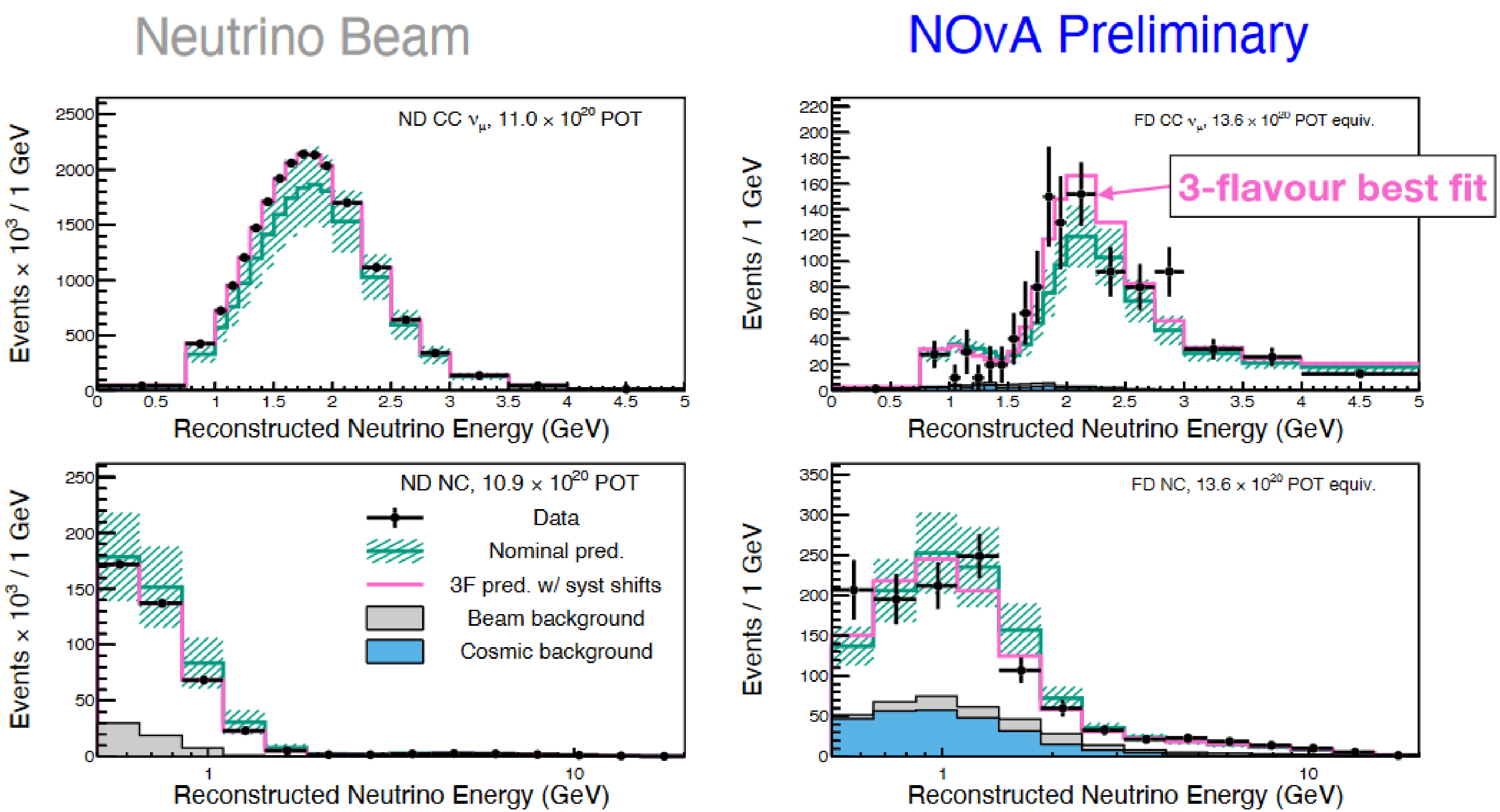
Sterile neutrino search results

Neutrino Beam

NOvA Preliminary



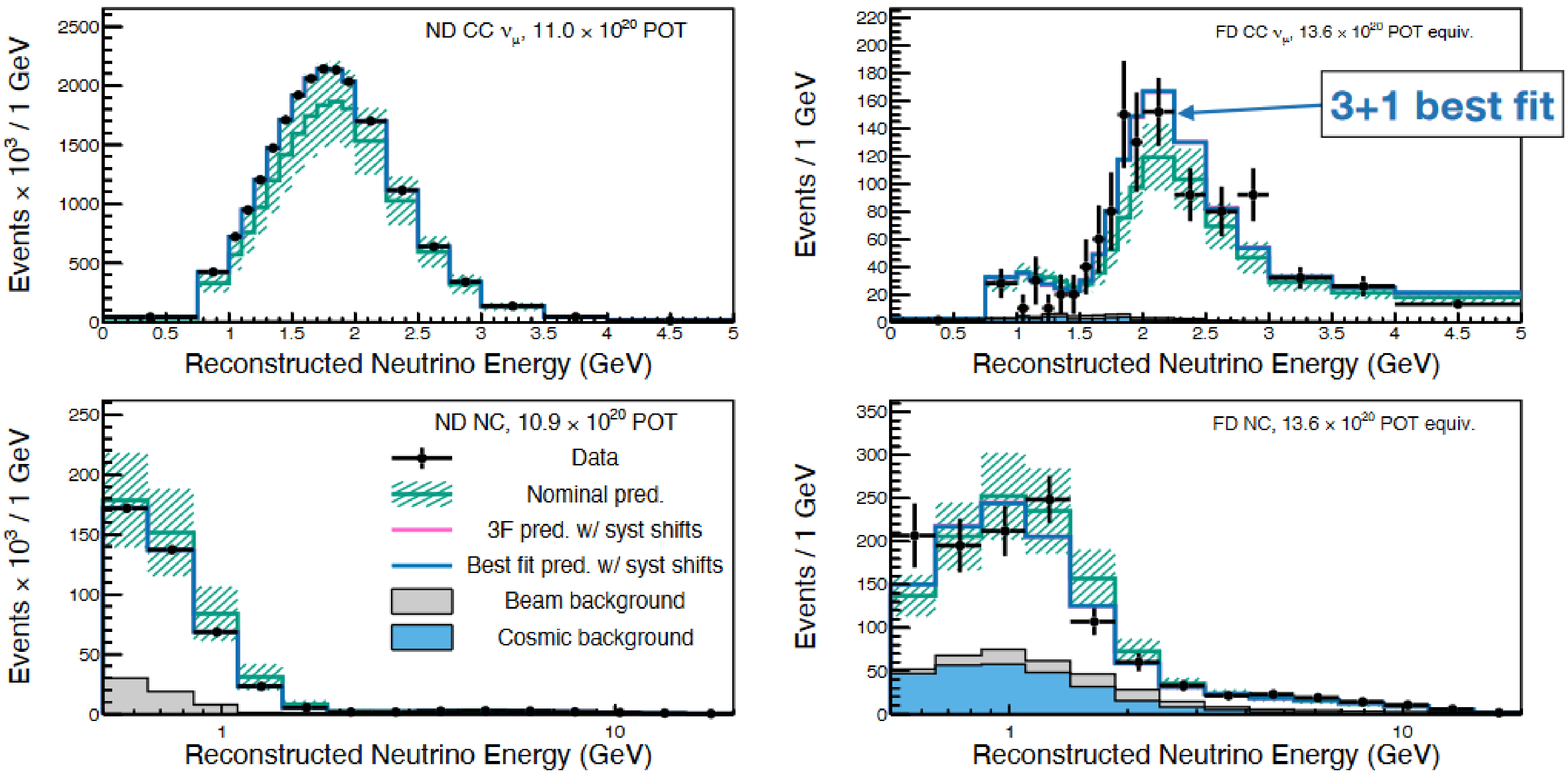
Sterile neutrino search results



Sterile neutrino search results

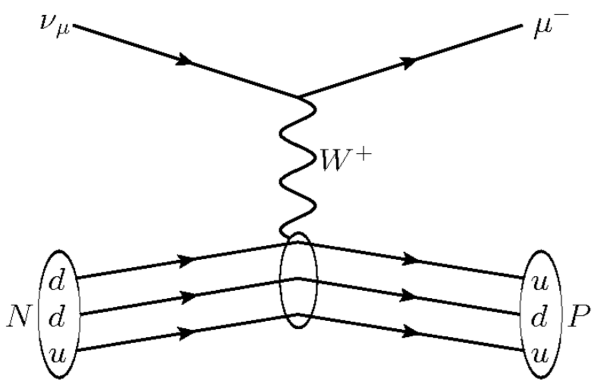
Neutrino Beam

NOvA Preliminary

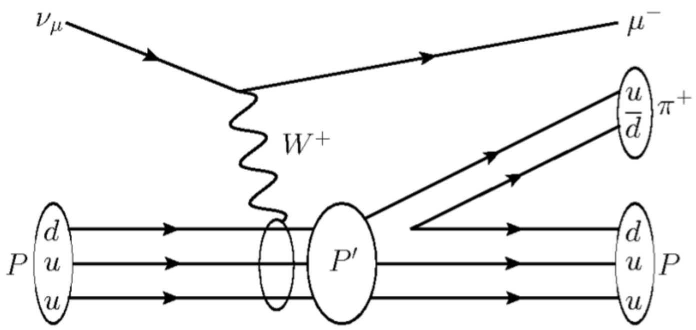


Neutrino interactions

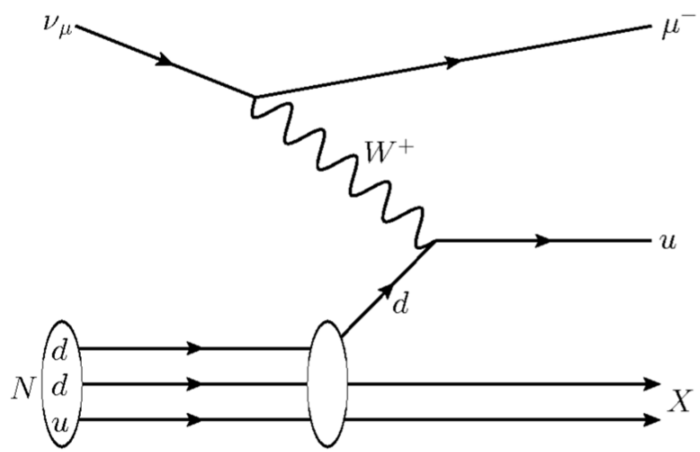
- Three principal types of neutrino interaction
