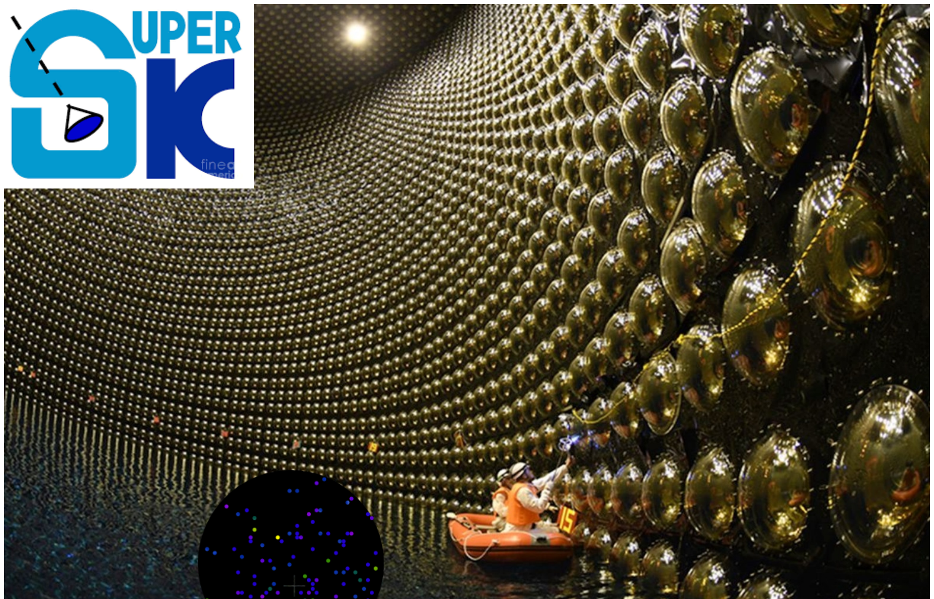
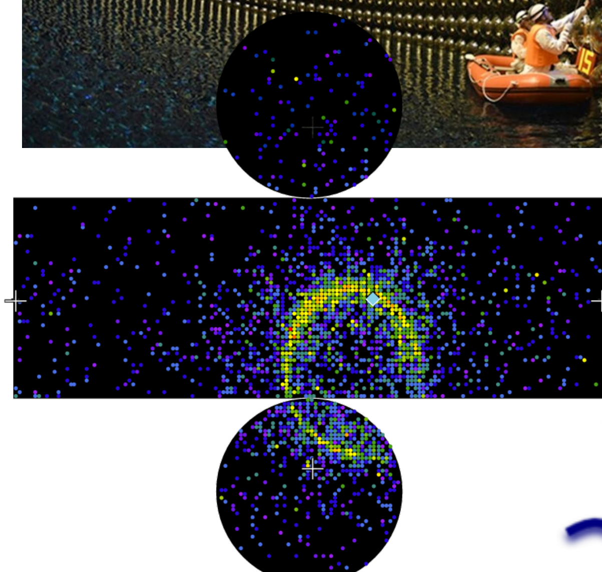
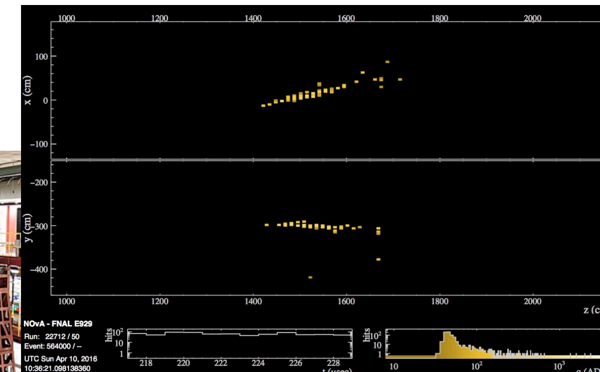
Challenges in multi-experiment neutrino oscillation analyses



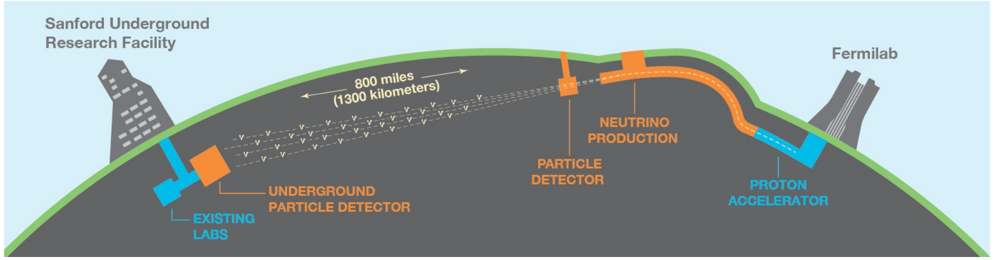




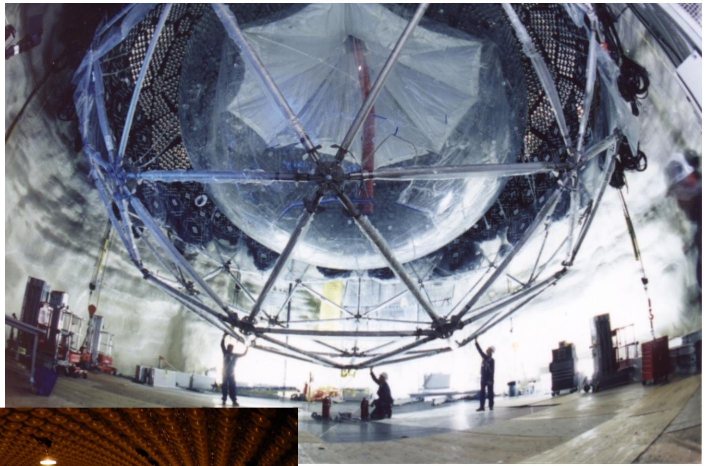
Clarence Wret
EDSU-Tools 2024, 6 June 2024
Île de Noirmoutier, France

Introduction

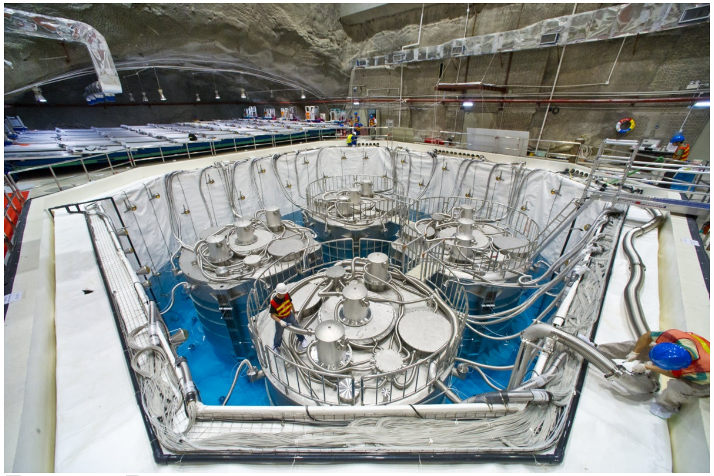
- Joint neutrino oscillation analyses can potentially involve many neutrino sources
  - Accelerators, atmospheric, reactor, solar, galactic? geological? SN?



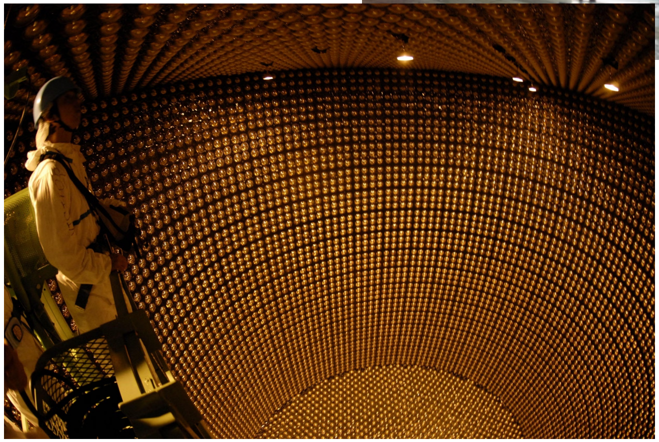
DUNE



SNO



Daya Bay



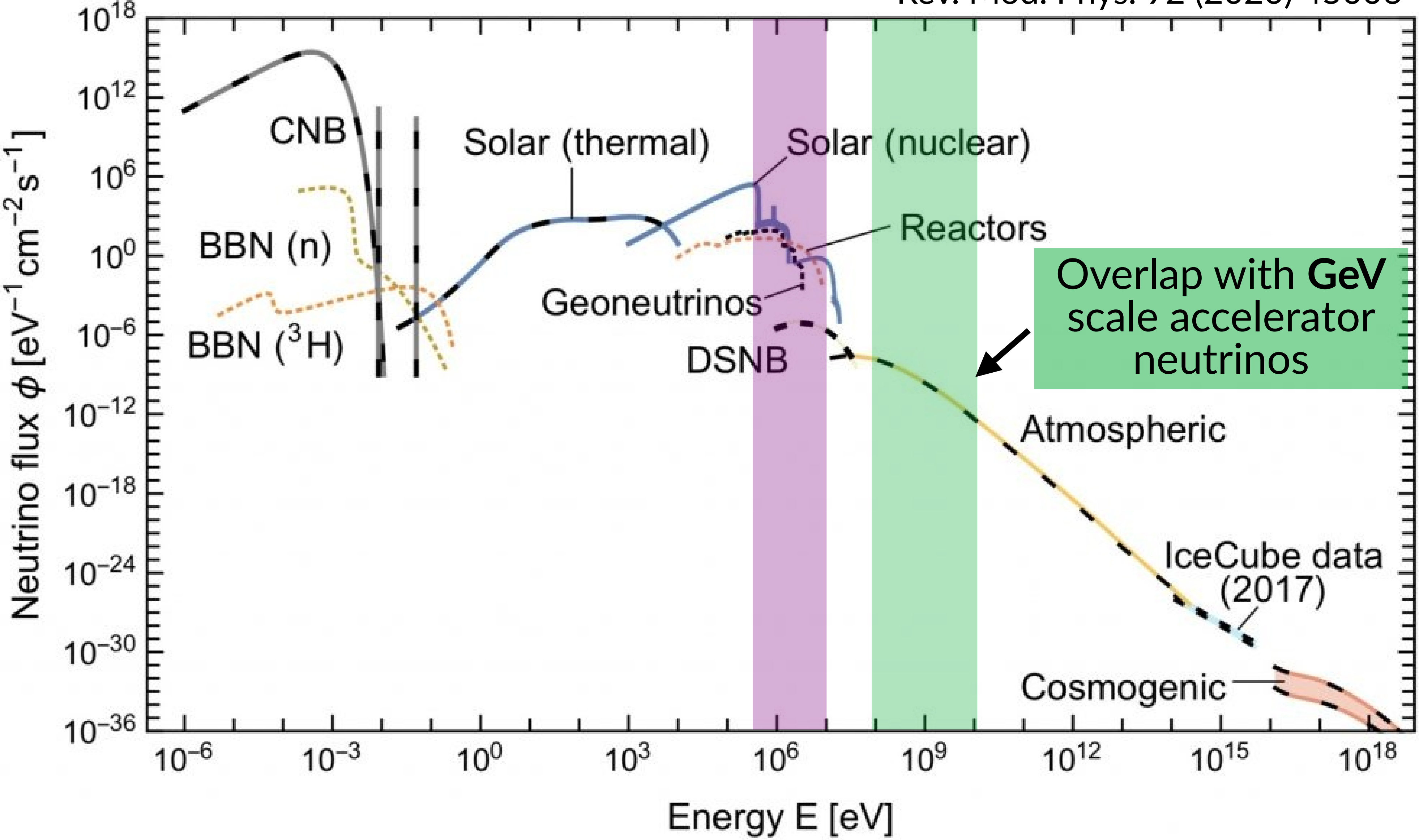
Super-Kamiokande

- Each constrain neutrino oscillation parameters, dependent on baseline and neutrino energy (**L/E** ratio)

Natural neutrino fluxes

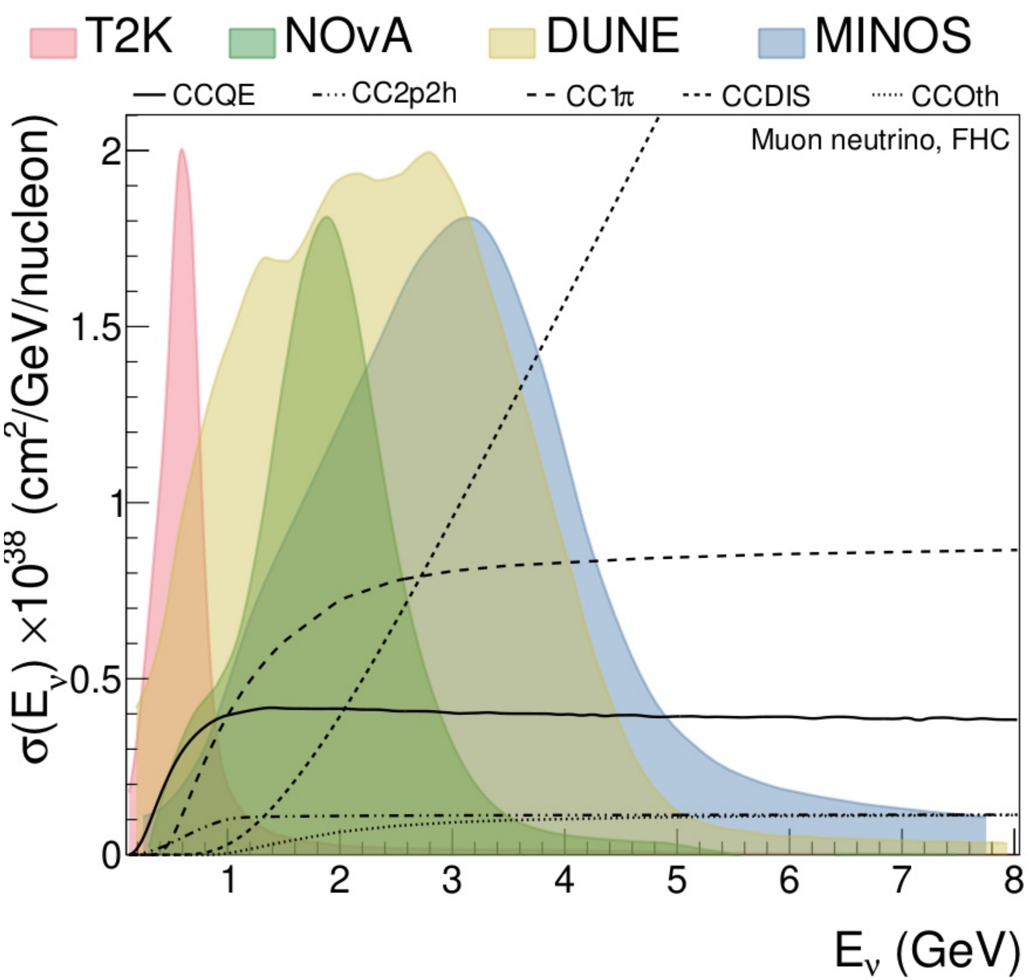
- Atmospheric neutrinos **significantly overlap with accelerators**

Rev. Mod. Phys. 92 (2020) 45006



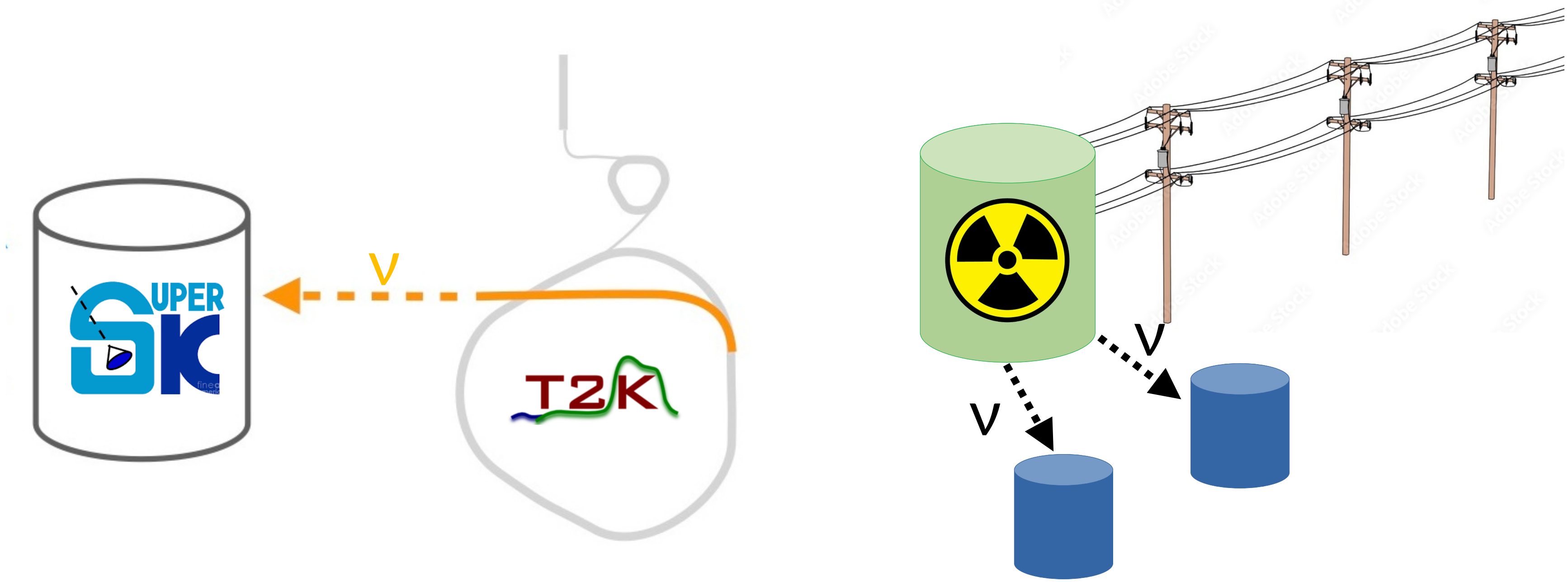
Accelerator neutrinos

- Accelerator neutrino oscillation experiments generally in the **0.5-5 GeV** region
  - Some with wide, some with narrow band beam
- Studying **(anti-)$\nu_\mu \rightarrow$(anti-)ν_μ** and **(anti-)$\nu_\mu \rightarrow$(anti-)ν_e**
- Complex scenario of **which systematics matter**
  - What matters for T2K, may matter less for NOvA, may matter less for DUNE, and vice versa
  - Measurements in one region might be difficult to reconcile with other regions
  - How **correlated** are the systematics between experiments?



