Impact of neutrino interaction uncertainties on oscillation measurements

Clarence Wret
April 15 2024
NuInt 2024, Sao Paolo

UNIVERSITY OF OXFORD

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Bias declarations:

T2K + (NOvA)

T2K + (Super SK)

ex- DUNE, MINERvA

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nuisance.hepforge.org NUISANCE

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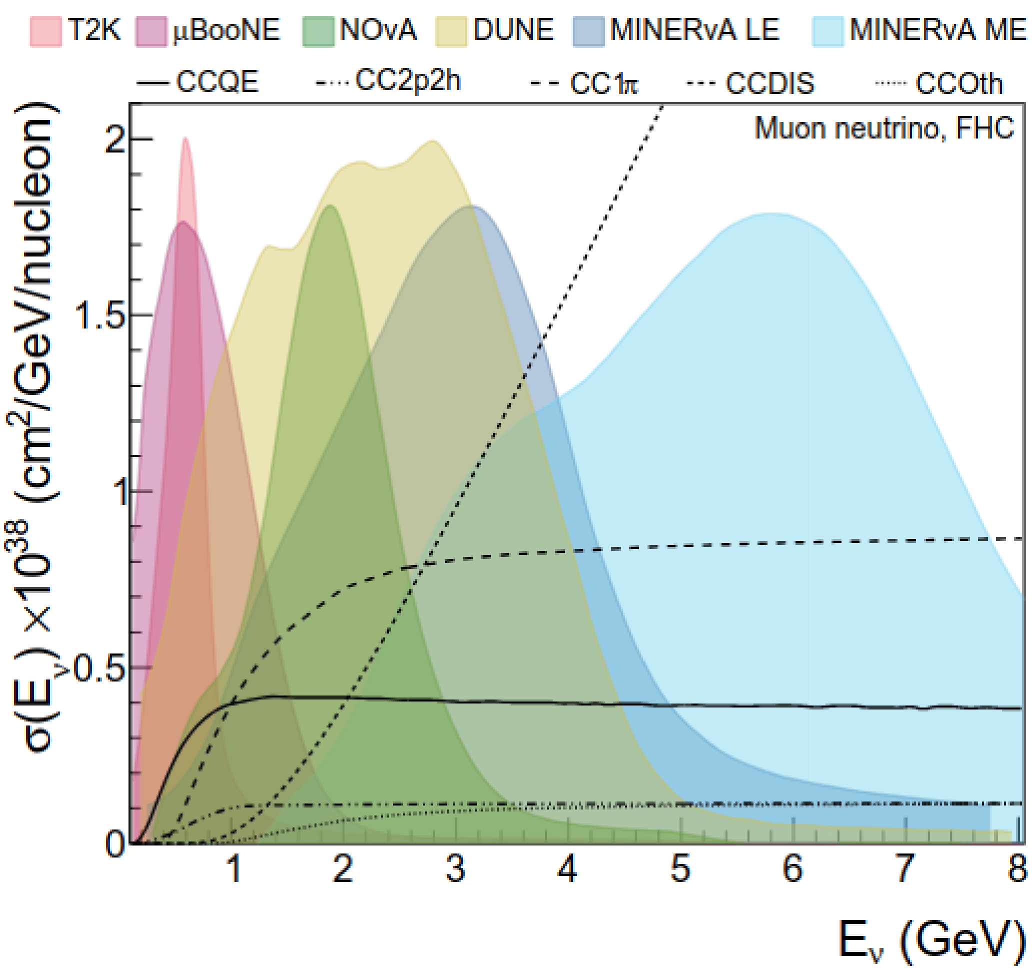
Introduction

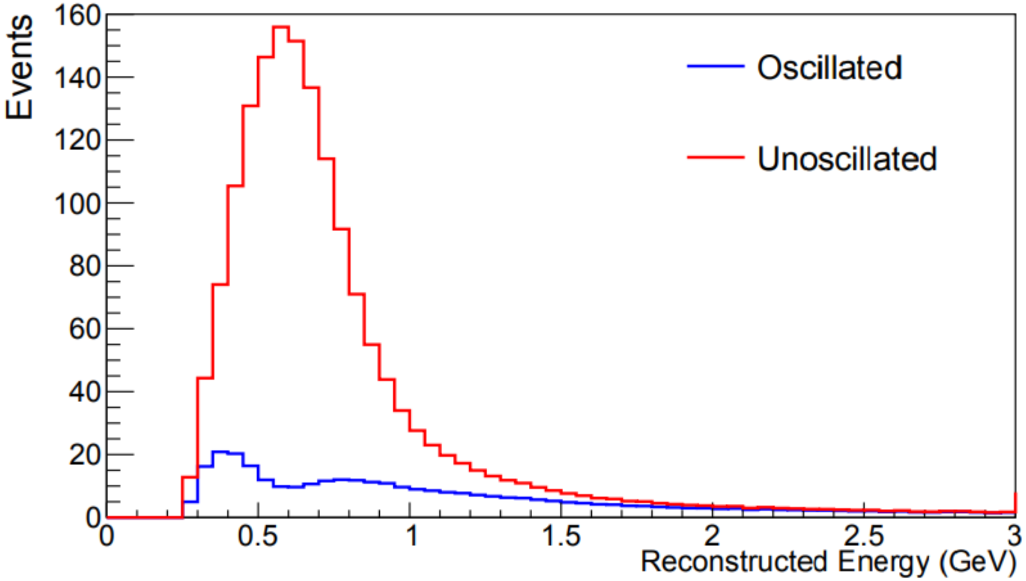
- Accelerator neutrino oscillation experiments generally in the **0.5-5 GeV** region
  - Some with wide, some with narrow band beam
- Studying (anti-)ν_μ disappearance and (anti-)ν_e appearance in an (anti-)ν_μ beam
- Complex scenario of which neutrino interactions matter
  - What matters for T2K, may not matter for NOvA, may not matter for DUNE
  - Measurements from a cross-section experiment may not extrapolate well to an oscillation experiment



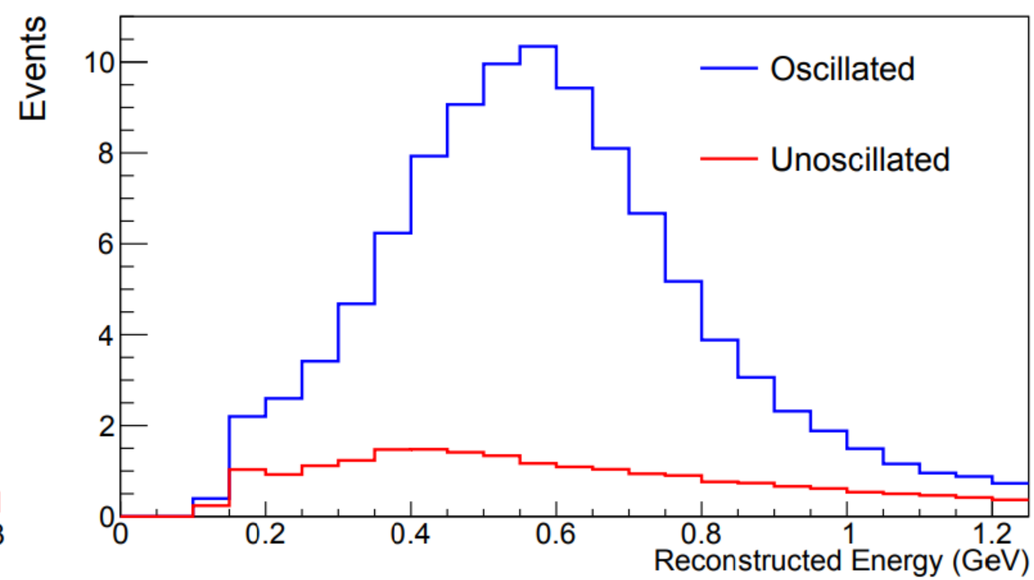
Introduction

- Oscillation parameters change the rate and shape of the appearing and disappearing neutrinos

T2K FHC 1Rμ



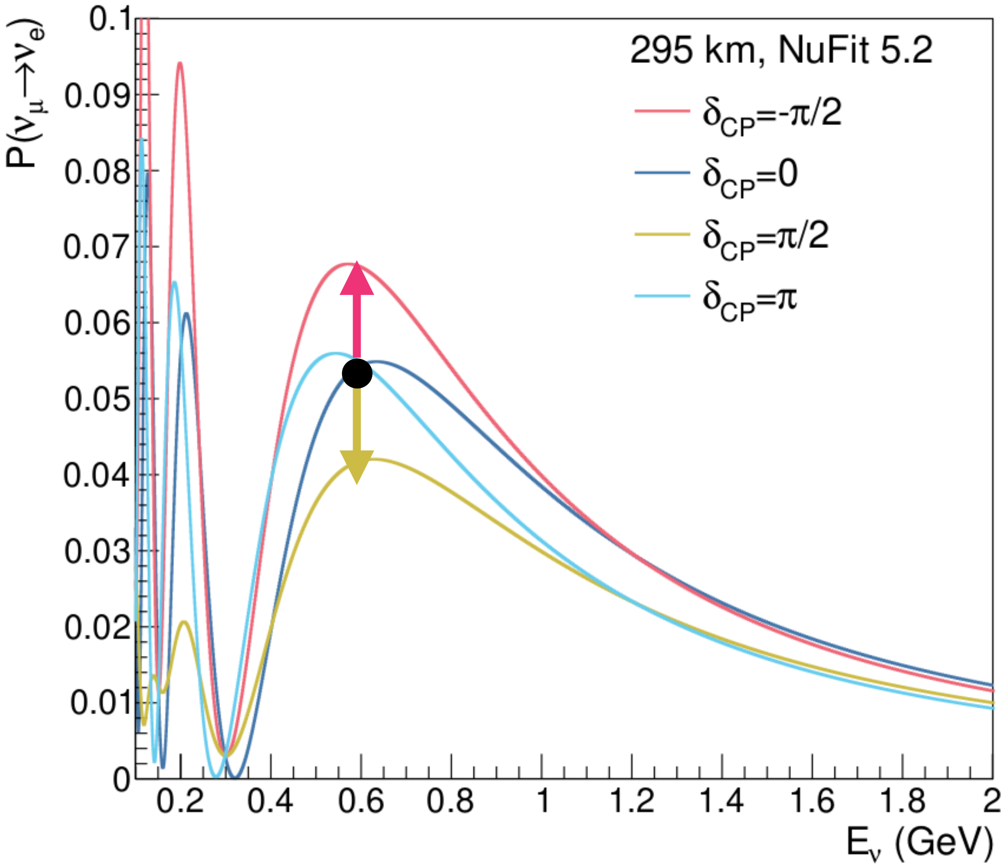
T2K FHC 1Re

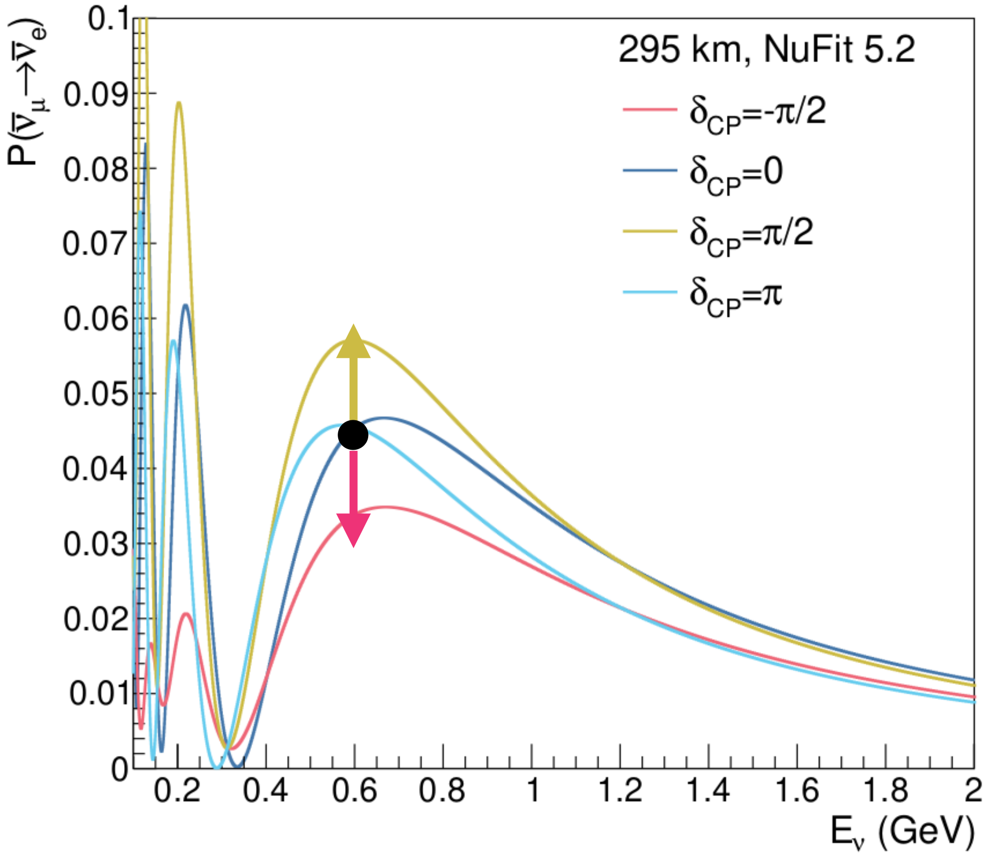


- Relies on the model prediction in the absence of oscillations
  - Constrain this model → constrain your oscillation parameters!
- Finding cross-section effects which are degenerate with oscillation parameters is the **nightmare** scenario

What can go wrong?