- Occur as both charged current (CC) and neutral current processes



Quasi-elastic (CCQE)

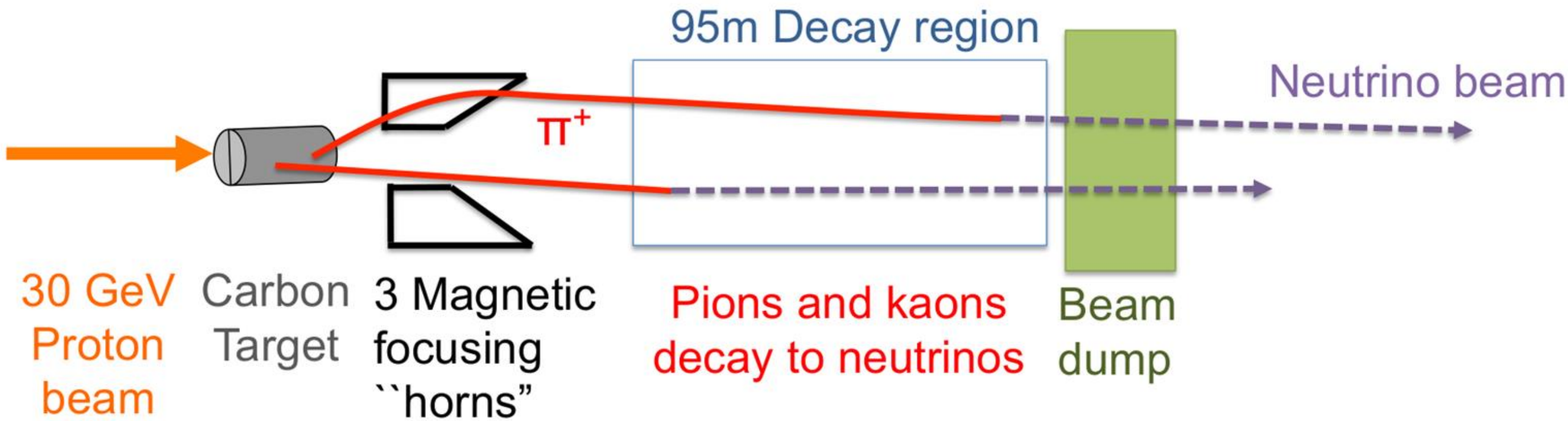


Single pion production

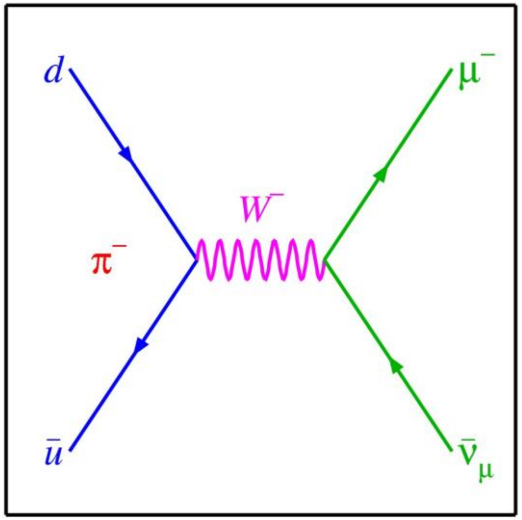


Deep inelastic scattering / Multi-pion production

Neutrino beams



- Proton beam collides with fixed target to produce charged mesons
- Focus positive or negative mesons to produce neutrino-dominated or antineutrino-dominated beam
- Wait for pions to decay into neutrinos



