Neutrino Interactions and Oscillations: Modelling Neutrino Cross Section Uncertainties for Fundamental Physics

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PPD Seminar

18.03.2026

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T2K

Introduction

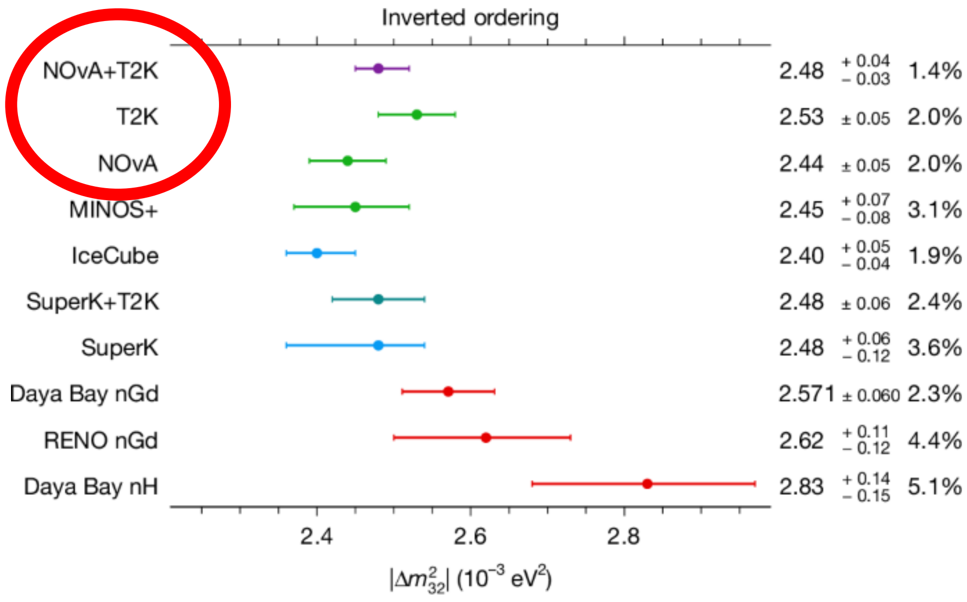
Neutrino experiments are reaching precision era measurement.

Recently join fit between two experiments **T2K** and **NOvA** has finished and got published in *Nature* 646 (2025) 8086, 818-824

To reach this precision, we need to have uncertainty under control

Especially modelling of neutrino interactions is challenging

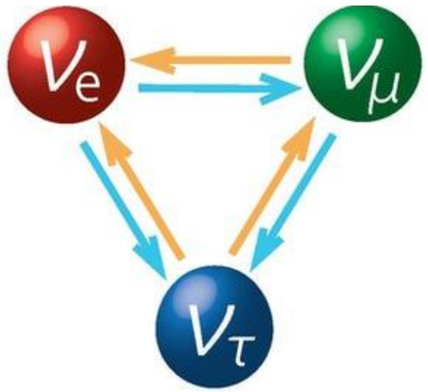
Spoiler Alert!!!



Prologue: Neutrinos

Neutrino Oscillations

Neutrinos while travelling can change the flavour, this phenomenon is called neutrino oscillations.



The crucial objective of current neutrino experiments is to study if there is CP violation in the lepton sector or not. **Appearance channel**

$$\begin{matrix} P(\nu_\mu \rightarrow \nu_e) \\ P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \end{matrix} \approx \sin^2(2\theta_{13})\sin^2(\theta_{23})\sin^2\left(\frac{1.27\Delta m^2_{32}L}{E}\right) \mp \frac{1.27\Delta m^2_{21}L}{E} 8J_{CP}\sin^2\left(\frac{1.27\Delta m^2_{32}L}{E}\right)$$

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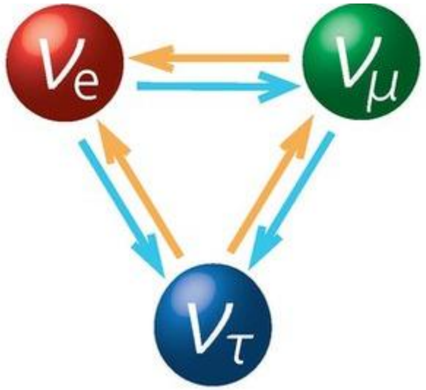

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CP violation in lepton sector means that neutrino oscillation probabilities are different than for antineutrino.

Parameter describing CP violation is $\boldsymbol{\delta_{CP}}$.

Jarlskog Invariant in general

$$J = \frac{1}{8}\,\mathrm{Im}\left[U_{23}U_{12}U^*_{22}U^*_{13}\right]$$

Jarlskog Invariant In lepton sector

$$J_{CP,l} = 0.033\sin(\delta_{CP})$$

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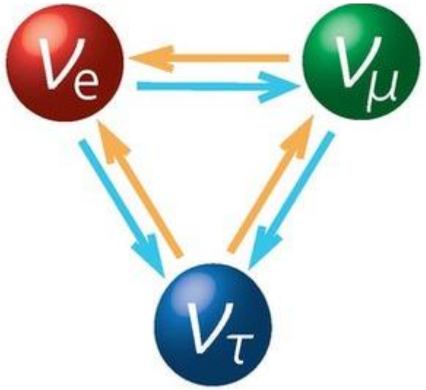

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Parameter describing CP violation is $\boldsymbol{\delta_{CP}}$.

Neutrino CP violation can be three magnitudes larger than in the quark sector.

Studying this effect has potential to answer the question of why there is more matter than antimatter in the Universe.

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Jarlskog Invariant In quark sector

$$J_{CP,q} = 3 \times 10^{-5}$$

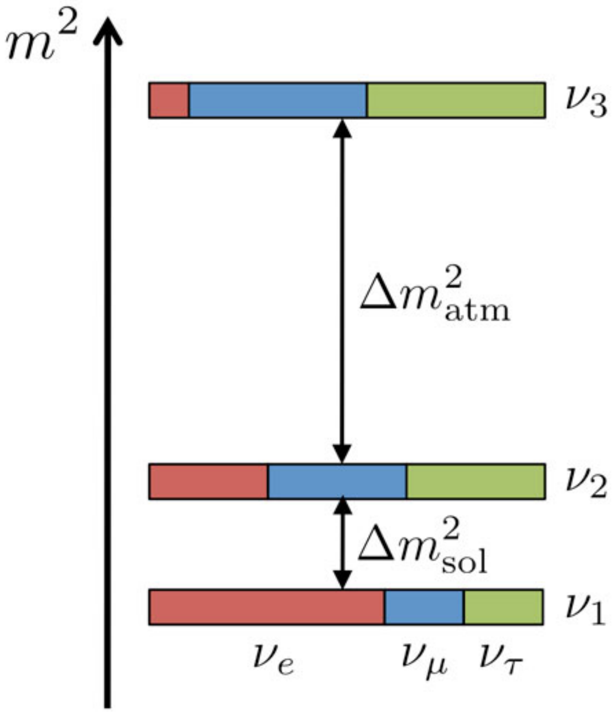
Mass Ordering

We do know neutrinos have mass.

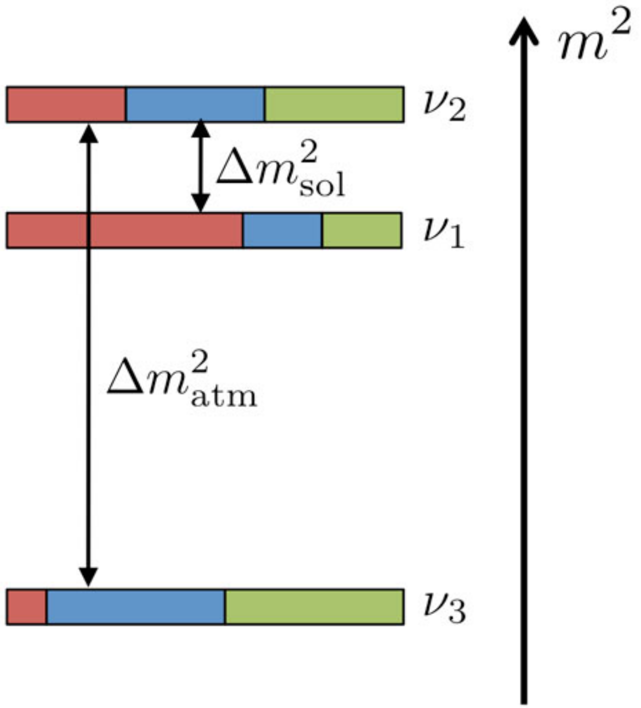
However, we do not know if 3rd eigenstate is largest or smallest

This is what we call mass ordering.

Normal Ordering (NO)



Inverted Ordering (IO)

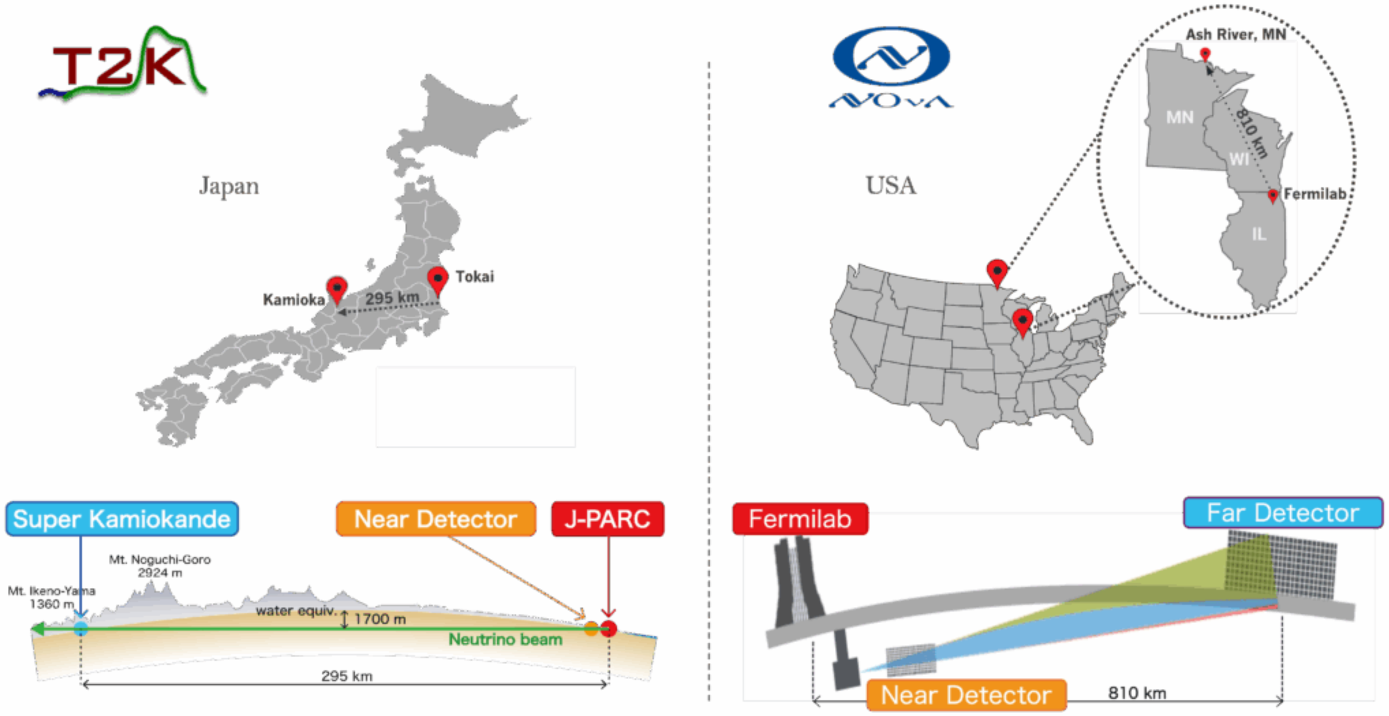


Long Baseline Neutrino Experiments

Two Long Baseline Neutrino experiment T2K and NOvA

Scheme:

1. Produce neutrino
2. Measure in Near Detector where oscillations are negligible
3. Measure in Far detector after oscillations.



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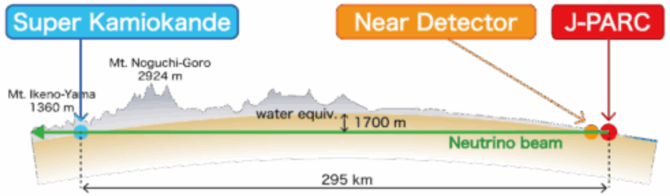
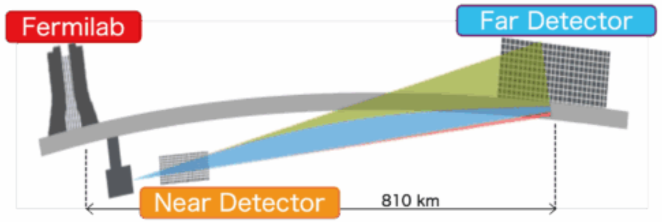
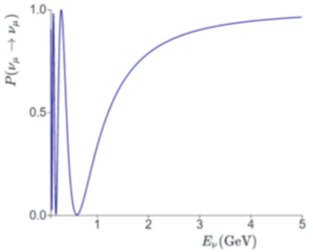
To measure neutrino oscillation probabilities, one simply need to measure **ONLY NEUTRINO ENERGY**







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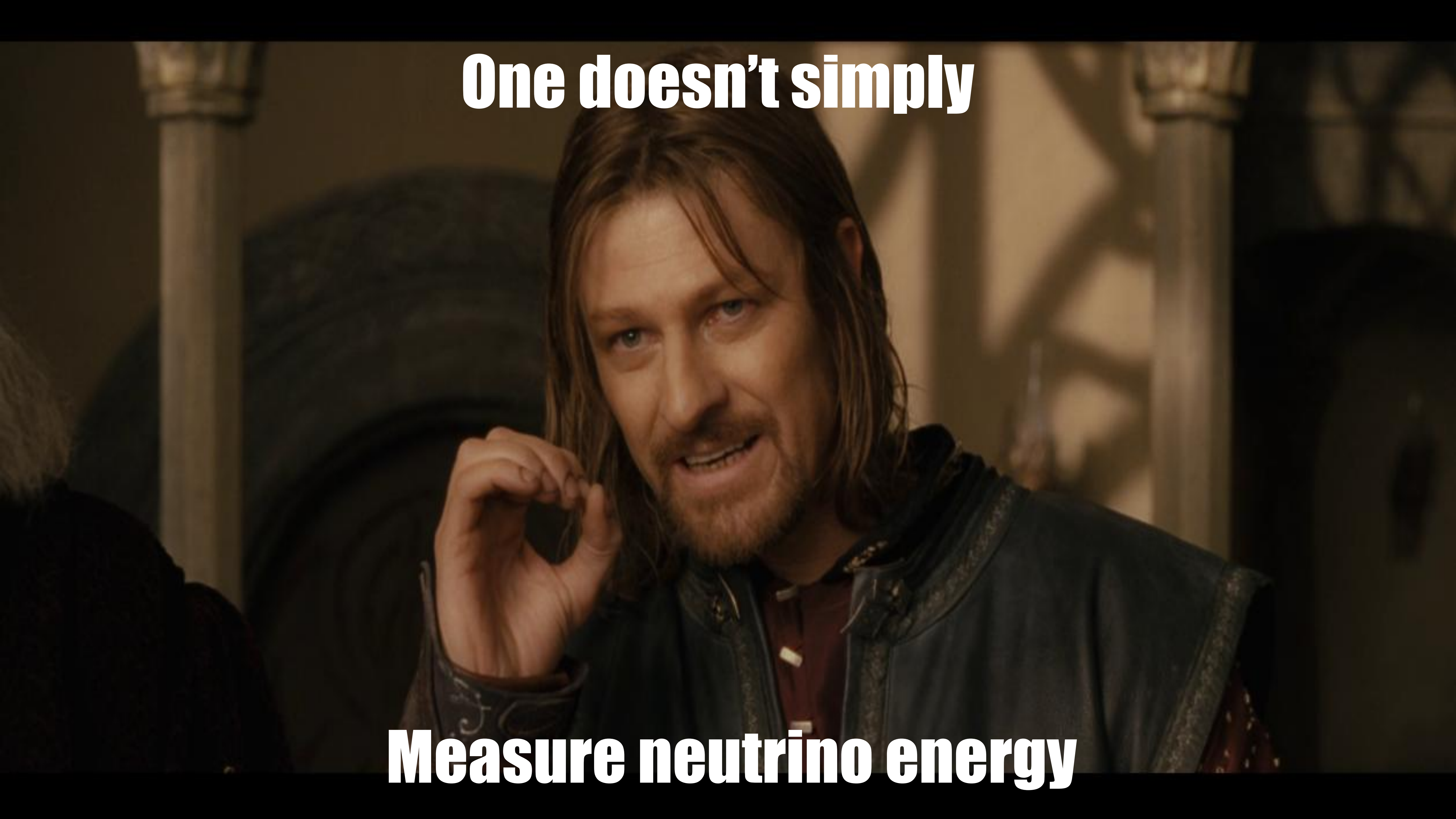
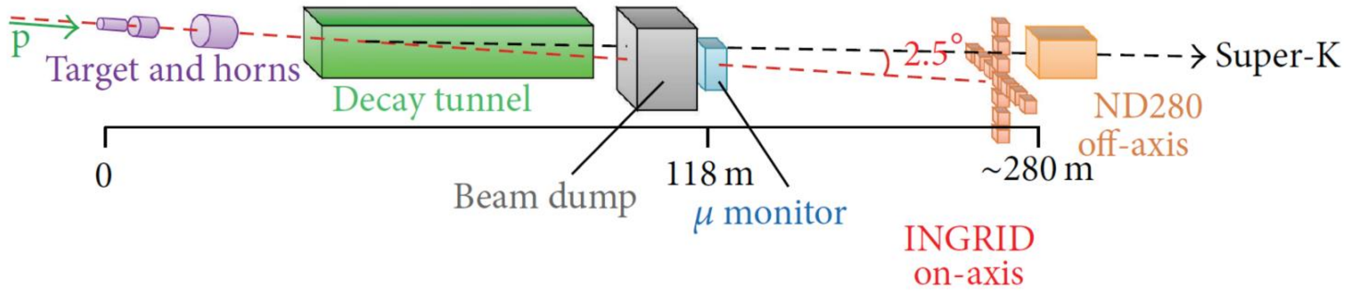

One doesn’t simply
Measure neutrino energy

Chapter I: Measuring Energy

Neutrino Flux

- Protons hit graphite and hadrons (π, K) which are focused and then decay into neutrinos
- Can select $\nu/\bar{\nu}$ beam mode based on horn polarity



$$\pi^+ \to \mu^+ + \nu_\mu, \qquad K^+ \to \mu^+ + \nu_\mu$$
$$\pi^- \to \mu^- + \bar{\nu}_\mu, \qquad K^- \to \mu^- + \bar{\nu}_\mu$$

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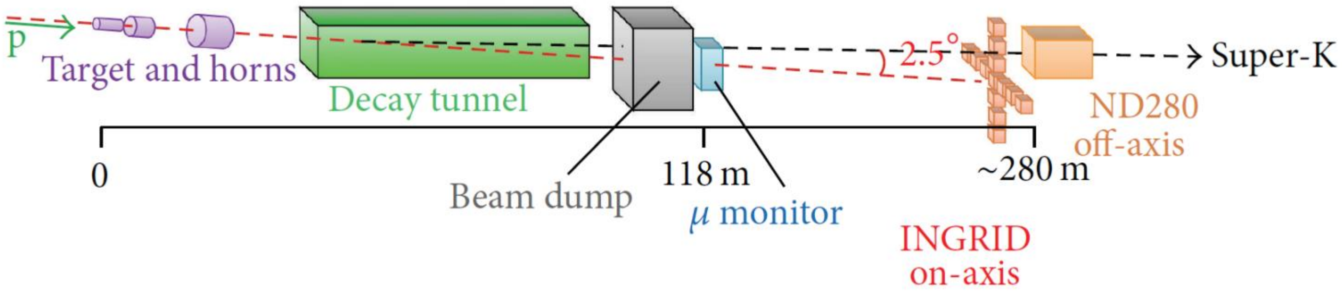

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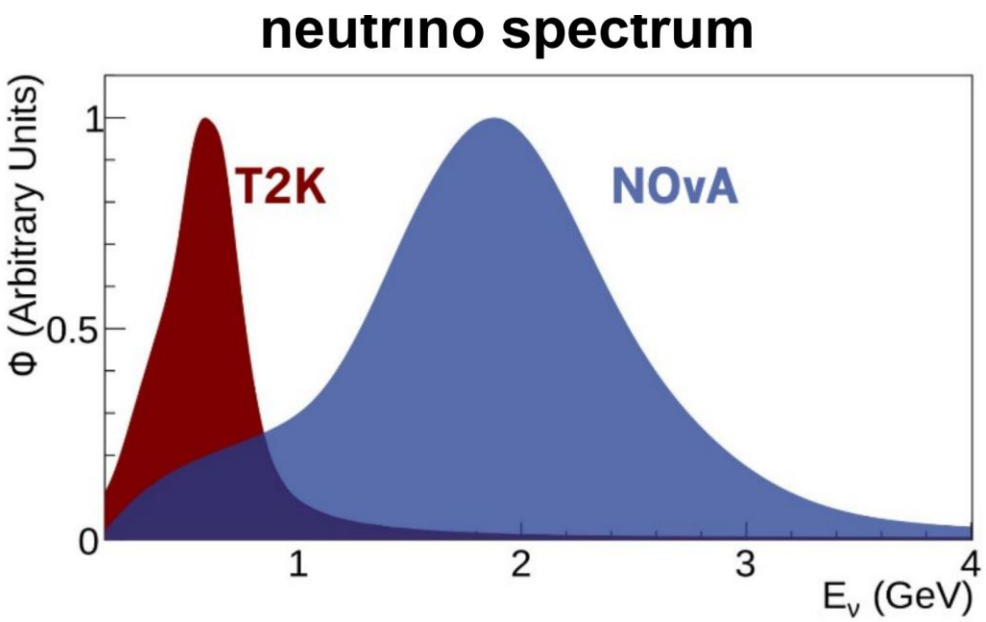
Therefore, we don't know Energy of incoming neutrino we have spectrum/flux!!!