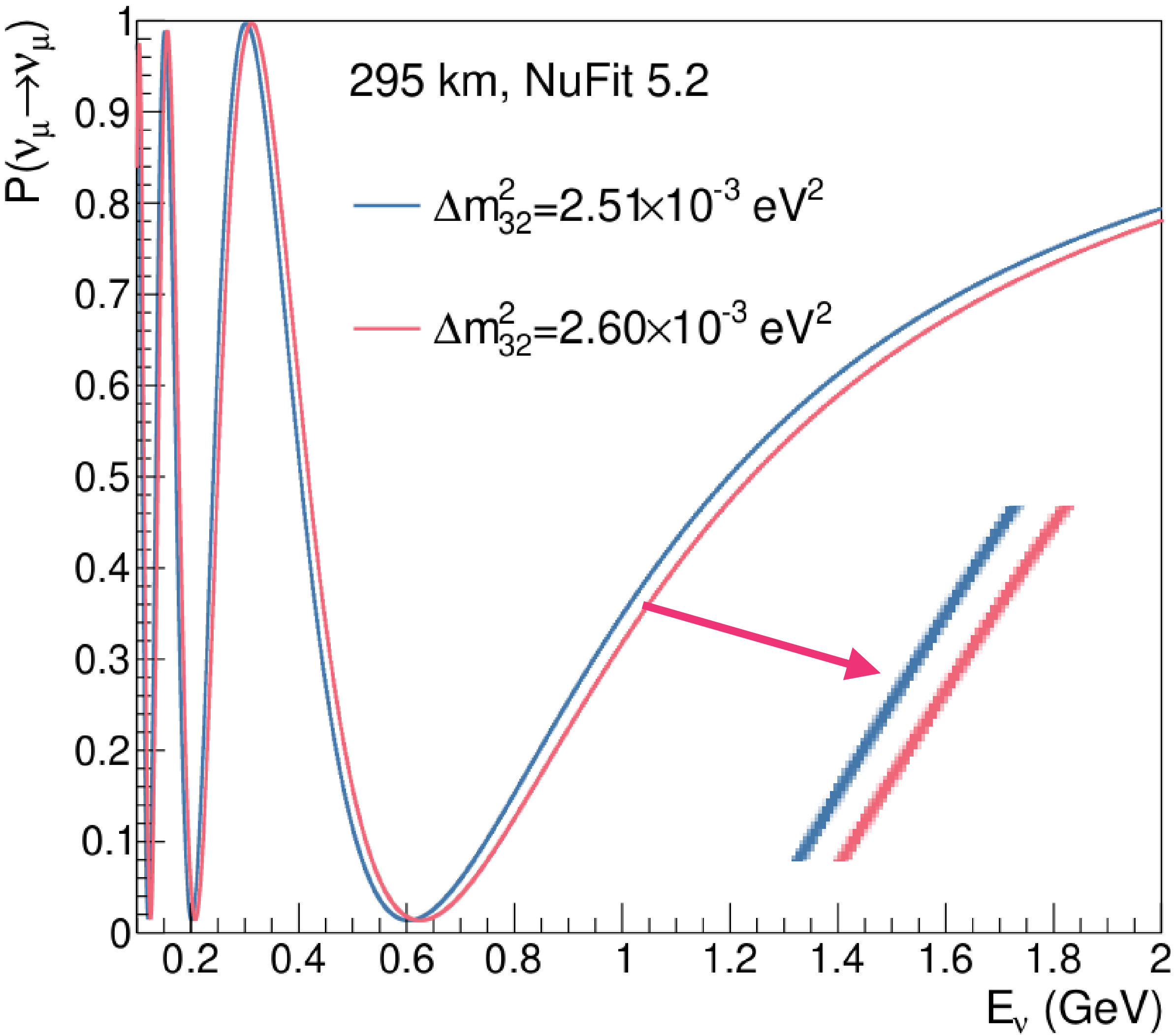
- **Flavour identification**
  - Is the increased rate of CC1e from oscillations, or is it a poorly modelled NC1π^0 background? Or NC1$\pi^\pm$ mistaken for CC1μ?
  - Attribute a cross-section effect of higher ν_e rate to oscillations → estimate a larger δ_{CP} and $\sin^2\theta_{13}$





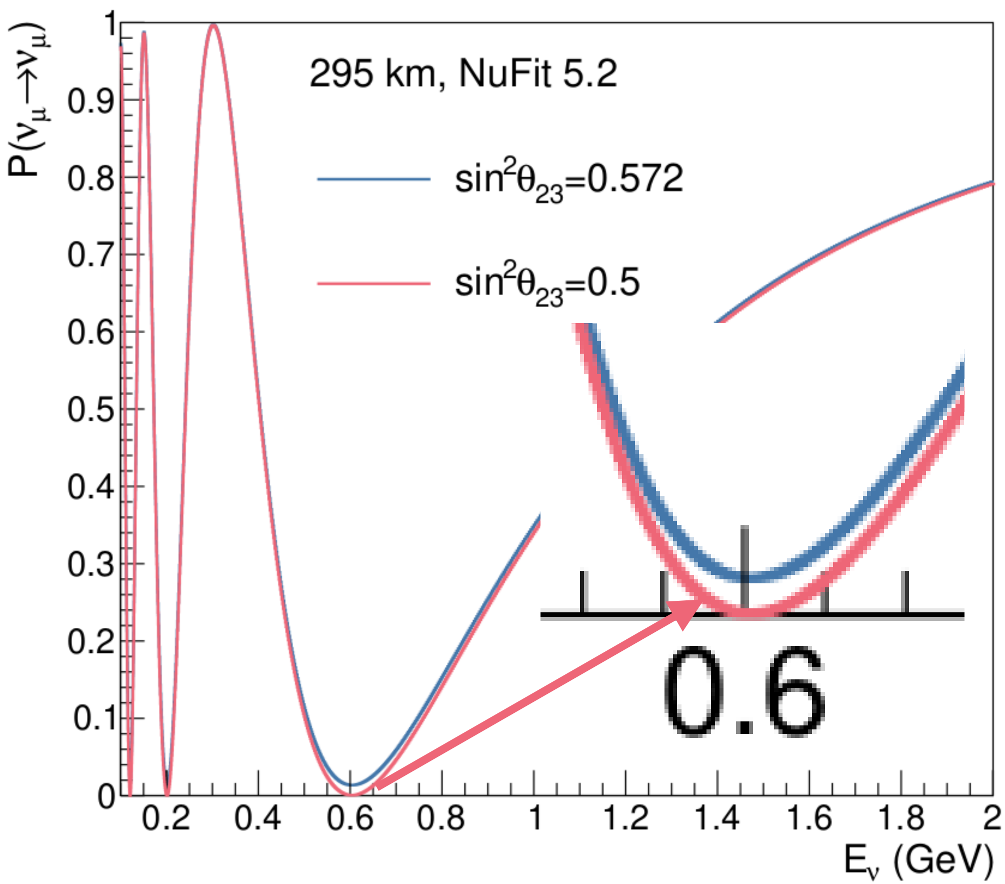
What can go wrong?

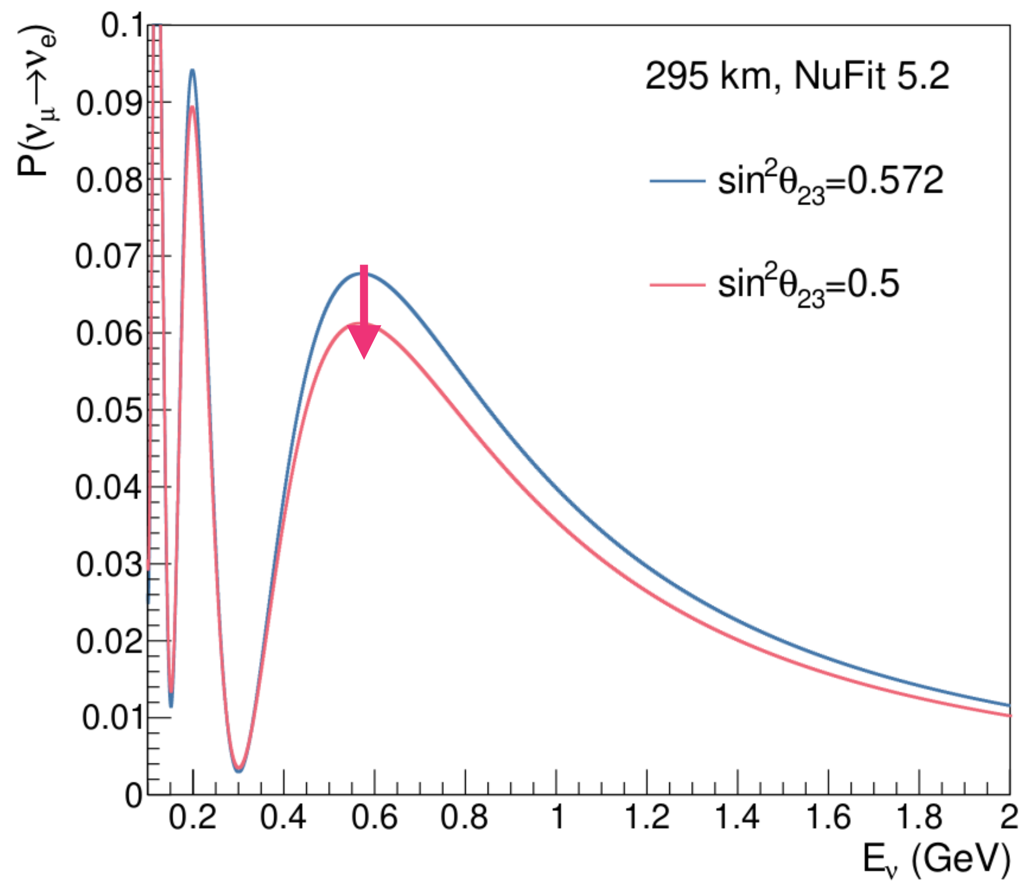
- **Neutrino energy estimation**
  - Is the frequency of the oscillation due to Δm^2, or biases in neutrino energy reconstruction from mismodelling?



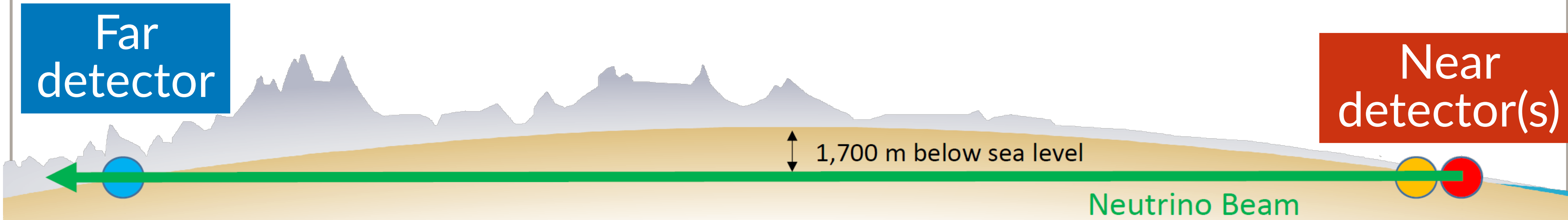
What can go wrong?

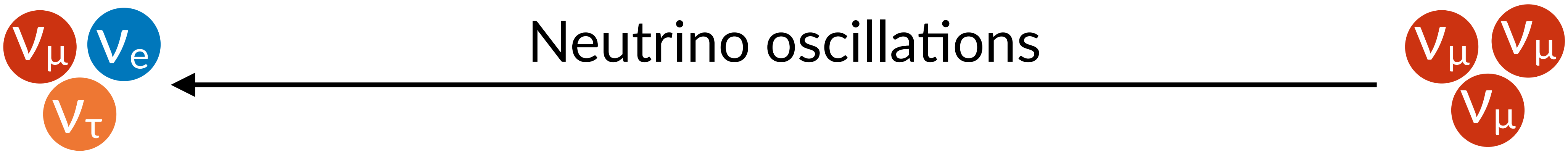
- **Rate of appearance and disappearance**
  - Is the ν_e rate higher because of a larger value of δ_{CP}, or is your model for $\nu_e \rightarrow \nu_\mu$ wrong?
  - Is the increased rate of ν_μ due to $\sin^2\theta_{23}$, or a larger cross section?