Introduction

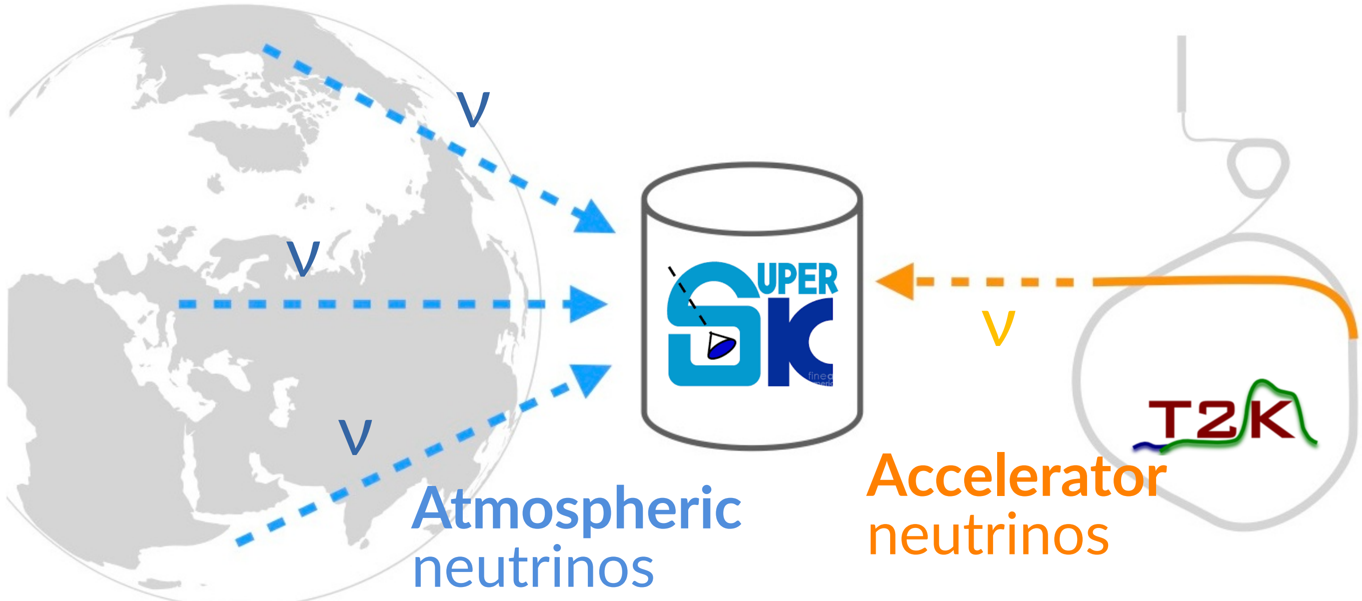
Beam + reactor



- Little to no overlap in neutrino flux, interaction, or detector uncertainties: **barely any systematics correlations**
- Potentially overlapping **oscillation measurements**
  - $\sin^2\theta_{13}$, Δm^2_{32}

Introduction

Atmospheric + beam



- Same **detector**: shared uncertainties
- Potentially similar **neutrino interactions**: constrained by **beam near detector**?
- Correlations in **neutrino flux**? Same process, different methods? Different energies?
- Overlaps in **oscillation** measurements; **complimentary** features
  - δ_{CP}, mass ordering, $\sin^2\theta_{23}$, Δm^2_{32}, ...

Introduction

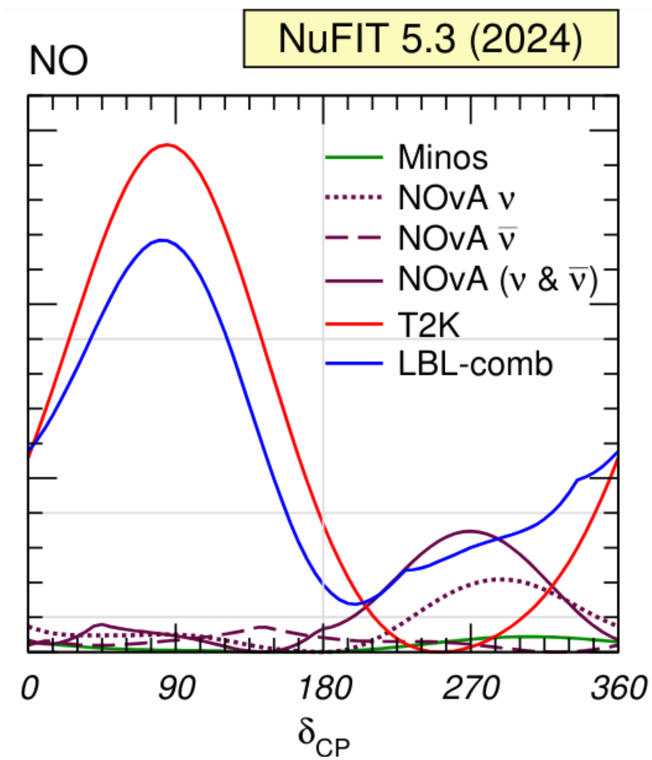
Beam + beam

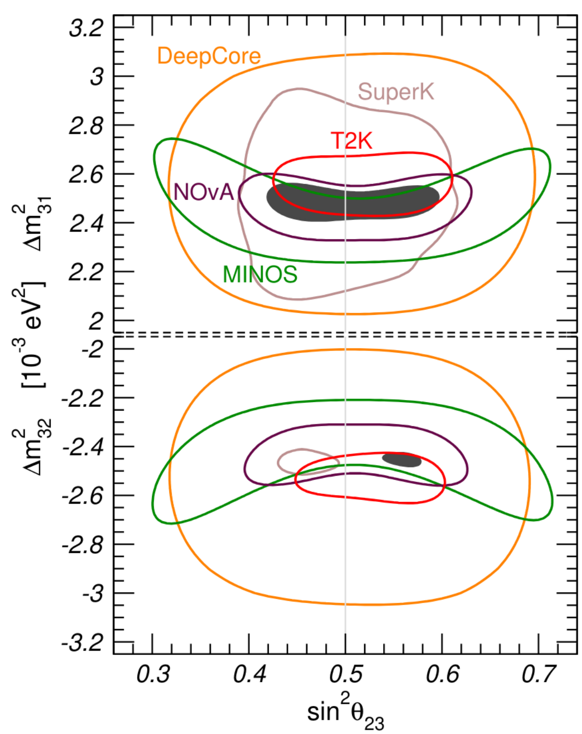
- Potentially **similar neutrino interactions**: constrained by both experiment's **near detectors**?
- Same process gives rise to neutrinos: potentially large **correlations in neutrino flux**
- Overlapping **oscillation measurements**; complimentary features
  - δ_{CP}, mass ordering, $\sin^2\theta_{23}$, Δm^2_{32}, …

Global fits

- Joint fits are regularly pursued by **global fitting groups**
  - e.g. NuFit (JHEP 09 (2020) 178), de Salas et al (JHEP 02 (2021) 071), ...
- Use fast (approximate) simulations of experiments, with **less sophisticated** systematics and selections
  - Compare $\Delta\chi^2$ for oscillation parameters, number of events at the far detector, etc to official publications to validate simulation

www.nu-fit.org



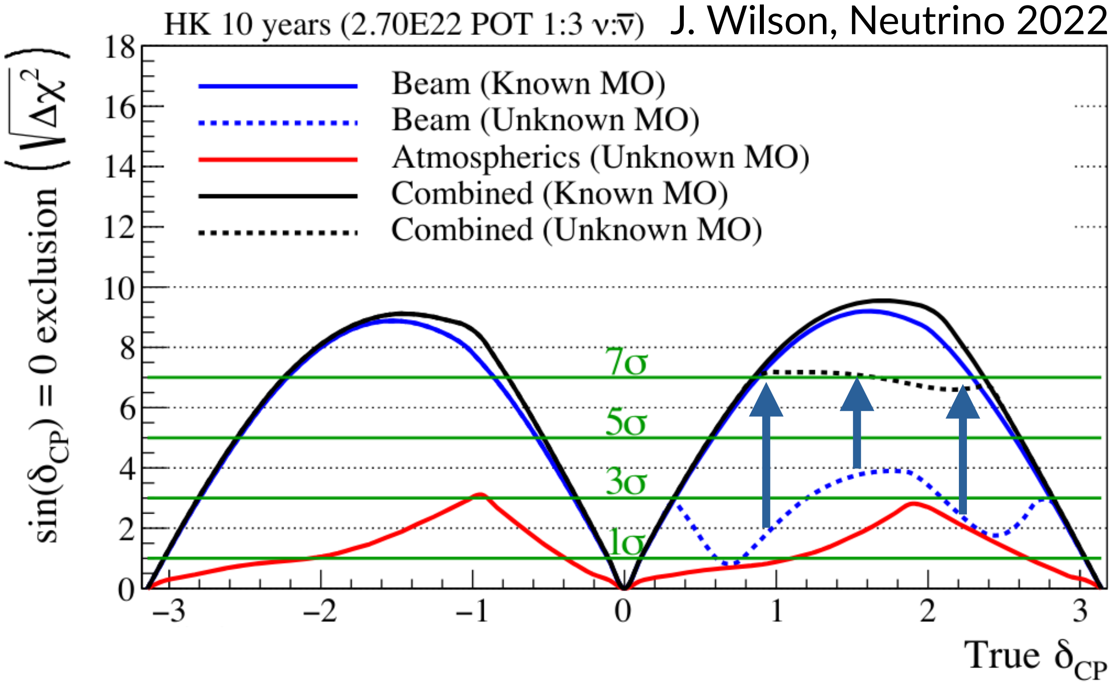


- Difficult to explore if possible **tensions come from systematics**

Why a joint SK+T2K analysis

- Beam+atmospheric analyses significantly **improve Hyper-K's δ_{CP} constraint if the mass ordering is not known**
  - **Competitive with DUNE**

J. Wilson, Neutrino 2022



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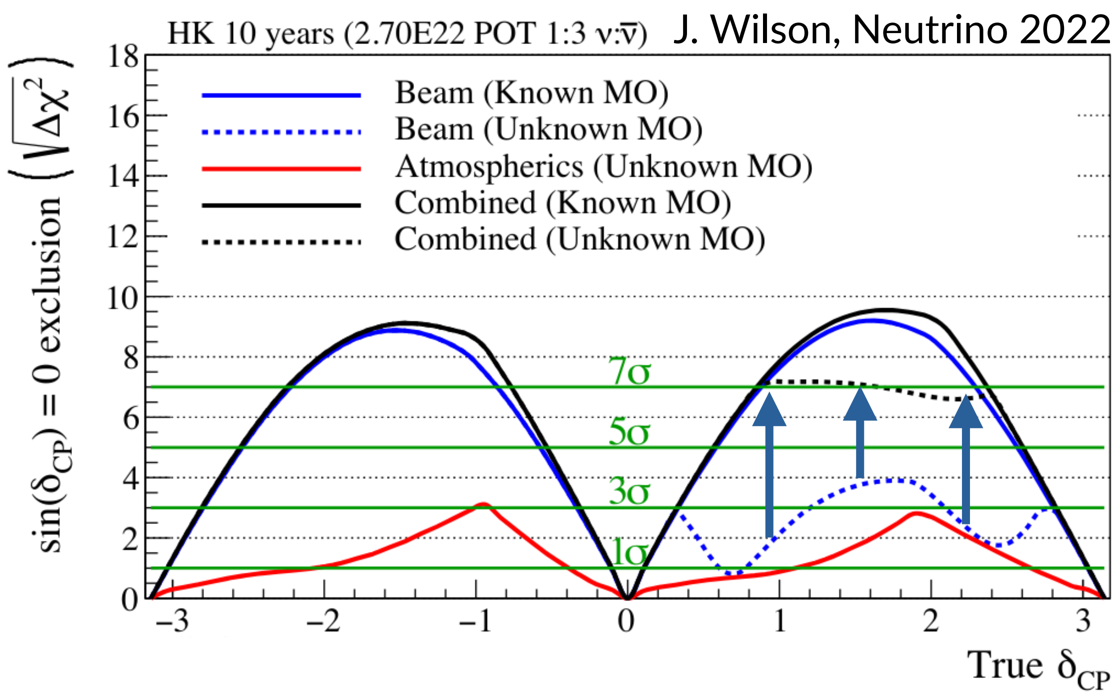
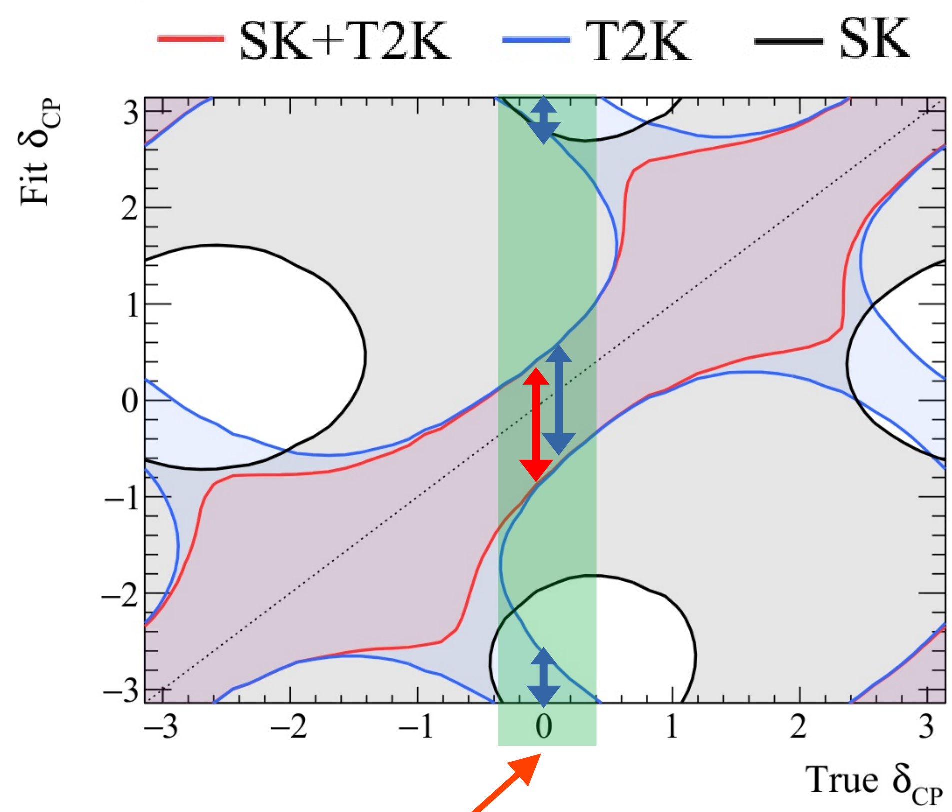
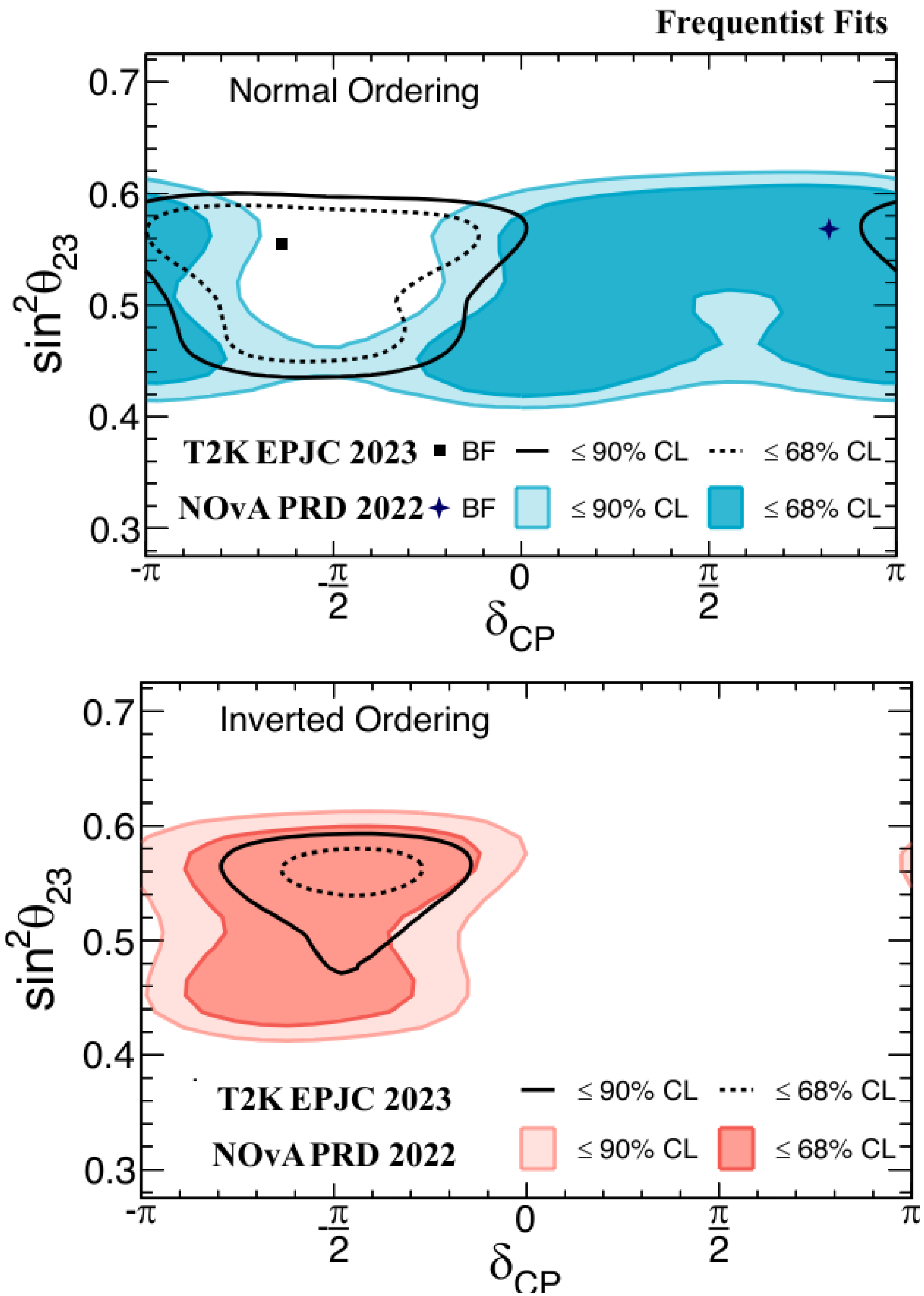