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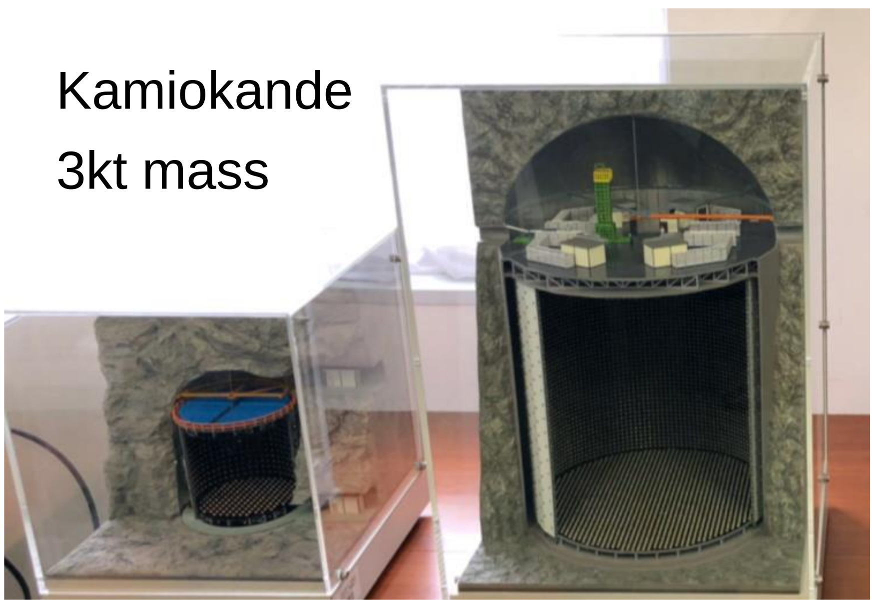
Water Cherenkov detectors in Kamioka

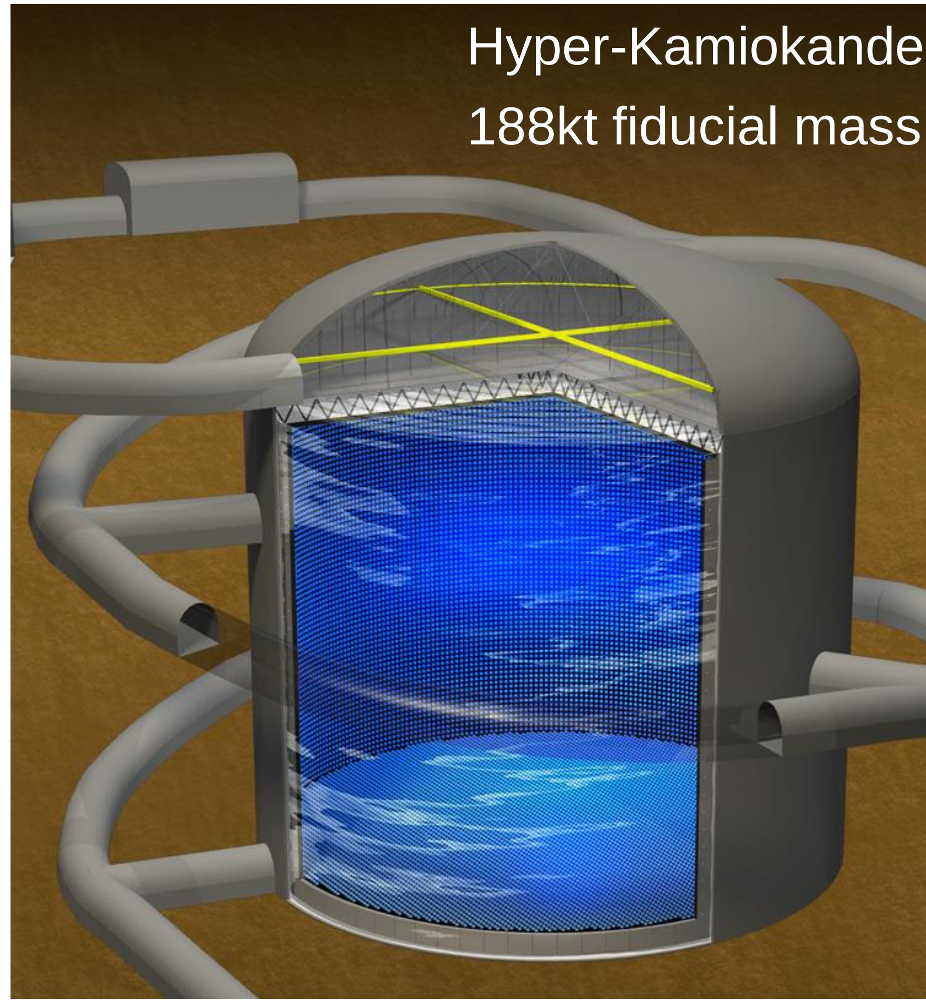
Super-Kamiokande

22.5kt fiducial mass

Kamiokande

3kt mass





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Super-Kamiokande
22.5kt fiducial mass