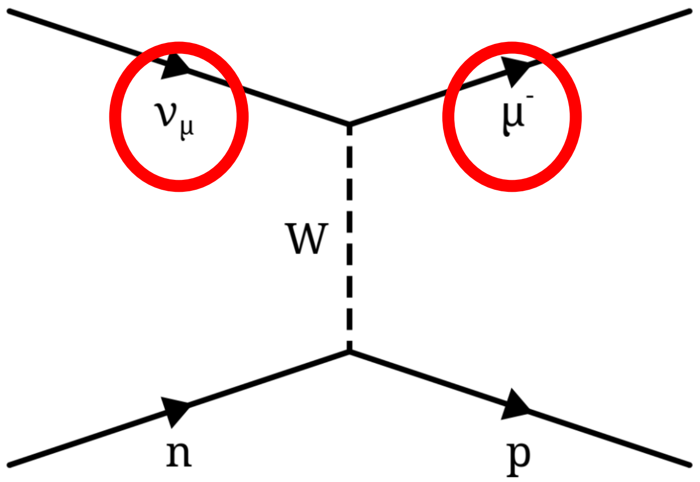
Neutrino Interaction

We can’t measure neutrino itself as they interact only weakly.

In neutrino interaction of **Charged Current** charged lepton is produced.

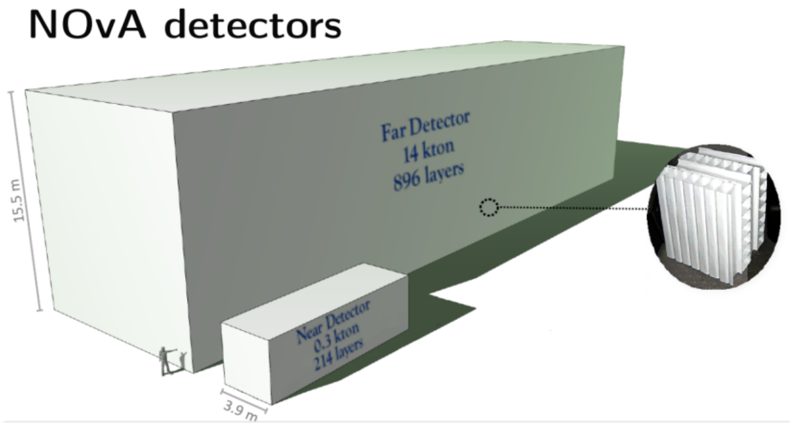
We have to try to measure neutrino Energy using product of interaction.

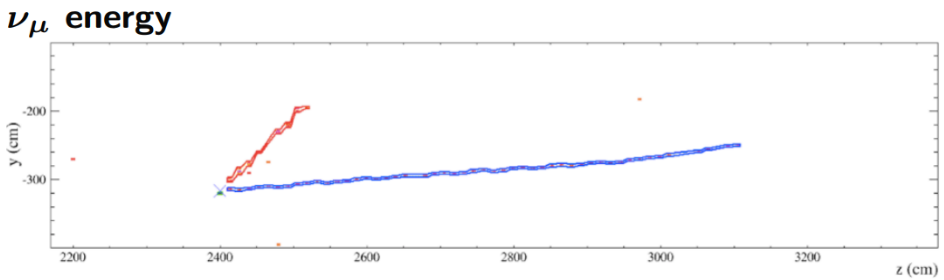
If we observe muon (electron) this means muon (electron) **neutrino** interacted.



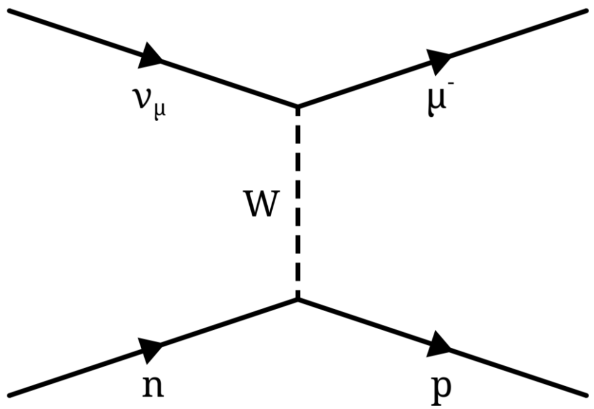
NOvA detector

- Consist of extruded plastic cells with alternating vertical and horizontal orientation for 3D reconstruction of neutrino interactions





$$E_{\nu_\mu} = E_\mu + E_{\text{had}}$$



- ν_μ energy is a sum of μ energy and hadronic part energy
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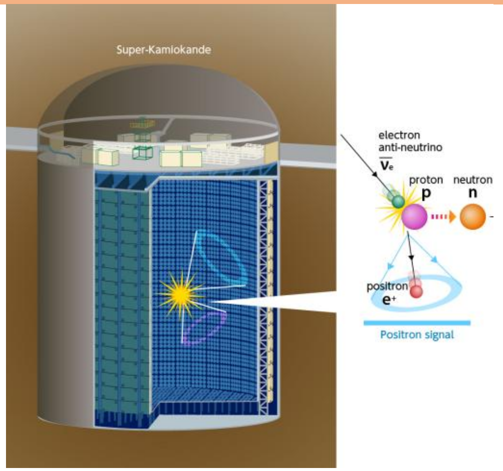
- Hadronic energy calorimetric reconstruction
- **What about particles not leaving signal in detector**

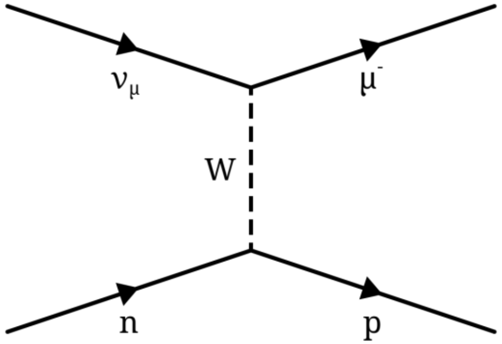
Reconstructing Neutrino Energy – T2K

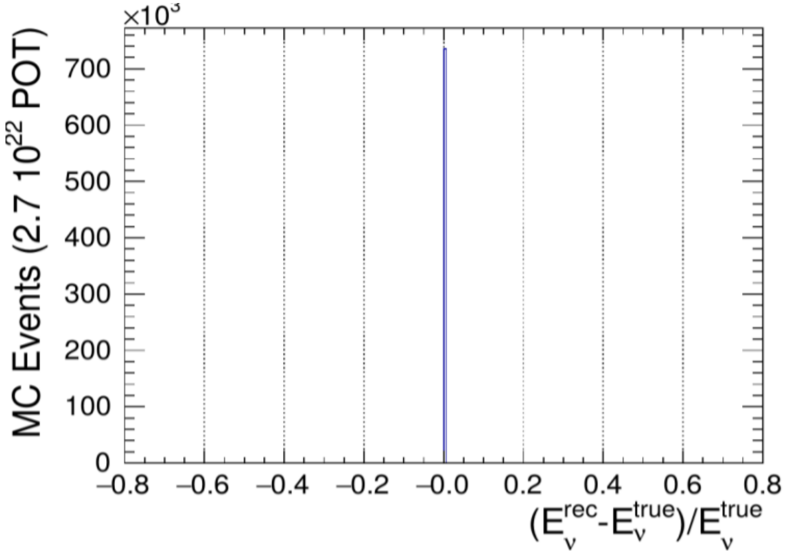
Lepton kinematics plays a crucial role in T2K. We may get neutrino energy from the following formula (for two body process):

$$E_\upsilon^{rec} = \frac{m_p^2 - (m_n - E_B)^2 - m_e^2 + (m_n - E_B)E_l}{2(m_n - E_B - E_l + p_l cos\theta_l)}$$

Only uses particle masses, lepton kinematics and nuclear model.







In ideal situation reconstructed should equal true.

Reconstructing Neutrino Energy – T2K

T2K far detector is water Cherenkov detector which do not see low energetic proton. Cannot use calorimetric measurement like NOvA

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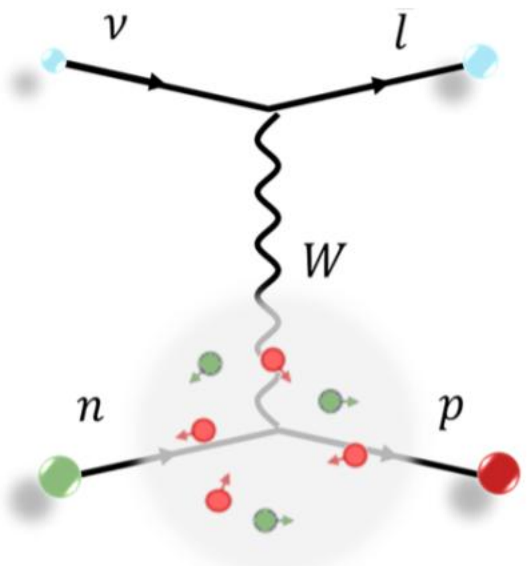

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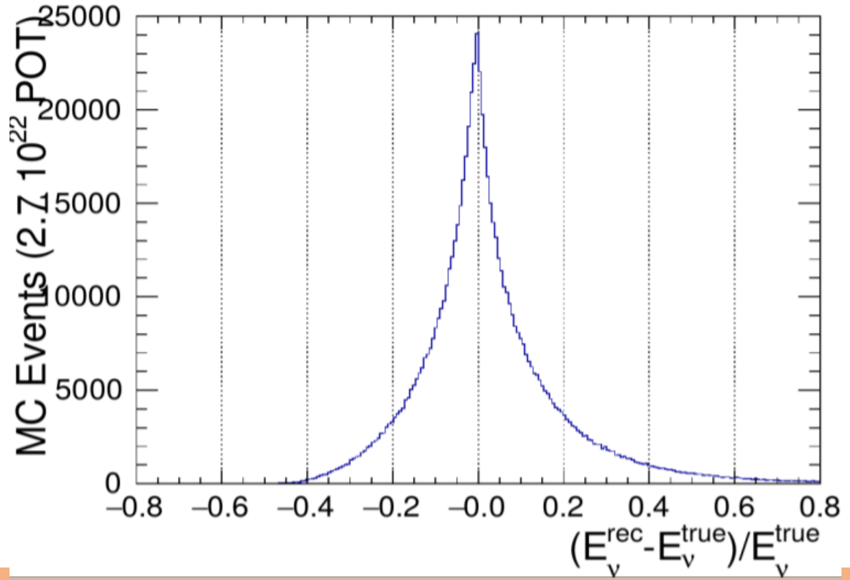

Neutrino interacts with nucleons in nuclei which smears reconstructed energy due to binding energy and nucleon momentum in nuclei.

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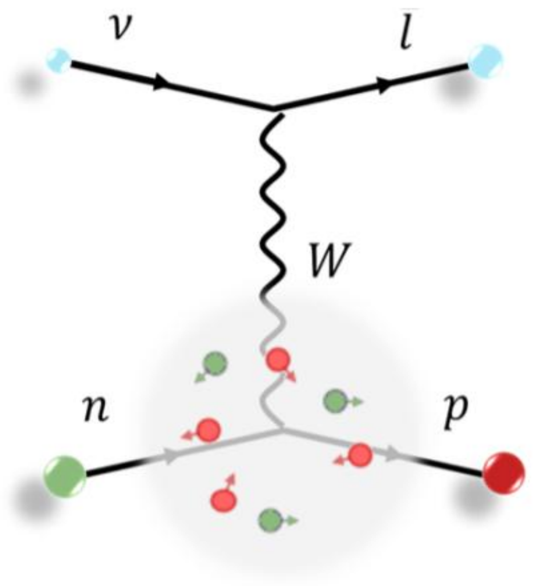
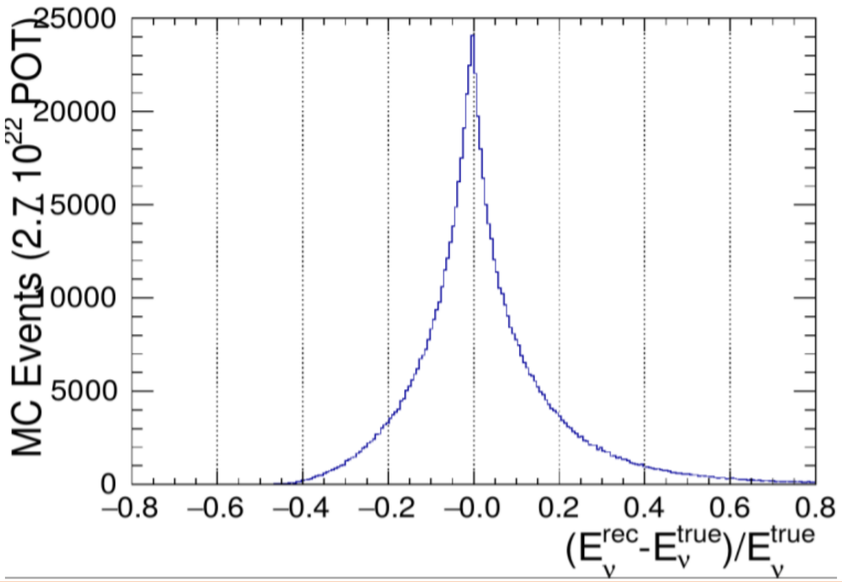
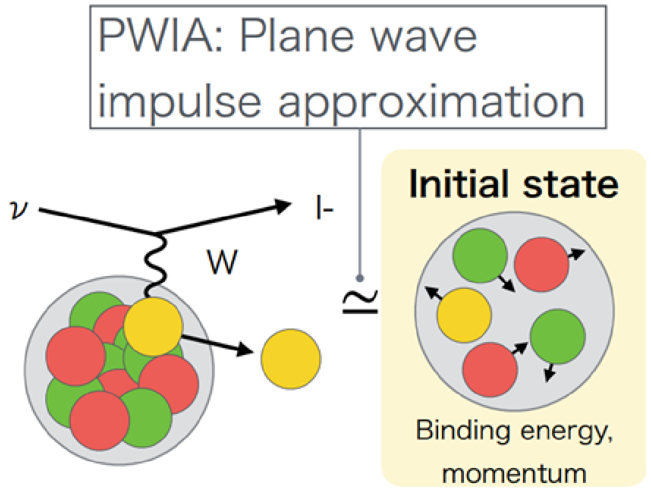







One doesn’t simply
Measure neutrino energy

Chapter II: Modelling of Interactions

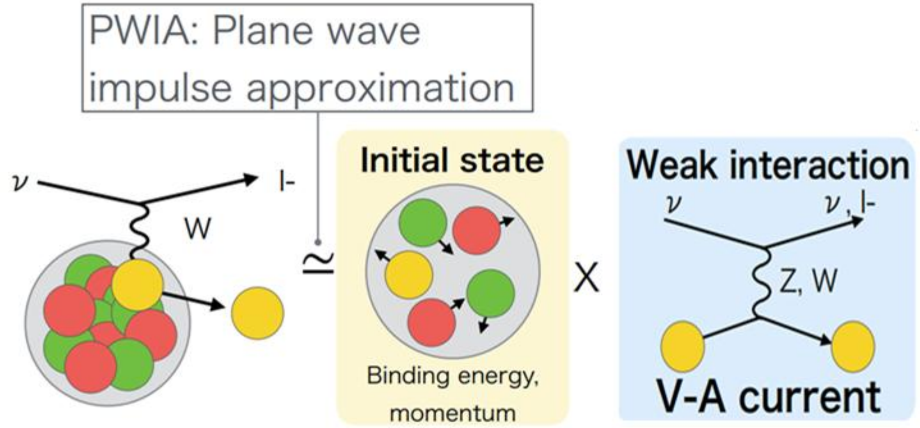
Summary

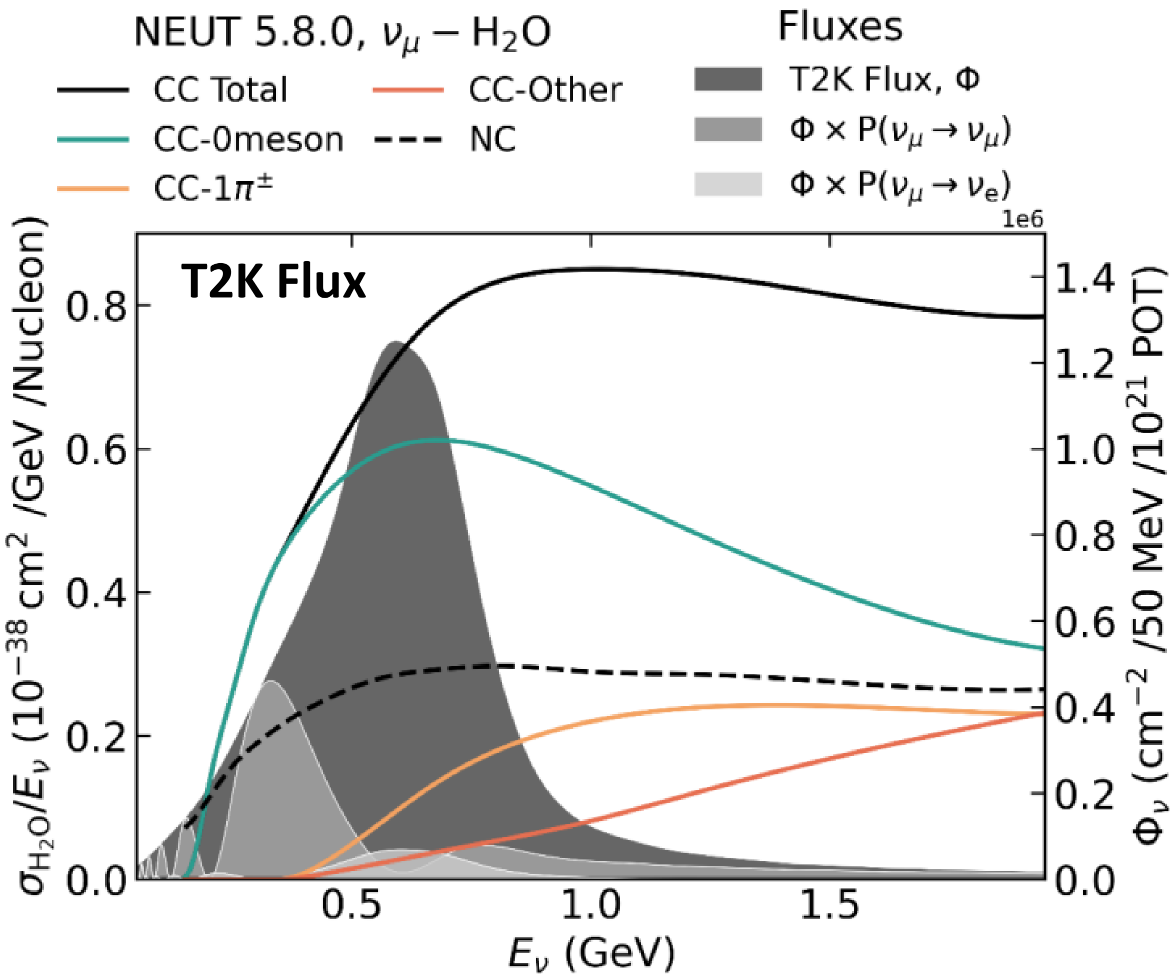
- To measure ν oscillation one need only energy
- We can measure Energy using products of ν interaction

Reconstruct Neutrino Energy

Neutrino can undergo several different reactions.