- Atmospheric neutrinos sensitive to CP conservation hypothesis, where T2K has degeneracy (δ_{CP}~0, ±π)

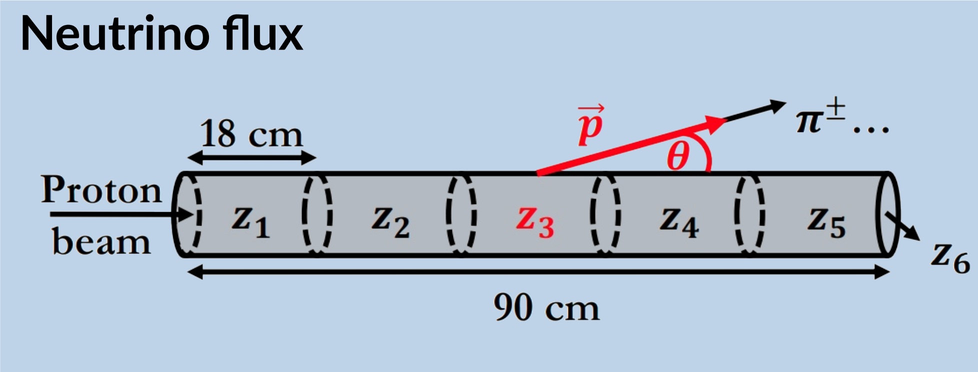
Why a joint T2K+NOvA analysis

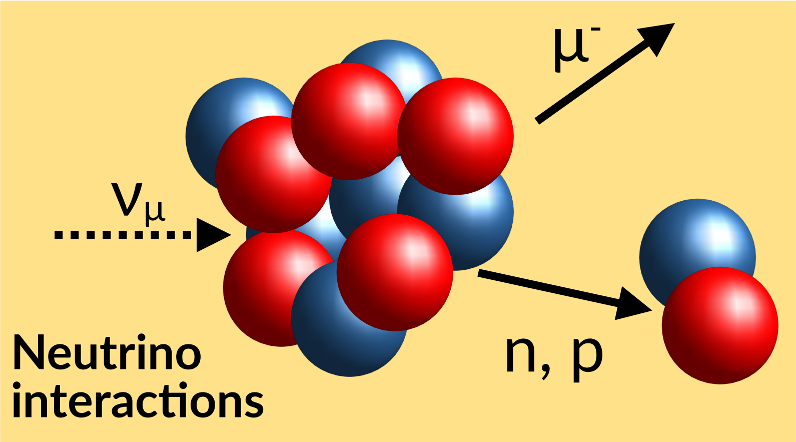
- Interesting developments in δ_{CP} and mass ordering preference
  - MO and δ_{CP} somewhat degenerate, but to different extent
  - δ_{CP}: 30% vs 25% effect
  - MO: 9% vs 19% effect
- T2K and NOvA individually prefer normal ordering (NO)
- In NO, **T2K prefers δ_{CP}~-π/2, NOvA prefers δ_{CP}~π**
  - Alleged "**tension**" at 90% CL
- In IO, **both experiments prefer δ_{CP}~-π/2**
- Impact of **syst. correlations** studied in the joint analysis



Challenges in joint analyses

- The **main challenge** is **correlating** the **systematic uncertainties**
  - **Neutrino interactions** and **neutrino flux** are obvious candidates





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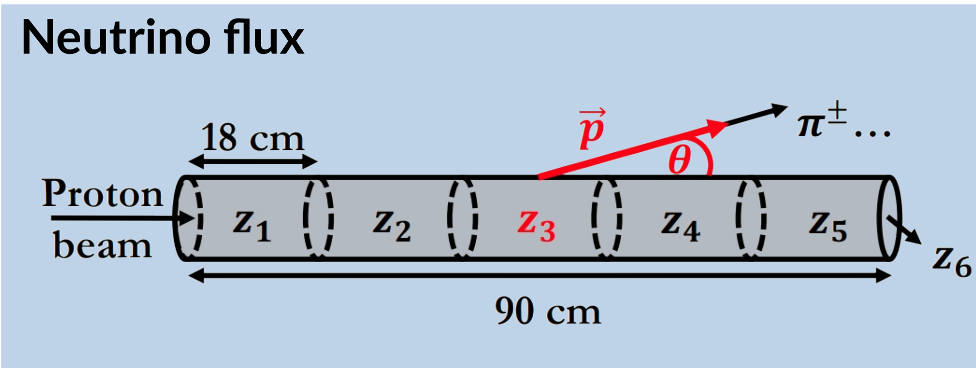

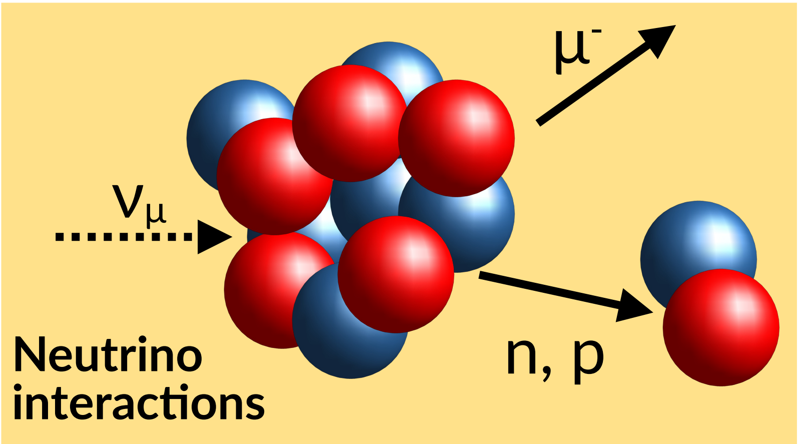

- Choices made by each experiment complicates this
  - T2K and NOvA use **different interaction generators**, **event formats**, etc: too complicated to unify for first iteration. **Studied worst case scenario**
  - Formation of **unified event format**: **NuHepMC** (inspired by LHC community), important in future **2310.13211 [hep-ph]**
  - T2K+SK had better starting point: studied phase space, use **T2K ND to constrain sub-GeV atmospheric** interactions, **correlate interactions**

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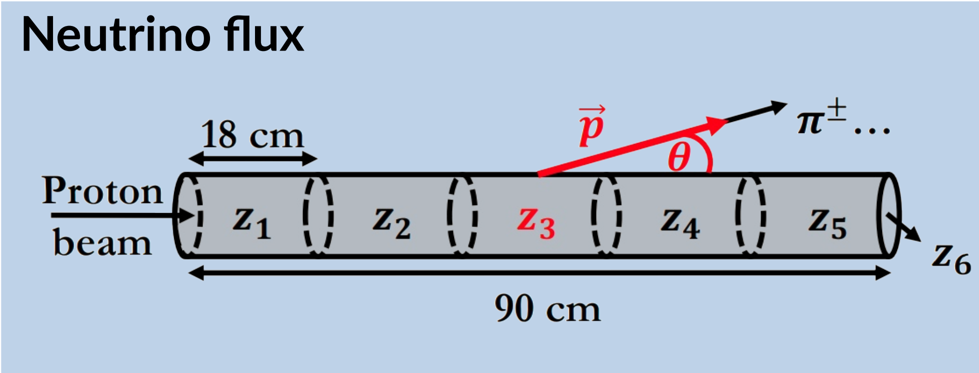

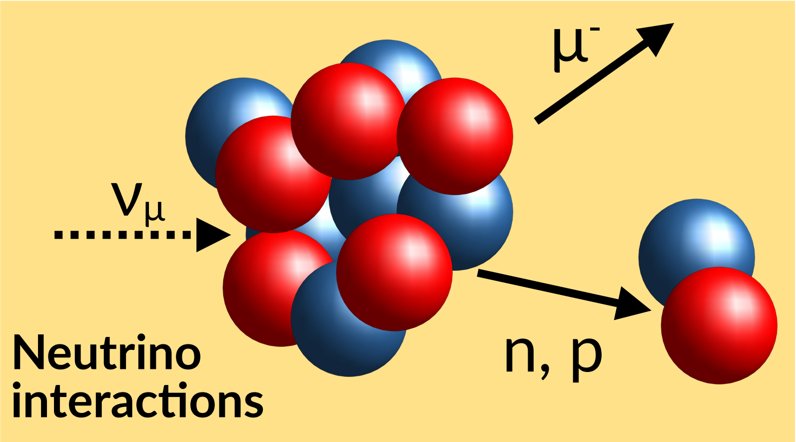

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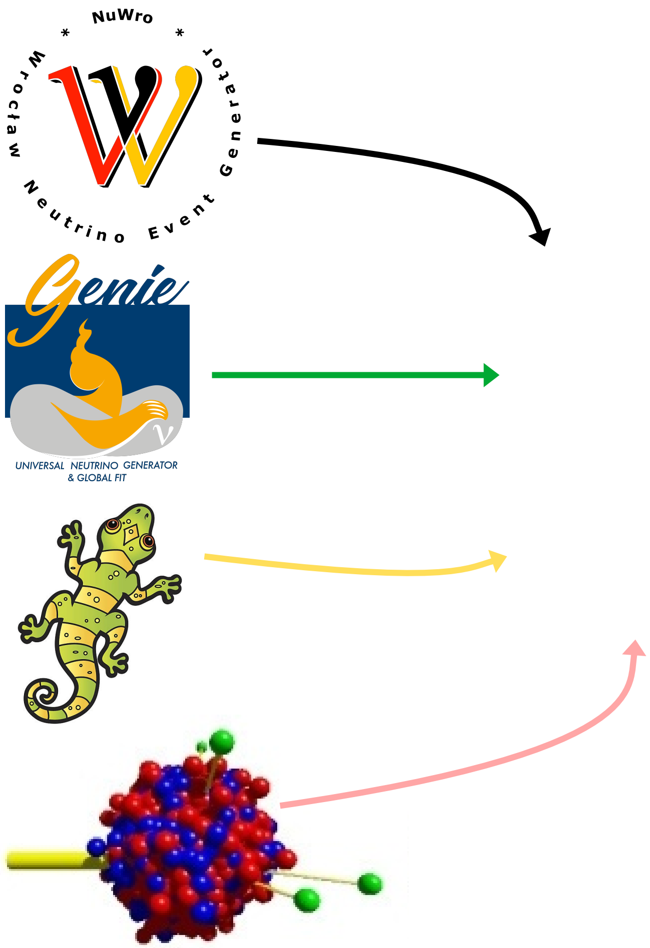
  - T2K+SK had better starting point: studied phase space, use **T2K ND to constrain sub-GeV atmospheric** interactions, **correlate interactions**
- Flux simulations tuned to **different hadron-scattering data**: interesting to study correlation, but not done for first analyses
  - Impact of flux uncertainties relatively **small** when ND is present

Interaction tool developments

- Compared details of **interaction generators**, and **experiment-specific tuning**, using NUISANCE **JINST 12 (2017) 01, P01016**

Generate events



See **Kamil's** talk for more!

Interaction tool developments

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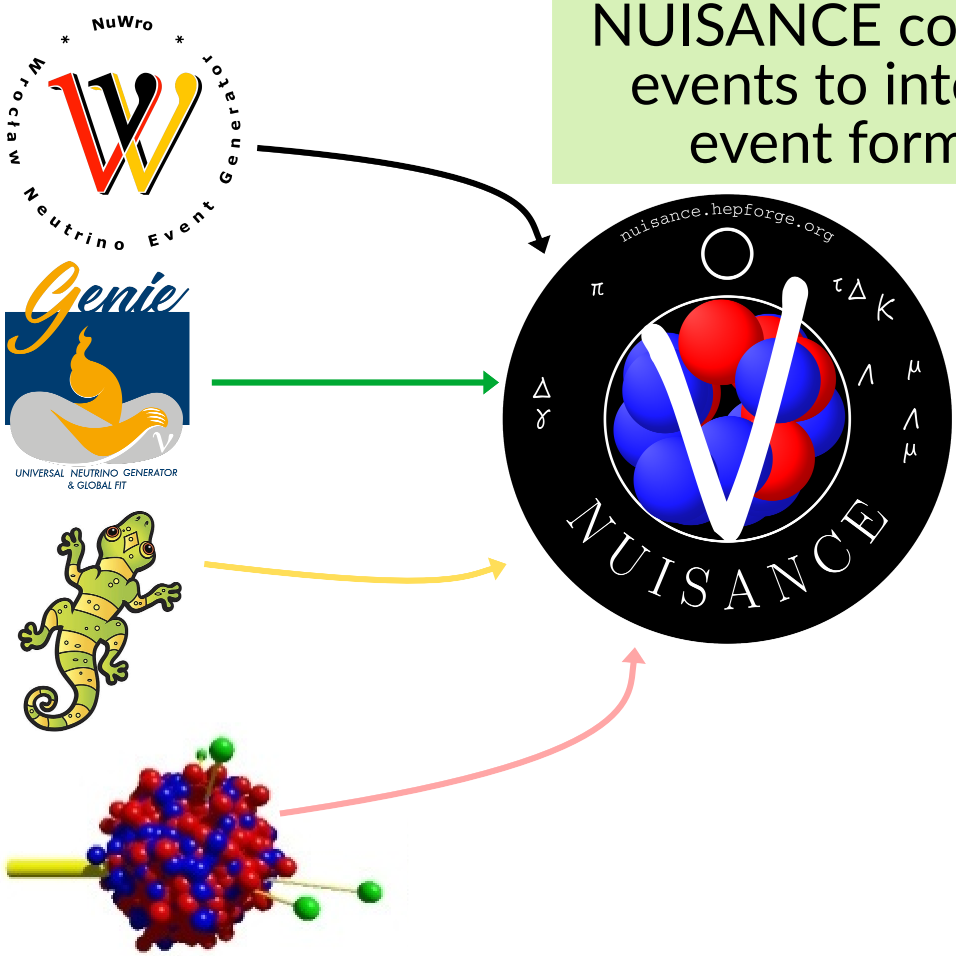
Generate events

NUISANCE converts events to internal event format



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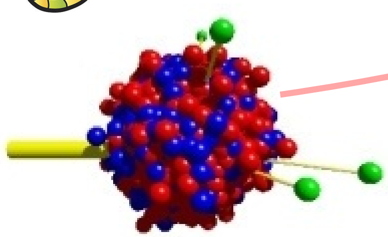
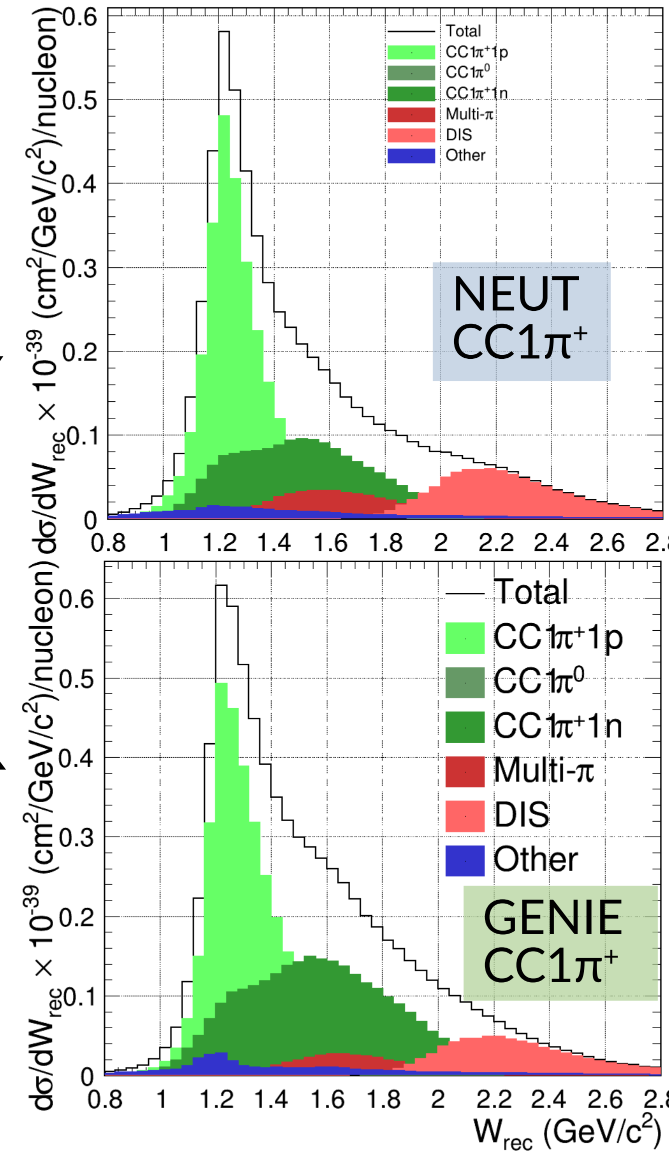