Kamiokande
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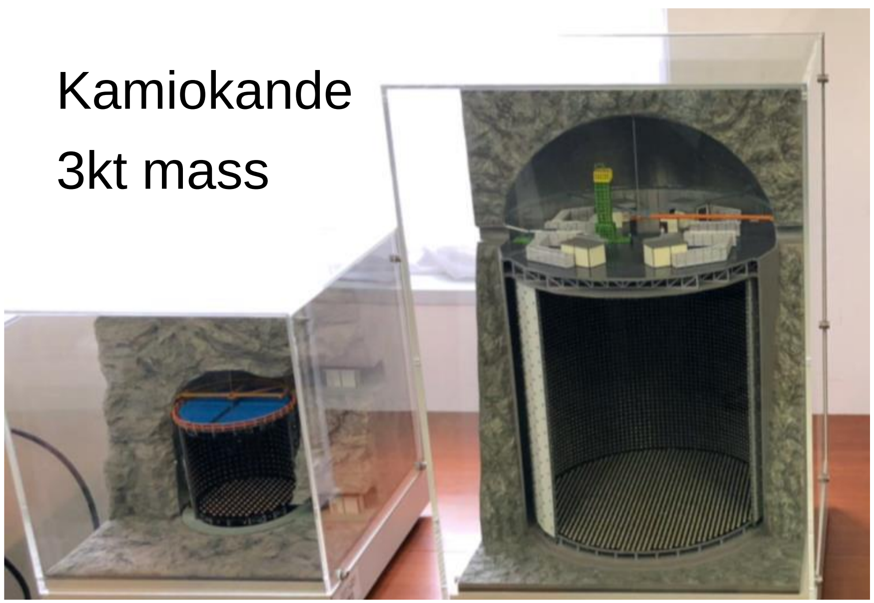
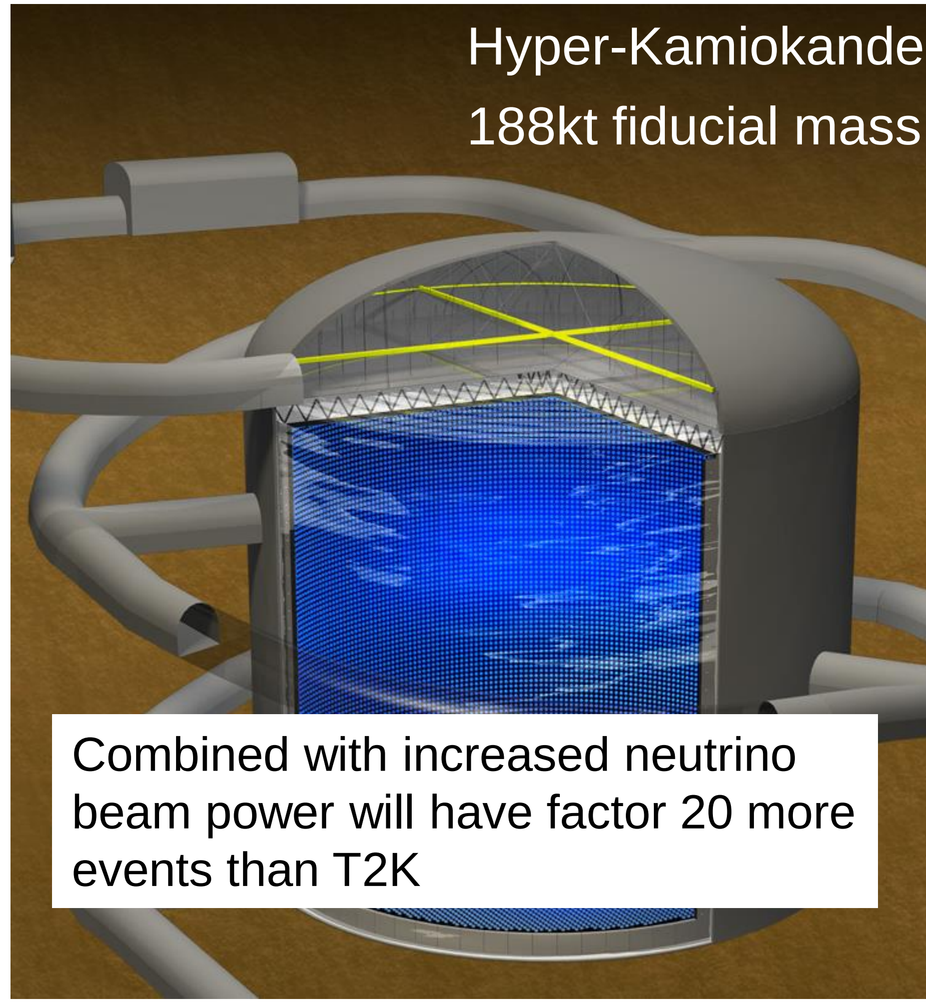
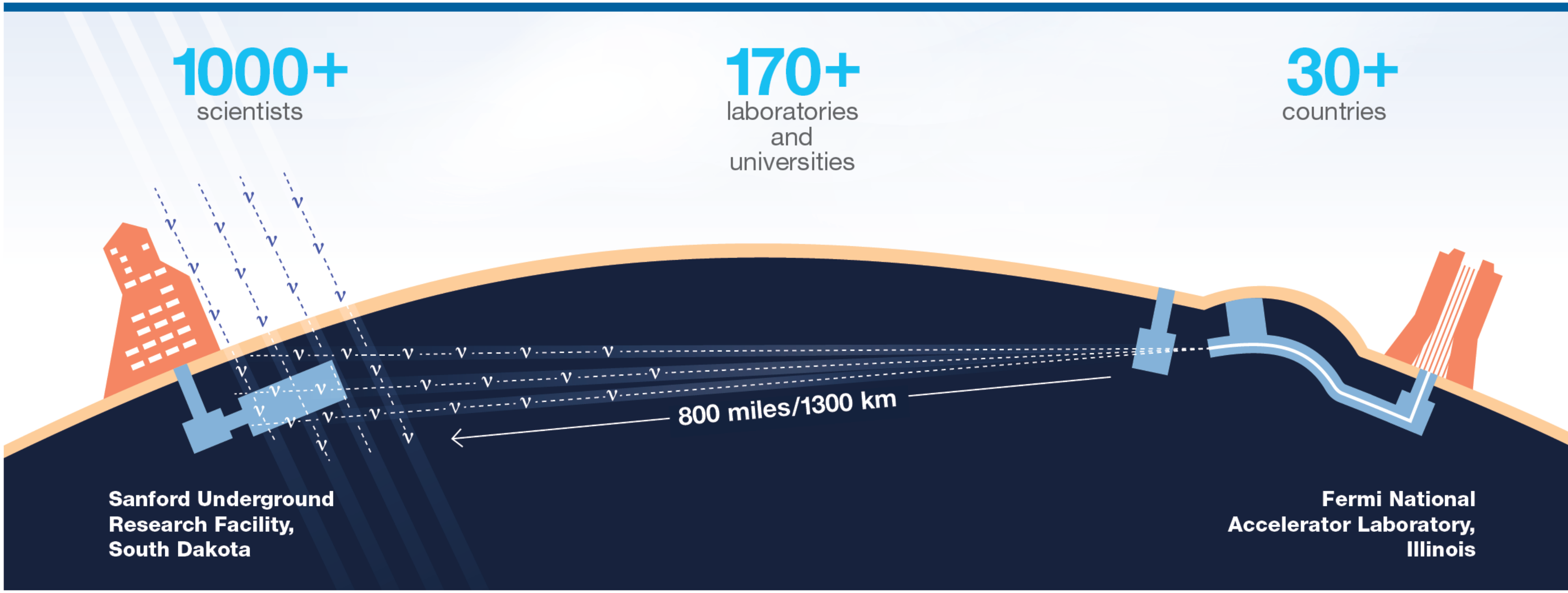




Future long-baseline experiments

DEEP UNDERGROUND NEUTRINO EXPERIMENT

- Liquid argon TPCs as far detector (40 ktonne)
- 1300km baseline
- 2 GeV neutrino energy