Role of the near detector





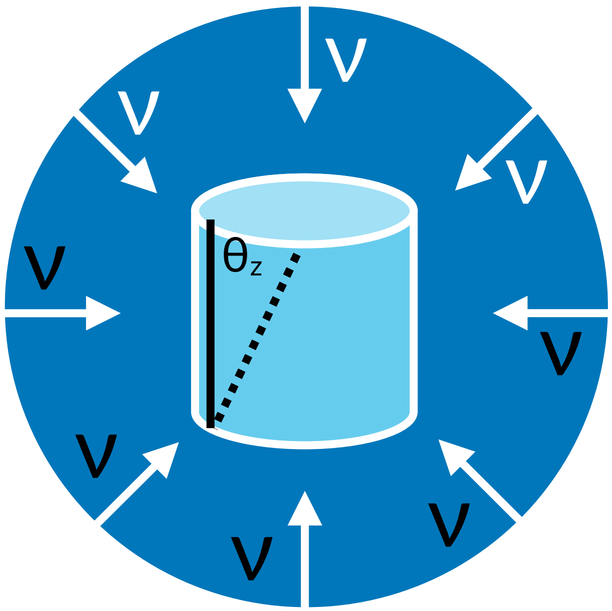
- The **beam** is **characterised** by **high-statistics samples** at the **near detector(s)** before long baseline oscillations
- Events observed at the far detector have many **shared uncertainties** with the near detector
  - Constrain **flux and interaction model** using near detector data

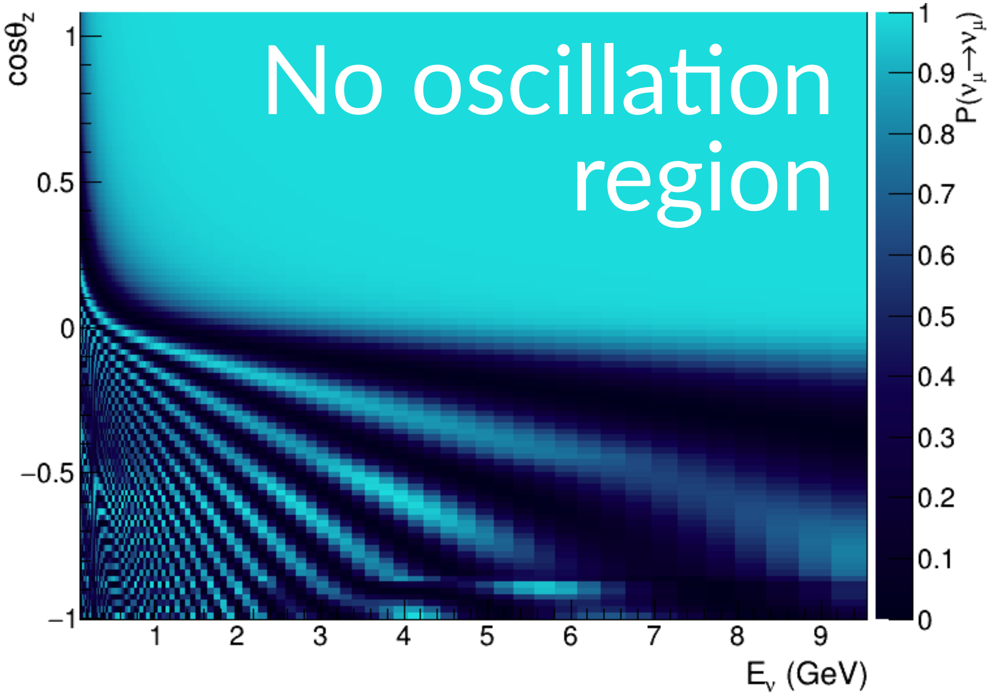
$$N^{\alpha}_{\mathrm{ND}}(\vec{x}) = \Phi^{\alpha}(E_{\nu}) \times \sigma^{\alpha}(\vec{x}) \times \epsilon^{\alpha}_{\mathrm{ND}}(\vec{x})$$

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

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

Role of atmos. down-going events

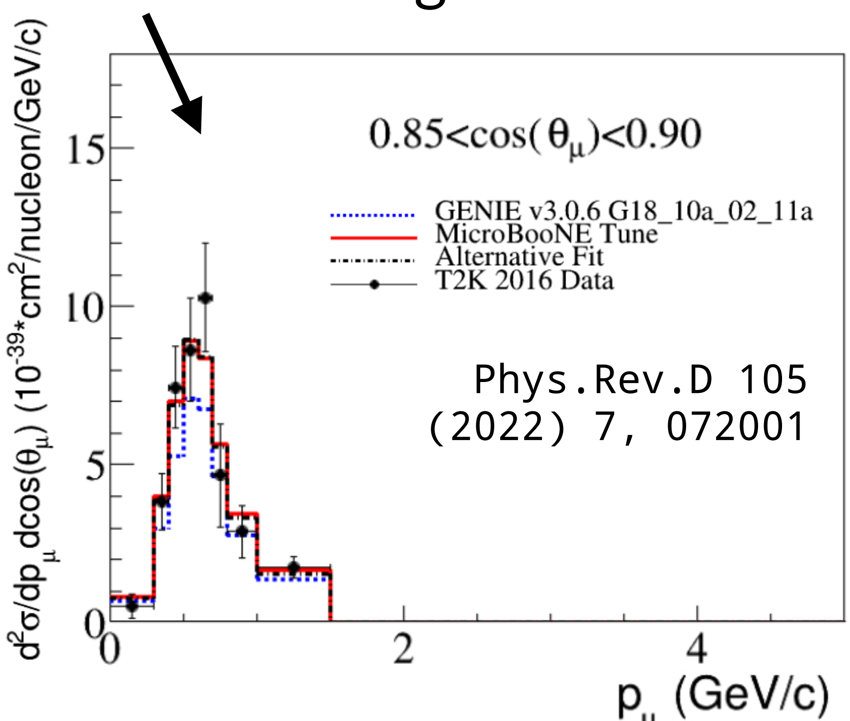


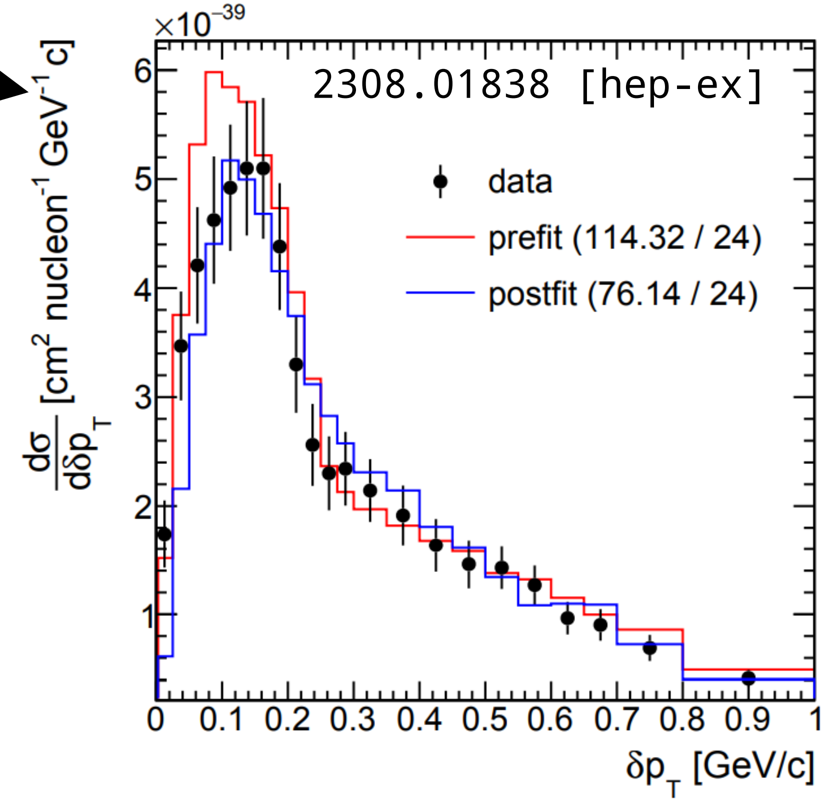


- For **atmospheric** neutrinos, there is no near detector, but it is largely addressed by **down-going neutrinos**
  - Very small oscillation probability in region
  - **Effectively acting as a near-detector** constraint throughout a large neutrino energy range

Role of external data

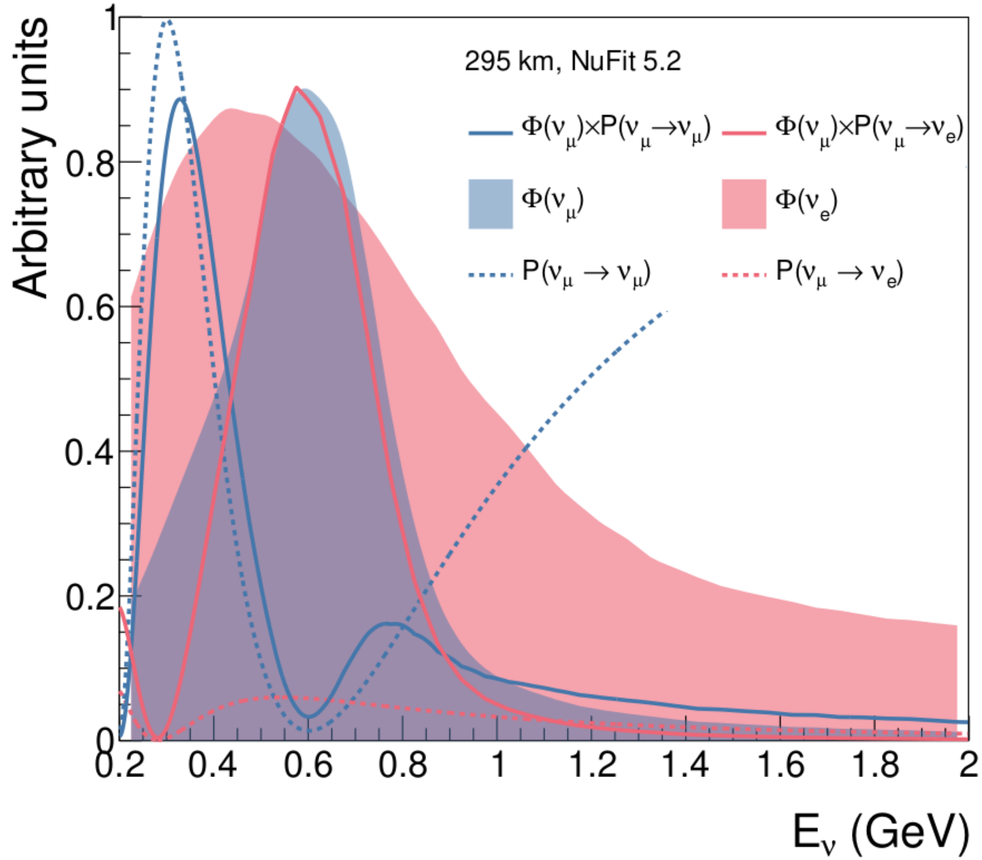
- In some cases, data from the **near detector might not suffice**
  - e.g. unmagnetised detector, but want NC1π^+ cross section to understand the background in ν_μ disappearance
- Or, you might not have a near detector!
- **External data** is often used to estimate **the cross section**, and prevent a **near-detector analysis from over-constraining** the model
  - T2K using MINERvA data
  - MicroBooNE using T2K data





Issues with the near detector

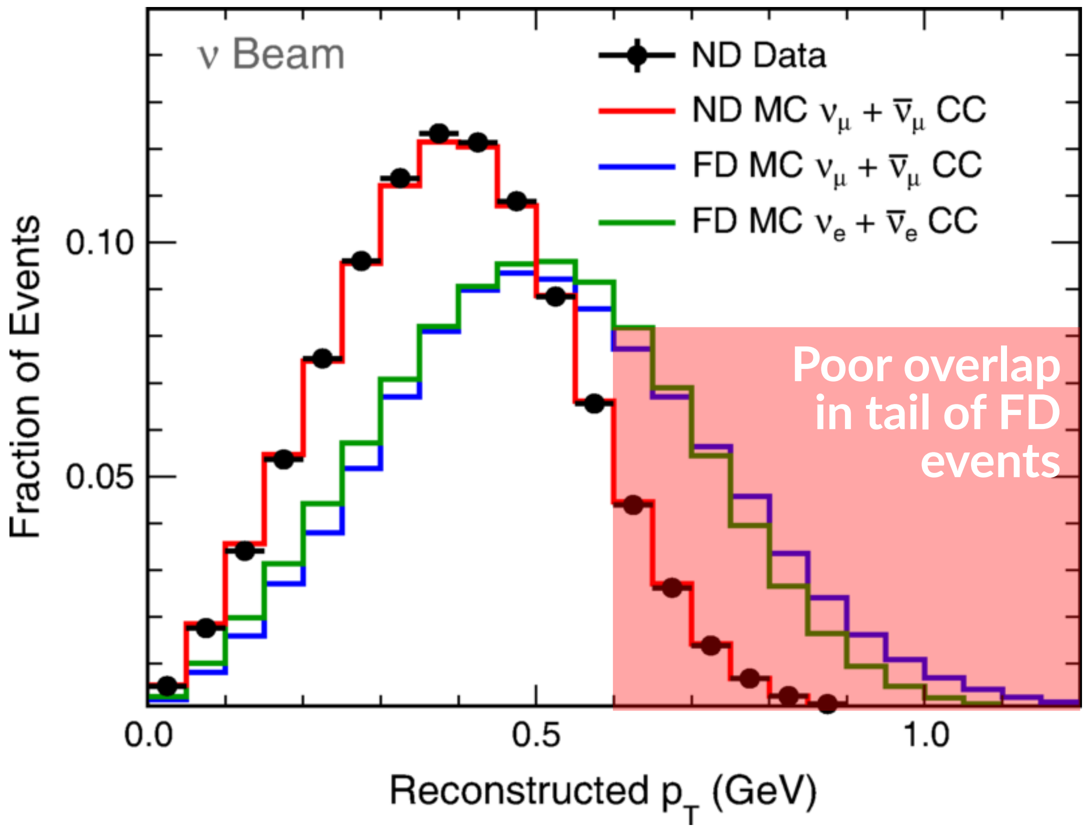
- The ν_μ **flux** at the **FD** has a **minimum** where the ν_μ **flux** at the **ND** has a **maximum**

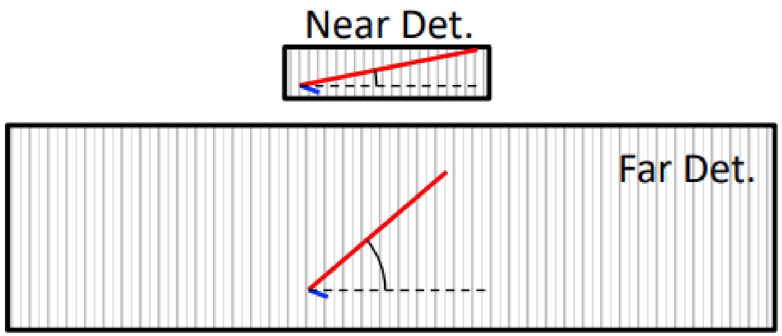


- Oscillated ν_μ flux gives rise to ν_e signal at the FD
- **Intrinsic** ν_e **at ND** do **not** have same **neutrino energy** spectrum as the ν_e **signal at FD**
- Reliance on model for **extrapolating in neutrino energy**