Compare generator features



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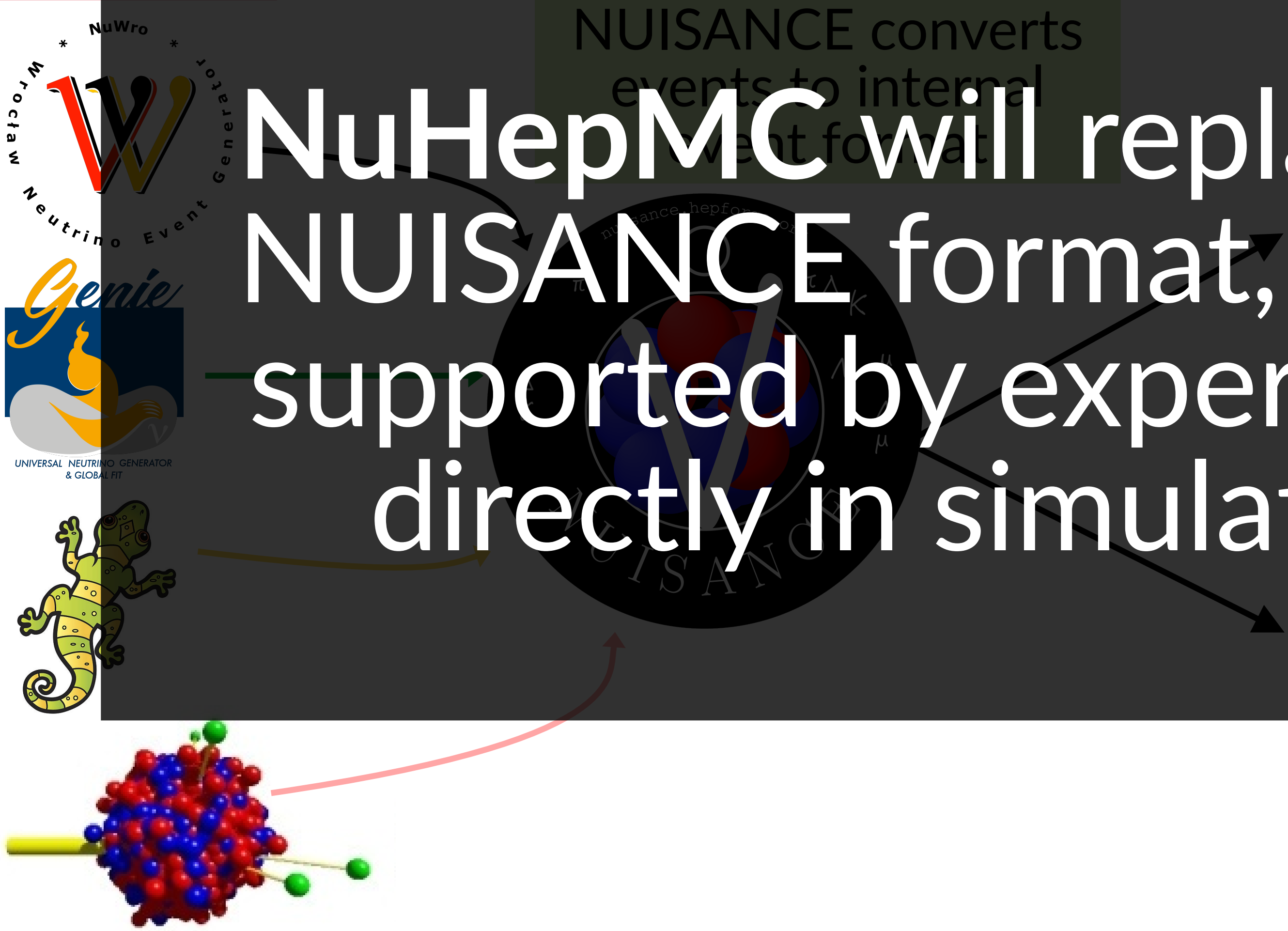


NuHepMC will replace the NUISANCE format, and be supported by experiments directly in simulations

2310.13211 [hep-ph]

See **Kamil's** talk for more!

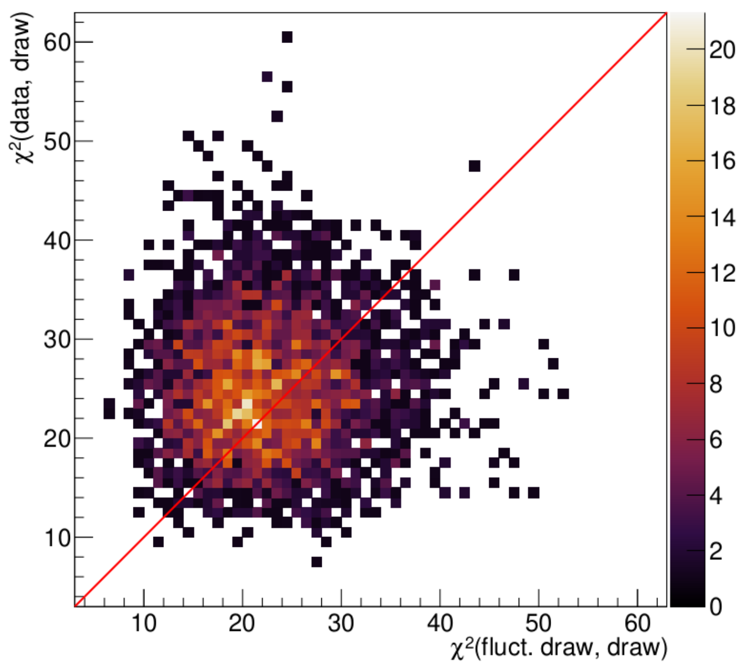
SK+T2K statistical developments

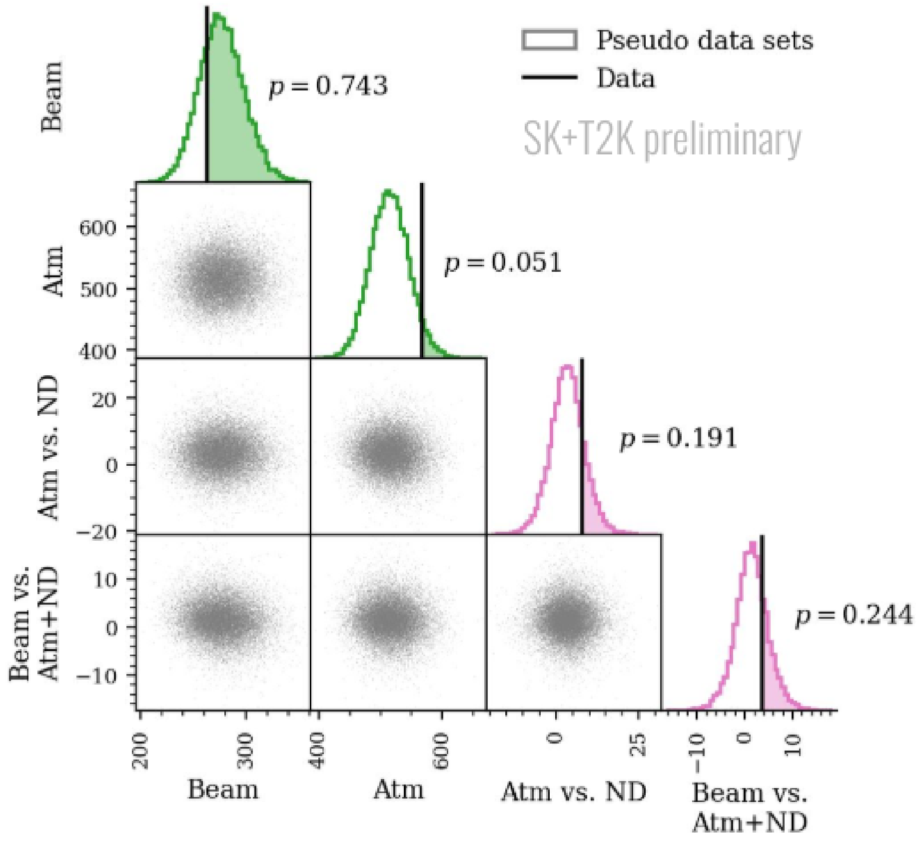
- Two MCMC analyses for Bayesian inference, one **GPU accelerated** and **simultaneous ND analysis**
- Two frequentist analyses, one **from SK** and one **from T2K** (GPU accelerated)
- Goodness of fit assessed by **posterior predictive p-values**, and **parameter goodness of fit**

Ann. Statist. 22(3): 1142-1160, 1994

Phys. Rev. D, 68:033020, 2003

Rate p-value = 0.42

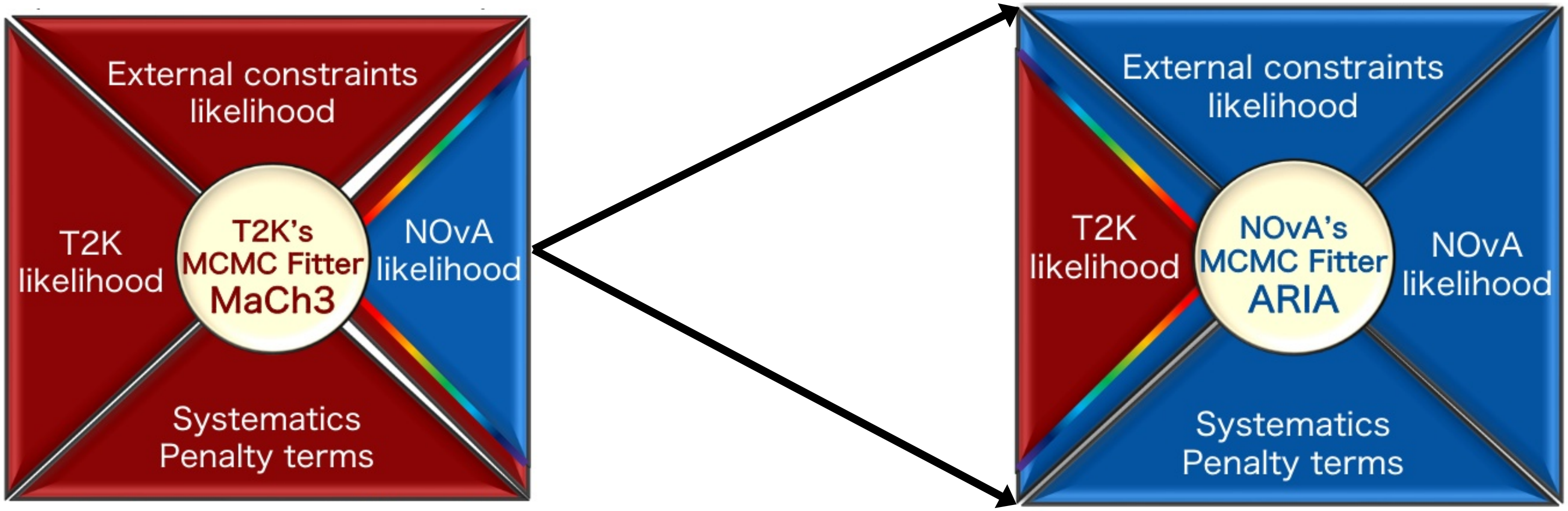




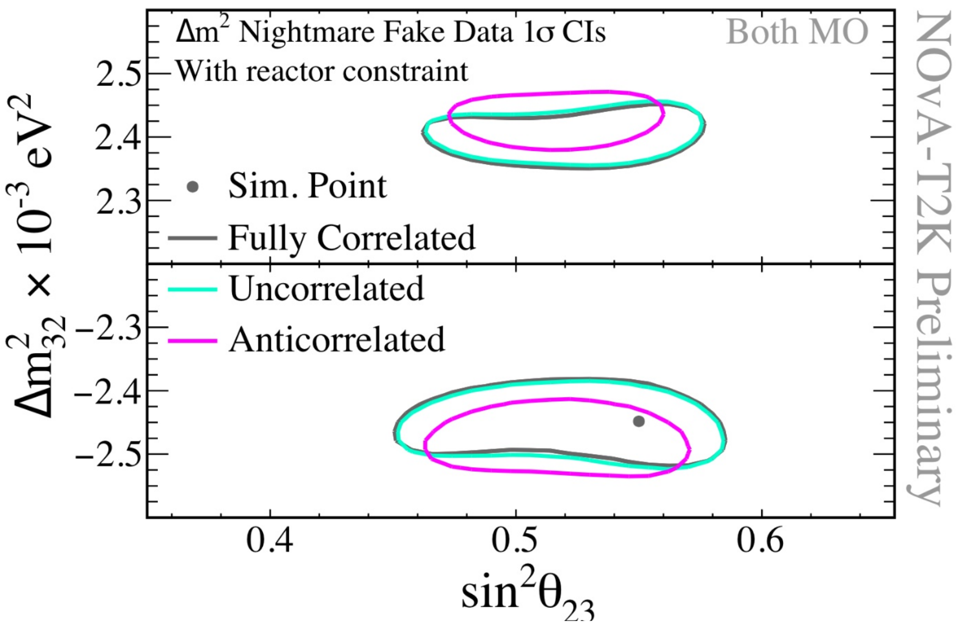
See **Kamil's** talk for more!

T2K+NOvA tool developments

- Developed obfuscation of other experiment's code: propose MCMC step → get likelihood via black box

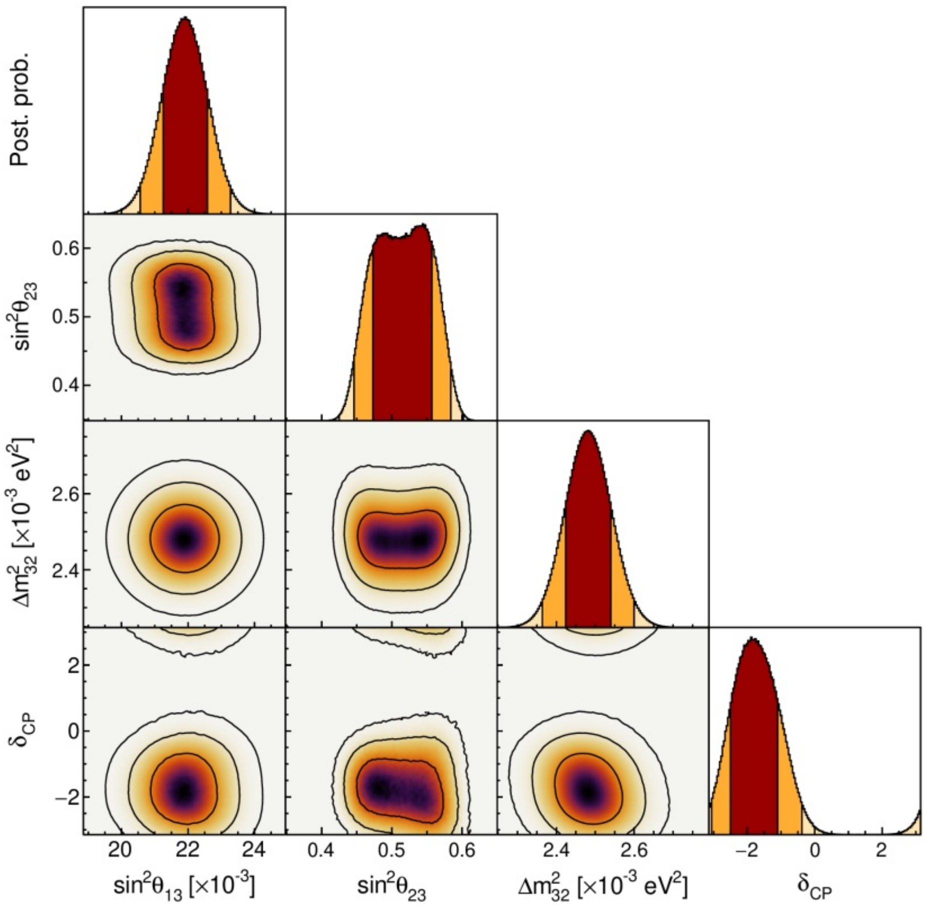


- Investigation of worst-case-scenario missing correlations and impact on joint analysis
- Both settling for **MCMC**, practical for high dimensionality
  - Similar method and tools to SK+T2K

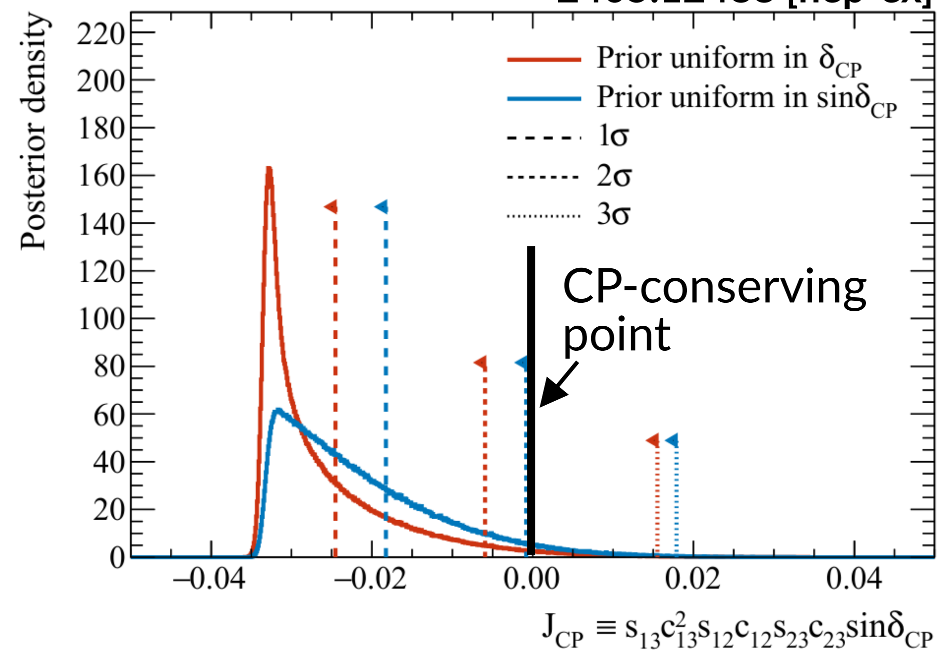


Results, SK+T2K

- Compatible Bayesian and frequentist results



2405.12488 [hep-ex]