Each reactions use
- Slightly different model
- Different set of uncertainties
- Different challenges





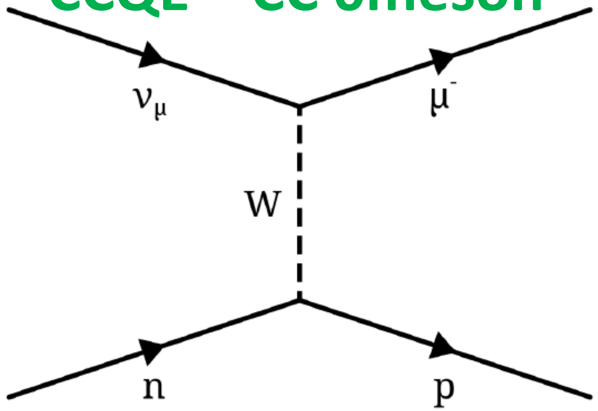
Plot from L. Pickering

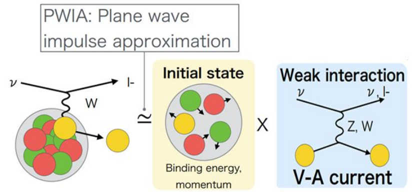
Reconstruct Neutrino Energy

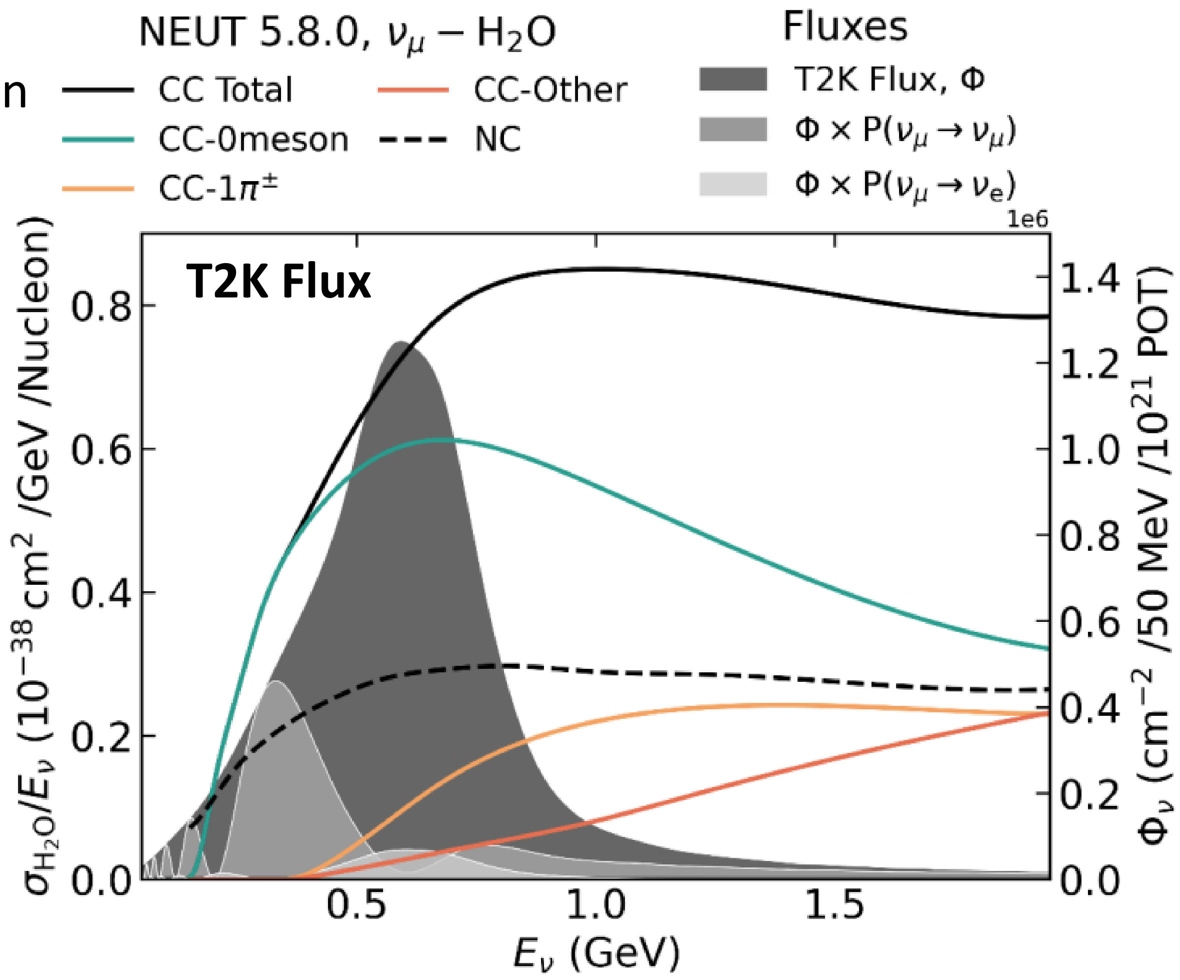
CCQE or CC 0meson.

- Simple topology
- Main signal for T2K and important for energy reconstruction method.

CCQE – CC 0meson





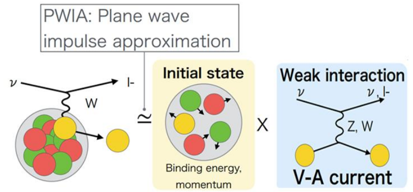


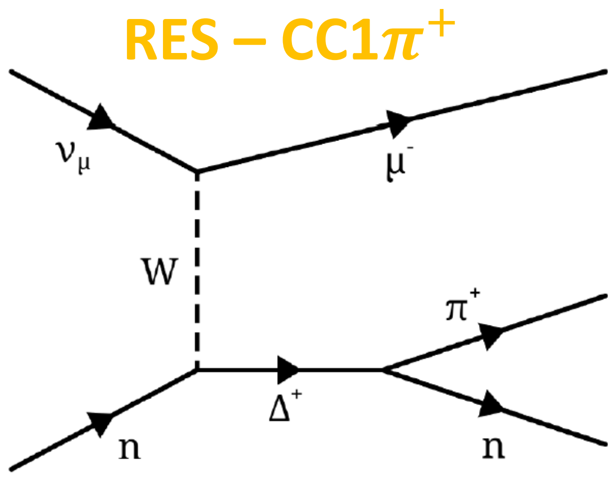
Plot from L. Pickering

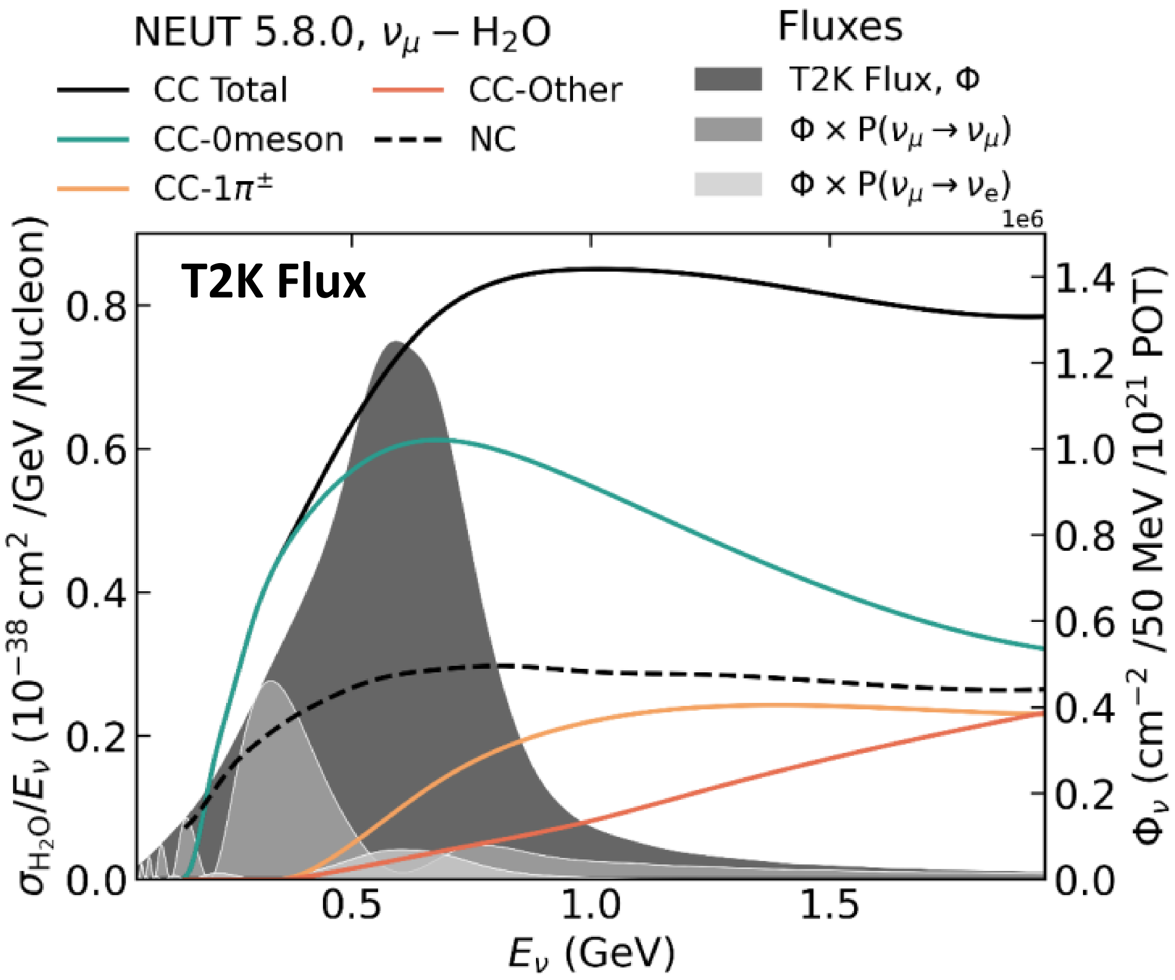
Reconstruct Neutrino Energy

CC1π^+ - mostly coming though resonance decay.

- Much more difficult due to numerous resonances.
- T2K dominated by very well-known delta resonance.



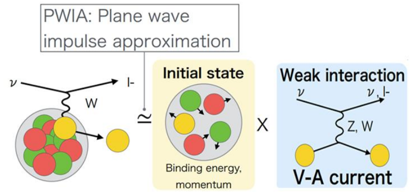


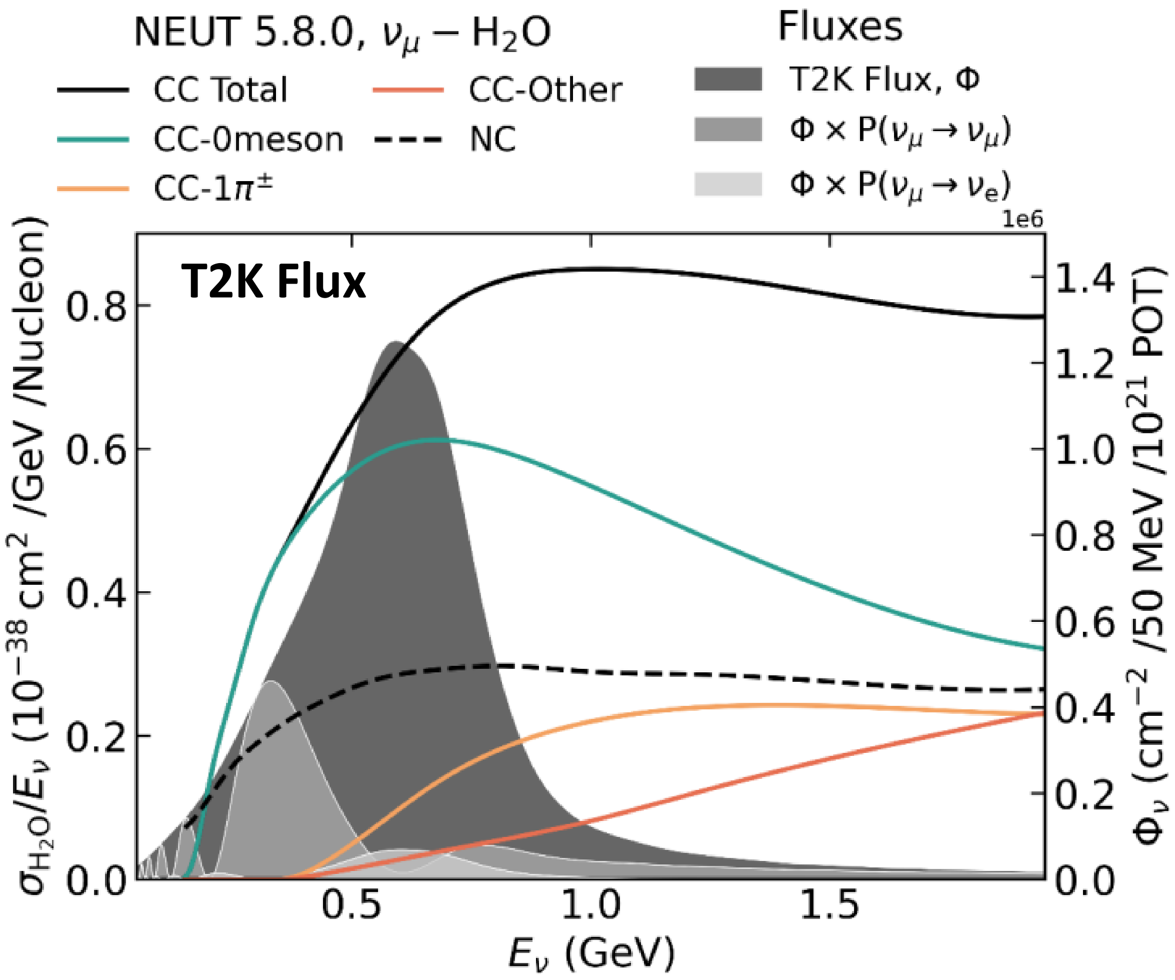


Plot from L. Pickering

Shallow and Deep-Inelastic Scattering

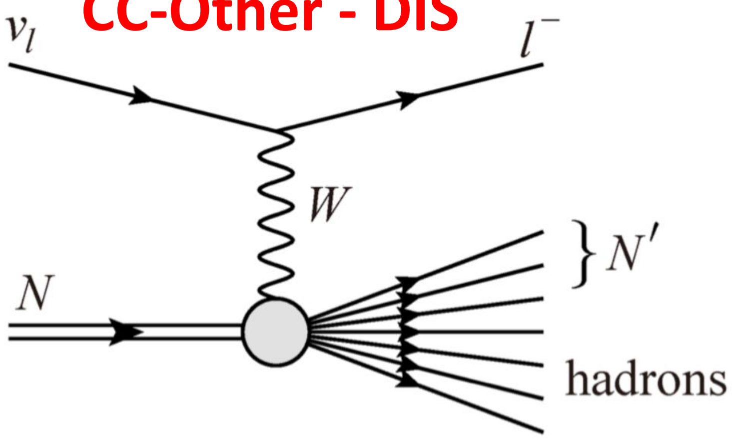
- Background for both experiments.
- Very diverse final state.





Plot from L. Pickering

CC-Other - DIS

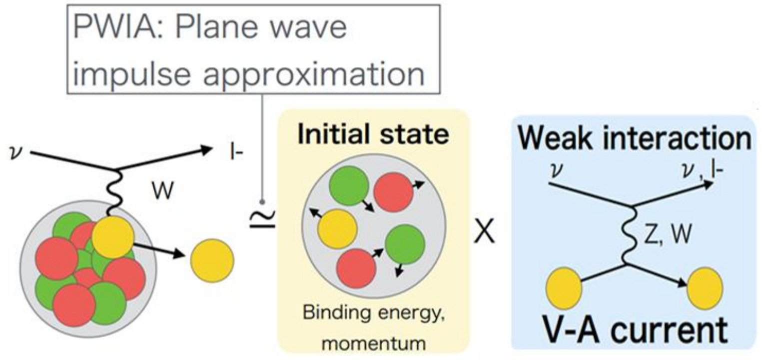


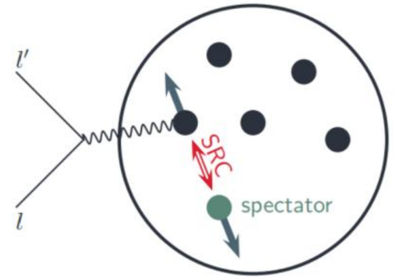
Correlations

Because interaction is happening inside nucleus there can be some inner nucleon correlations.

Then neutrino is interacting with two nucleons and two nucleons are ejected.

Often refers as two particles two holes (**2p2p**).





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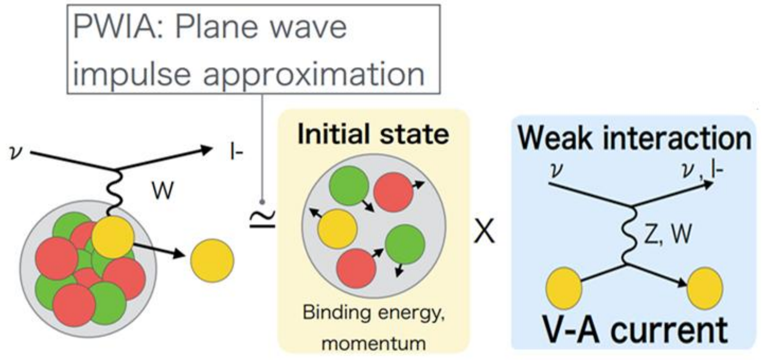

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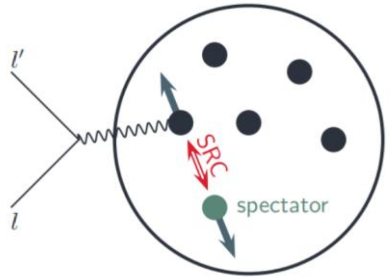
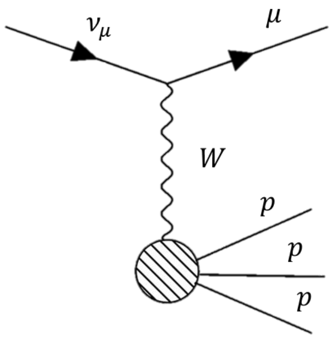


Often refers as two particles two holes (**2p2p**).