Issues with the near detector

- Acceptance differences from **different size**
  - Functionally identical does not mean identical acceptance

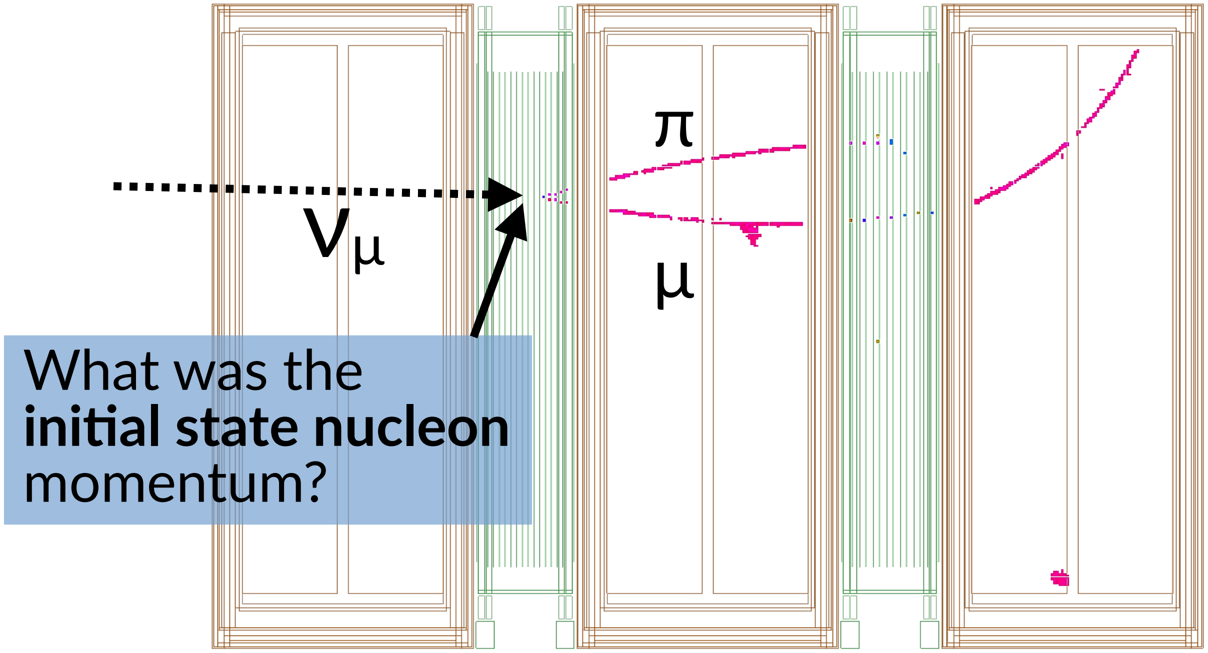




- **Different target material** and **detector design** means additional model dependence in $CH \rightarrow H_2O$
- **Different detector technologies** and **geometry** may mean different particle acceptance

Energy reconstruction

- Energy reconstruction method is function of **selection** and **detector technology**
- Need to understanding mapping between **observed events** and the **not-observed neutrino energy**



- **<u>All estimators are biased</u>**
  - Try to **reduce** the amount of bias
  - Understand the **uncertainty on the bias**

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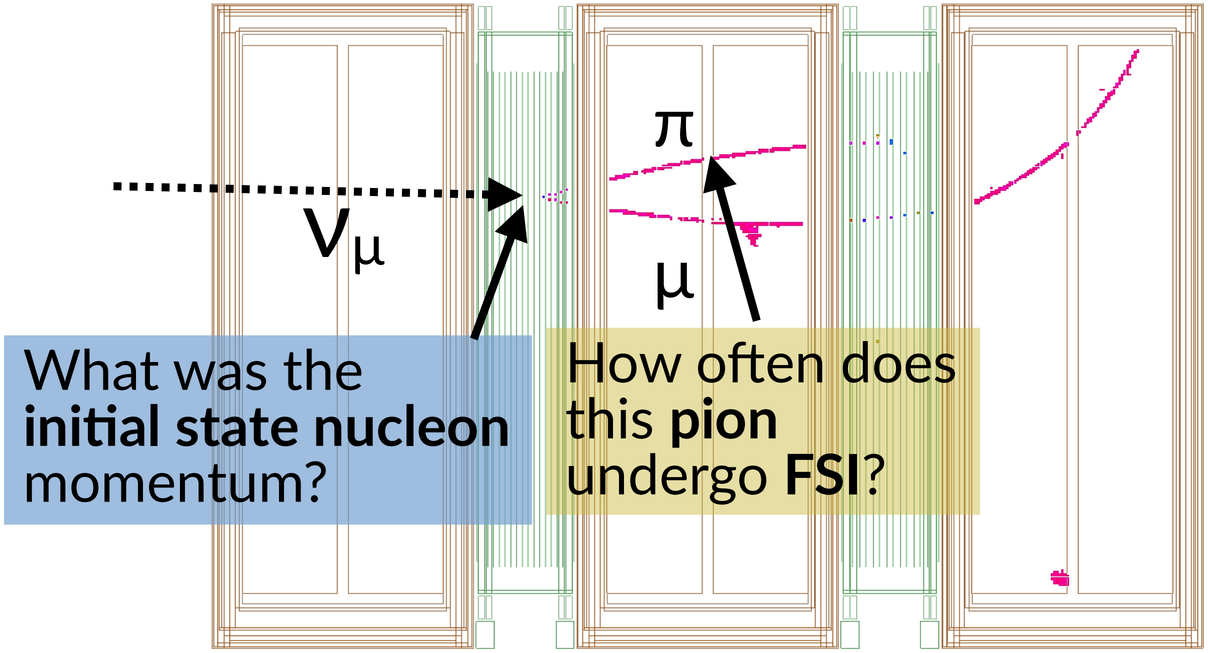

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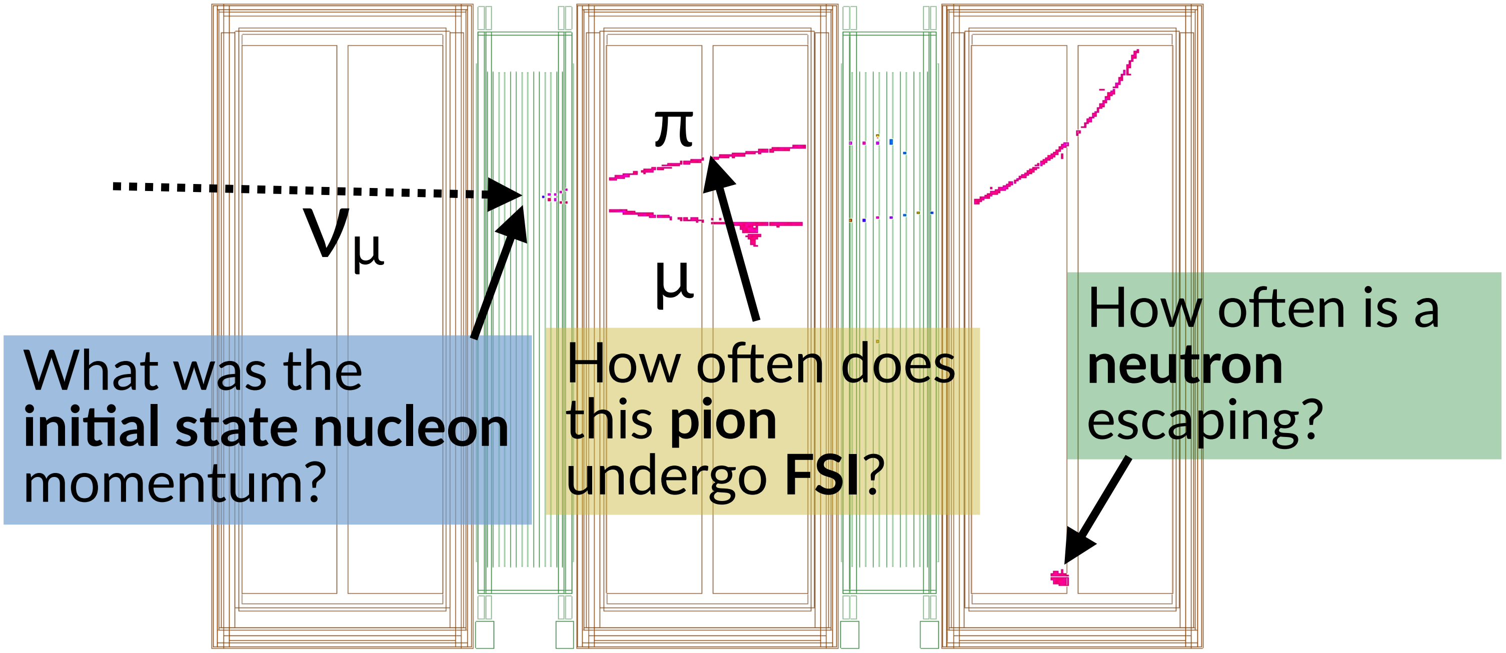

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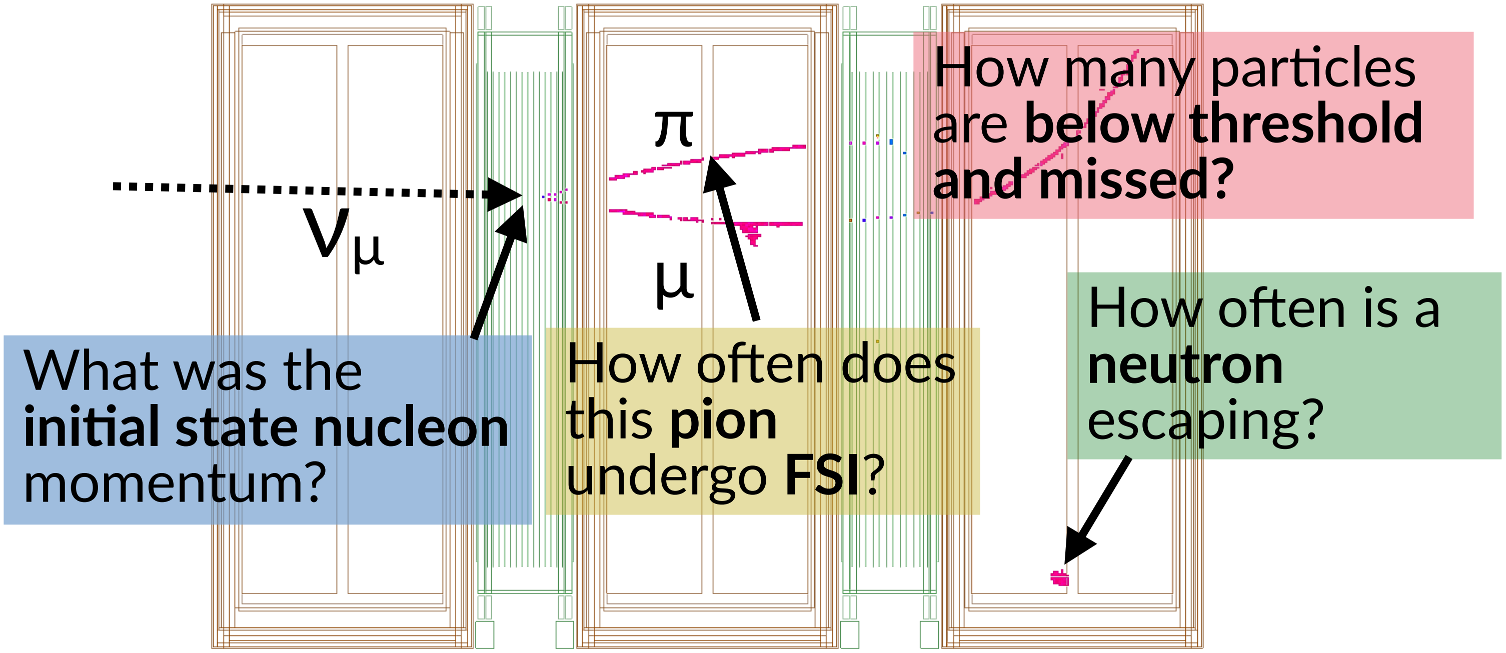