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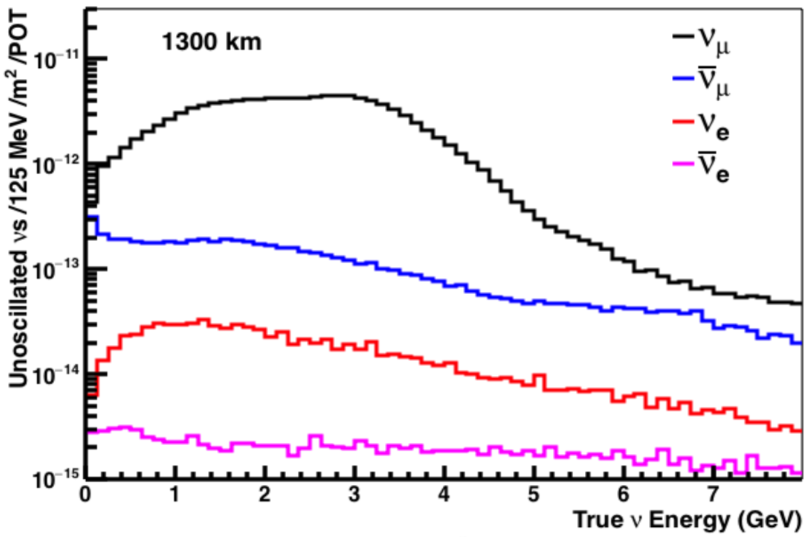
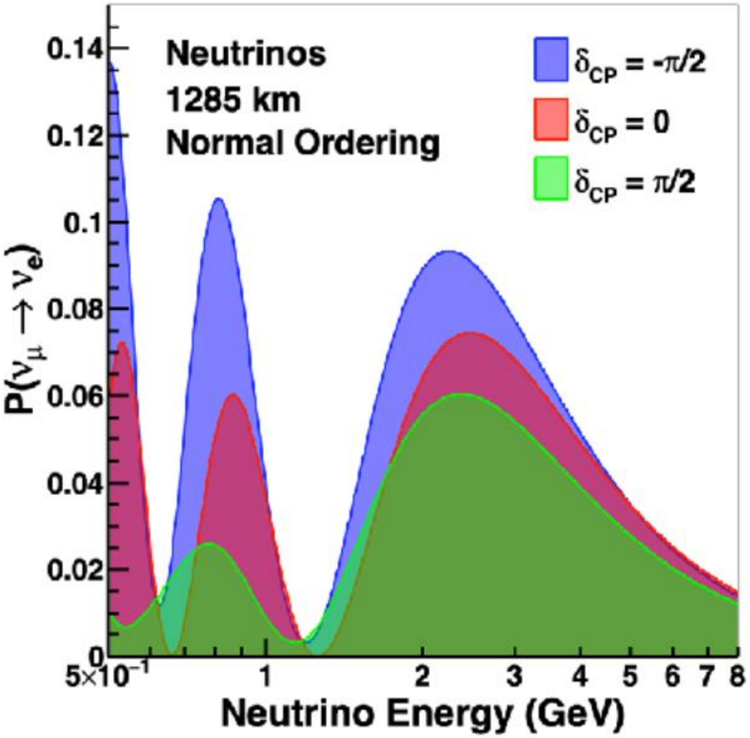
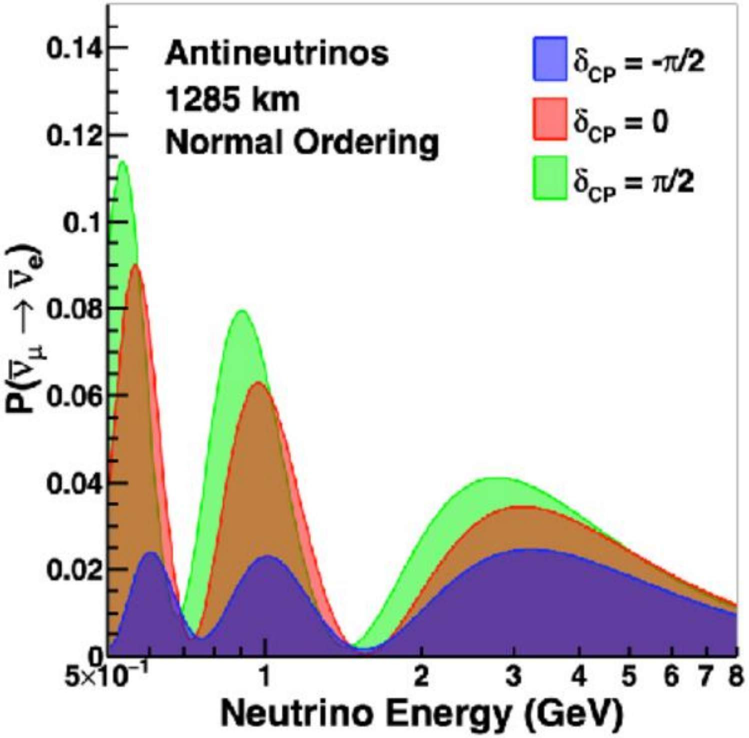
DUNE physics

- Difference between neutrino and anti-neutrino probability larger at low energies
  - $\Delta m^2 L/E = 3\pi/2$, second oscillation maximum

Neutrino Flux at 1300 km (CDR Optimized Beam)







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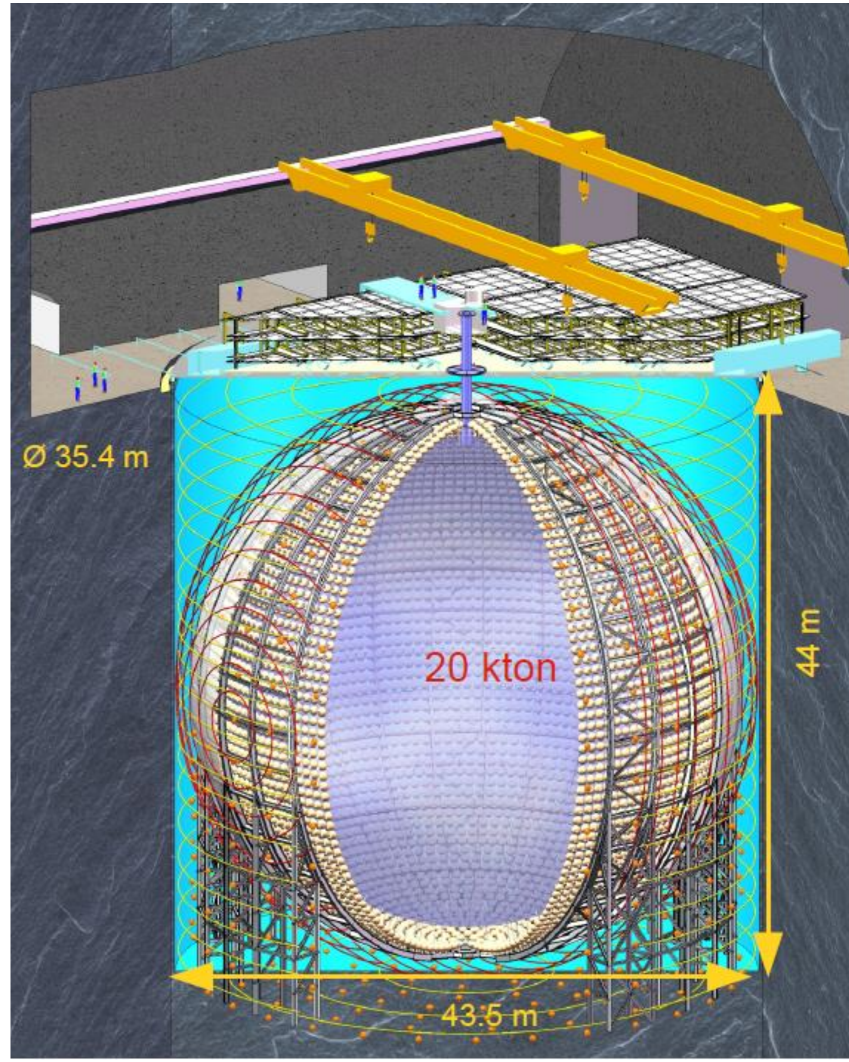
JUNO