There can be more correlation resulting in even **3p3h**



Final State Interactions - Cascade

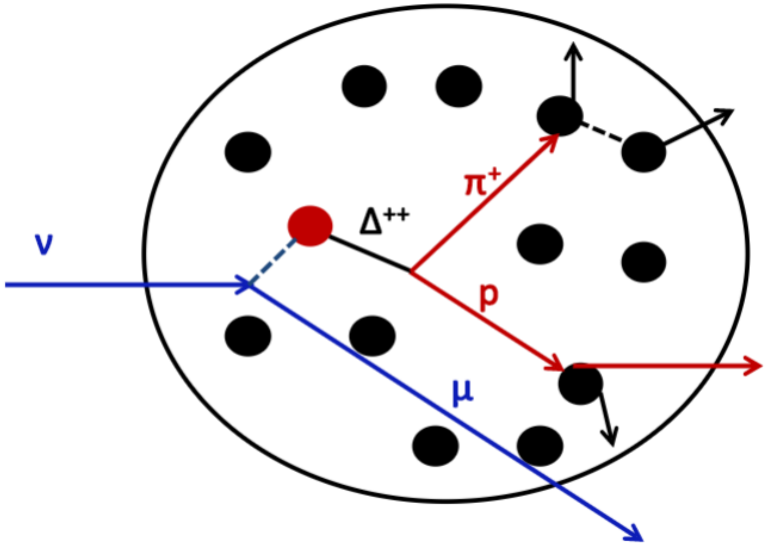
Up to this point we discussed „initial interaction”

After initial interaction particles have to „leave” nucleus.

We assume billiard ball like interactions often call it cascade

Due to cascade for example pion can be absorbed.

In other words, this means CC1pi+ interaction can be „seen” as CC0pi ☹



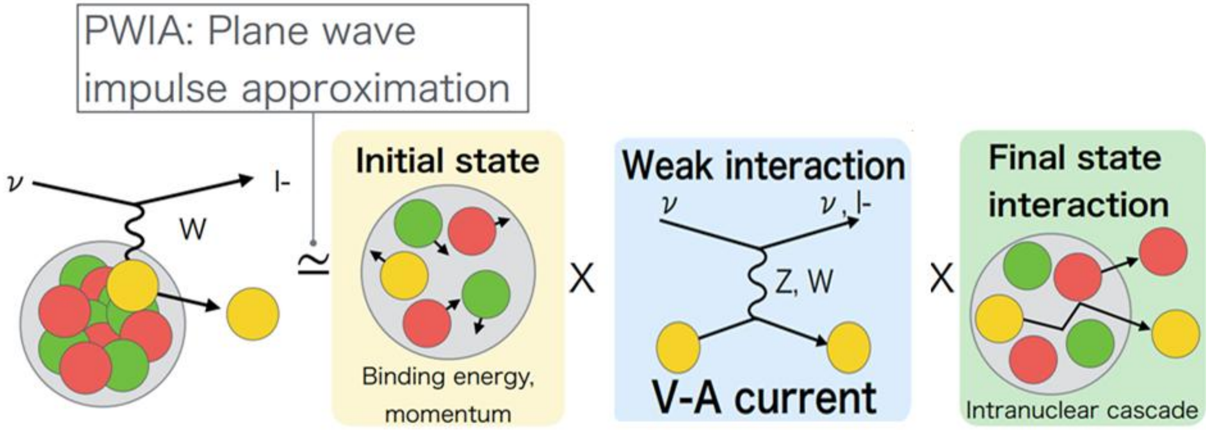


Figure from Seisho

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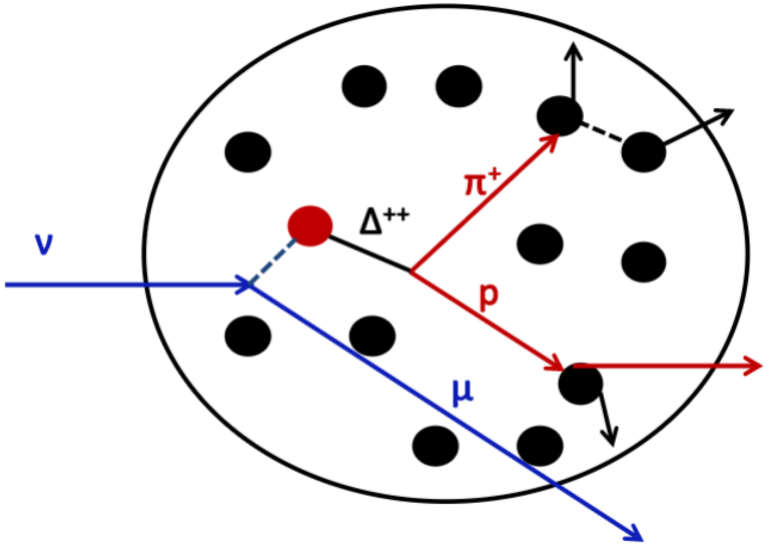
There is also deexcitation but less important for T2K and NOvA but it becomes more relevant.



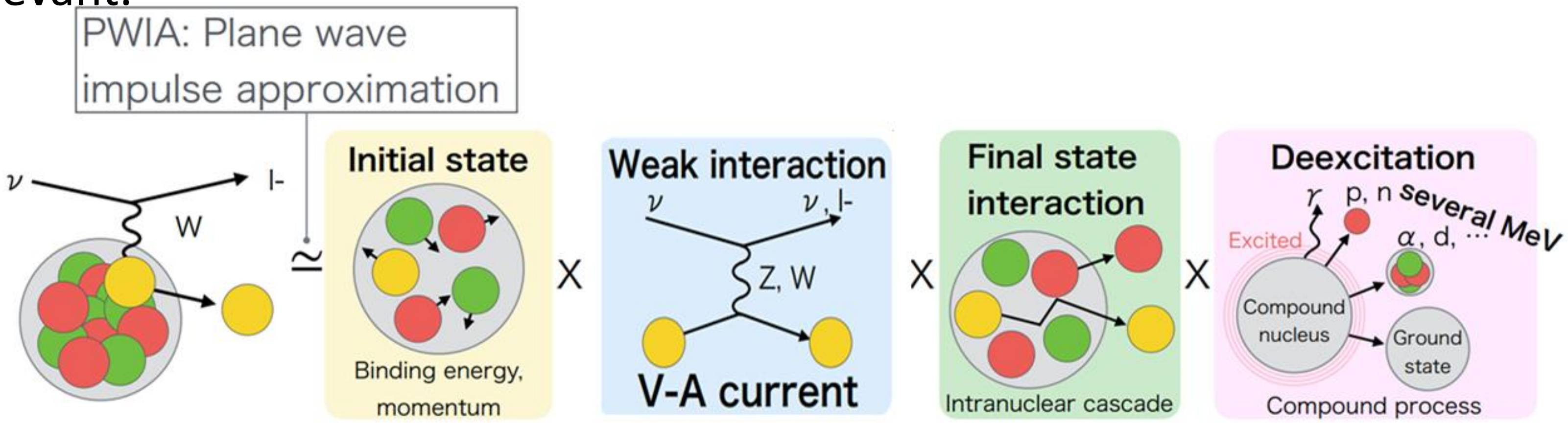
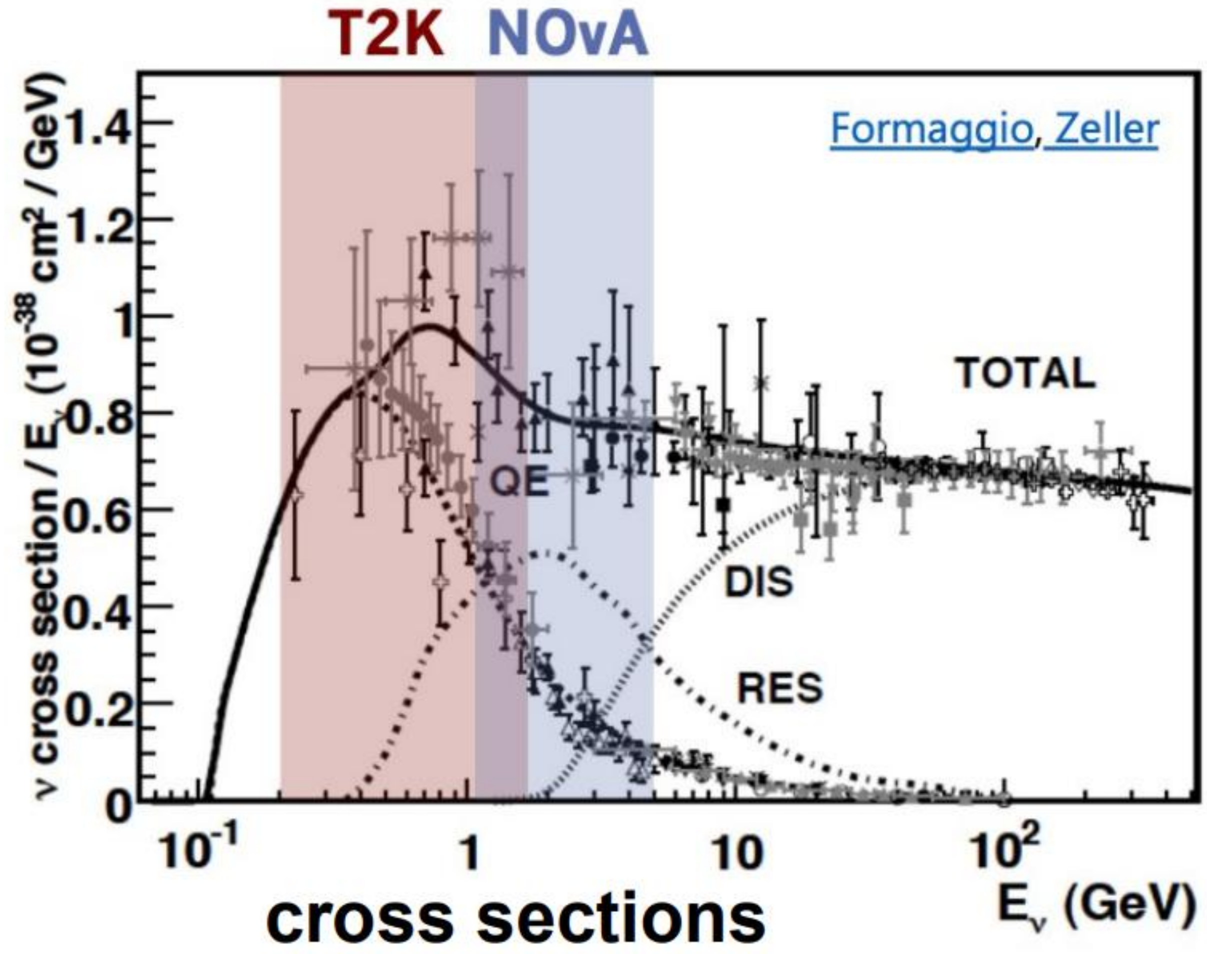


Figure from Seisho

Due to different neutrino flux, importance of different reaction reactions varies between T2K and NOvA.



T2K + NOvA

Due to different neutrino flux, importance of different reaction reactions varies between T2K and NOvA.

T2K is much more dominated by CCQE.

This is why T2K can effectively use Erec formula

$$E_{\upsilon}^{rec} = \frac{m_p^2 - (m_n - E_B)^2 - m_e^2 + (m_n - E_B)E_l}{2(m_n - E_B - E_l + p_l cos\theta_l)}$$

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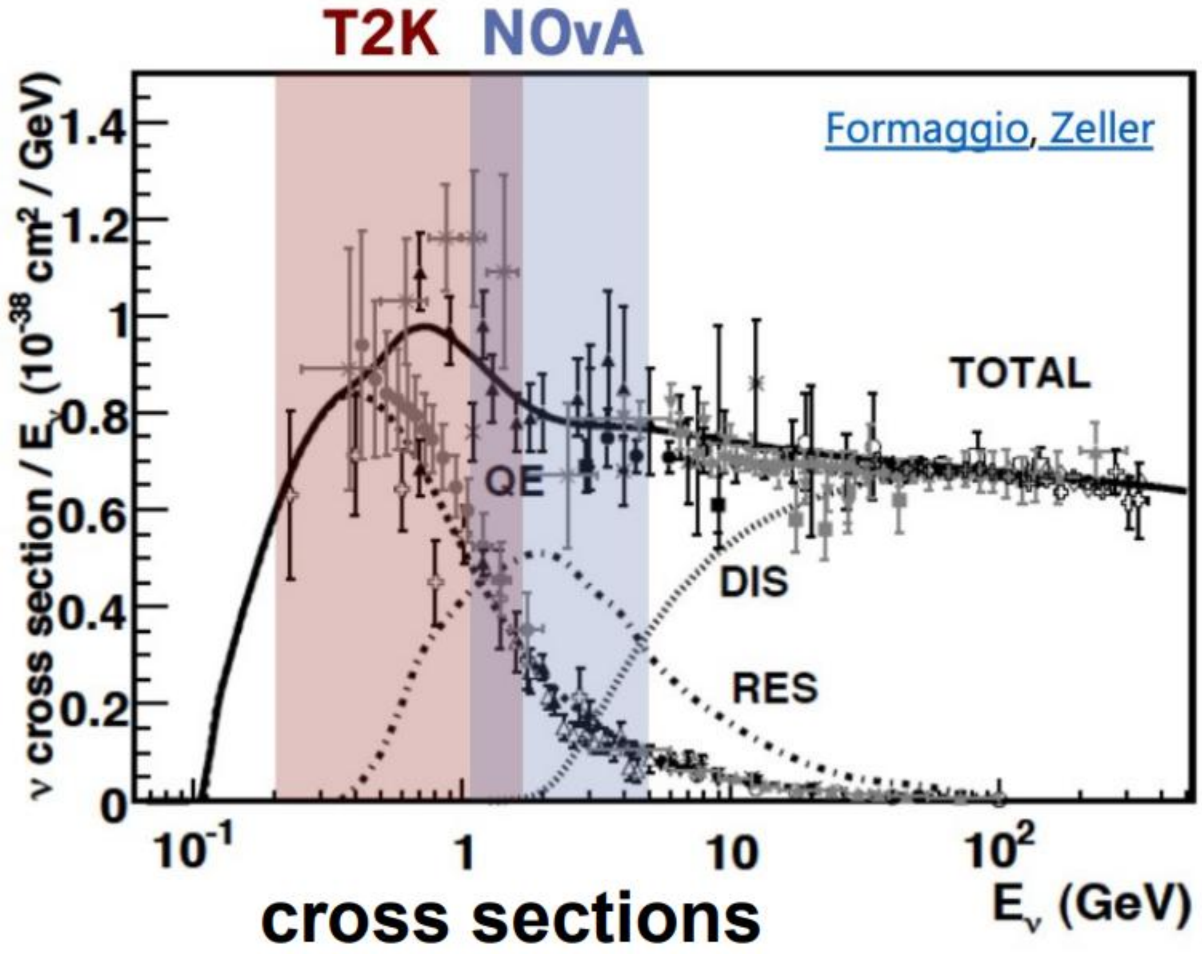


Different Neutrino Generators

Neutrino generator have access to different models and vary how consistently modelled are implemented.

NEUT used by **T2K** and other Japanese based experiments

- Development driven by needs of these experiments
- Wide range of processes

GENIE used by **NOvA** and other USA based experiments

- Developed experimentalists and theorists
- Wide range of processes

Different Neutrino Generators

Generator have access to different models and vary how consistently modelled are implemented.

In neutrino physics we have wide range access to generators

Allow exploring impact of different effects and analysis biases

NEUT used by **T2K** and other Japanese based experiments

- Development driven by needs of these experiments
- Wide range of processes

GENIE used by **NOvA** and other USA based experiments

- Developed experimentalists and theorists
- Wide range of processes

NuWro

- Mainly developed by theorists
- Wide range of processes

GiBUU

- Mainly developed by theorists
- Consistent theoretical framework for physics processes

ACHILLES

- Development driven by theorists
- New generator

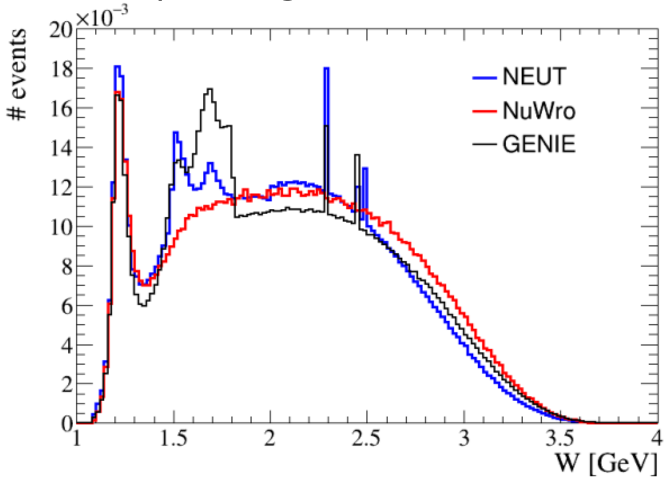
Different Neutrino Generators

Generator have access to different models and vary how consistently modelled are implemented.