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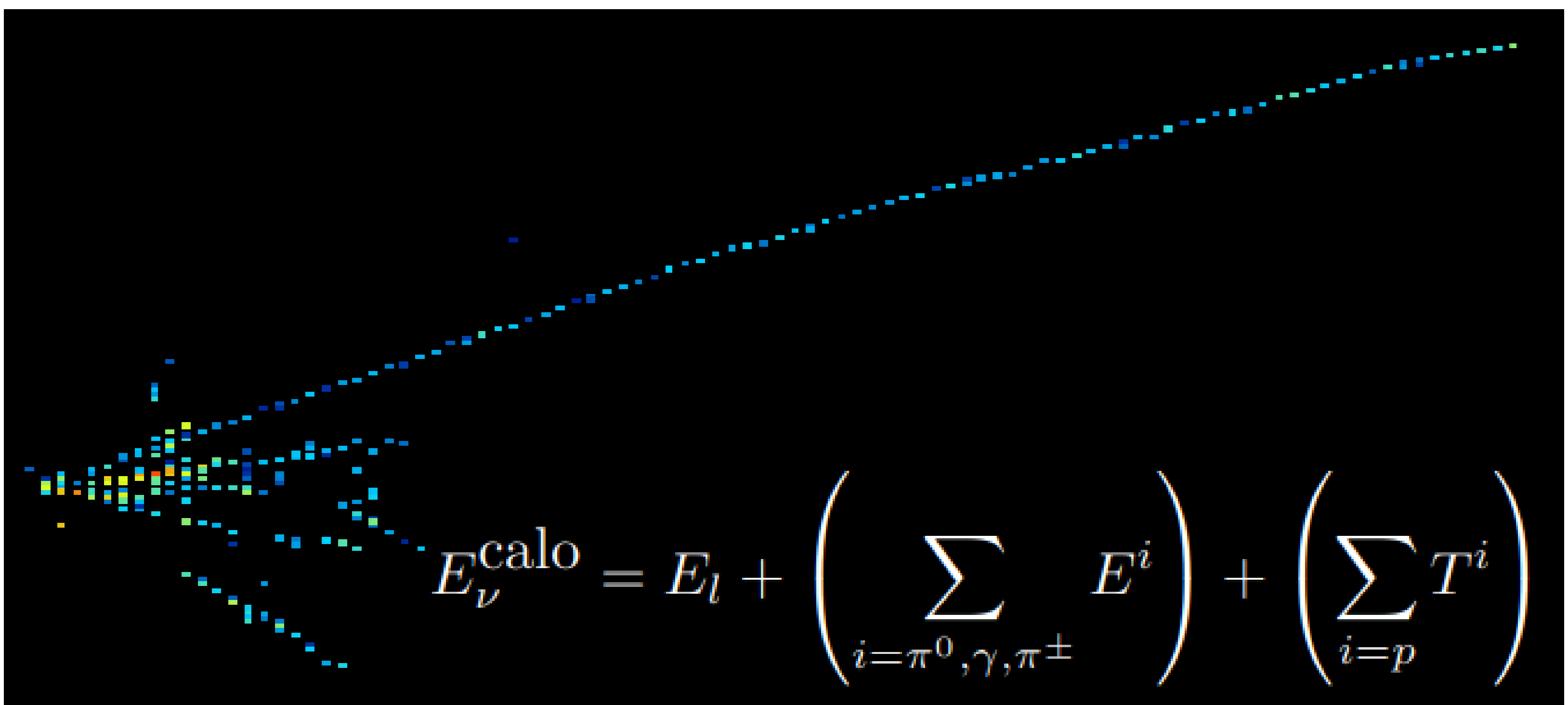
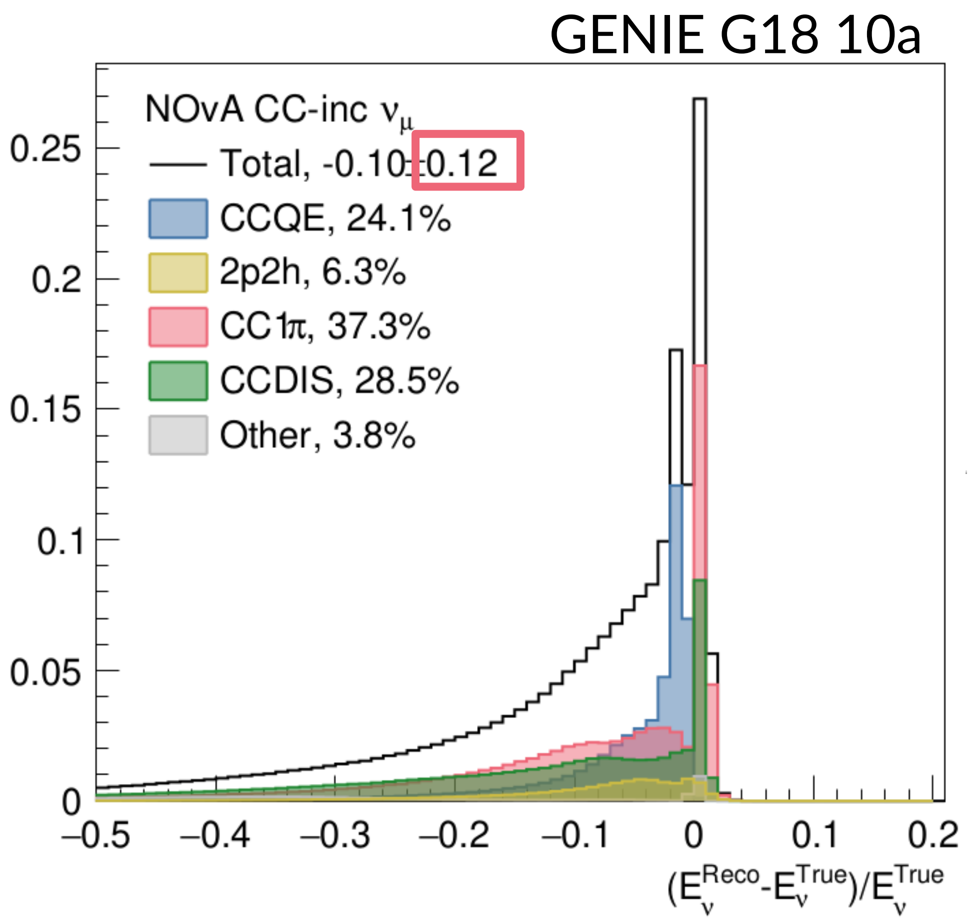
Energy reconstruction

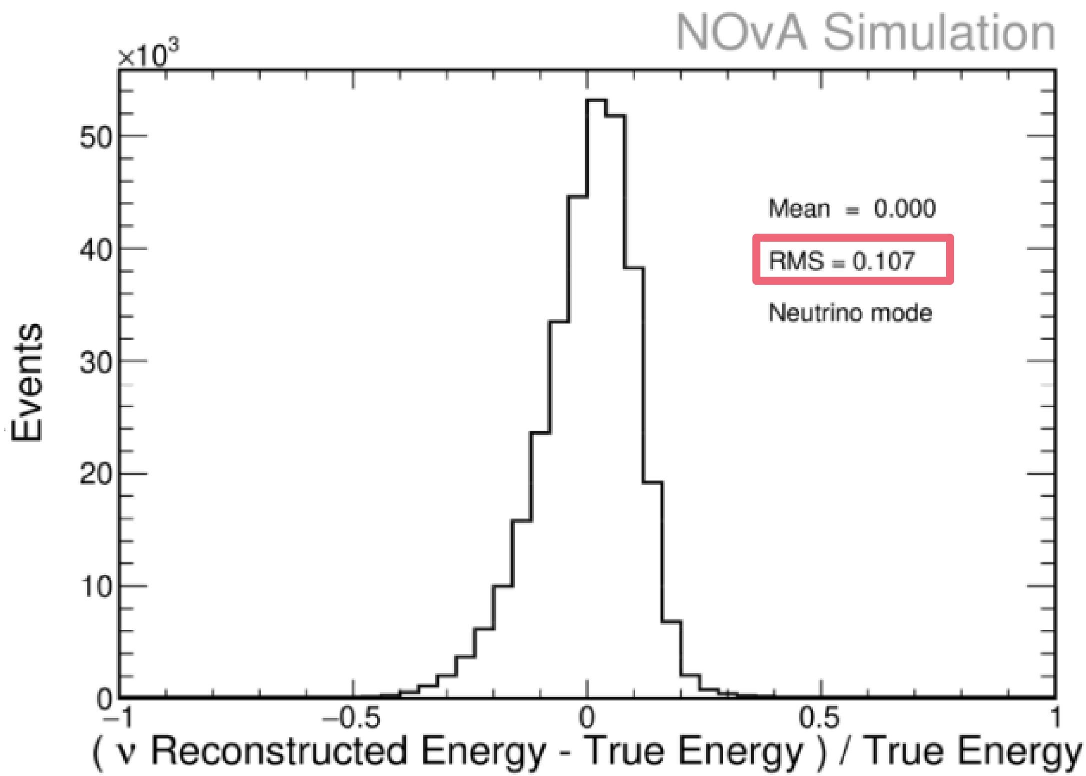
- Energy reconstruction method is function of **selection** and **detector technology**
- NOvA, DUNE and SBN have **sampling calorimeters** and often **events with multiple tracks**
  - **CC-inclusive** selection
  - Energy estimator which **sums up energy deposits**



Calorimetric energy reconstruction

- Simple simulation result agrees well with NOvA official figure: ~11% RMS





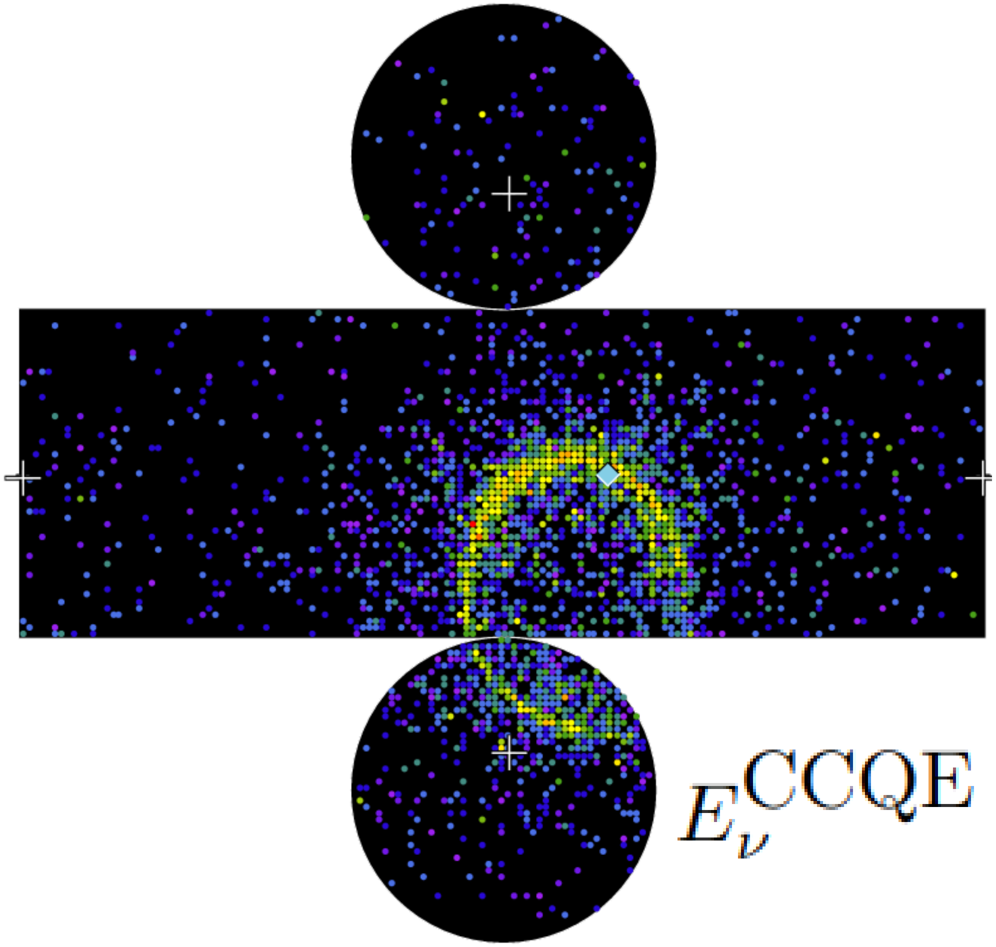
- Interaction modes bias differently, e.g. DIS has multiple missing neutrons and pion FSI

Calorimetric energy reconstruction

- Generally **more precise energy estimate** than kinematic method
- Susceptible to **missing neutrons** and other particles
- **Final-state interactions** directly bias the estimator
- Relies on **correct PID of every track**, otherwise risk bias by rest mass (e.g. mistake proton for pion)
- Will always have bias from **initial state motion**
  - Smaller impact at higher energies, e.g. NOvA and DUNE
- CC-inclusive selection means **complex contributions from multiple interaction modes**

Kinematic energy reconstruction

- Energy reconstruction method is function of **selection** and **detector technology**
- T2K and HK are dominated by **CC0π interaction**, and Cherenkov threshold for proton is >1 GeV in H_2O