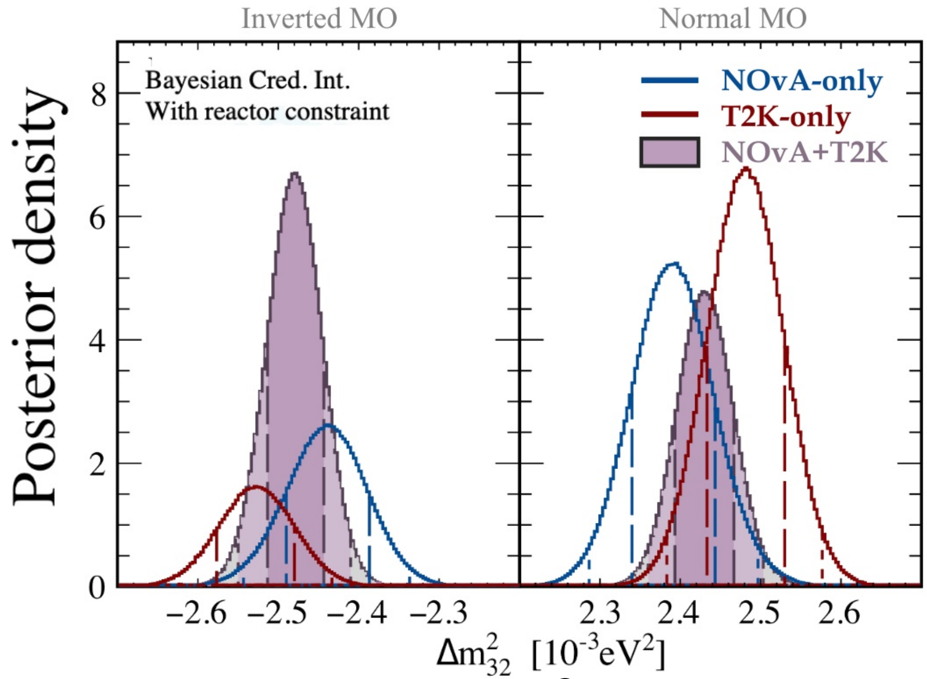
Hypothesis	p-value
CP conservation	0.037
Inverted ordering	0.079

- **1.9-2.3σ** exclusion of CPC

- 90% of posterior probability in **normal ordering**
- 61% of posterior probability in **upper octant**

Results, NOvA+T2K

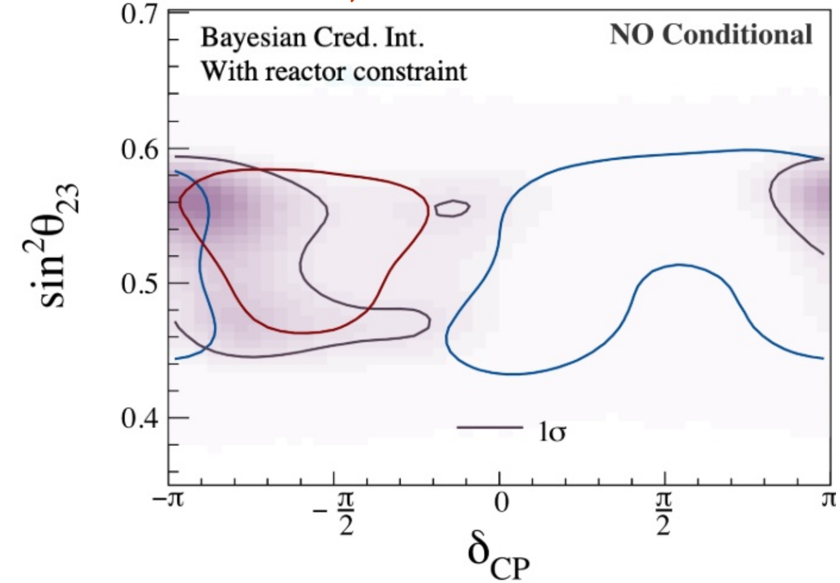
Z. Vallari, Fermilab Wine & Cheese

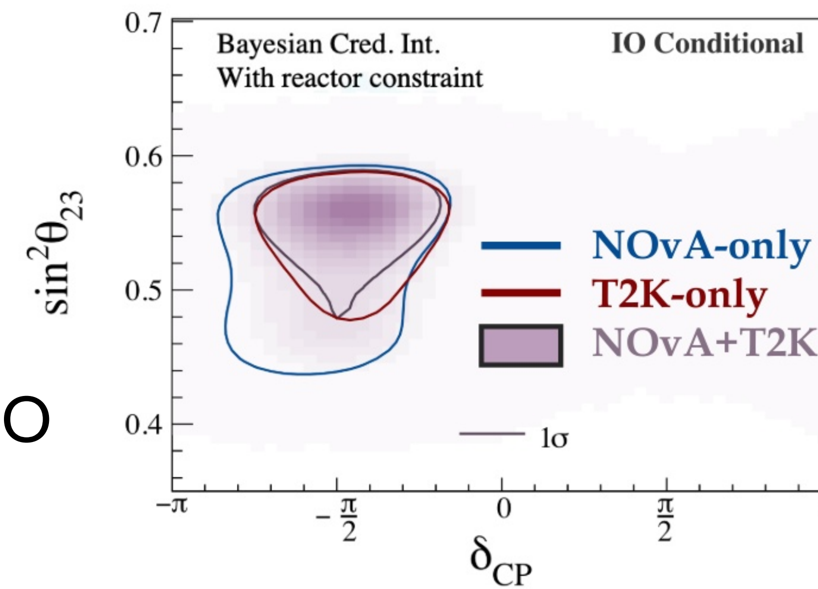


- **Strongest Δm^2_{32} constraint!**

	NOvA only	T2K only	NOvA+T2K
Bayes factor	2.07 Normal/Inverted ~67% : ~33% posterior	4.24 Normal/Inverted ~81% : ~19% posterior	1.36 Inverted/Normal ~58% : ~42% posterior

- **No preference** for MO
- Individually **weakly prefer NO**





	NOvA – T2K – w/ reactor
Bayes factor	3.59 Upper Octant/Lower Octant ~78% : 22% posterior

- **More data needed to explore "tension"!**

Summary

- Joint oscillation analyses can **lift multiple degeneracies** in individual oscillation experiments
  - Degeneracies both through **oscillation** and **nuisance** parameters
  - e.g. mass ordering and CP violating phase in Hyper-K
- **Large joint oscillation analyses have begun**, using official analysis tools by the experiments
  - Main challenge is evaluating the **cross-correlations**
- Tools developed for interaction model investigations and statistical techniques; **flux correlations not included**
  - Interest in studying flux further!
- Weak preference for **normal ordering**, **upper octant**, and **CP violation**; **NOvA no preference for ordering**
  - **If inverted ordering, 3σ exclusion of CP conservation**
- Joint analyses increasingly important as statistical uncertainties drastically decrease, e.g. HK and DUNE
  - Work needs to start **now to unify treatment**

Backups

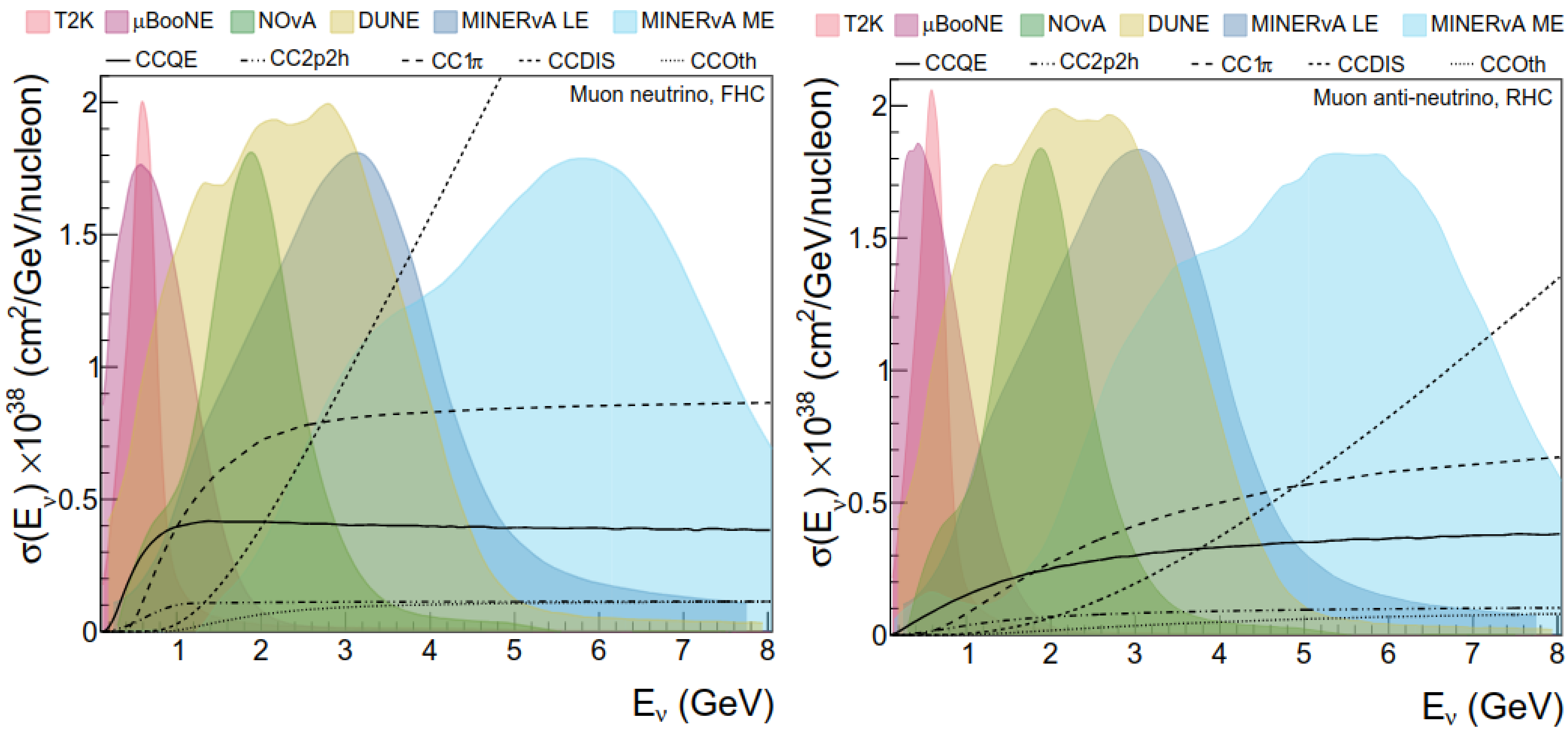
Event counts at the FDs

Sample	T2K	NOvA	Hyper-Kamiokande	DUNE
N_μ^{rec} FHC	318	211	10000	7000
N_μ^{rec} RHC	137	105	14000	3500
N_e^{rec} FHC	108	82	3000	1500
N_e^{rec} RHC	16	33	3000	500

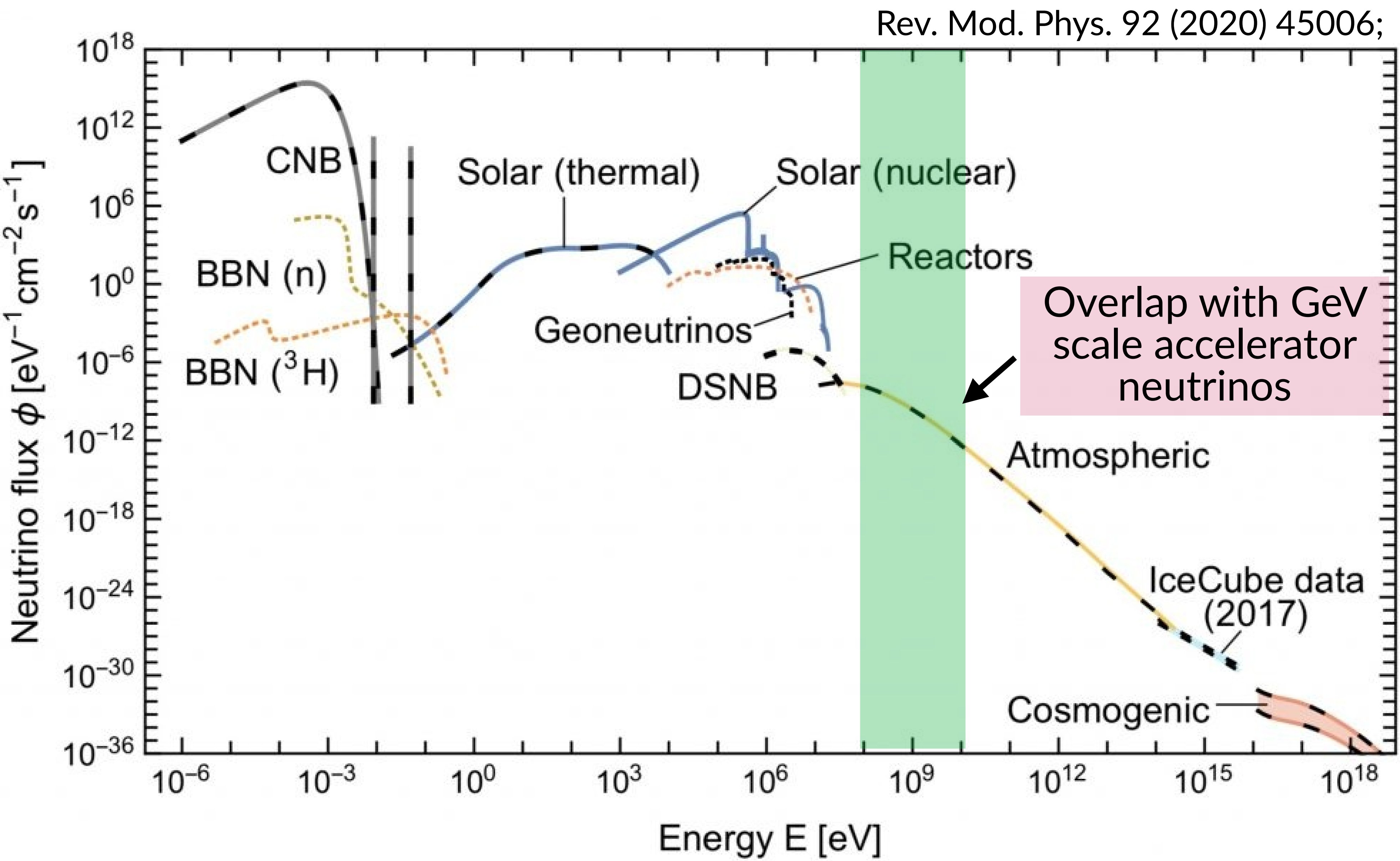
- HK and DUNE will have **enough events** to be limited by the **~3% (anti-)ν_e uncertainty**
- Current experiments at the **3-5% level** uncertainties*

*Exception of T2K's single-pion-below-threshold sample (10-15%)