In neutrino physics we have wide range access to generators

Allow exploring impact of different effects and analysis biases

Example of generator differences



NEUT used by **T2K** and other Japanese based experiments

- Development driven by needs of these experiments
- Wide range of processes

GENIE used by **NOvA** and other USA based experiments

- Developed experimentalists and theorists
- Wide range of processes

NuWro

- Mainly developed by theorists
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GiBUU

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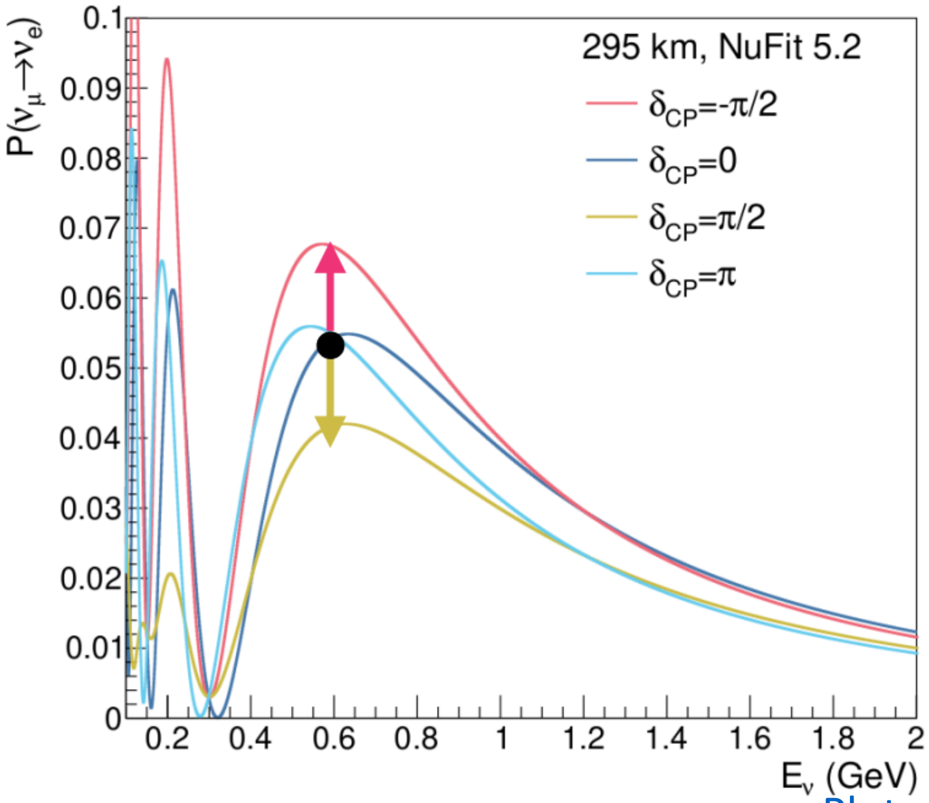
- Consistent theoretical framework for physics processes

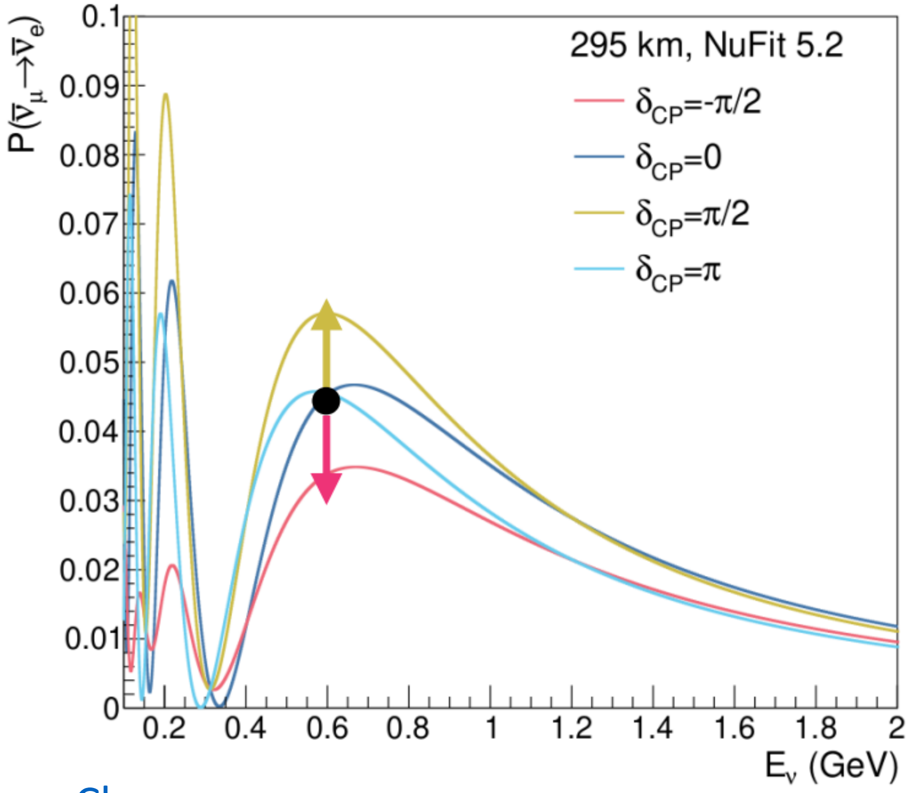
ACHILLES

- Development driven by theorists
- New generator

Example of mismodeling

Is the increased rate of CC1e from oscillations?
Is it a poorly modelled NC1π^0 background?
Is NC1$\pi^{\pm}$ mistaken for CC1μ?

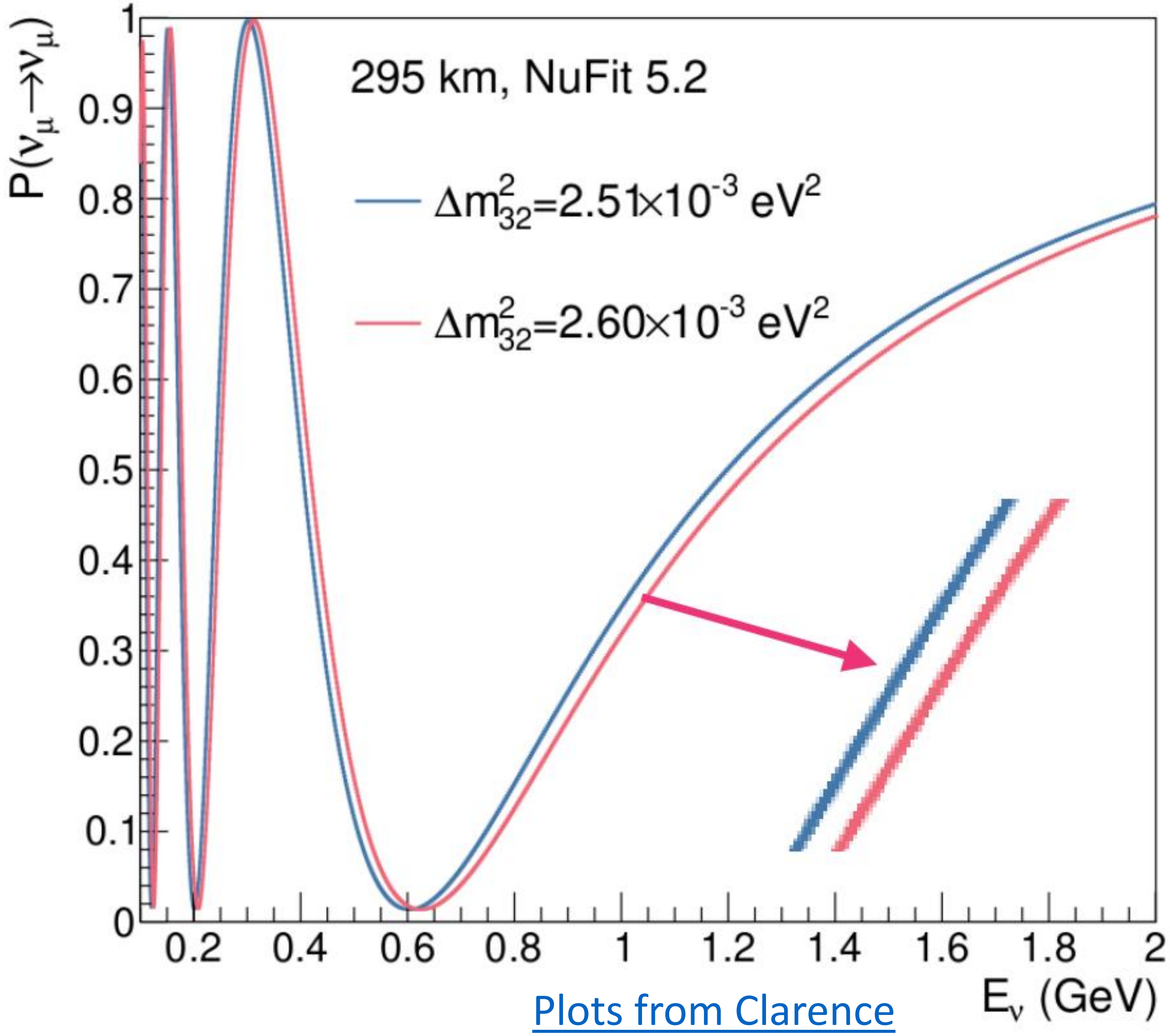




Plots from Clarence

Example of mismodeling

Is the frequency of the oscillation due to Δm^2_{32}, or biases in neutrino energy reconstruction from mismodelling?



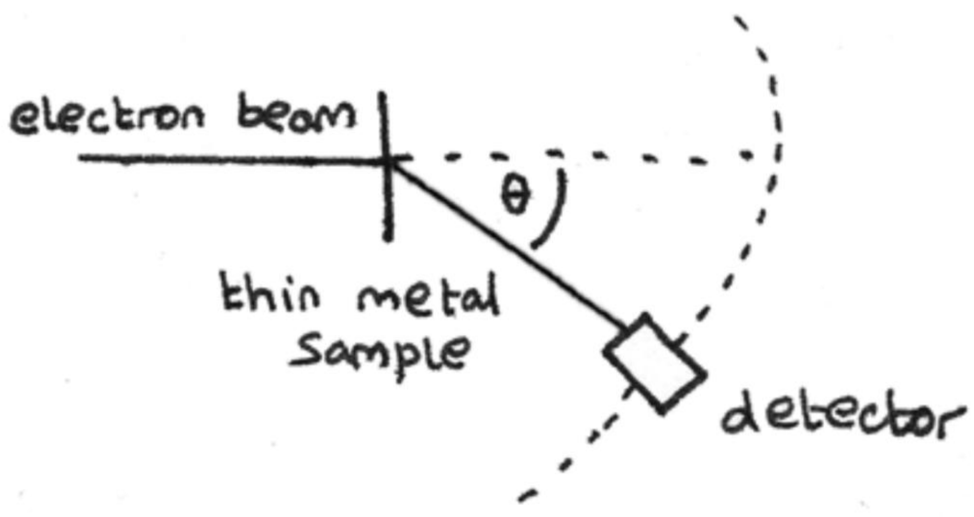
[Plots from Clarence]

Chapter III: Electron Scattering

Summary

- To measure ν oscillation one need only energy
- We can measure Energy using products of ν interaction
- Modelling of interactions is difficult ☹

- Electron scattering, we have very good control of incoming and outcoming angle and momentum
- Both neutrino and electron scatterings can be simulated using the same nuclear model.
- **A lot of old electron scattering data**



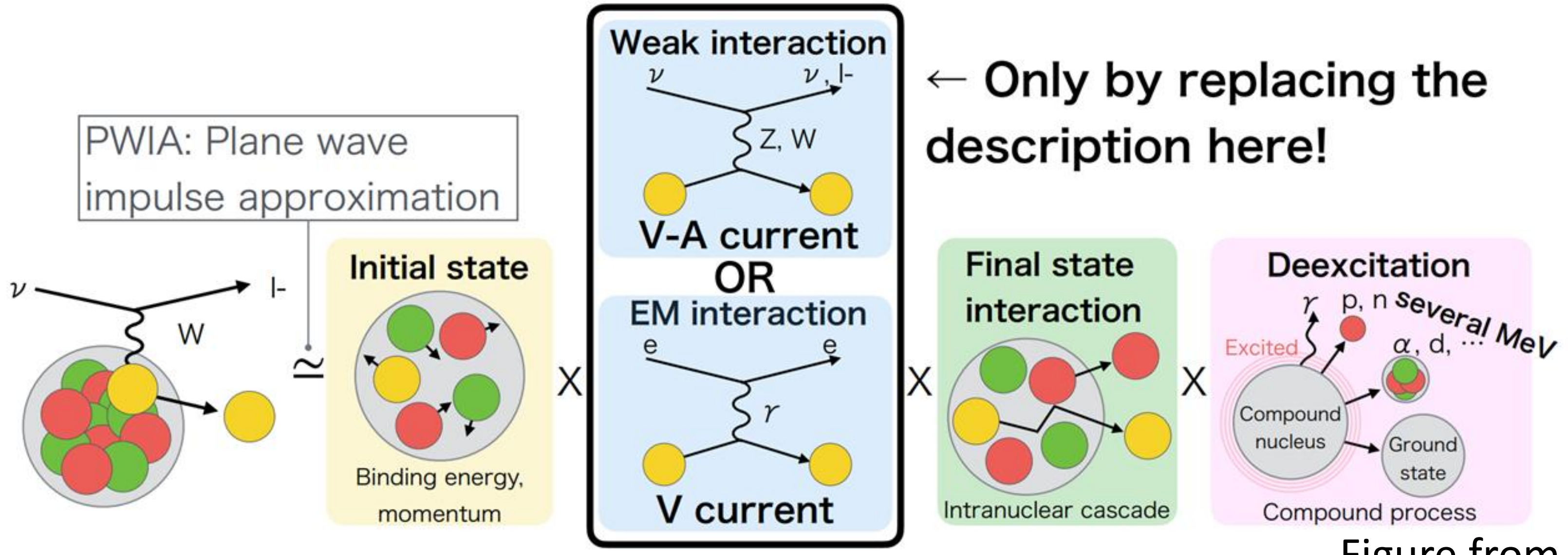
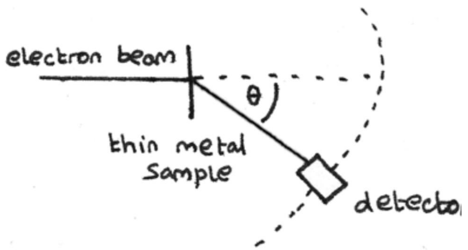
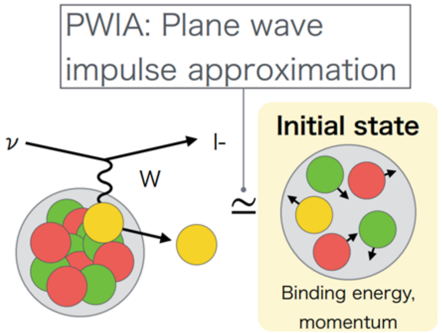


Figure from Seisho

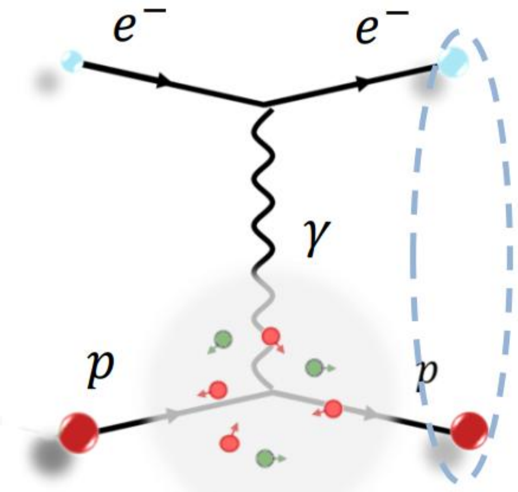
We can measure initial state with electron scattering

We know the incoming $e-$ energy / momentum in e-scattering experiments!





$$e + p \rightarrow e' + p'$$



Phys Rev C, **49**, 2 (1994)
(M. Leuschner et al.)

Improving Initial State Description

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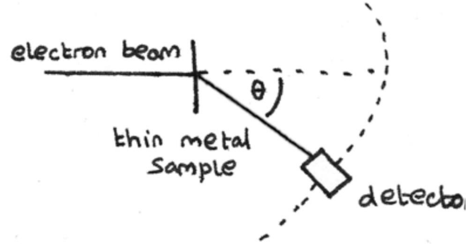
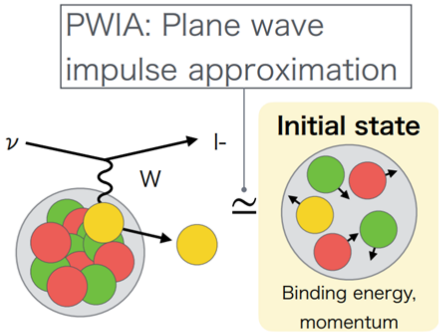
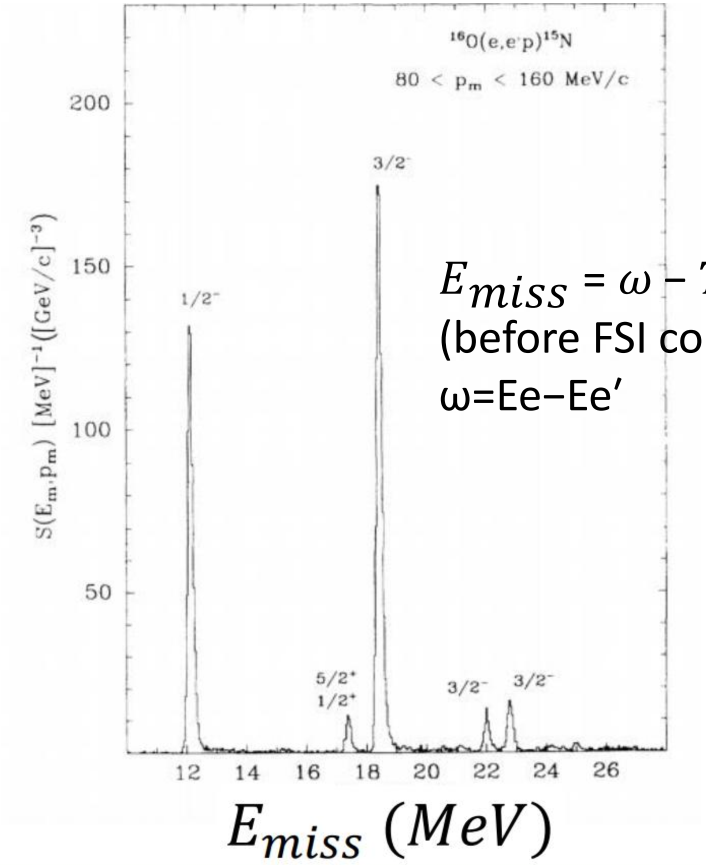
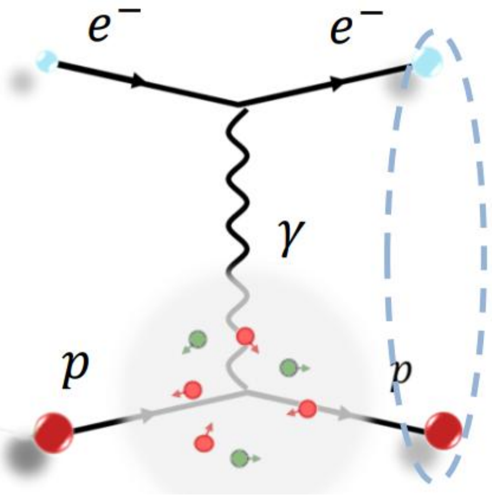






$E_{miss} = \omega - Tp' - T_{rem}$
(before FSI corrections)
ω=Ee−Ee′

$e + p \rightarrow e' + p'$



Phys Rev C, **49**, 2 (1994)
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Based on [Stephen's]

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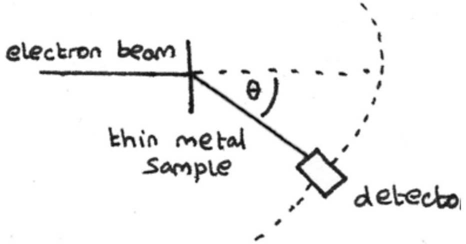