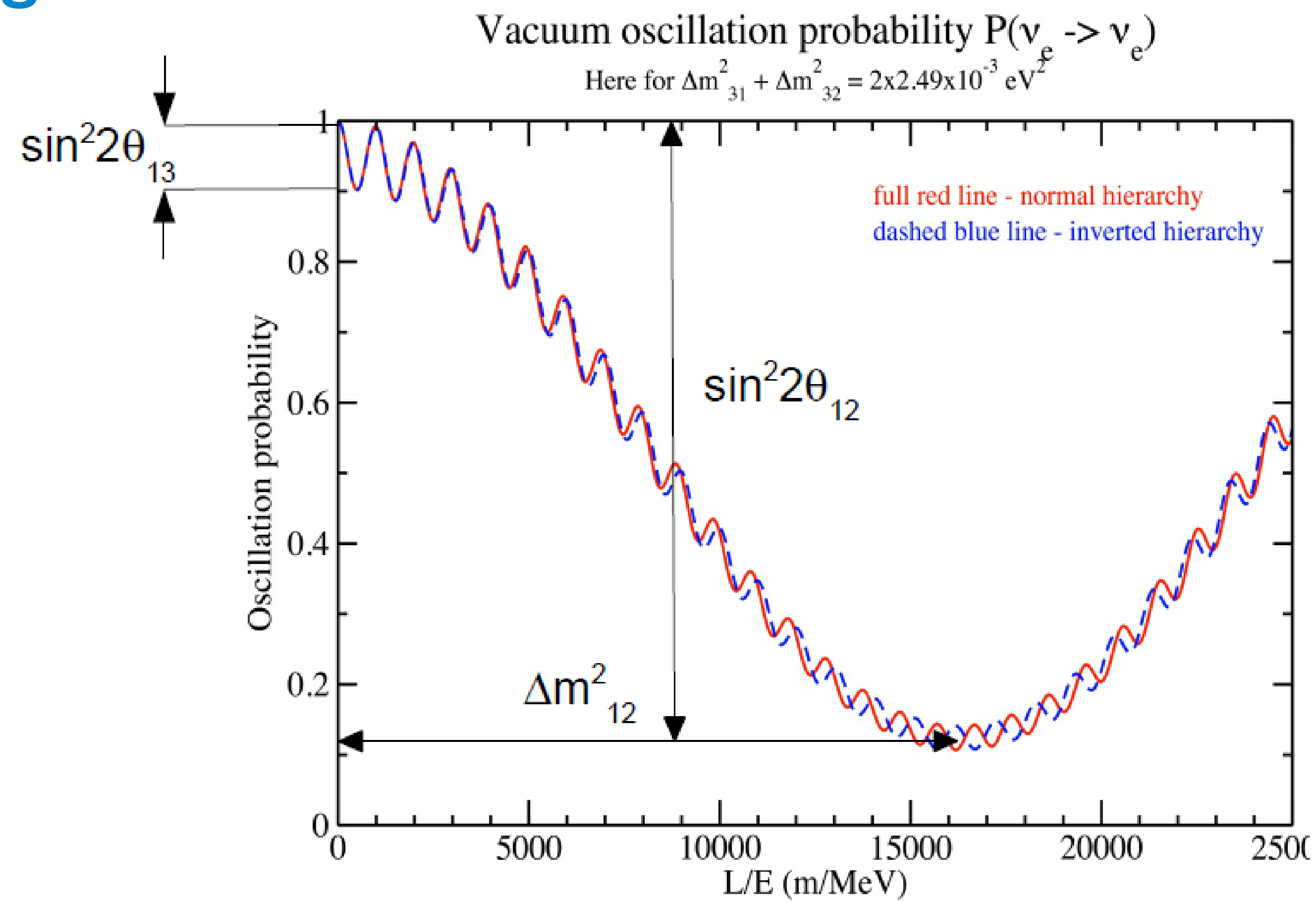
- **J**iangmen **U**nderground **N**eutrino **O**bservatory
  - 20kt liquid scintillator detector
  - 53km from two nuclear power plants

B. Wonsak, Neutrino 2018



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…



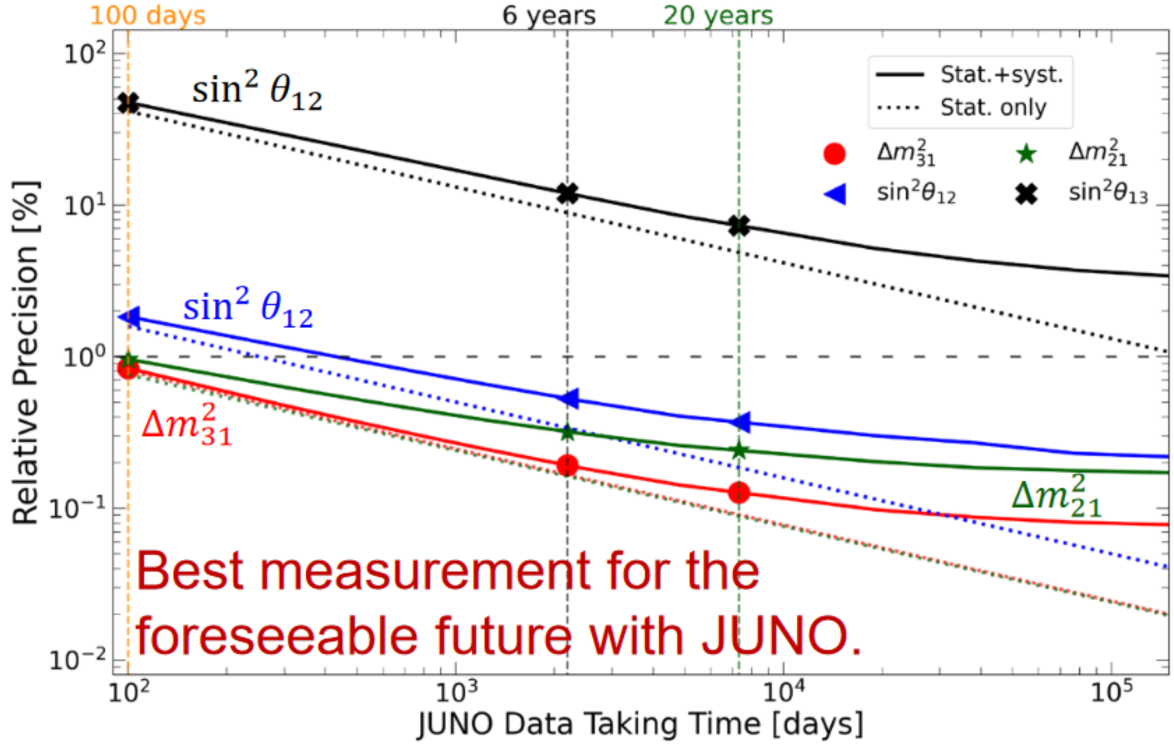
B. Wonsak, Neutrino 2018

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…

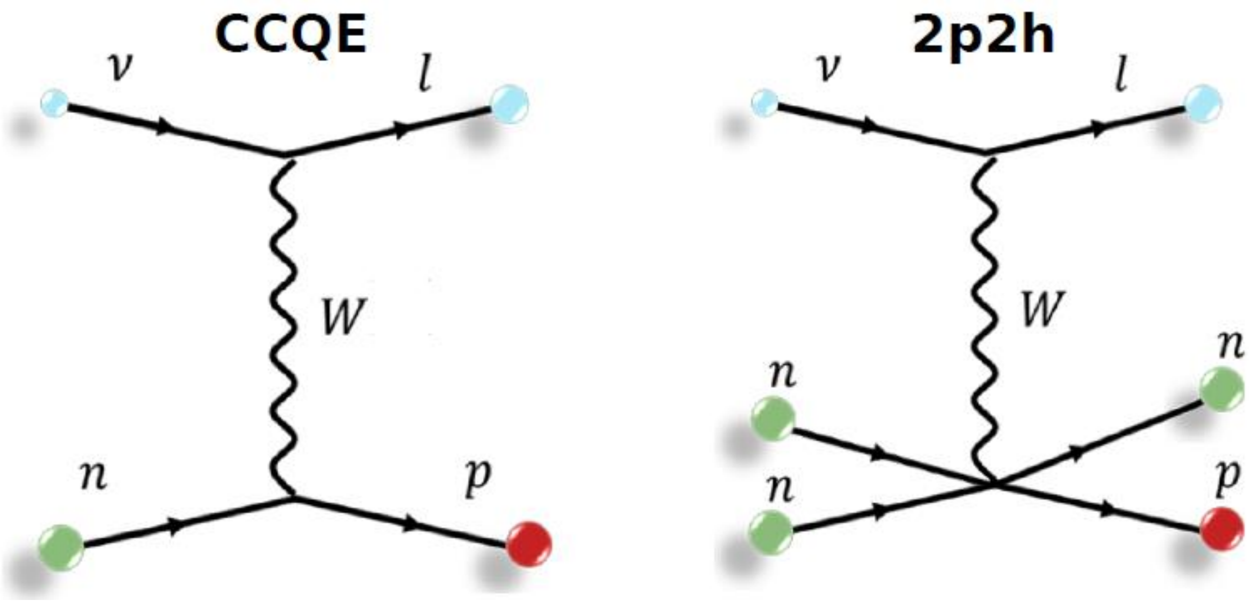
Precision of $\sin^2\theta_{12}$, Δm^2_{21}, $|\Delta m^2_{31}|/|\Delta m^2_{32}|$ < 0.5% in 6 yrs