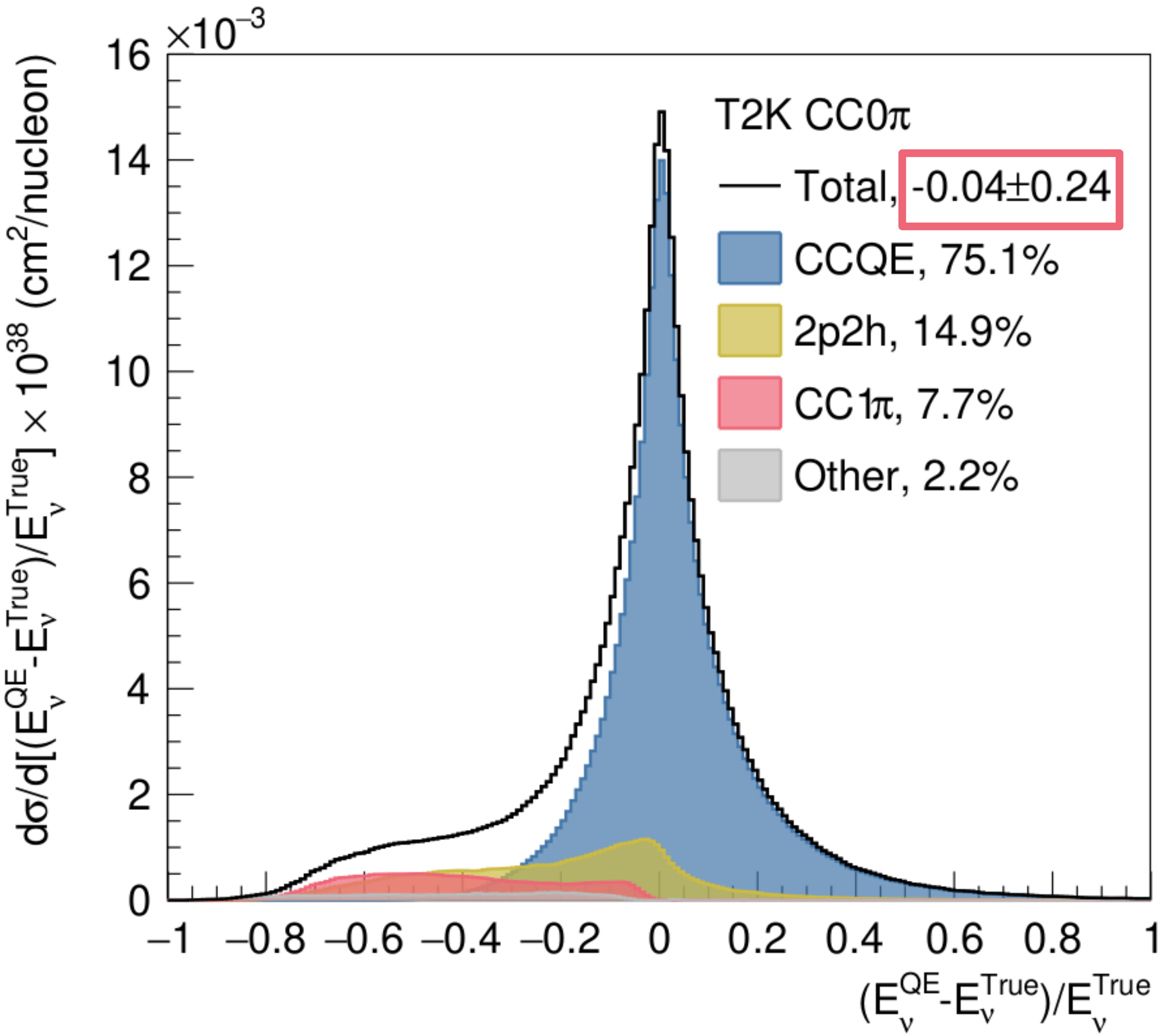
- **Single-track** events
- Kinematic reconstruction using **only lepton** information
- Assumes **4 legged CCQE** interaction, and **initial state nucleon at rest**

$$E_\nu^{\mathrm{CCQE}} = \frac{2m_N E_l - m_l^2 + m_{N'}^2 - m_N^2}{2\left(m_N - E_l + p_l \cos\theta_{\nu,l}\right)}$$

Kinematic energy reconstruction

- **CCQE** contribution largely **unbiased**
- **20-25% RMS**
- CC1π+FSI and 2p2h contribution **less than 25%of total signal**
- When applied to CC1π sample, replace m_p with m_Δ
  - Works because T2K Δ(1232) dominated

$$E_\nu^{\mathrm{CCQE}} = \frac{2m_N E_l - m_l^2 + m_{N'}^2 - m_N^2}{2\left(m_N - E_l + p_l \cos\theta_{\nu,l}\right)}$$



Kinematic energy reconstruction

- Important to get the **CCQE, 2p2h and CC1π contributions correct**
  - They bias the estimator differently: mistaking non-CCQE for CCQE imposes a bias
- Direct **dependence** on **nuclear initial-state model**
  - Relatively large contribution at E_ν=0.6 GeV
- Only dependent on **FSI in the absorption**
  - Proton may lose energy to nucleus; does not matter in estimator
  - Secondary dependence on FSI through **missing particles**: think it's four-limbed interaction when it was not
- **Small contribution** from higher W resonances, SIS and DIS contributions

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

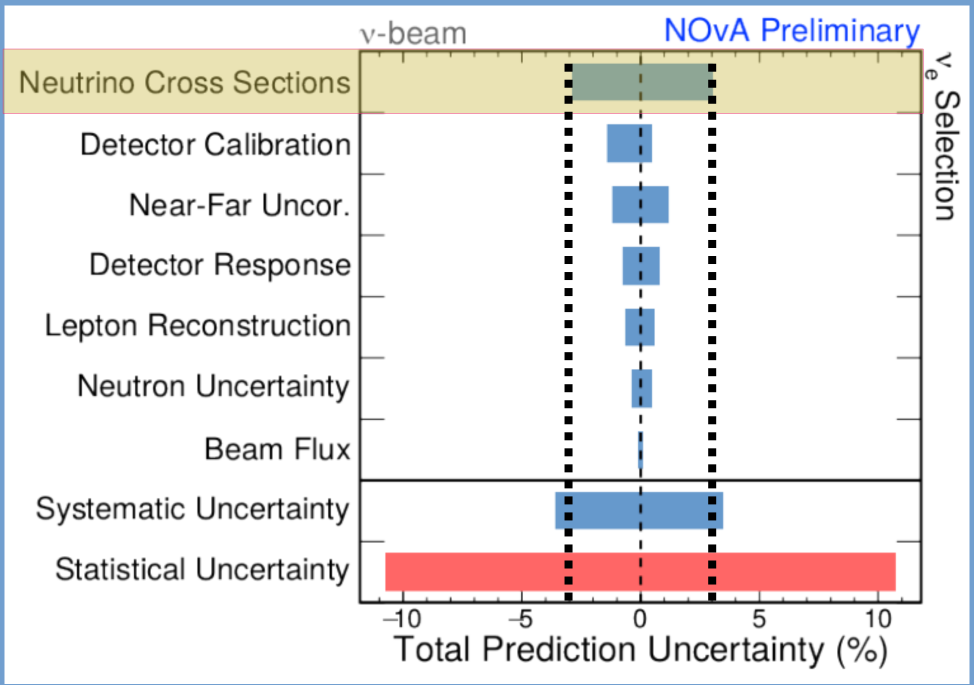
- HK and DUNE will have **enough events** to be limited by the **~3% (anti-)ν_e uncertainty**
- Current experiments at the **3-5% level** uncertainties*

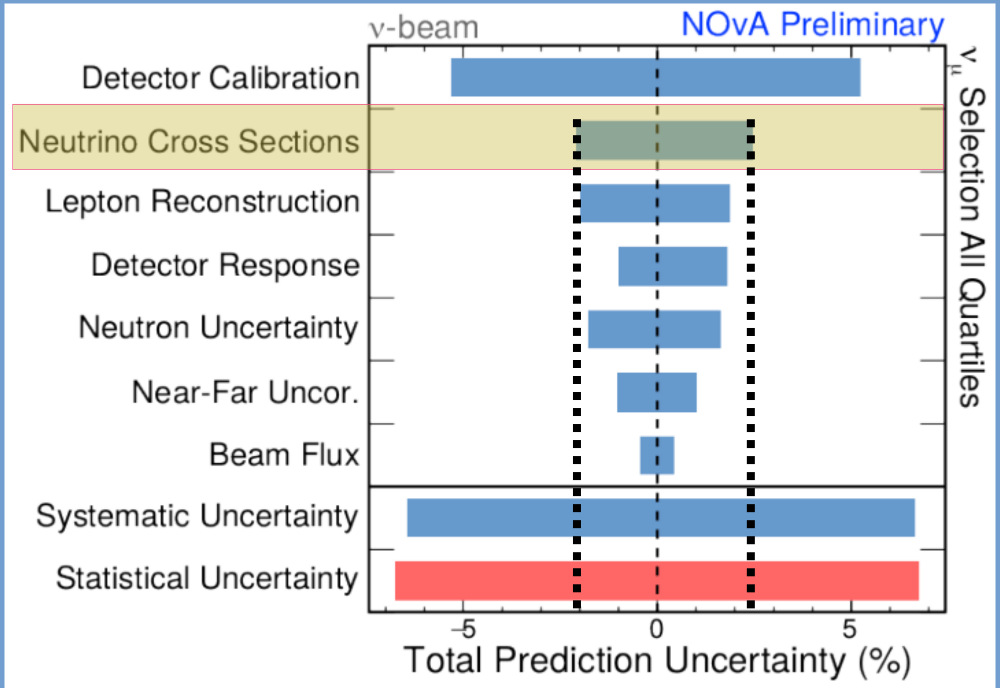
*Exception of T2K's single-pion-below-threshold sample (10-15%)

Impact of systematics at the FD

- Neutrino cross-section uncertainties contribute **~3%** to number of ν_e on NOvA and T2K

M. Elkins, T. Nosek, Neutrino 2020 poster





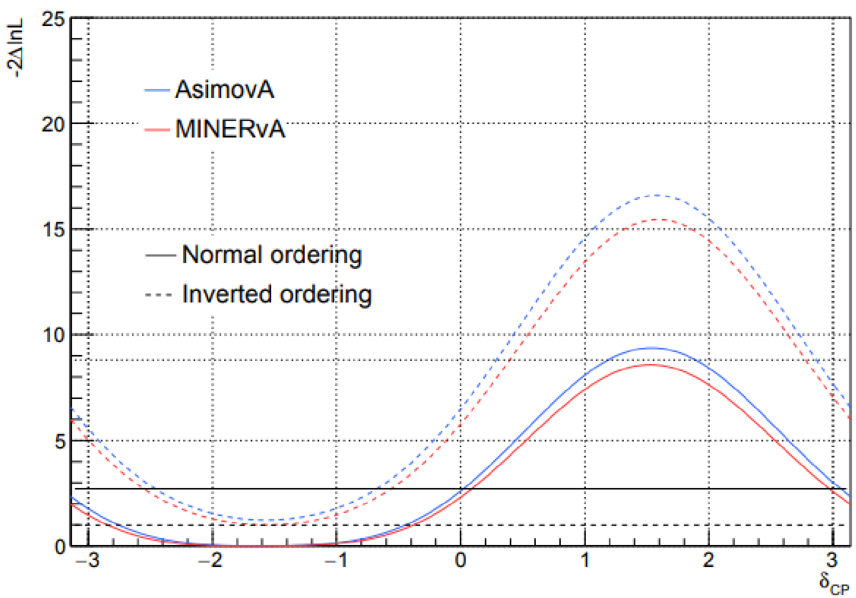
Sample		Uncertainty source (%) Flux	Interaction	FD + SI + PN	Flux⊗Interaction (%)	Total (%)
1Rμ	ν	2.9 (5.0)	3.1 (11.7)	2.1 (2.7)	2.2 (12.7)	3.0 (13.0)
	$\bar{\nu}$	2.8 (4.7)	3.0 (10.8)	1.9 (2.3)	3.4 (11.8)	4.0 (12.0)
1Re	ν	2.8 (4.8)	3.2 (12.6)	3.1 (3.2)	3.6 (13.5)	4.7 (13.8)
	$\bar{\nu}$	2.9 (4.7)	3.1 (11.1)	3.9 (4.2)	4.3 (12.1)	5.9 (12.7)
1Re1de	ν	2.8 (4.9)	4.2 (12.1)	13.4 (13.4)	5.0 (13.1)	14.3 (18.7)