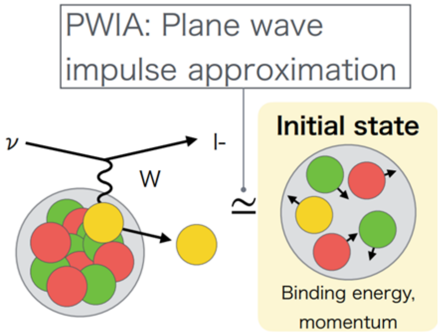

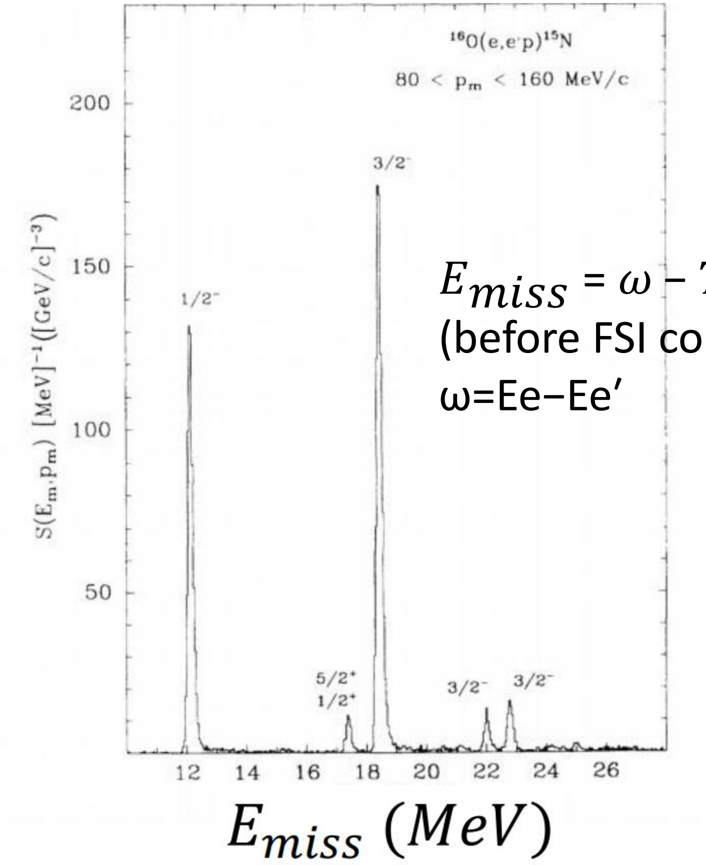

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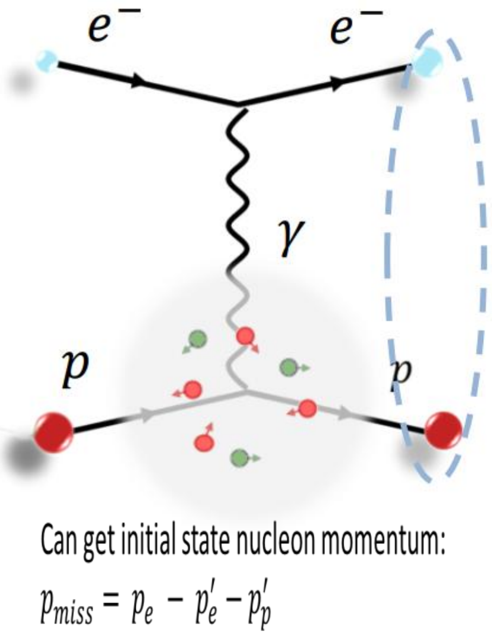
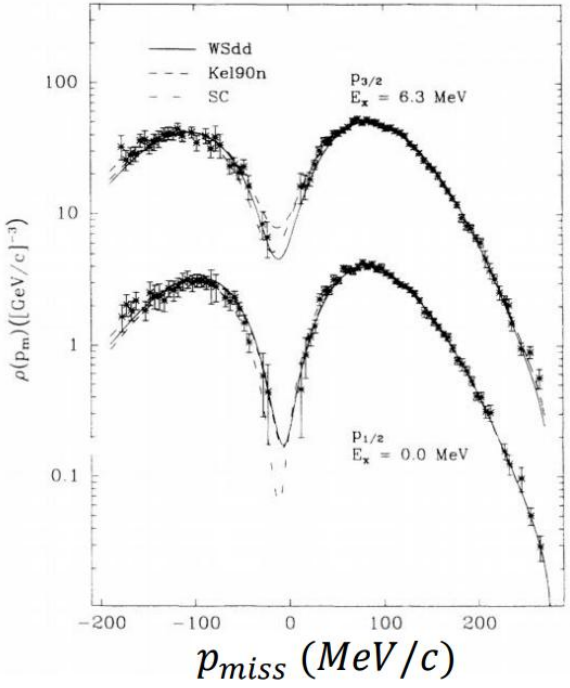


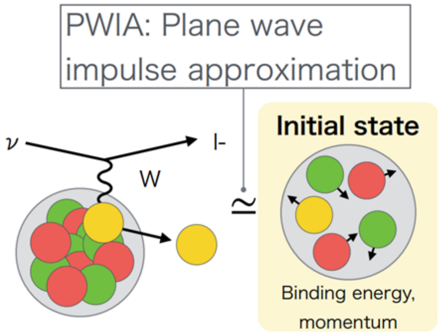
Can get initial state nucleon momentum:
$p_{miss} = p_e - p'_e - p'_p$

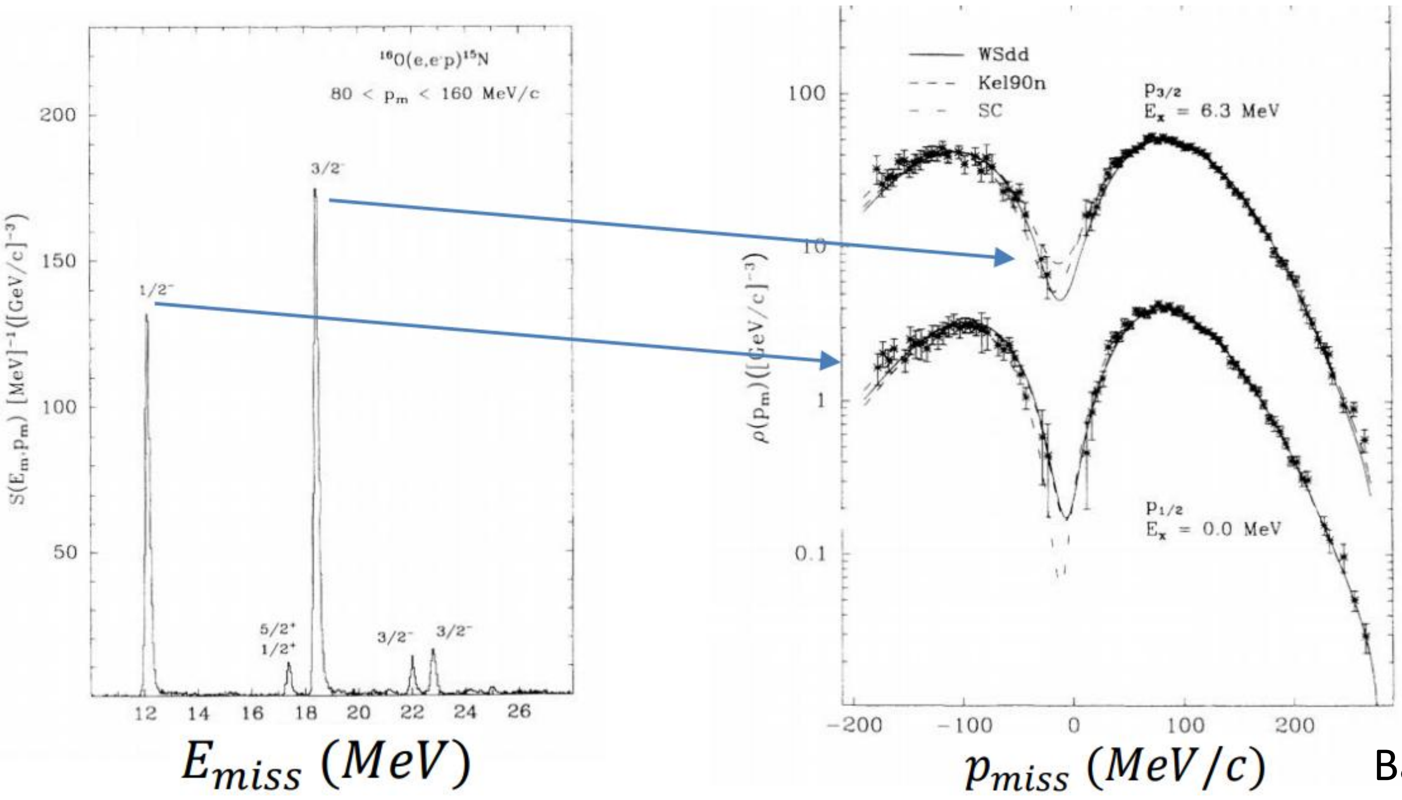


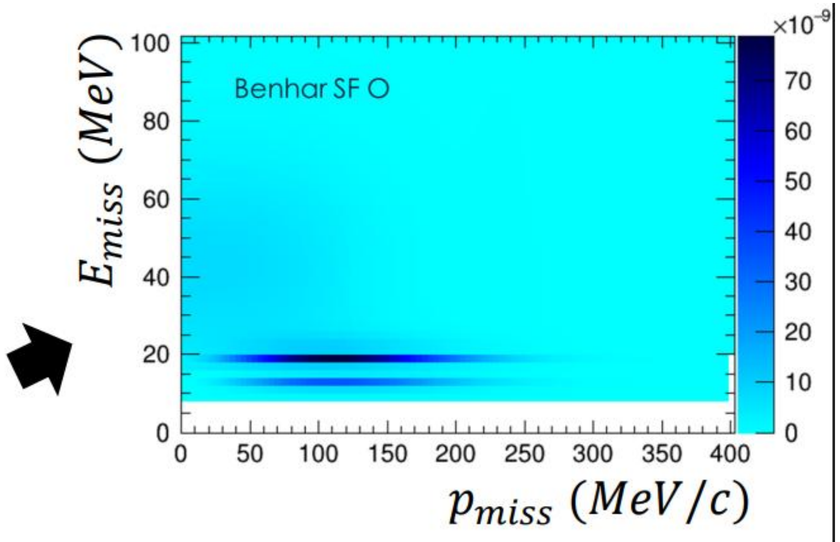
Based on [Stephen's]

Improving Initial State Description

Scan through E_{miss} and measure p_{miss} (or vice-versa) to build probability of what initial state is.







Phys Rev C, **49**, 2 (1994)
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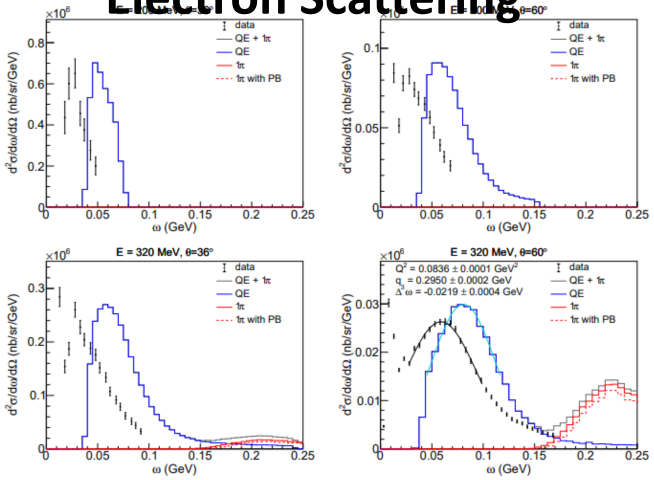
Based on Stephen's

Electron Scattering

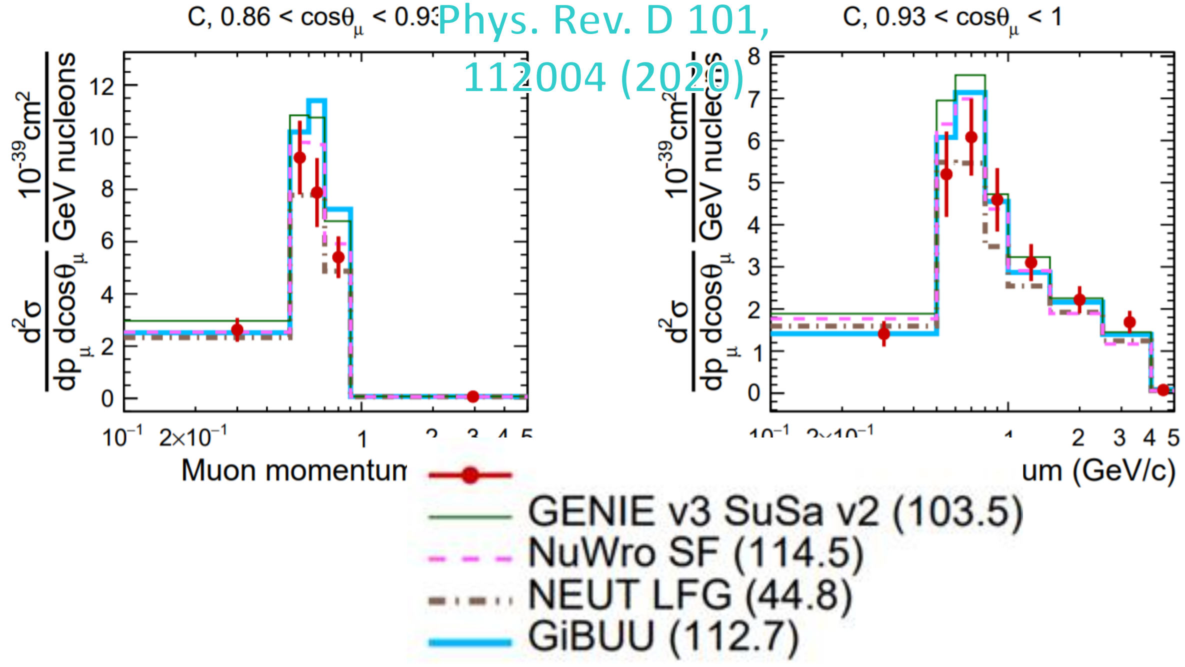


We generally observe large discrepancy using same model between electron and neutrino scattering.

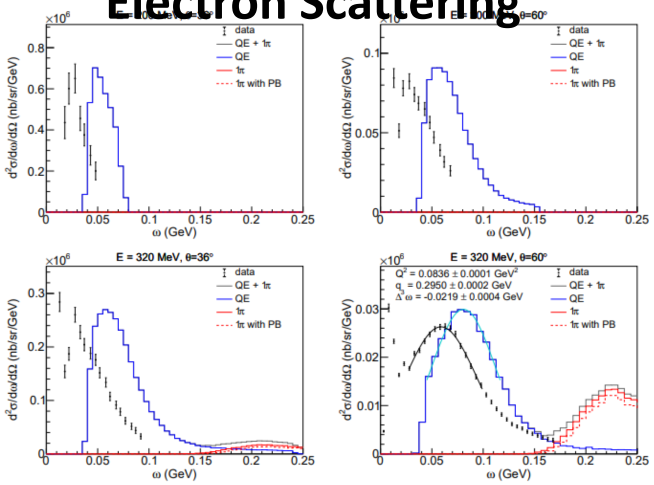
Due to nature of neutrino interactions, we cannot make perform as precise measurement as electron scattering

Neutrino Scattering

Phys. Rev. D 101, 112004 (2020)

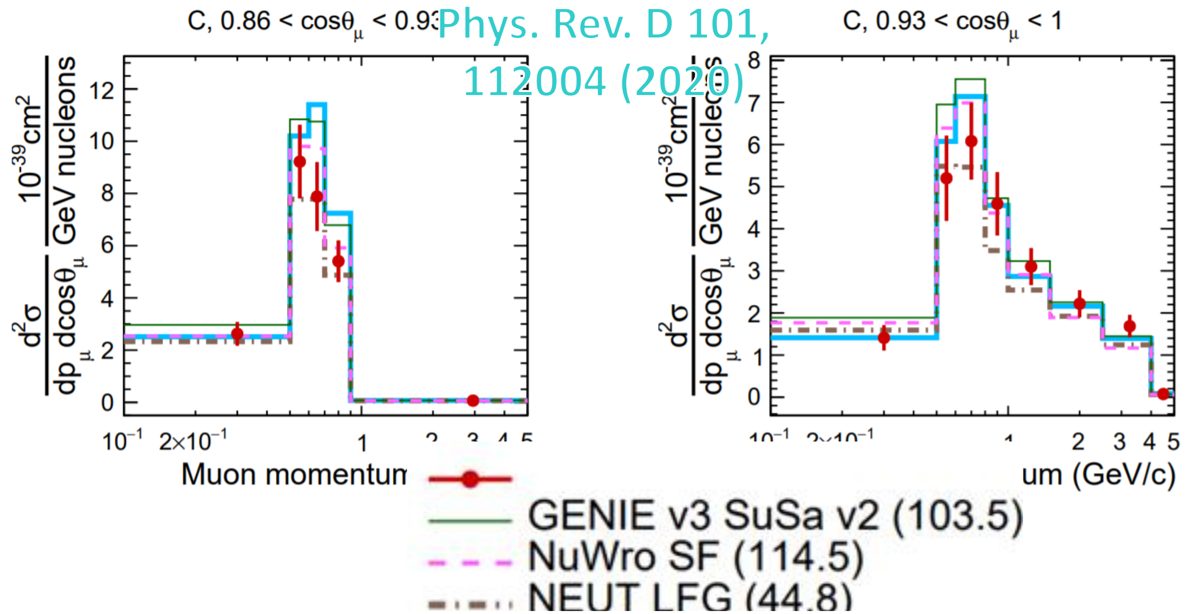


Electron Scattering



Neutrino Scattering

Phys. Rev. D 101, 112004 (2020)



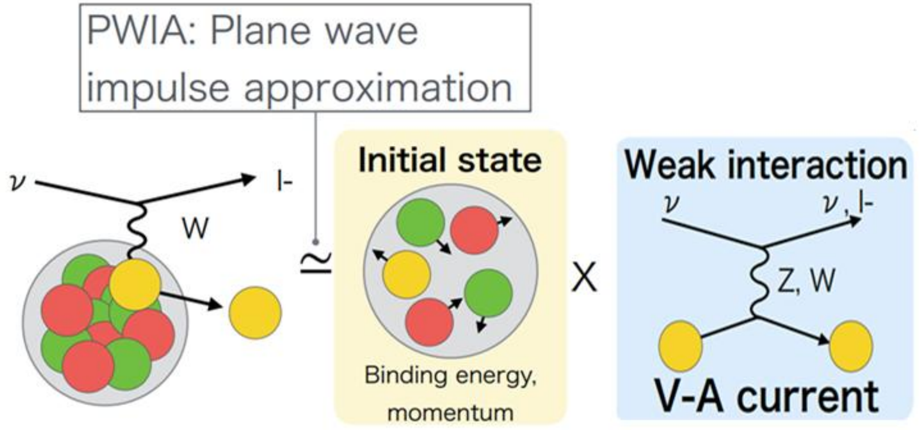
We generally observe large discrepancy using same model between electron and neutrino scattering.

Due to nature of neutrino interactions, we cannot make perform as precise measurement as electron scattering

Main problem is we used model with Plane Wave Impulse approximation.

Because lepton is travelling through nucleus there are quantum mechanical effects „DISTORTING" wave.

They are very important for low Energy transfer phase-space



When accounting for distorted wave and including elastic FSI we can recover mismatch with electron scattering.