	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%)



J. Zhang, NuFact 2022

Example energy bias – 2p2h interactions



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

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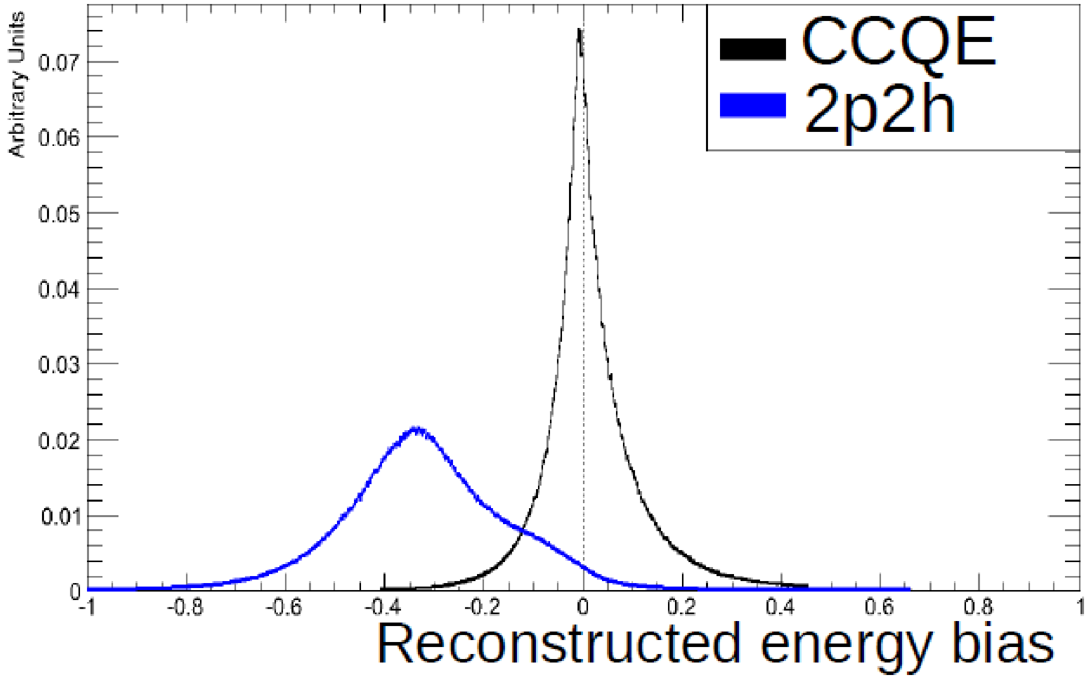
Example energy bias – 2p2h interactions



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

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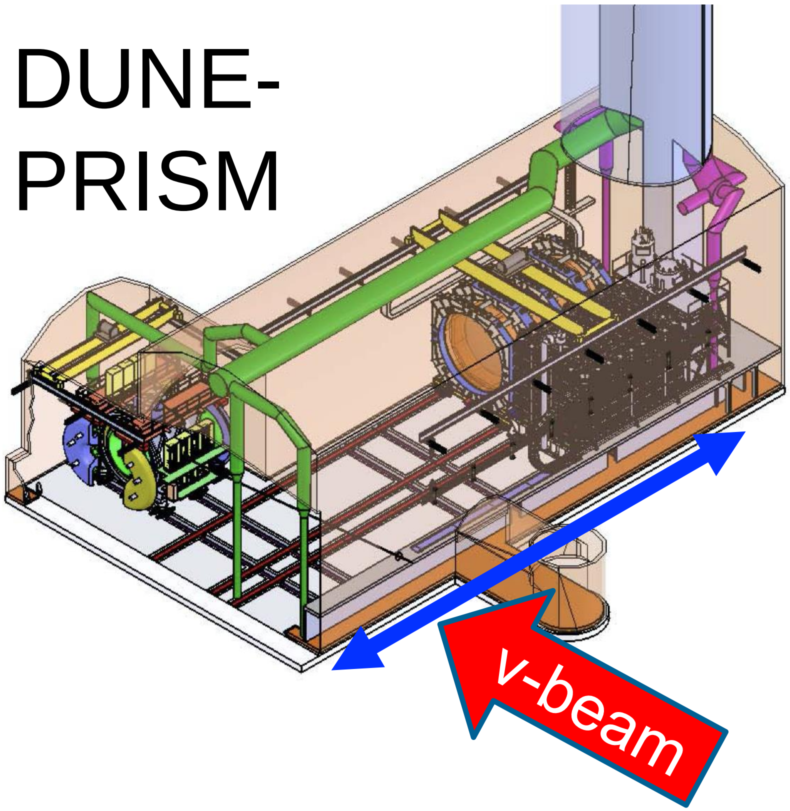
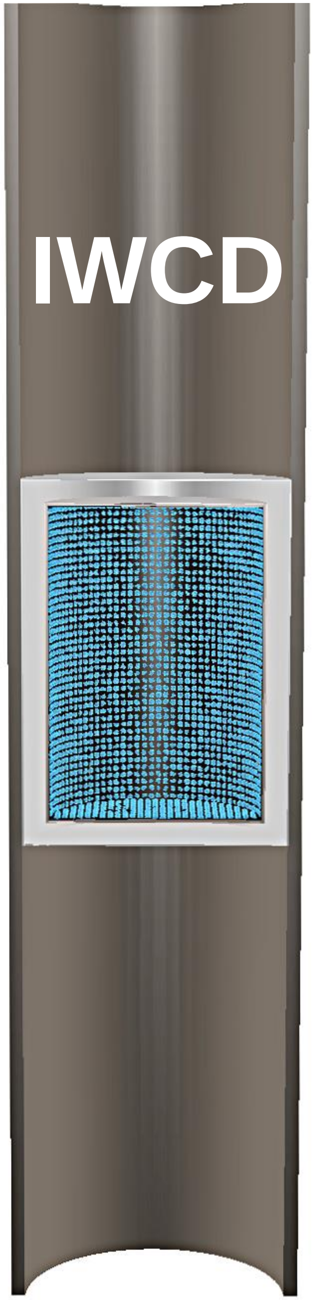
DUNE-PRISM and IWCD