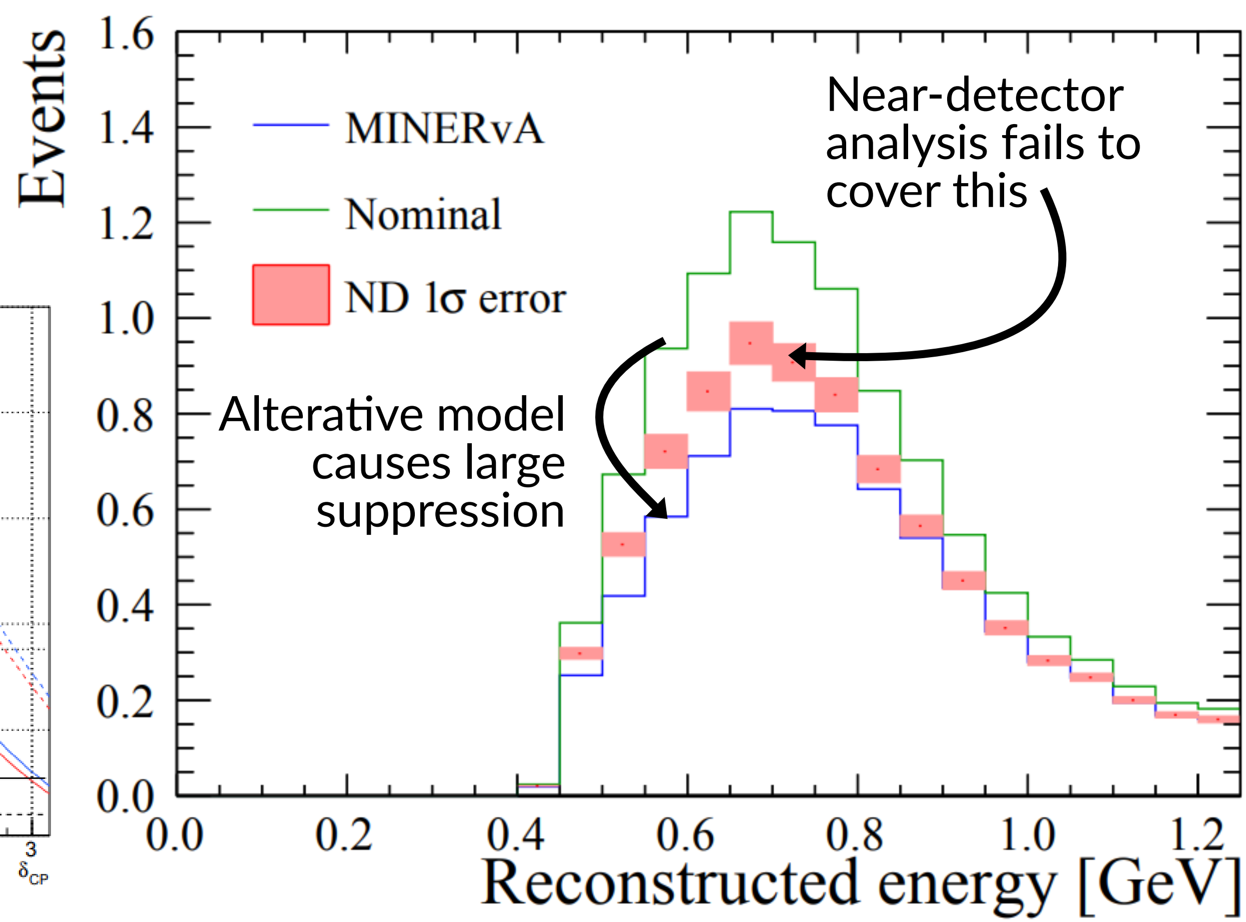
Fake-data studies

- 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

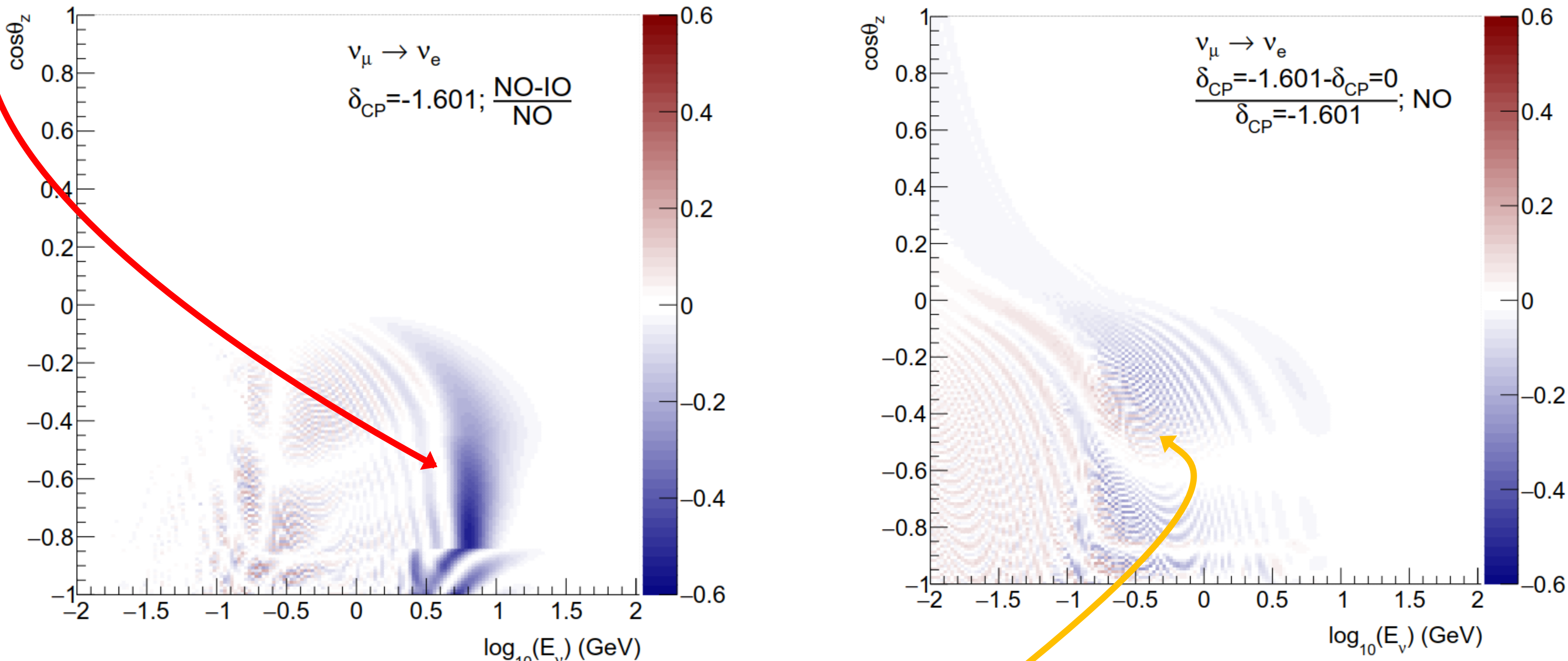
- Use an alternative model to make a prediction for near and far detectors
- Fit to the alternative model at the near detector
  - Set of parameters that best describe the alternative model
- Propagate result to far detector, perform oscillation analysis





Atmospheric neutrinos

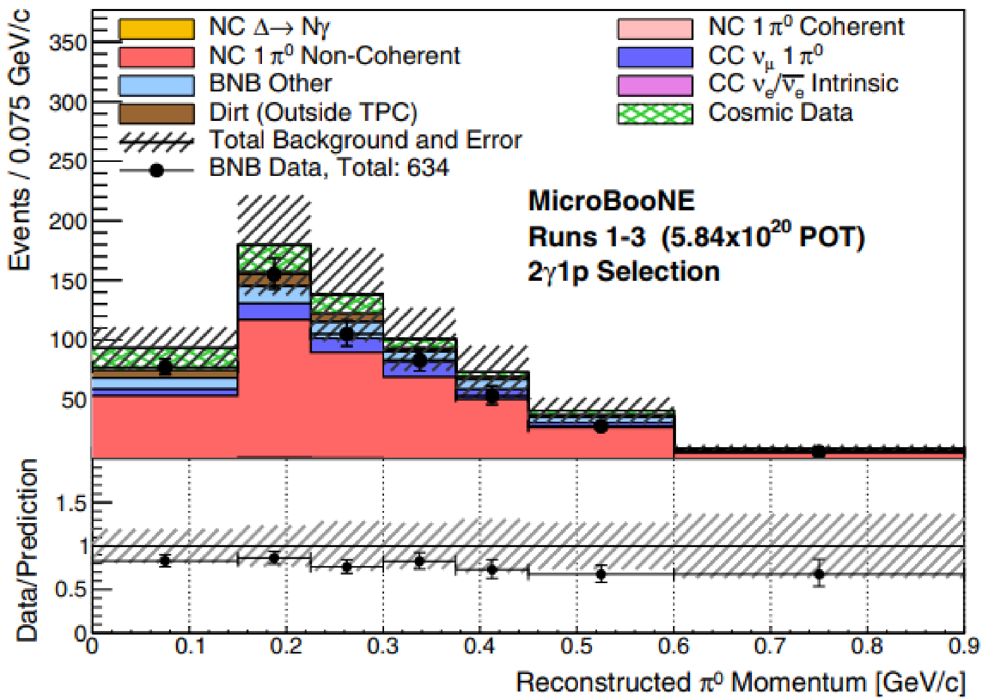
- Atmospheric neutrinos have sensitivity to mass ordering via 3-10 GeV resonance
  - Opposite effect for neutrino and anti-neutrinos: **need to separate**
  - Contribution from $\boldsymbol{\nu_\mu \rightarrow \nu_\tau}$, where ν_τ enters multi-ring ν_e sample



- δ_{CP} sensitivity from ν_e below 1 GeV → ν_e/ν_μ important
- **Neutrino flavour differences** also limiting atmospheric results

SBN

- For SBN programme and appearance searches, anything mimicking ν_e appearance is important
  - e.g. NC1γ, NC1π^0 DIS, NC1π^0 resonant, NC1π^0 coherent
  - Many constrained by dedicated measurements and sidebands



Phys. Rev. Lett. 128, 111801

- ν_e/ν_μ differences from nucleon and nuclear environment, especially considering ^{40}Ar

What do I worry about?

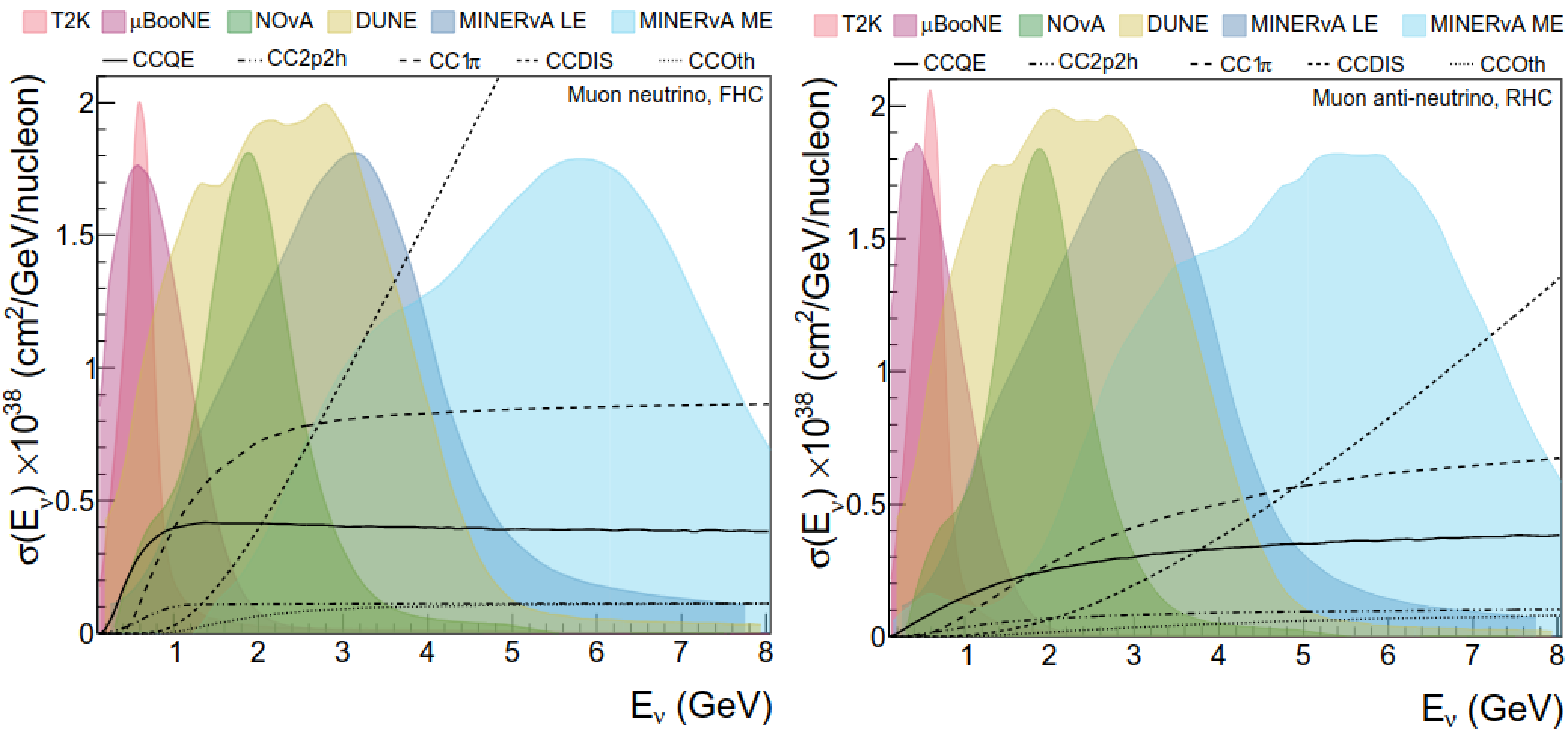
- Will **(anti-)ν_e** uncertainties fall below 2-3%?
  - Critical for δ_{CP}, mass ordering, for both **atmospheric** and **accelerator** experiments, and **MiniBooNE LEE**
- Do we understand **transition, SIS and DIS** interactions sufficiently for **DUNE**?
  - Worry that the day DUNE ND turns on, it'll show how poorly we describe these samples
- Will we understand **nuclear effects in ^{40}Ar** nuclear in 10 years time?
- Will we understand **neutron final-state interactions** sufficiently to use them for e.g. **energy estimators** and **tagging events**?
- **ν_τ uncertainties** for **atmospheric neutrinos** and **mass ordering** sensitivity
- How do we diagnose **low momentum pion modelling**