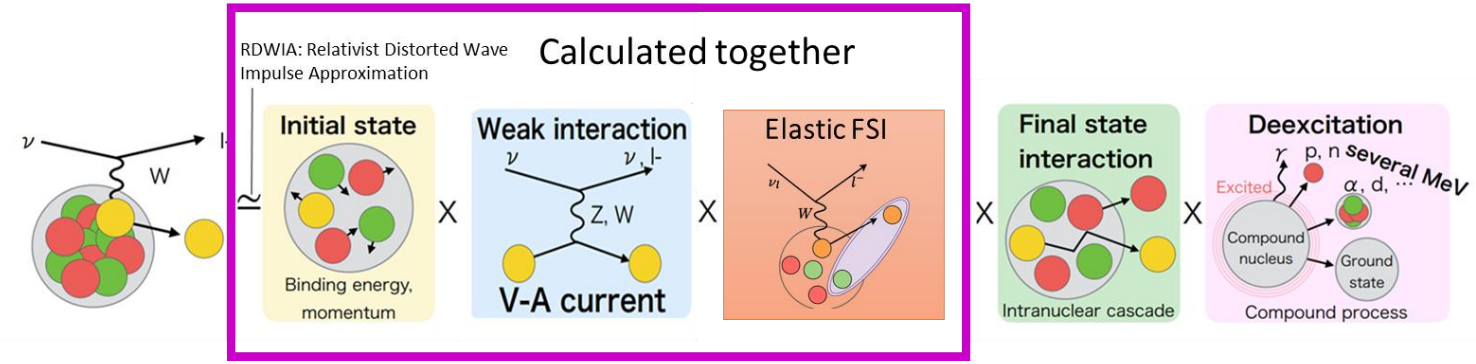
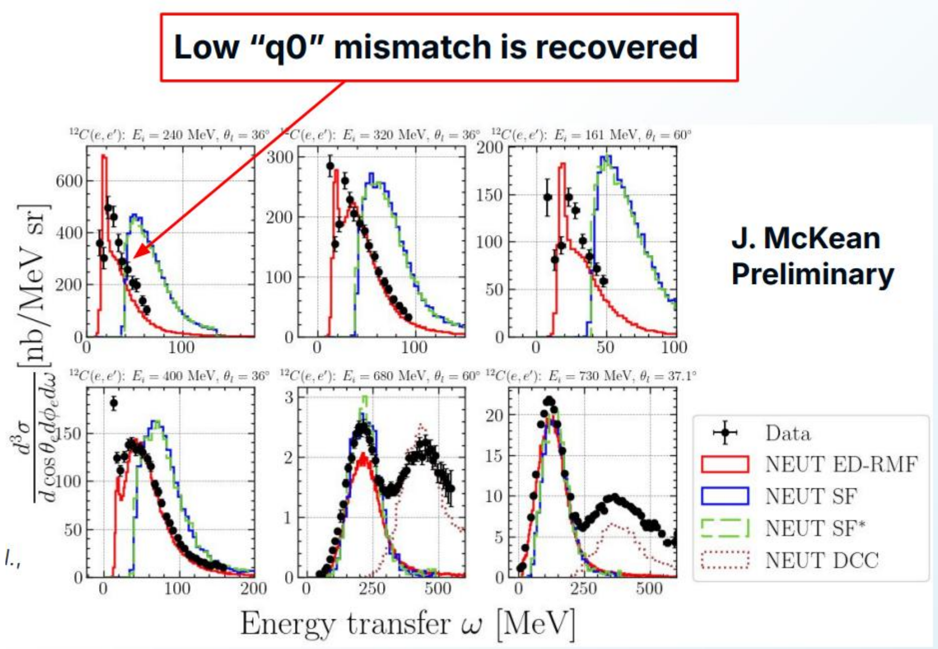
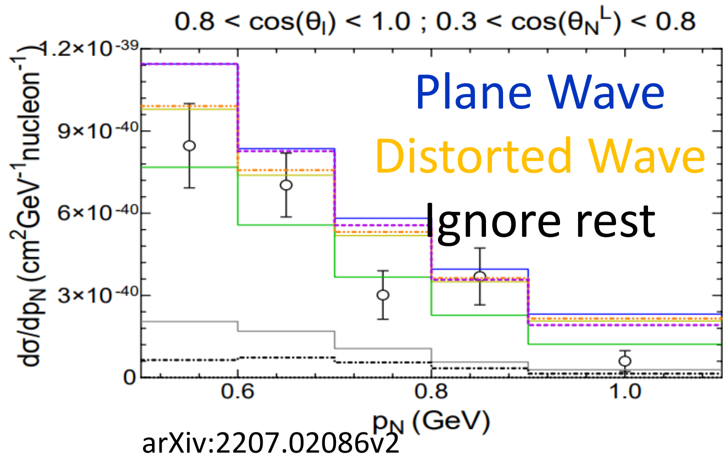


Figure adapted from S. Abe and Jake

Electron Scattering



Neutrino Scattering



arXiv:2207.02086v2

Electron Scattering – Summary

- Some data is old from 60/70 errors not understood and hand scanning plots ☹
- Not every model has ability to switch to electron scattering like popular 2p2h Nieves model ☹
- Perfect agreement with electron scattering doesn't guarantee great agreement for neutrino ☹

Electron Scattering – Summary

- Some data is old from 60/70 errors not understood and hand scanning plots ☹
- Not every model has ability to switch to electron scattering like popular 2p2h Nieves model ☹
- Perfect agreement with electron scattering doesn't guarantee great agreement for neutrino ☹

However

- More and more generators and model have ability to use electron scattering ☺
- There are new collaboration build on providing electron scattering for neutrino measurements ☺
- If model doesn't agree with electron scattering it is very unlikely it will ever agree with neutrino ☺

Chapter IV: Neutrino Scattering

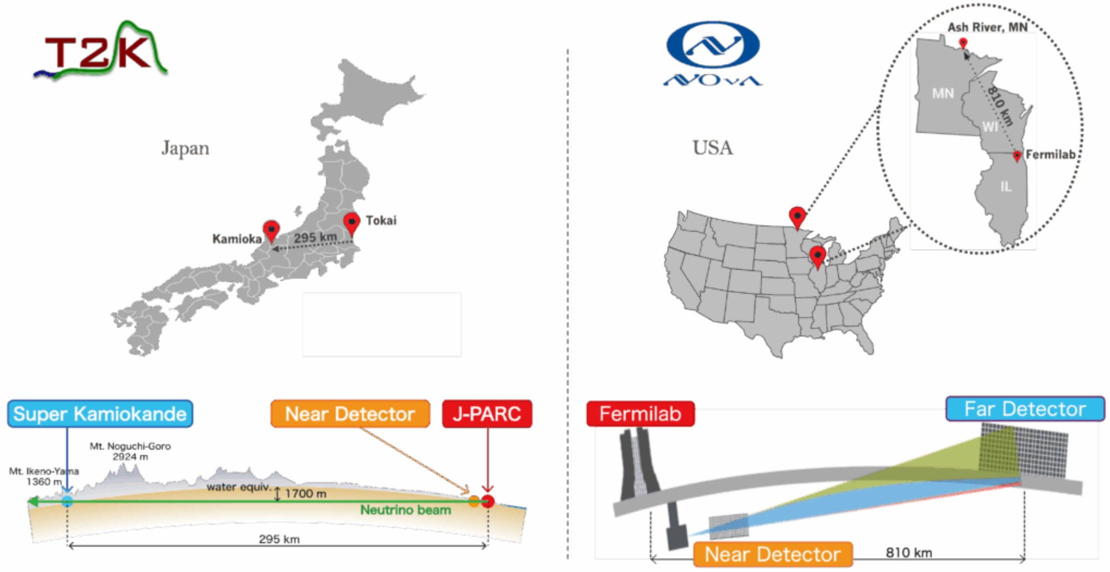
Summary

- To measure ν oscillation one need only energy
- We can measure Energy using products of ν interaction
- Modelling of interactions is difficult ☹
- Using electron scattering to develop better models

Near Detectors

Both T2K and NOvA have near detector

- Oscillations are negligible (due to small **L**)
- Relatively high number of events, order of hundred thousands vs hundreds in Far Detector
- Measure neutrino cross-section
- Constrain fit parameters

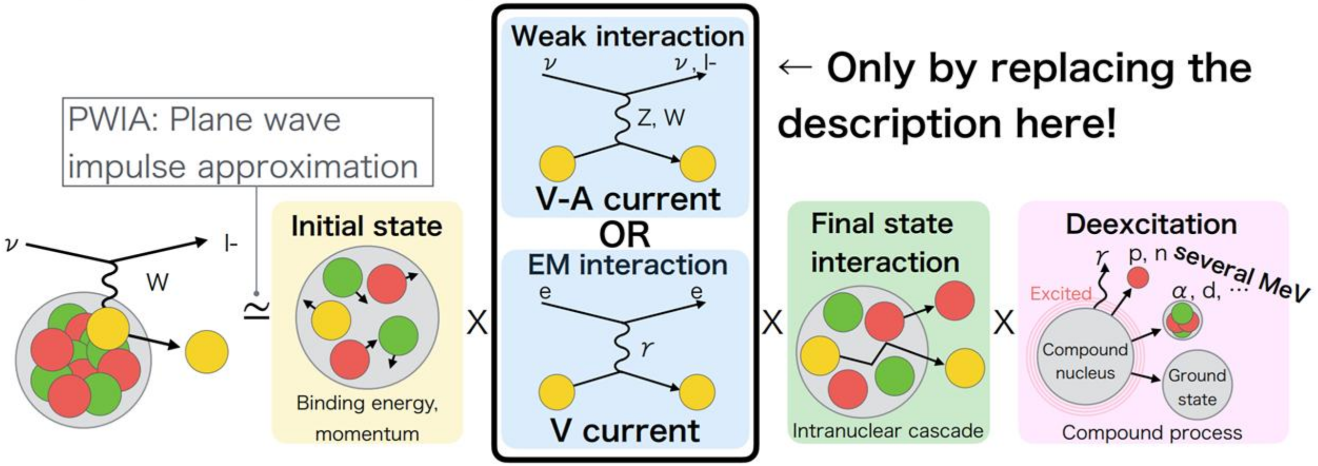


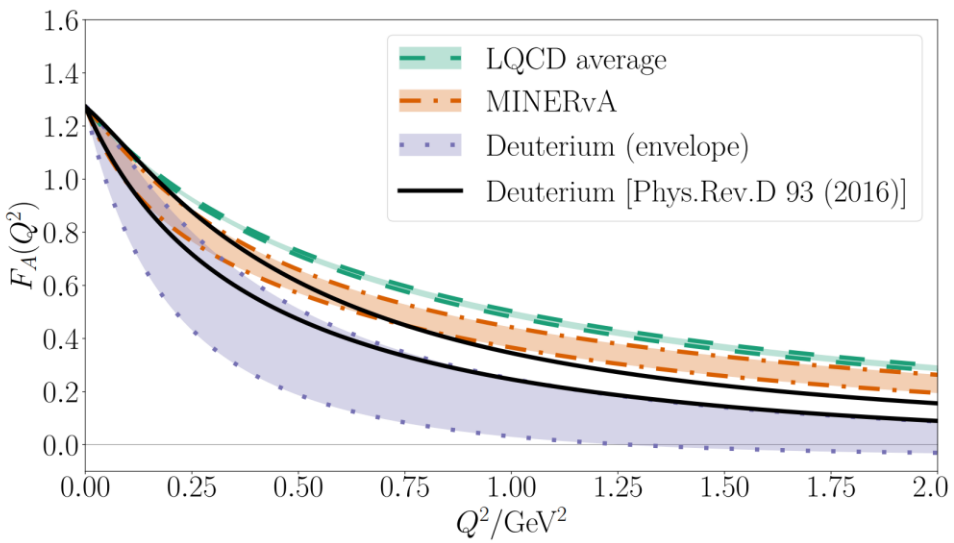
Neutrino Scattering

Axial form factor are property of weak interactions

Need neutrino data.

Using neutrino scattering allows us to measure parameters like „axial mass” necessary to describe form factors.

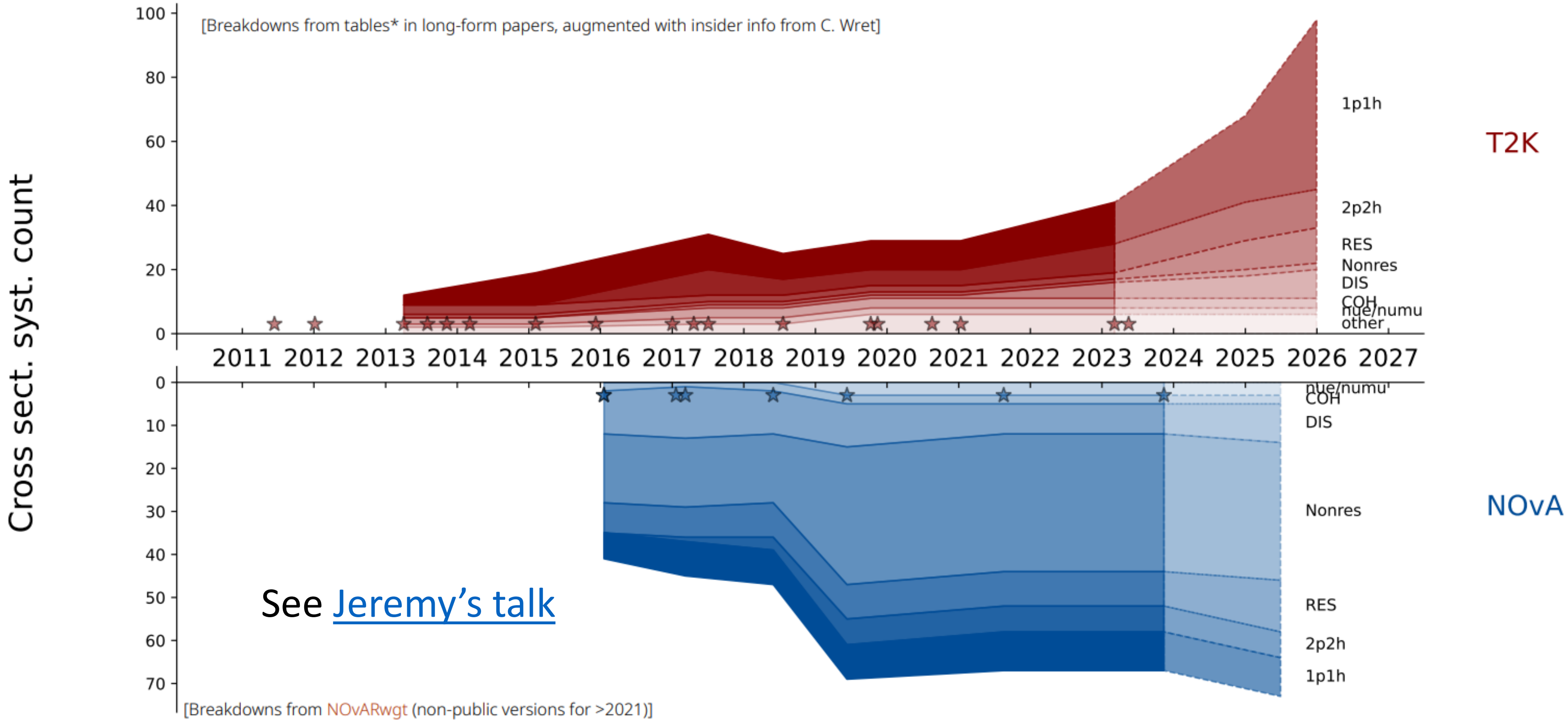




T2K+NOvA

There has been impressive progress of theory inputs.
Allowing to get better models and more realistic uncertainties describing reactions like CCQE, RES FSI etc.

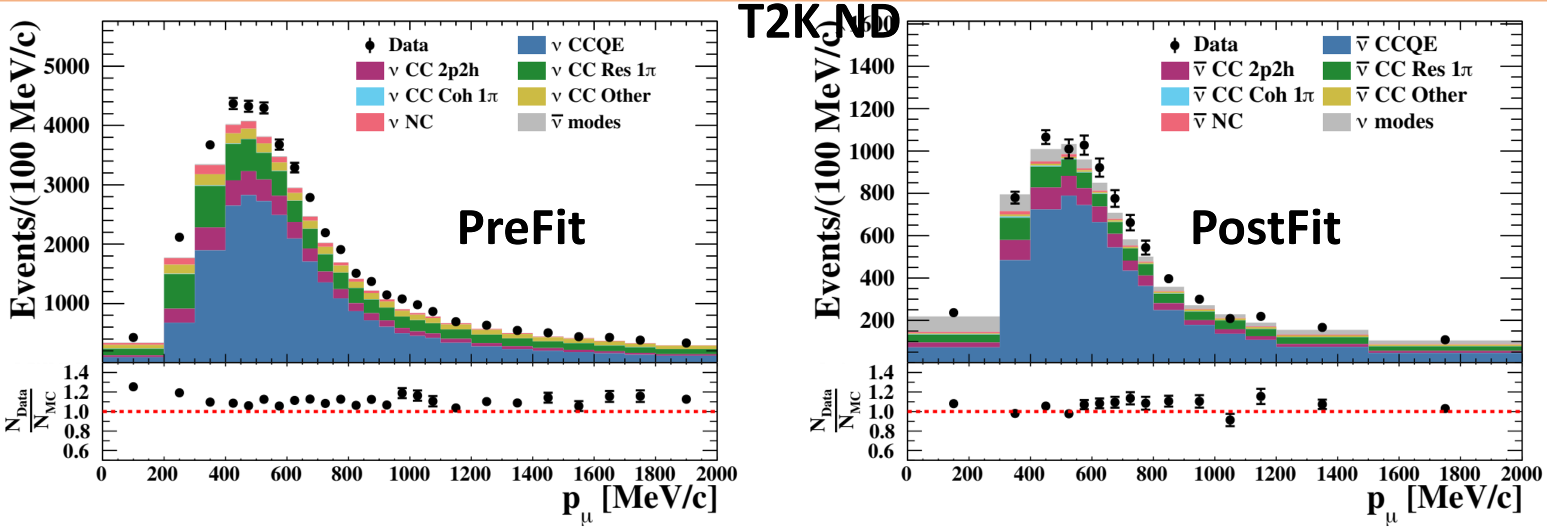
Near detectors are becoming more significant as the number of uncertainties rises.



Impact of near detectors

Near Detector allows to improve data MC agreement significantly

T2K ND



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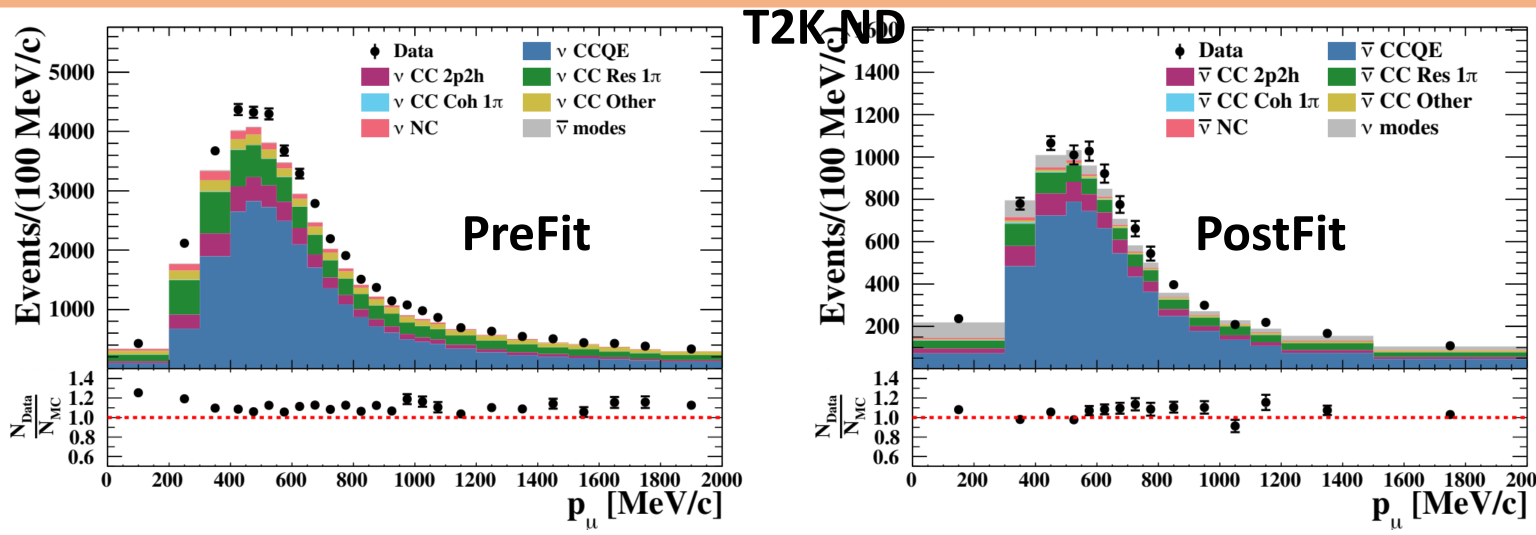
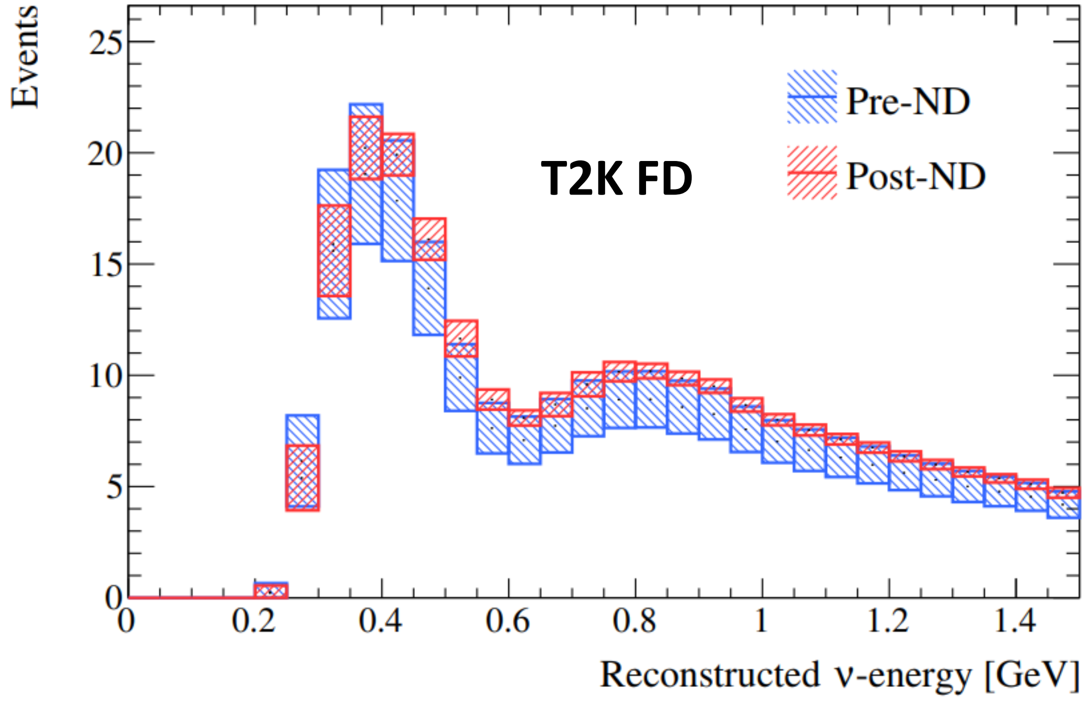


But also, significantly reduces uncertainty on predictions in fat detector.