- 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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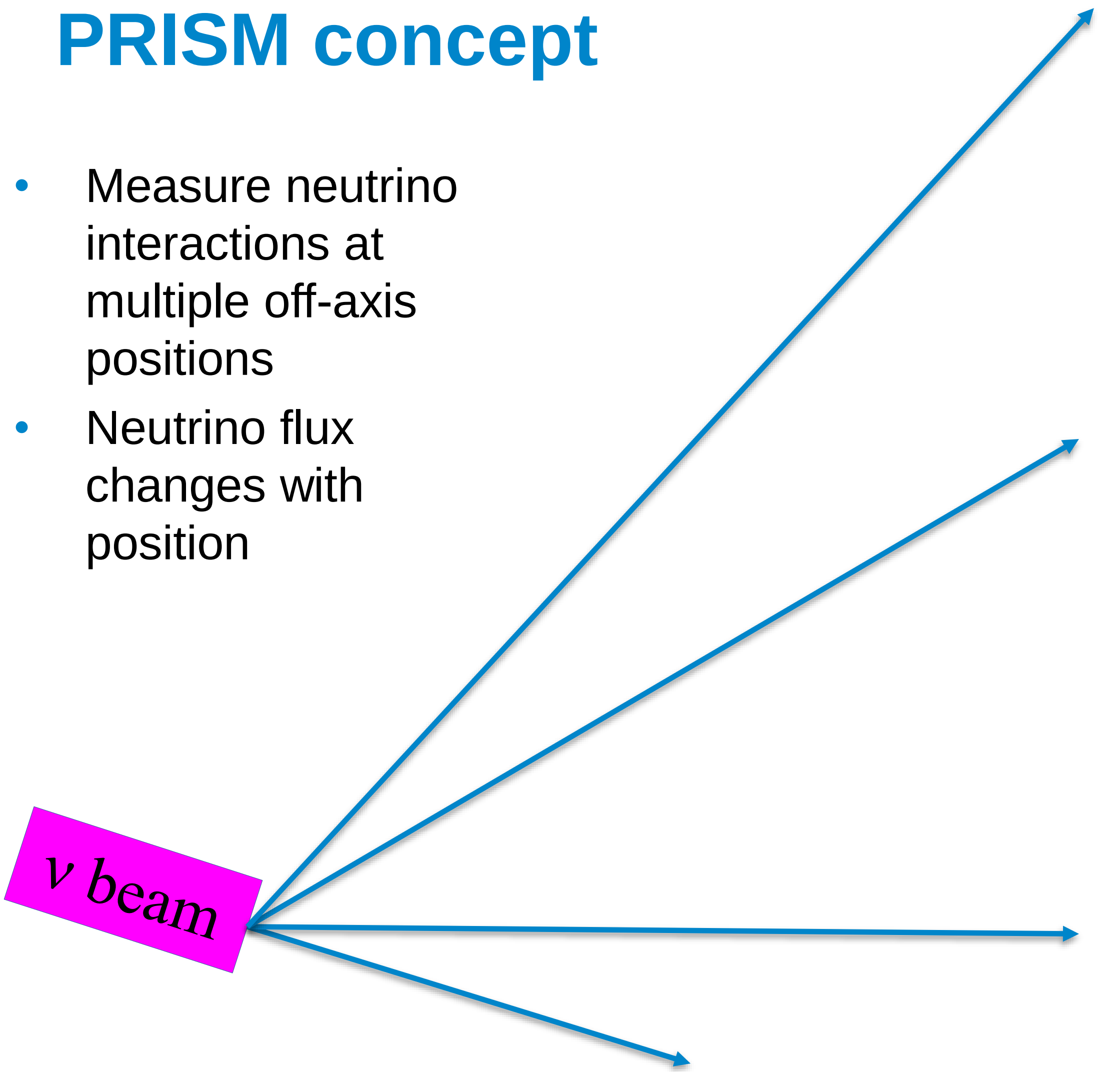
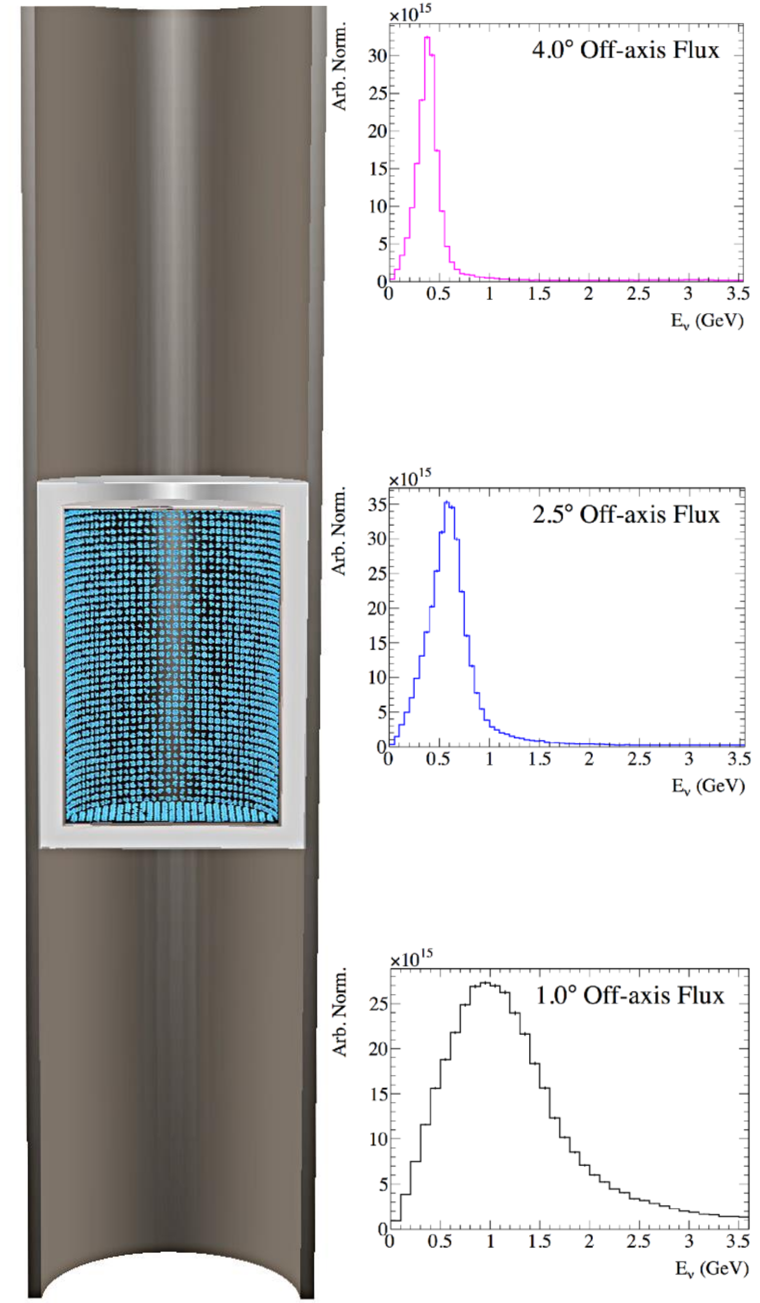
PRISM concept

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





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