Summary

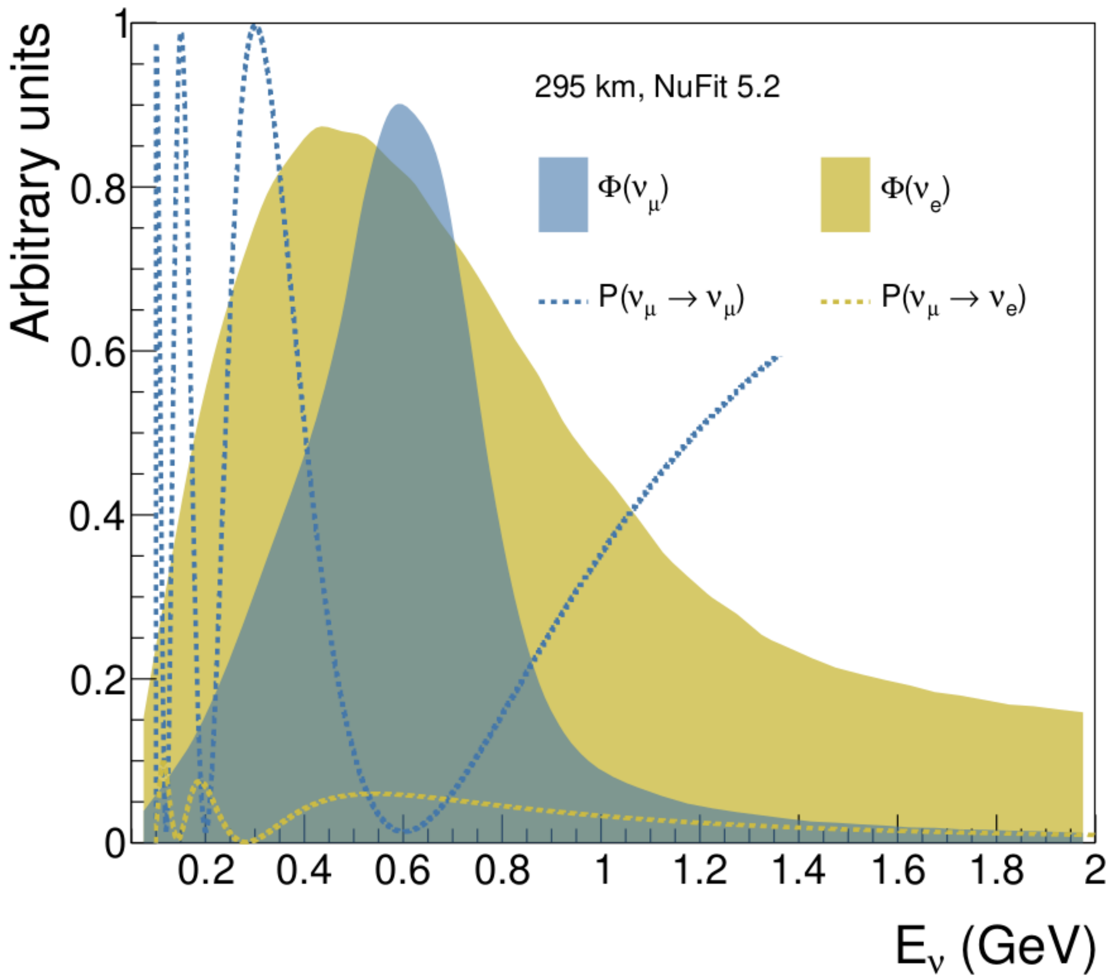
- Neutrino interactions are a central ingredient to the accelerator and atmospheric neutrino measurements
  - Starting to see importance on current-generation experiments like T2K, NOvA, SK
  - Critical for next-generation experiments HK and DUNE
- Experiments and generator groups are including latest model developments
- Theory community gaining people and working hard at developing modelling
  - e.g. ^{40}Ar spectral functions, 2p2h models and uncertainties, single pion production, sophisticated nuclear models…
- Very exciting time for the field, and an excellent week to be in Sao Paolo!

Backups

Neutrino fluxes

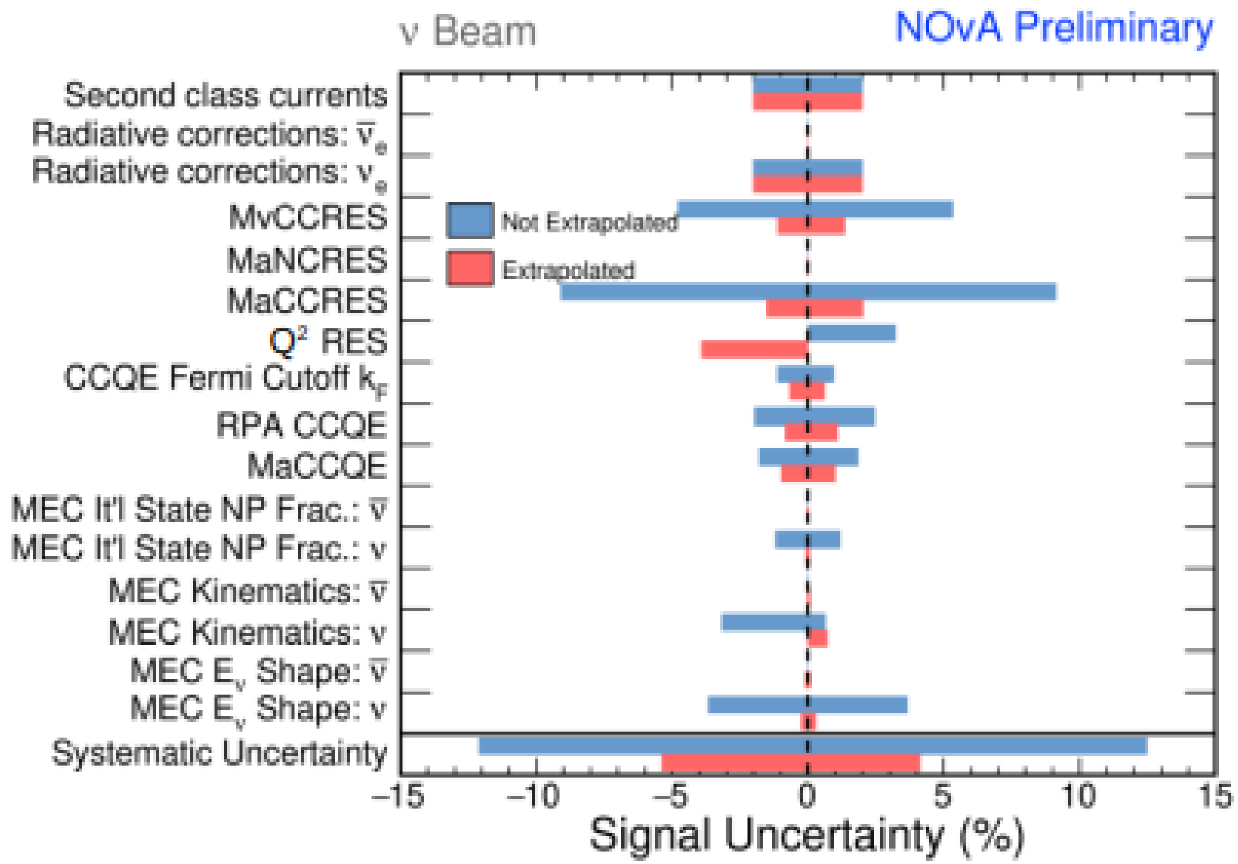


Neutrino fluxes



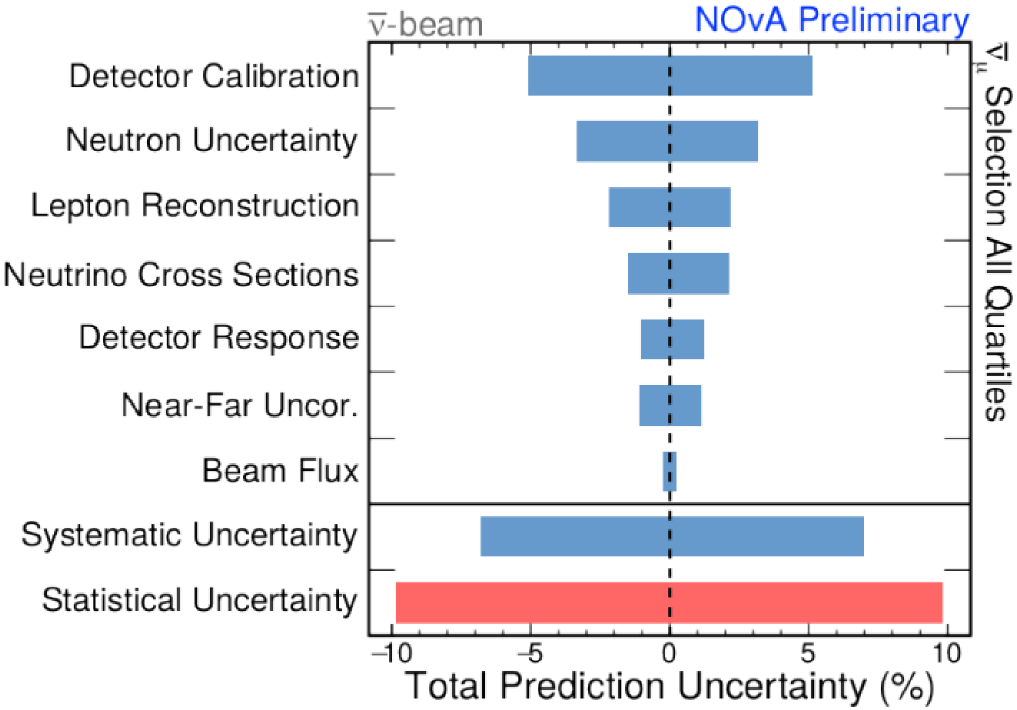
NOvA

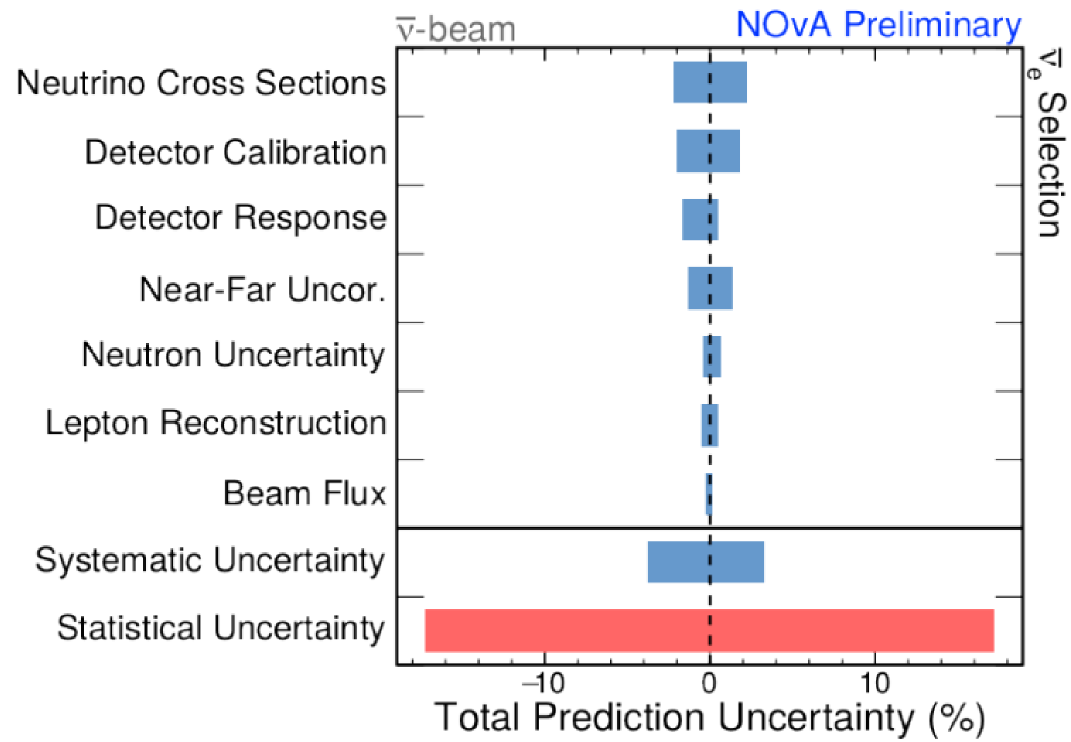
- Jeremy Wolcott, NuInt17



NOvA

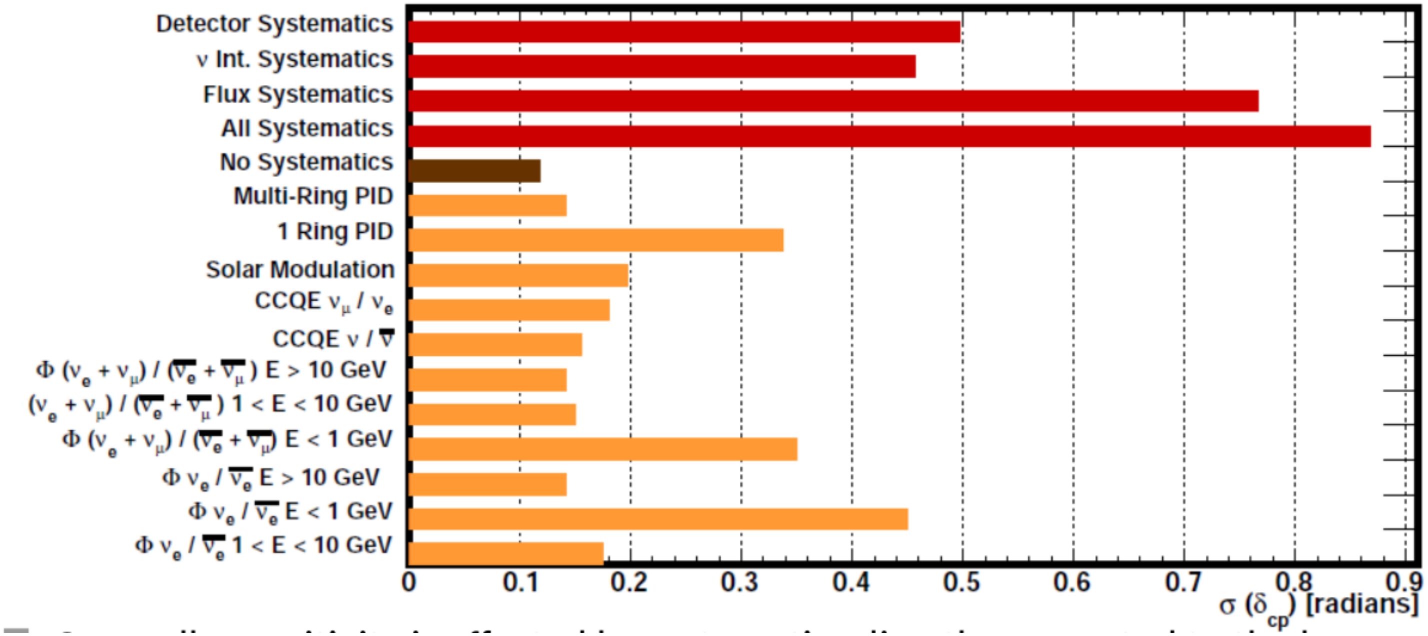
M. Elkins, T. Nosek, Neutrino 2020 poster





Atmospheric

Hyper-K's Sensitivity to δ_{cp} with Atmospheric neutrinos



Systematic Effect on Hierarchy Sensitivity at Super-K