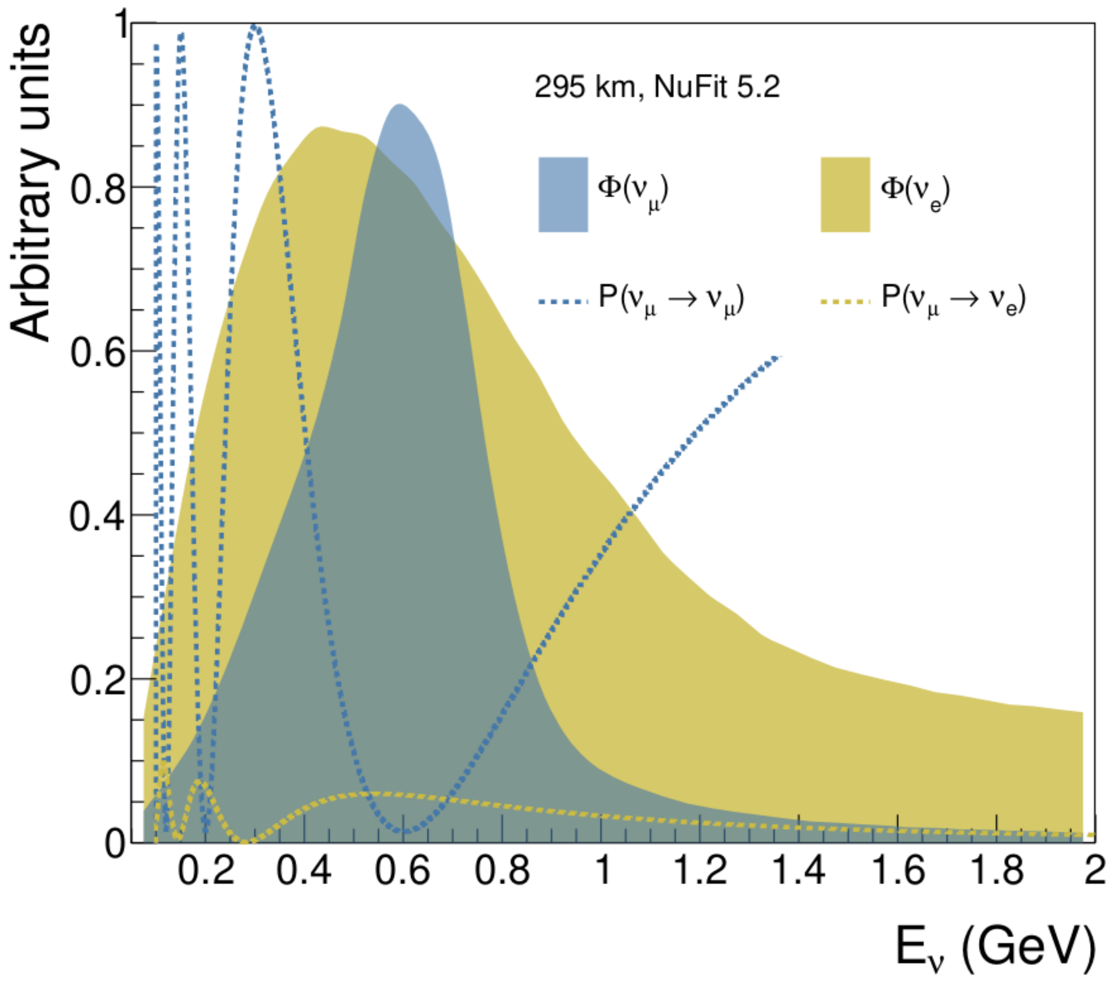
Neutrino fluxes



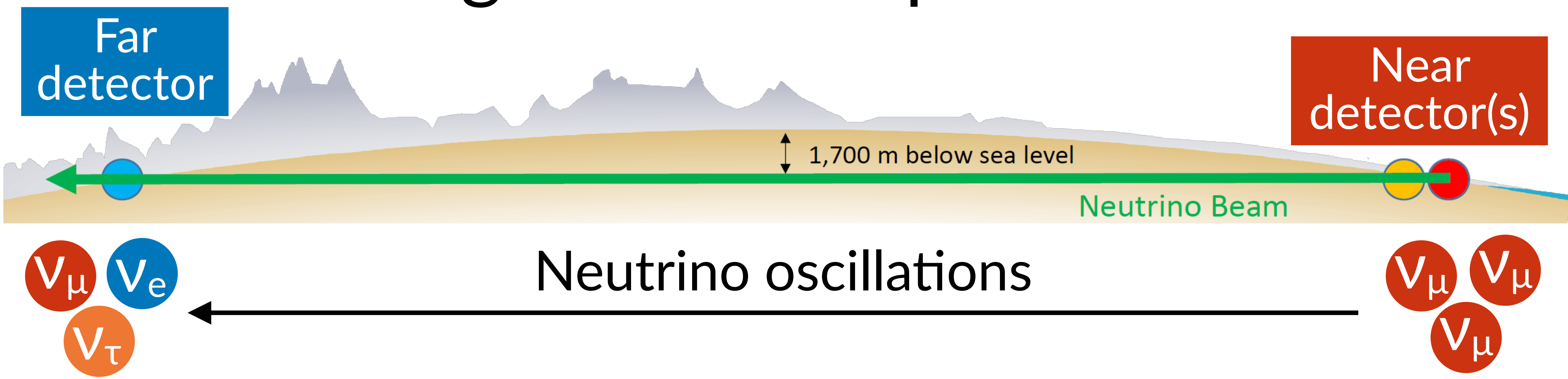
Neutrino fluxes



Neutrino fluxes



Long baseline experiments



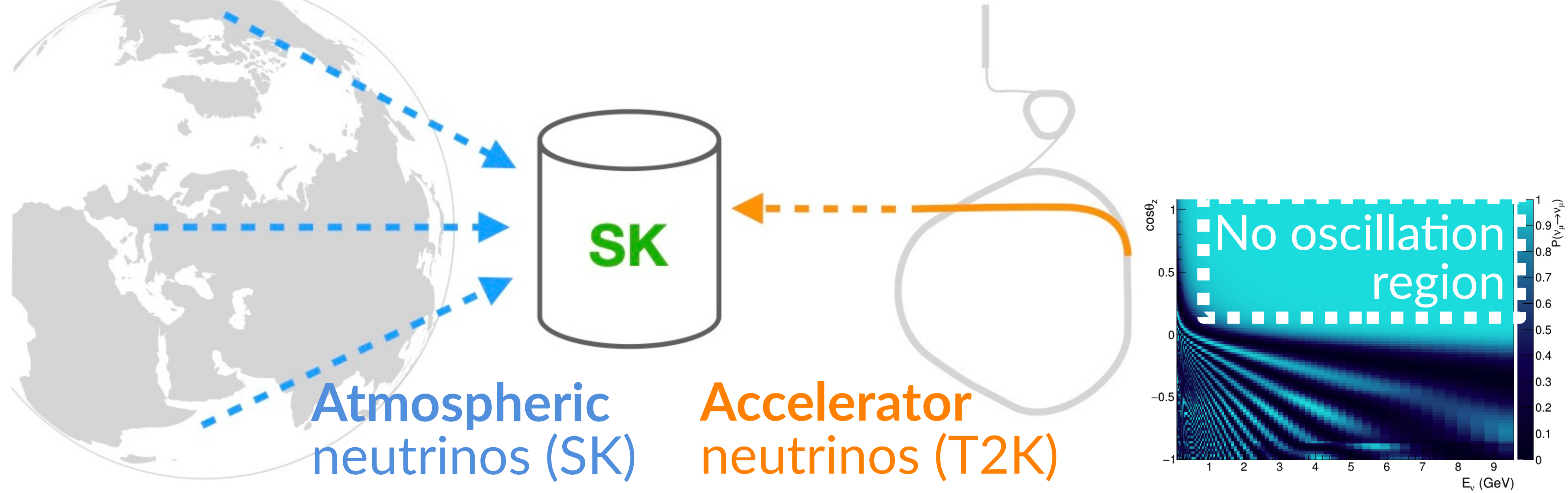
- The **beam** is **characterised** by **high-statistics samples** at the **near detector(s)** before long baseline oscillations
- Events observed at the far detector have many **shared uncertainties** with the near detector
  - Constrain **flux and interaction model** using near detector data

$$N^{\alpha}_{\mathrm{ND}}(\vec{x}) = \Phi^{\alpha}(E_{\nu}) \times \sigma^{\alpha}(\vec{x}) \times \epsilon^{\alpha}_{\mathrm{ND}}(\vec{x})$$

$$N^{\alpha}_{\mathrm{FD}}(\vec{x}) = P(\nu_{\alpha} \rightarrow \nu_{\alpha}) \times \Phi^{\alpha}(E_{\nu}) \times \sigma^{\alpha}(\vec{x}) \times \epsilon^{\alpha}_{\mathrm{FD}}(\vec{x})$$

- **Mitigates many of the systematics**, e.g. size of cross sections

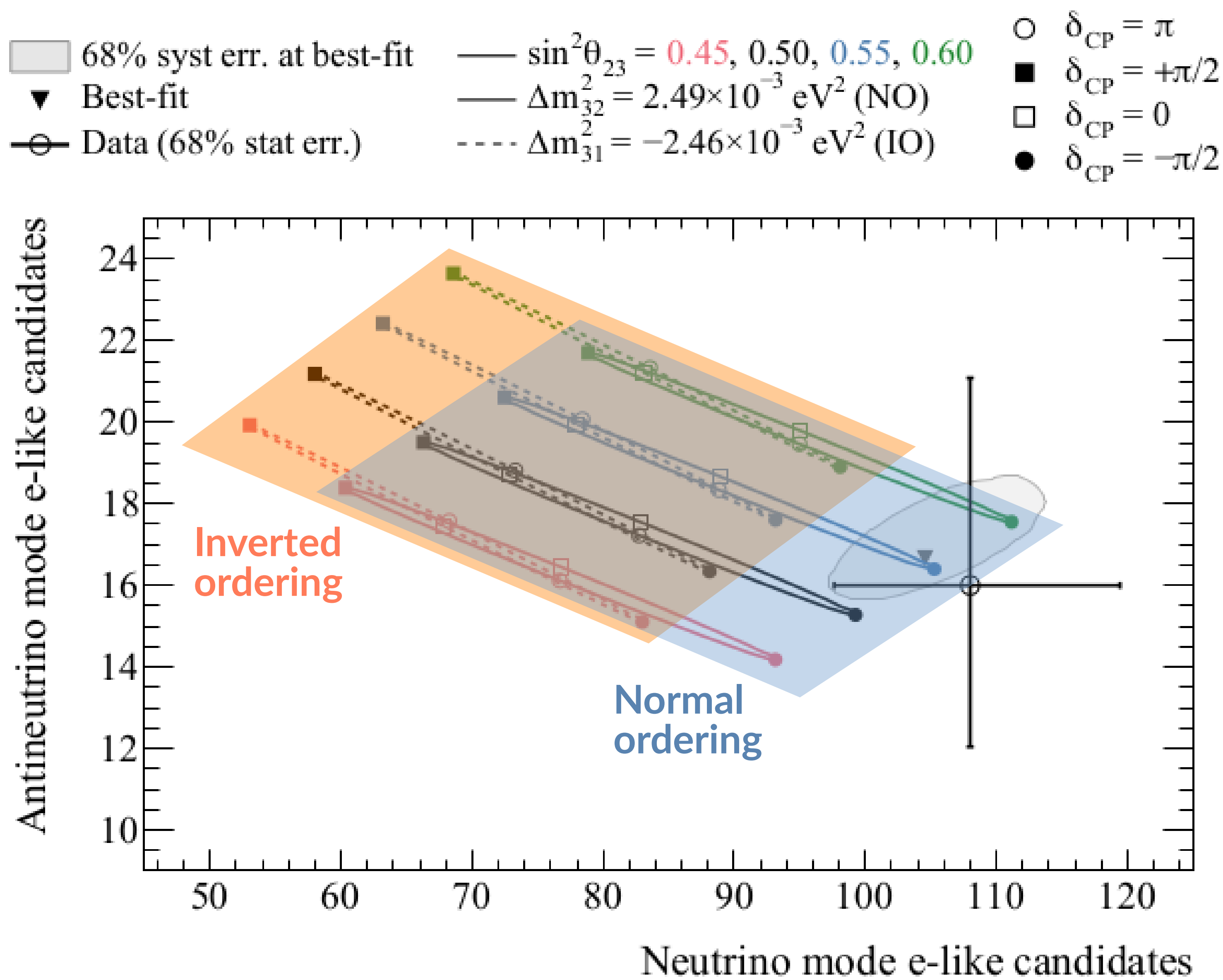
Atmospheric experiments



- For **atmospheric** neutrinos, there is no near detector, systematics instead addressed by **down-going neutrinos**
  - Very small oscillation probability in region
  - **Effectively acting as a near-detector** constraint throughout a large neutrino energy range
- Nowhere near the same constraining power as T2K near detector
  - **Appropriately correlate detector** and **interaction** systematics
  - **Improve atmospheric constraints** via **oscillation** and **interaction** parameters; **improve beam constraint** via **detector** parameters

Why a joint atmospheric analysis

- T2K has degeneracies with δ_{CP} and mass ordering



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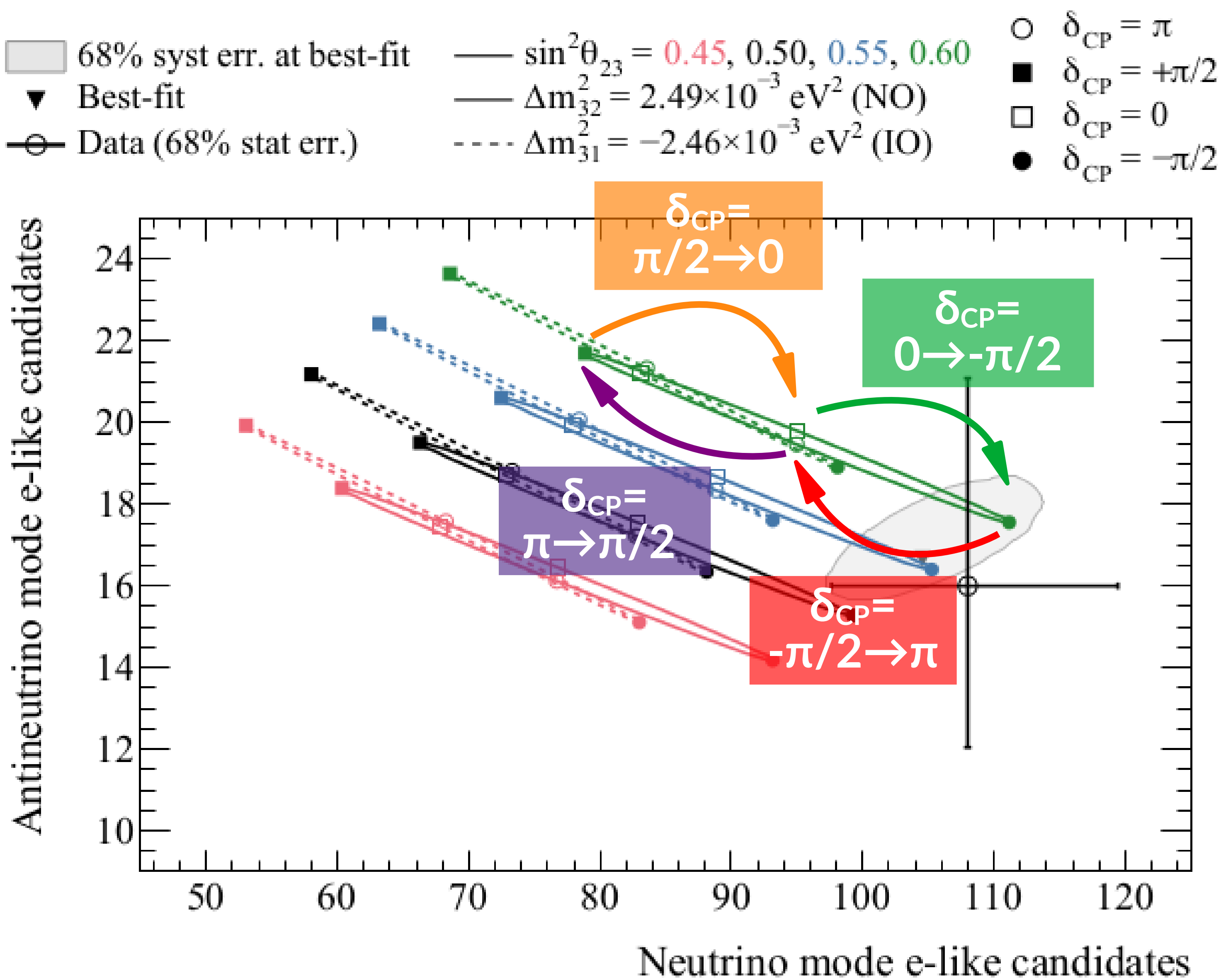
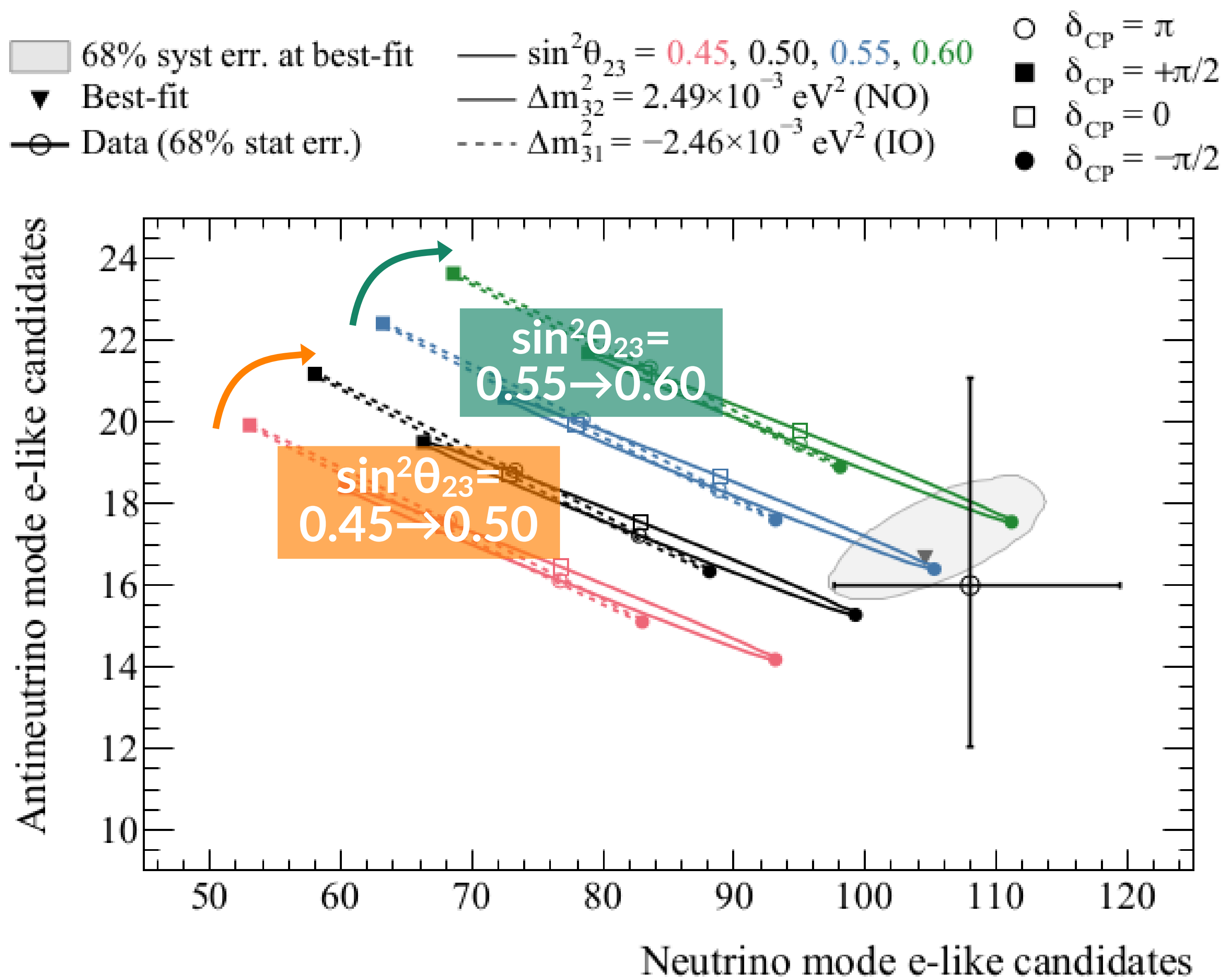


Why a joint atmospheric analysis

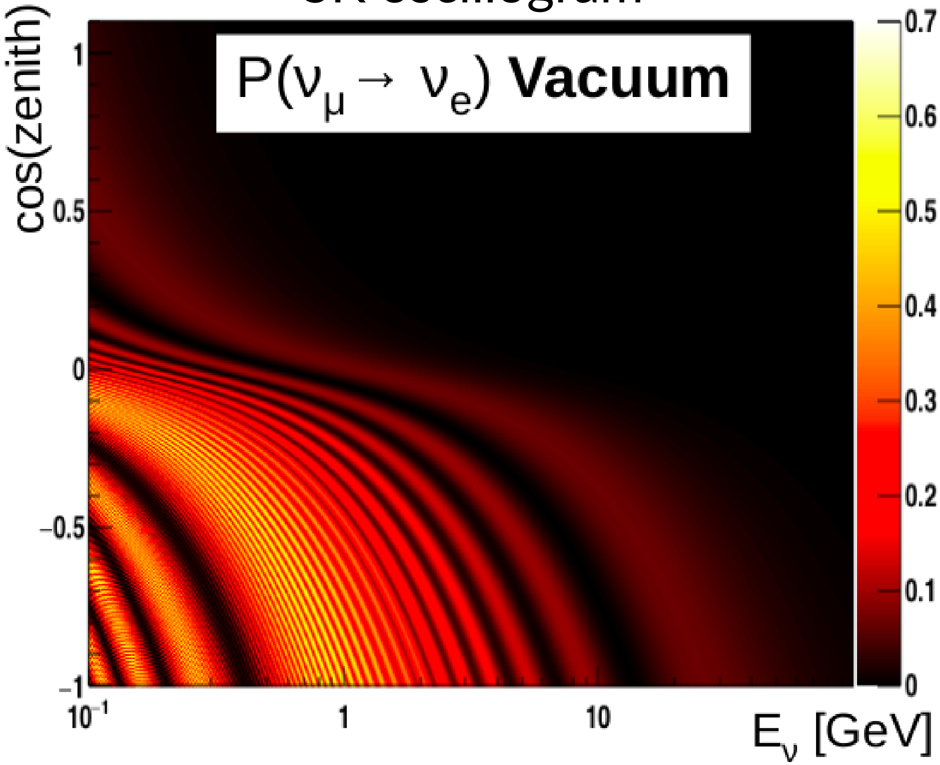
- But, T2K has good sensitivity to mixing angle $\sin^2\theta_{23}$



Why a joint atmospheric analysis

- Both experiments are sensitive to δ_{CP} from ν_e appearance
- T2K is not sensitive to mass ordering, but good constraint on δ_{CP}
- **<u>SK has good constraint on mass ordering</u>**, but barely on δ_{CP}: sees an average effect, due to energy resolution
  - T2K's $\sin^2\theta_{23}$ constraint helps reducing degeneracies in SK

SK oscillogram



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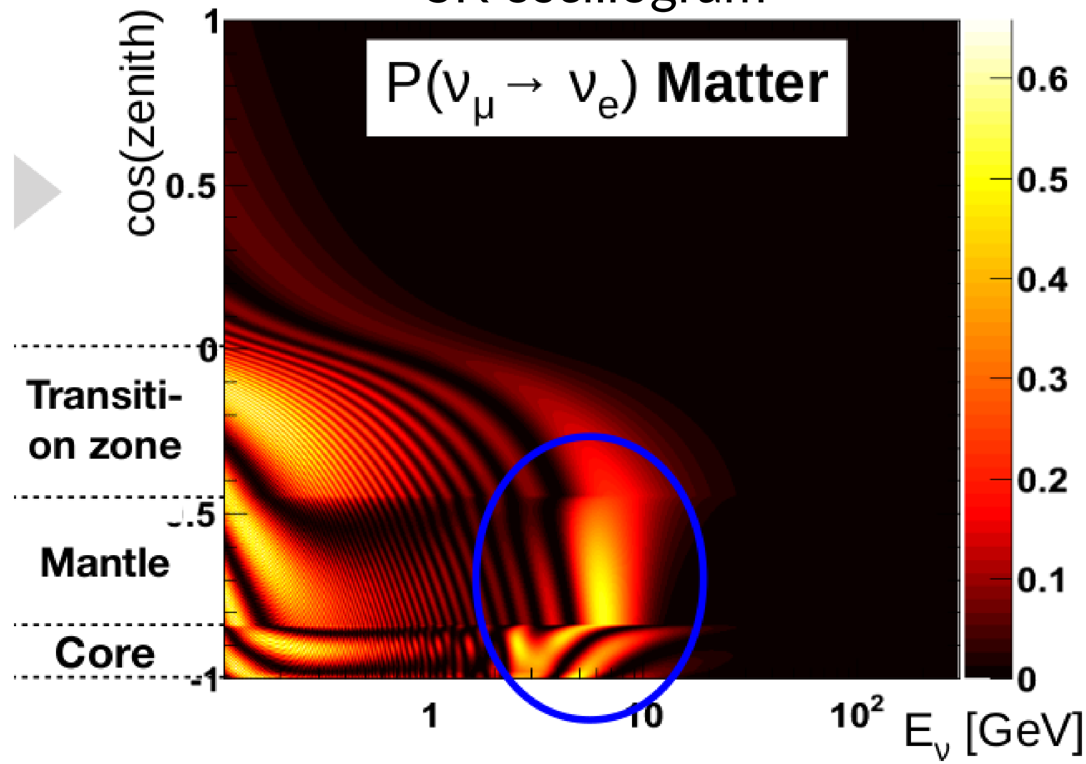
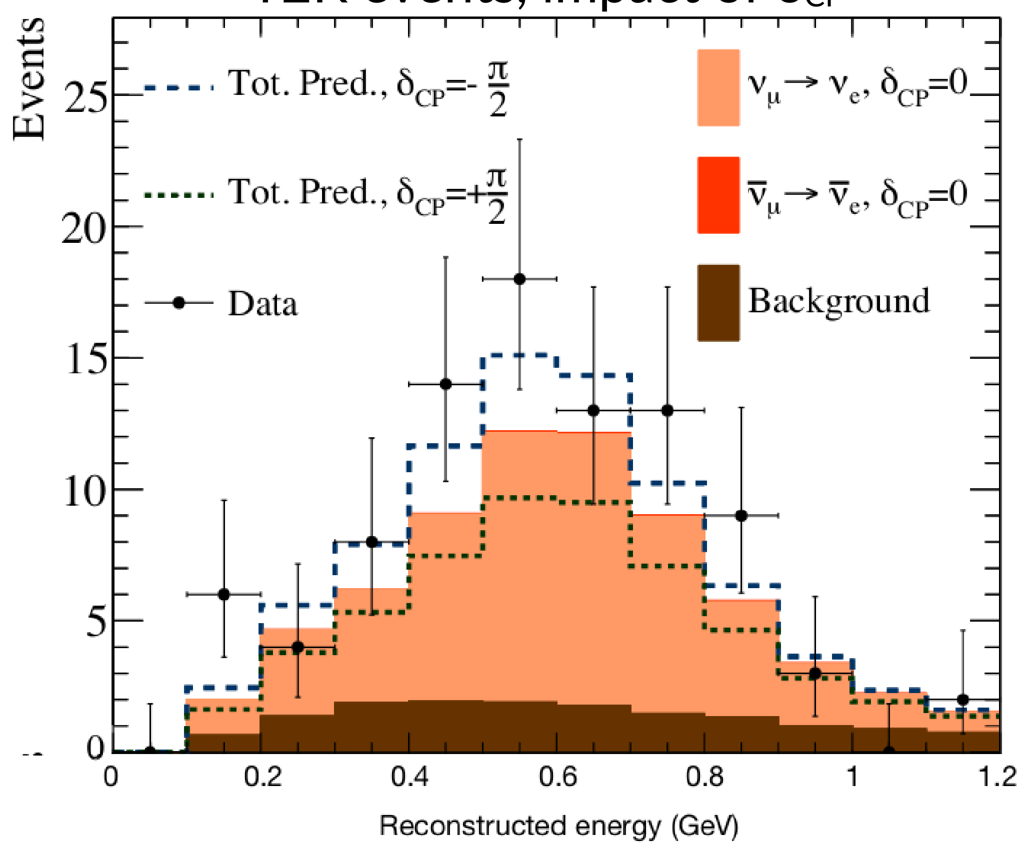


If **normal ordering**, **resonance** appears for **neutrinos**
If **inverted ordering**, **resonance** appears for **anti-neutrinos**

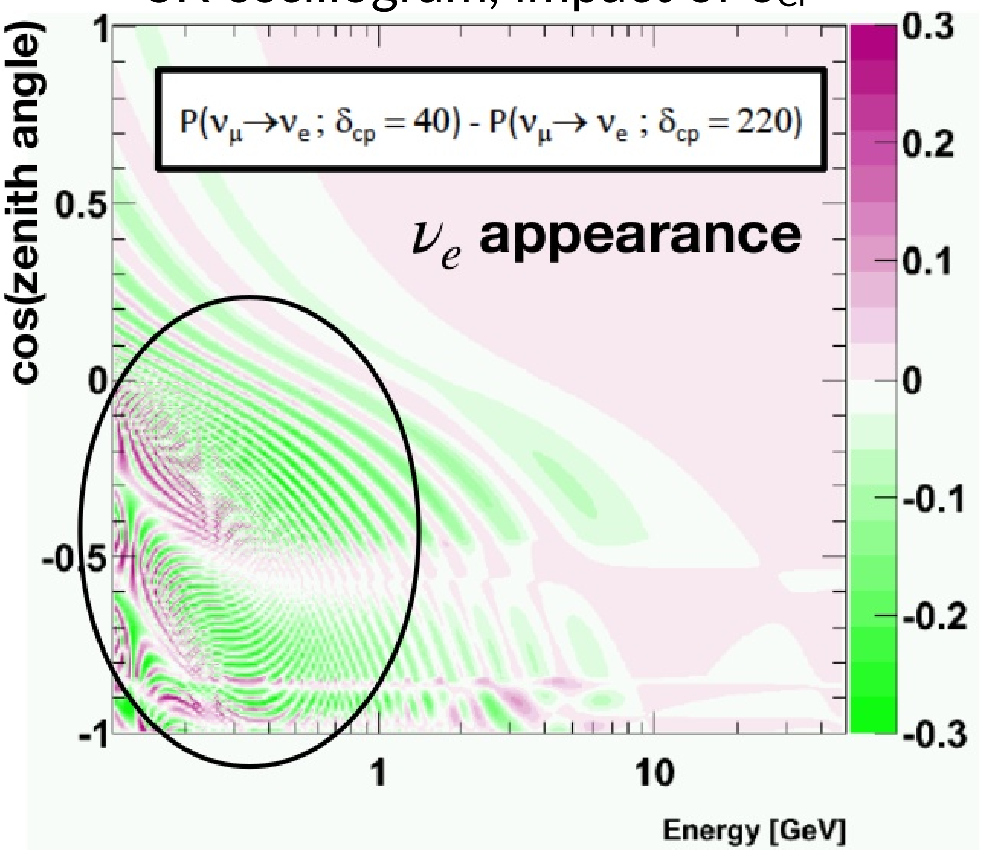
Why a joint atmospheric analysis

- Both experiments are sensitive to δ_{CP} from ν_e appearance
- T2K is not sensitive to mass ordering, **but good constraint on δ_{CP}**
- SK has good constraint on mass ordering, **but barely on δ_{CP}**: sees an average effect, due to energy resolution
  - T2K's $\sin^2\theta_{23}$ constraint helps reducing degeneracies in SK

T2K events, impact of δ_{CP}

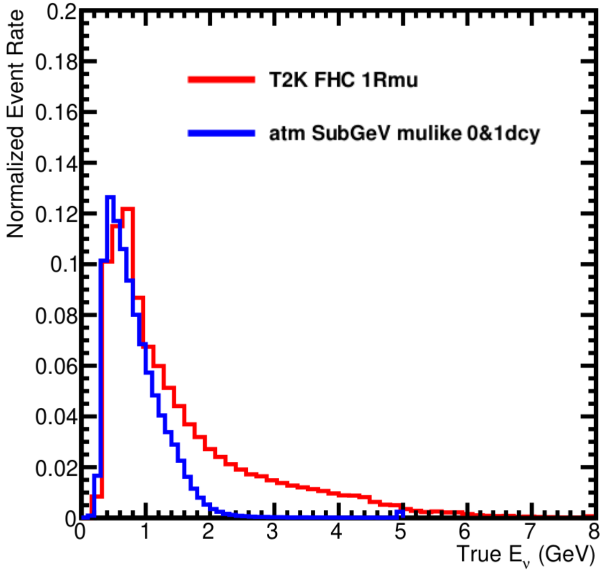


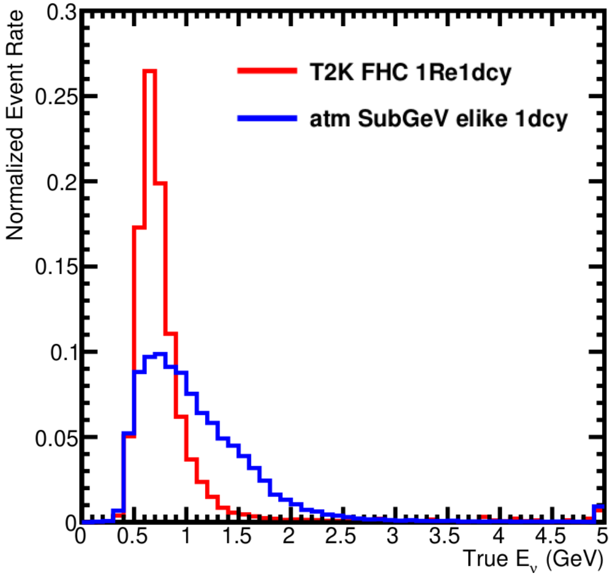
SK oscillogram, impact of δ_{CP}



Why a joint atmospheric analysis

- SK sees multiple neutrino sources: here we use **atmospheric** neutrinos, and **beam neutrinos** from T2K



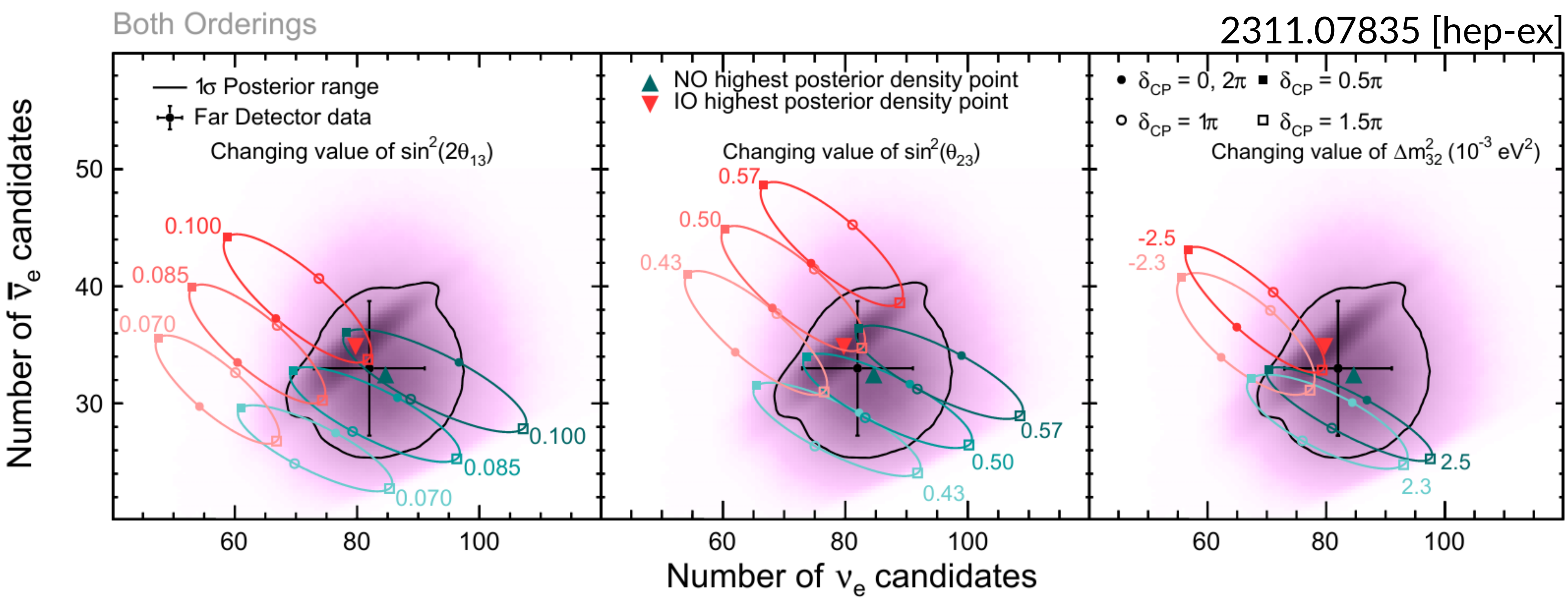


- Same detector, sometimes similar selections and fluxes
  - **Unify systematics and selections where possible**
  - Improved oscillation constraints through sharing systematics, and using high-statistics SK samples to inform T2K samples
  - Utilise high-statistics near-detector samples from T2K to constrain aspects of atmospheric selections: expose tensions
- Beam+atmospheric analysis may be required for Hyper-Kamiokande competitiveness with DUNE (depending on mass ordering and δ_{CP})

Why a joint beam analysis

- NOvA experiment higher neutrino energy, longer baseline compared to T2K
  - Stronger mass ordering sensitvity, weaker δ_{CP} sensitivity

2311.07835 [hep-ex]

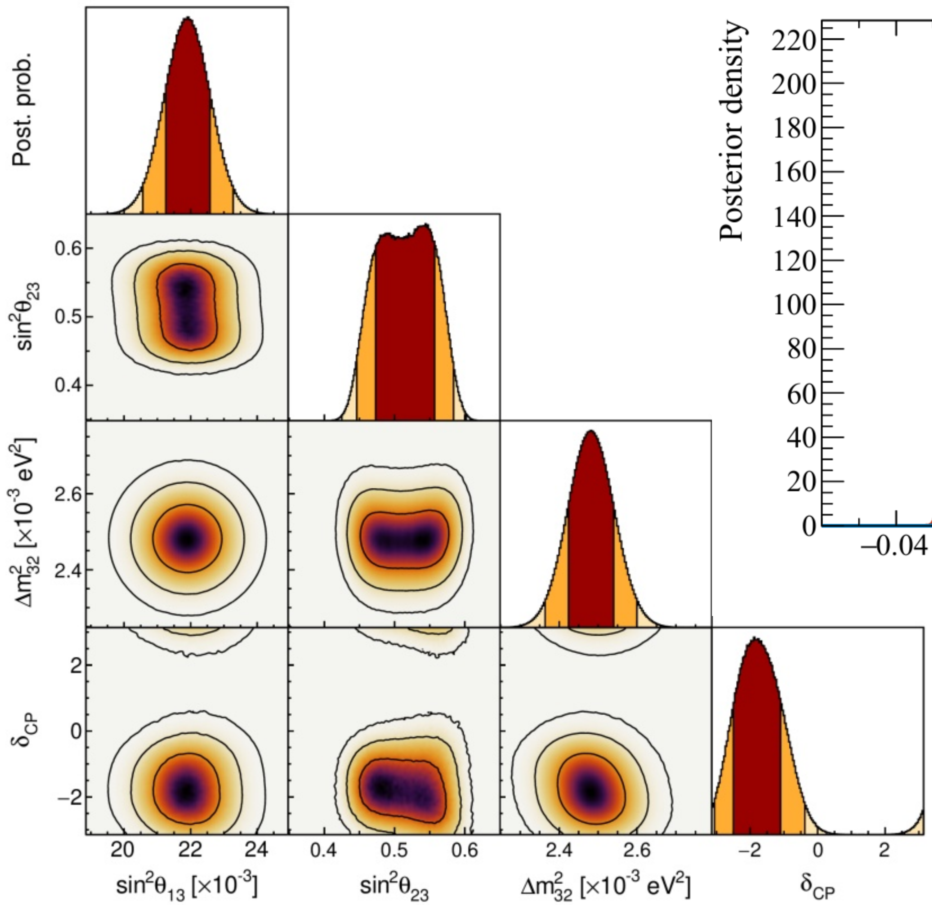


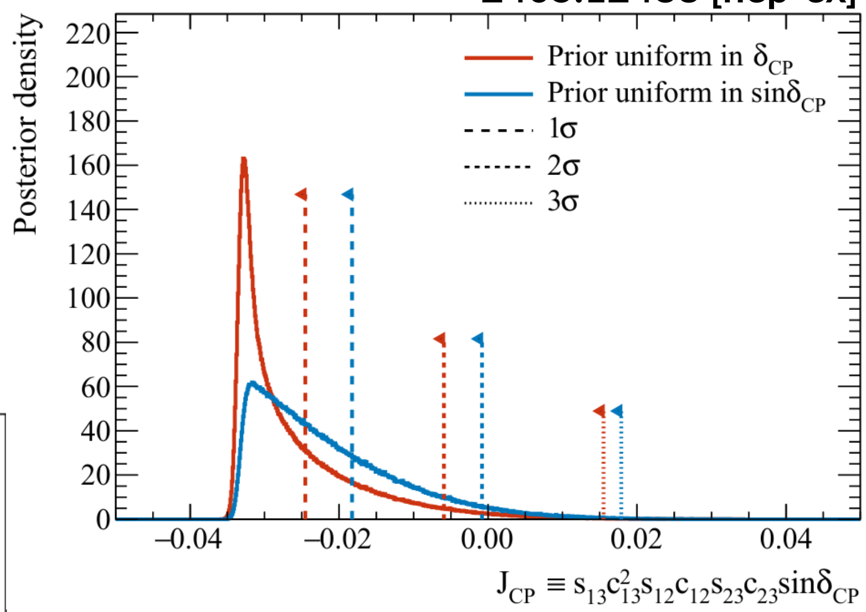
- Should be some correlation in neutrino interactions?

Results, SK+T2K

- Compatible Bayesian and frequentist results

2405.12488 [hep-ex]





Hypothesis	p-value
CP conservation	0.037
Inverted ordering	0.079
Normal ordering	0.58

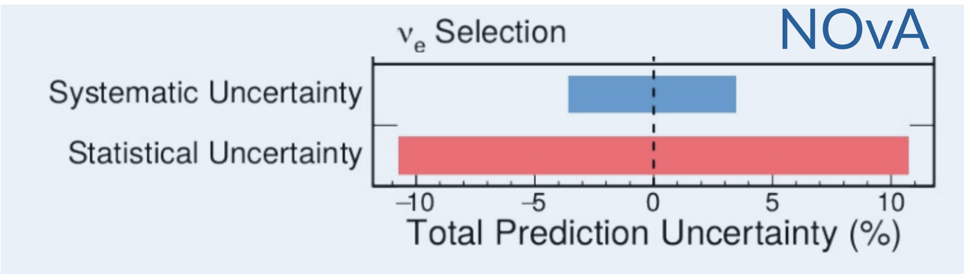
- 1.9-2.3σ exclusion of CPC
- Weak preference for normal mass ordering

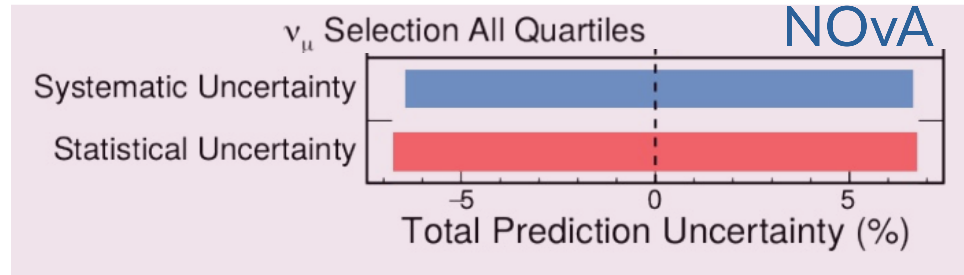
	SK only	T2K only	SK+T2K
Upper octant	0.318 (0.337)	0.785 (0.761)	0.611 (0.639)
Normal ordering	0.654 (0.633)	0.832 (0.822)	0.900 (0.887)

Posterior probabilities

Importance of systematics

- **Details of systematic** uncertainties are becoming **important** for high-statistics long-baseline experiments





T2K	Syst.	Stat.
$\nu_e, \overline{\nu}_e$ appearance (%)	4.7, 5.9, 14.3	10.3, 25.0, 26.7
$\nu_\mu, \overline{\nu}_\mu$ disappearance (%)	3.0, 4.0	5.6, 8.5

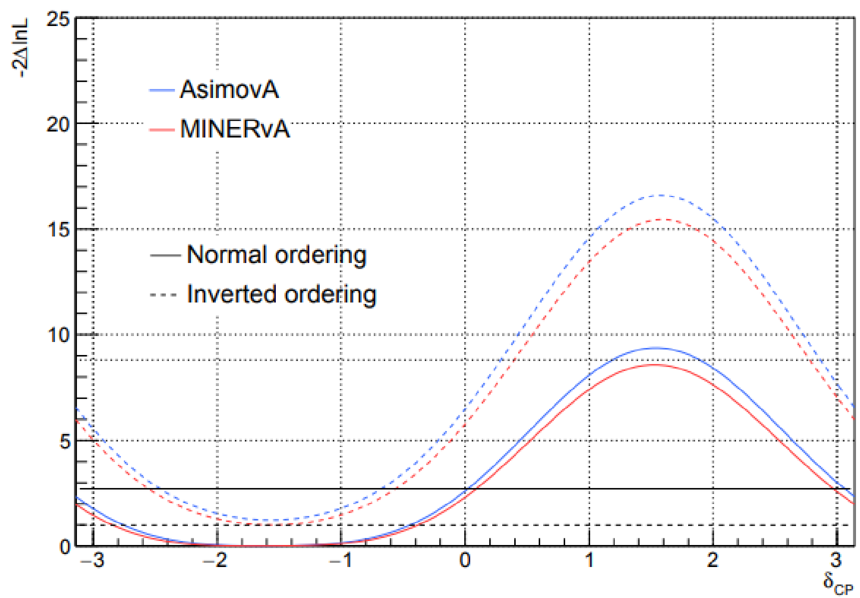
- **ν_μ selections** seeing impact of **systematics**: **$\sin^2\theta_{23}$** and **Δm^2_{32}**
- **ν_e selections** still **statistics** limited: **δ_{CP}**, **mass ordering**, and **$\sin^2\theta_{23}>0.5$**
- Assessing **cross-experiment correlations** becoming increasingly important, especially as tensions arise
  - Not possible via global fits outside experiments
- Next-generation experiments (HK, DUNE) will have **order of magnitude** more data: **systematic uncertainties critical**

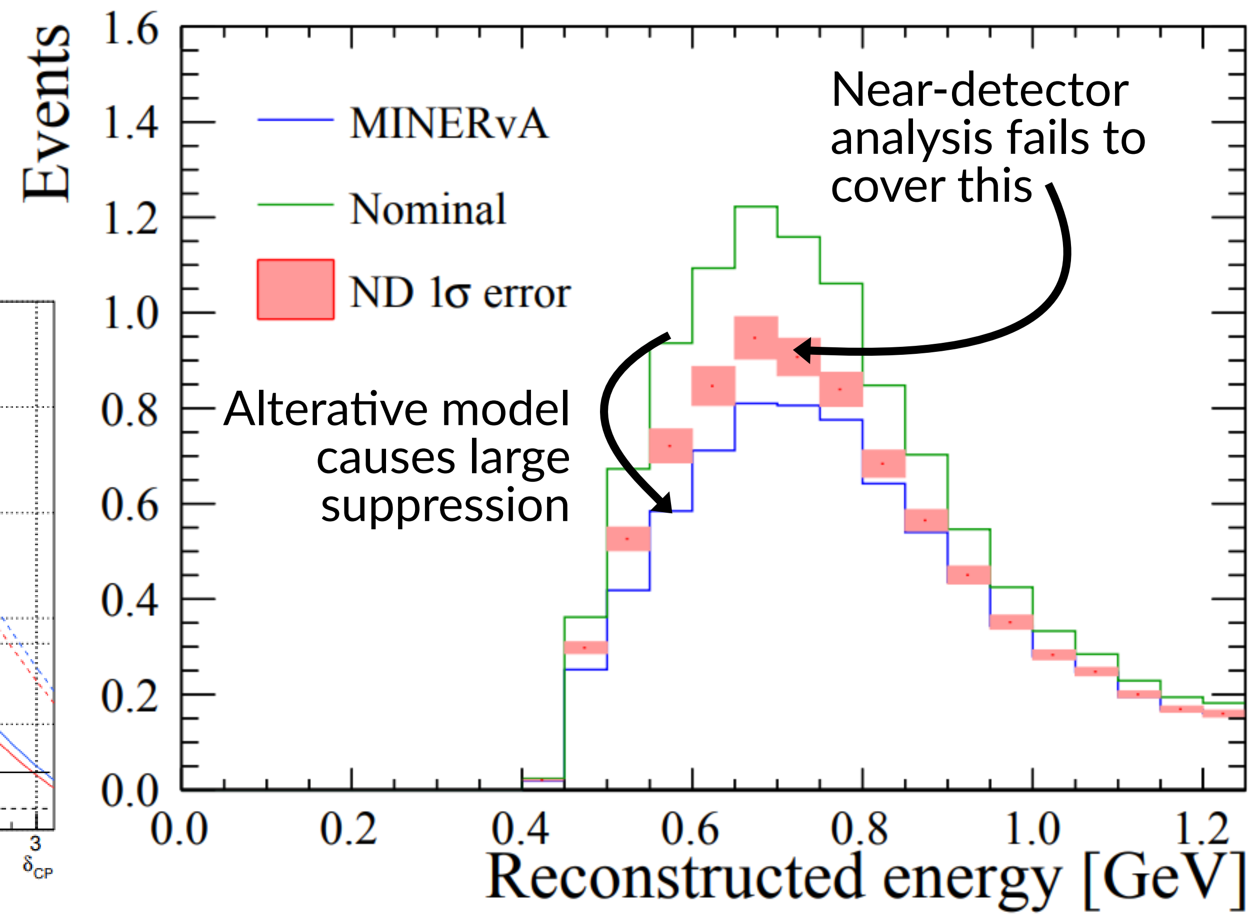
Fake-data studies

- Realistically, won't have a perfect interaction model for a ***timely*** oscillation analysis
- Reasonable best case scenario: a model that fits the experimental data, but is not applicable to other experiments
  - The model is ***effective***, but **not complete**
  - The physics is **not modelled exactly**, but **approximately**, with effects soaked up in the wrong part of the model
- What if nature is described by a different model; **what bias** is incurred on **oscillation parameters**?
- The bias this may cause is generally mitigated by "**fake-data studies**"
- **Can change exclusion statements and model choices**

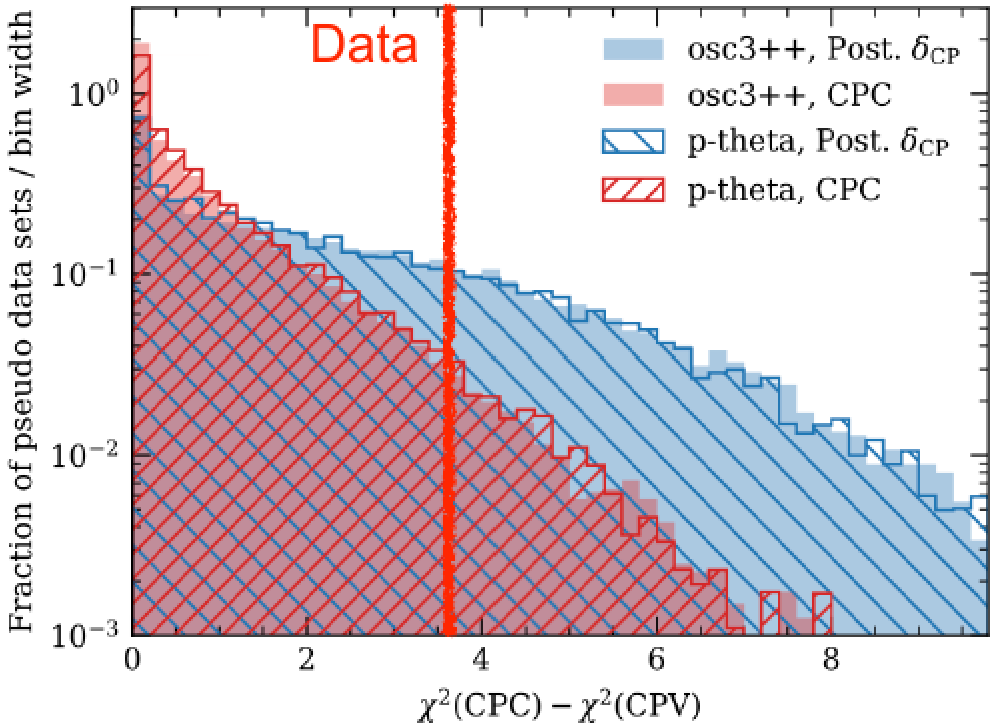
Fake-data studies

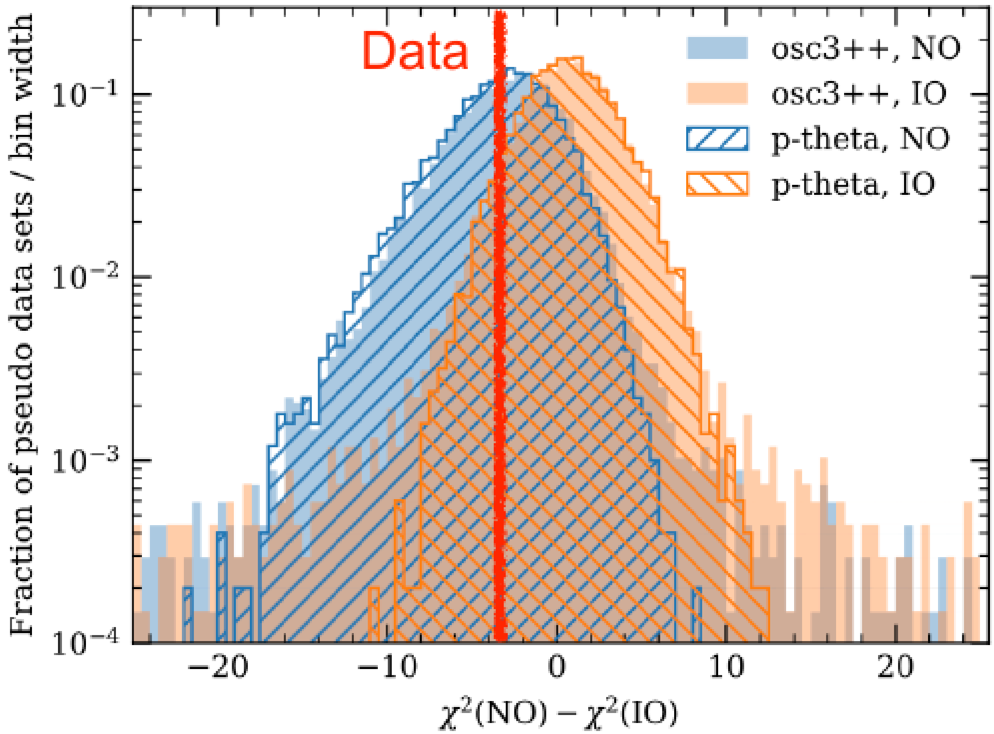
- Use an alternative model to make a prediction for near and far detectors
- Fit to the alternative model at the near detector
  - Set of parameters that best describe the alternative model
- Propagate result to far detector, perform oscillation analysis





Frequentist p-values for SK+T2K





	Osc3++	PTheta (GPU)
ΔX^2(CPC-CPV)	3.78	3.66
p(CPC)	0.030	0.035
p(CPV)	0.754	0.757

	Osc3++	PTheta (GPU)
ΔX^2(MO)	-3.39	-3.12
p(NO)	0.58	0.52
p(IO)	0.077	0.076
CLs (IO)	0.183	0.158

MINOS

- First ever beam+atmospheric, and neutrinos/anti-neutrios, MINOS, numu only: Phys.Rev.Lett. 110 (2013) 25, 251801

- Follow up, including nue: Phys.Rev.Lett. 112 (2014) 191801
- 10.71E20 POT numu, 3.36E20 POT numubar, 37.88 kton years
- Bartol flux, NEUGEN3 interaction beam, NUANCE interaction atmospheric

- Final analysis Phys.Rev.Lett. 125 (2020) 13, 131802
- 10.56E20 POT numu, MINOS, 3.36E20 POT numubar, MINOS,
  0.15E20 POT numu, MINOS 9 GeV, 37.88 kton years, MINOS

- 22.87 kton years extra atmospheric, 9.69E20 POT numu MINOS+
- Bartol flux, NEUGEN3 interaction beam atmospheric, Surrounding rock NUANCE

- Difficulty in measuring nue/anti-nue, no nue samples in MINOS+ analysis due to NC backgrounds
- Fully correlated energy scale parameter
- Other correlations ignored due to statistics