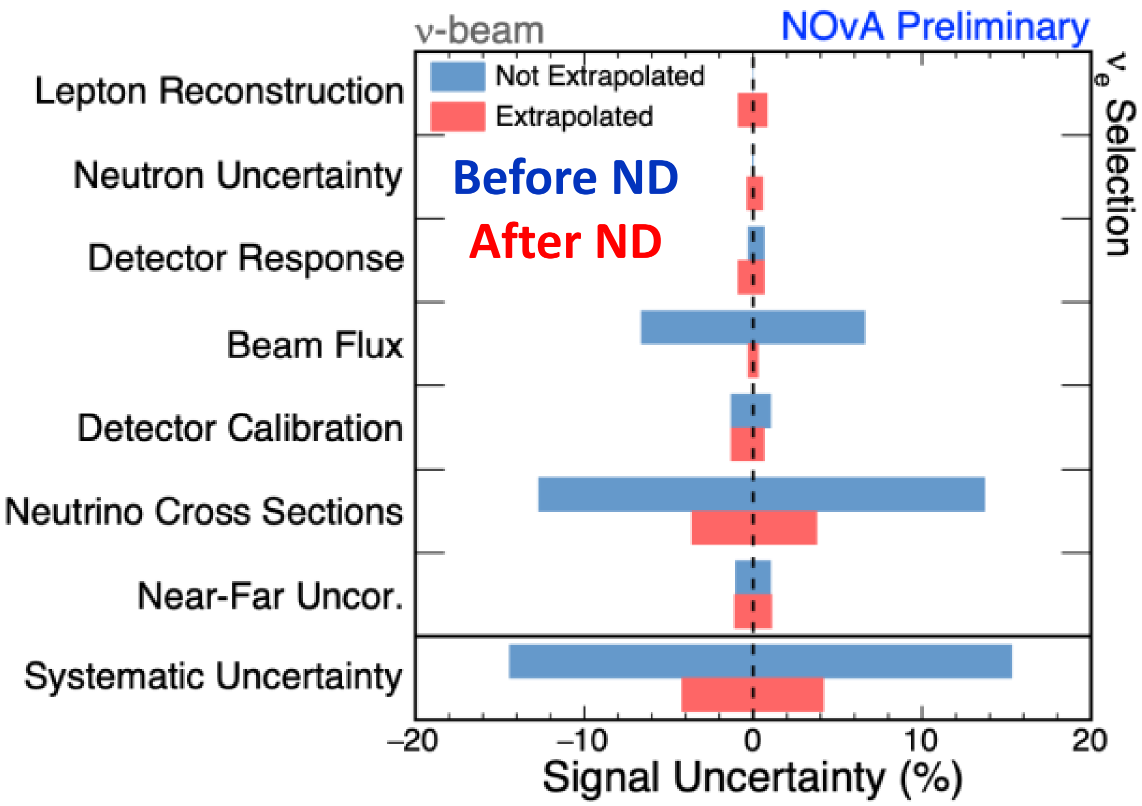


Notice scale of events observed at ND and FD

Impact of near detectors

We can see for NOvA ND also allows to significantly reduce uncertainties.

Especially one related to modelling of neutrino interactions.



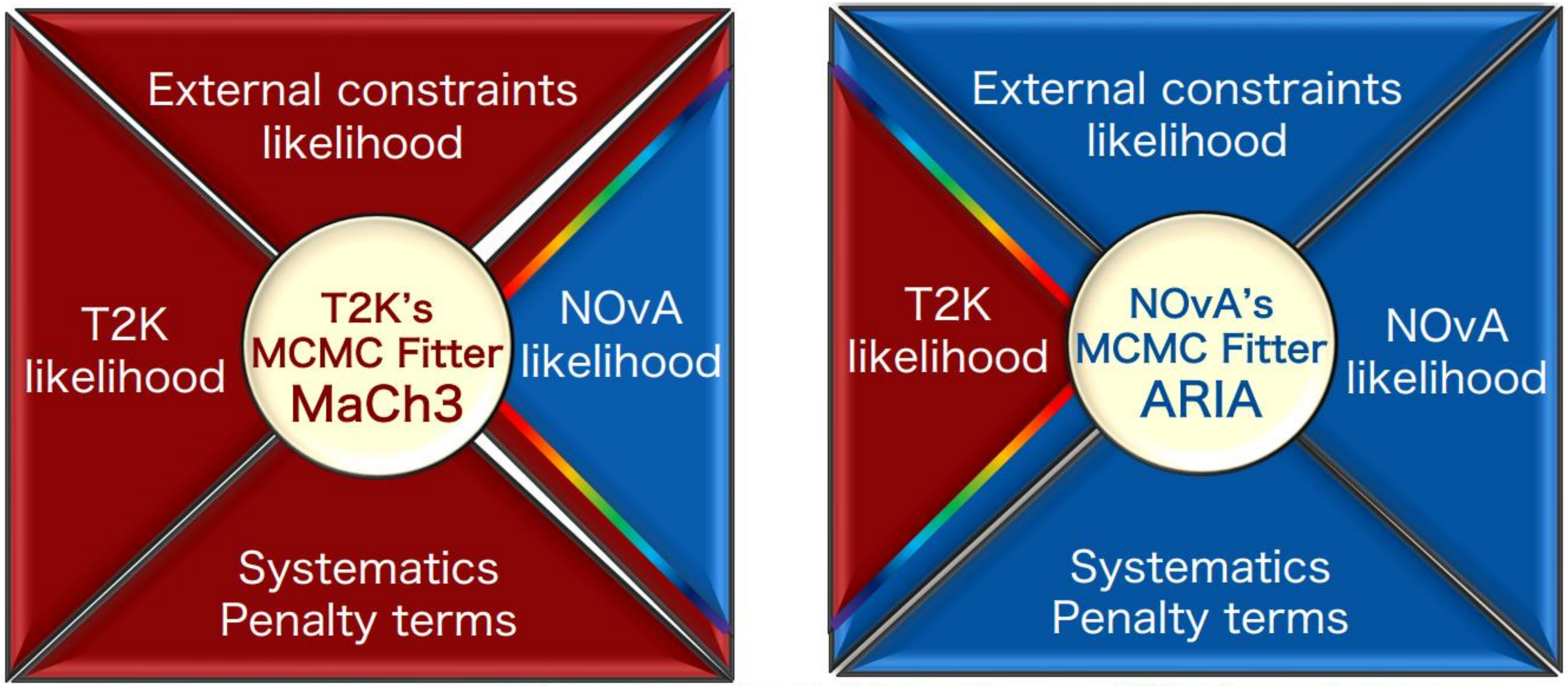
Chapter V: T2K+NOvA Methodology

Summary

- To measure ν oscillation one need only energy
- We can measure Energy using products of ν interaction
- Modelling of interactions is difficult ☹
- Using e/ν scattering to develop better models
- Near detectors are used for ν scattering and error reduction

T2K+NOvA

- Both T2K and NOvA have used their Bayesian Markov Chain Monte Carlo (MCMC) fitters.
- Both produce same output format: Posterior densities and credible intervals for parameters-of-interest.
- Independent implementation of the framework provided rigorous validation of the joint fit.



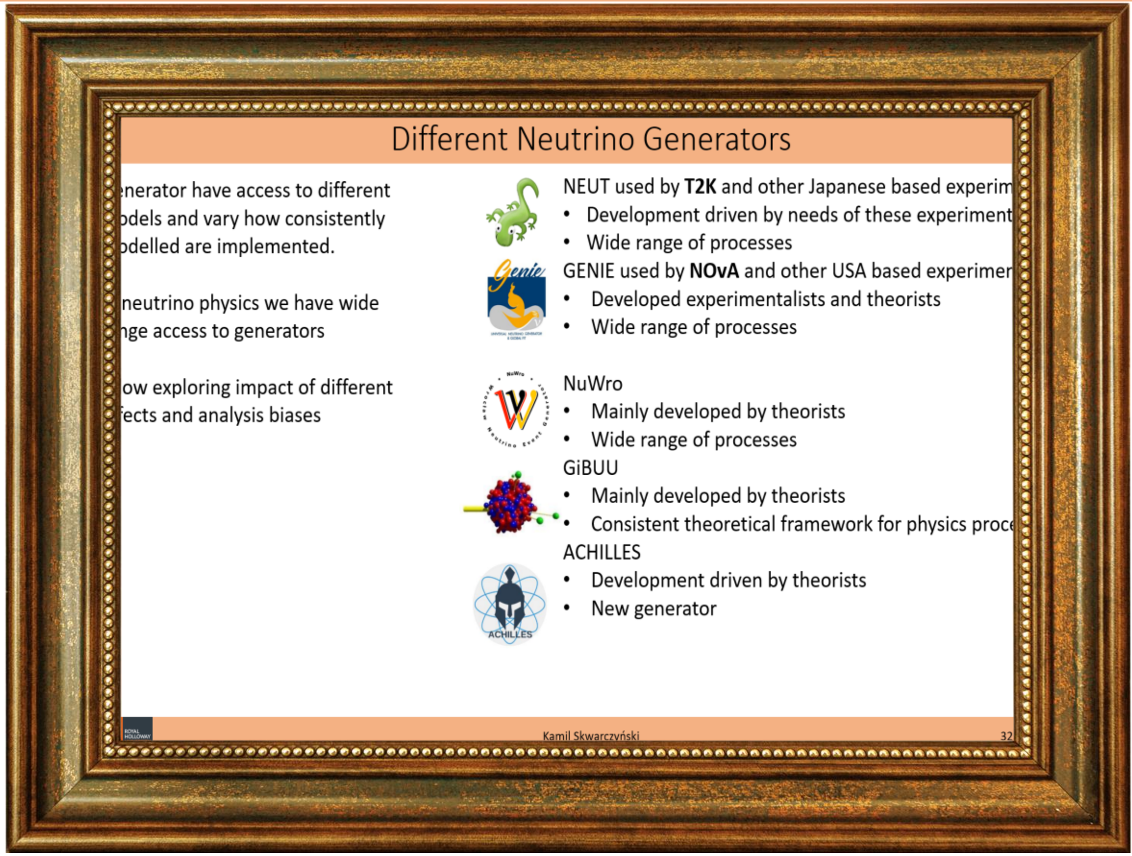
Red represents T2K codebase & blue shows NOvA codebase.

Simulated Data Studies

We have plethora of generators with multiple models available
We can run data fit with only one models configuration.
Uncertainties are built for single configuration

We know uncertainties can't cover all effects.

How to treat such unknown uncertainty?



Simulated Data Studies

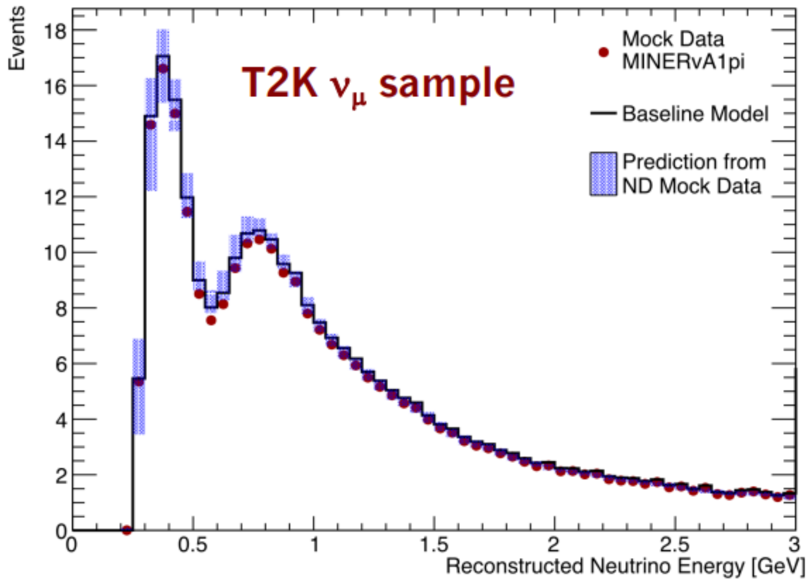
How to treat such unknown uncertainty?

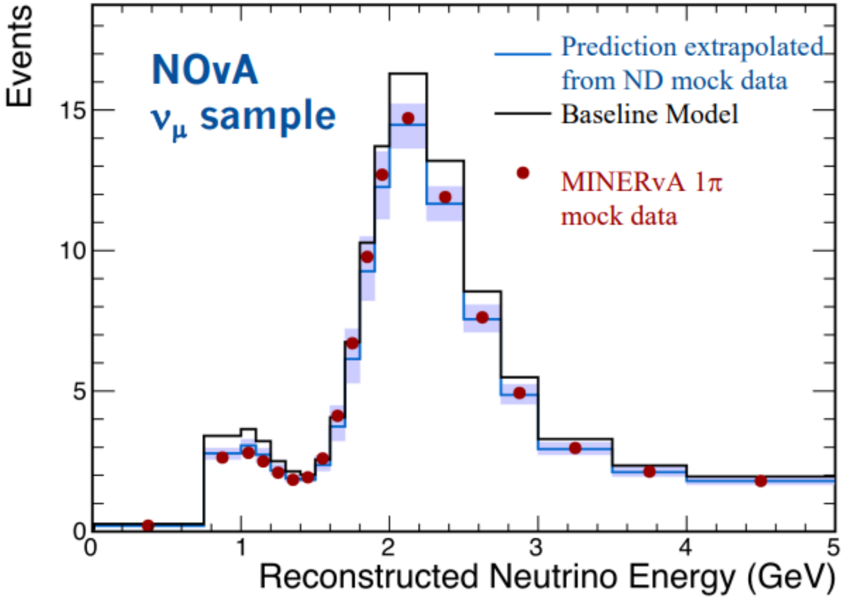
We use simulated data to evaluate the robustness of the fit against various alternate models

Reweight MC to alternative model and treat it as (simulated) „data".

Perform fit both for near and far detector

Compare with default fit





Simulated Data Studies

How to treat such unknown uncertainty?

We use simulated data to evaluate the robustness of the fit against various alternate models

Reweight MC to alternative model and treat it as (simulated) „data".

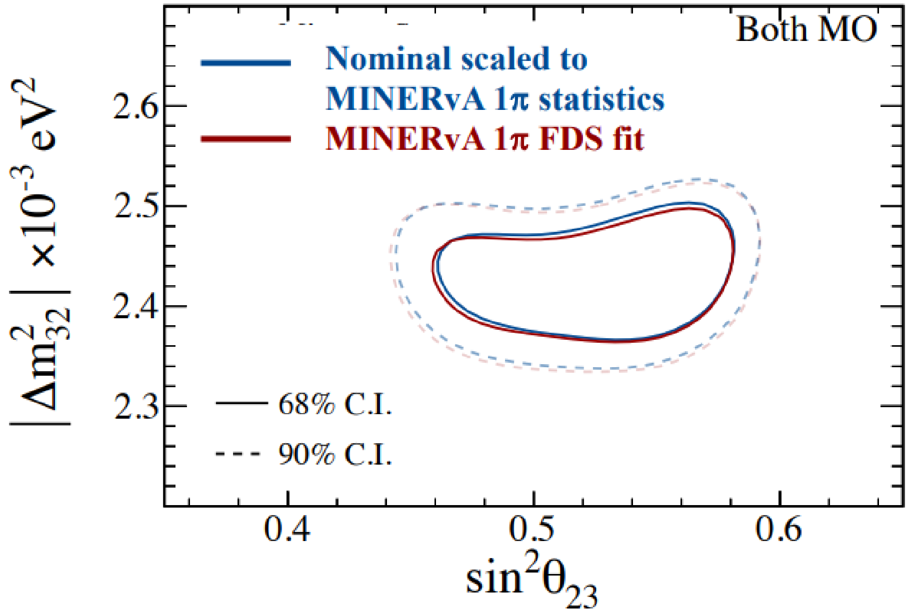
Perform fit both for near and far detector

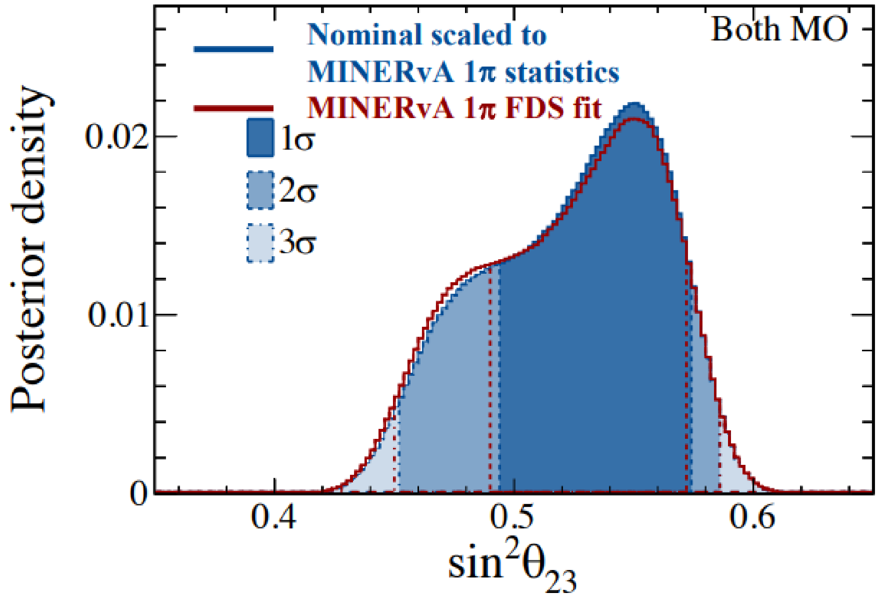
Compare with default fit

Run fit and analyse.

All simulated data were below set criterion

No need to inflate error due to out of model effects

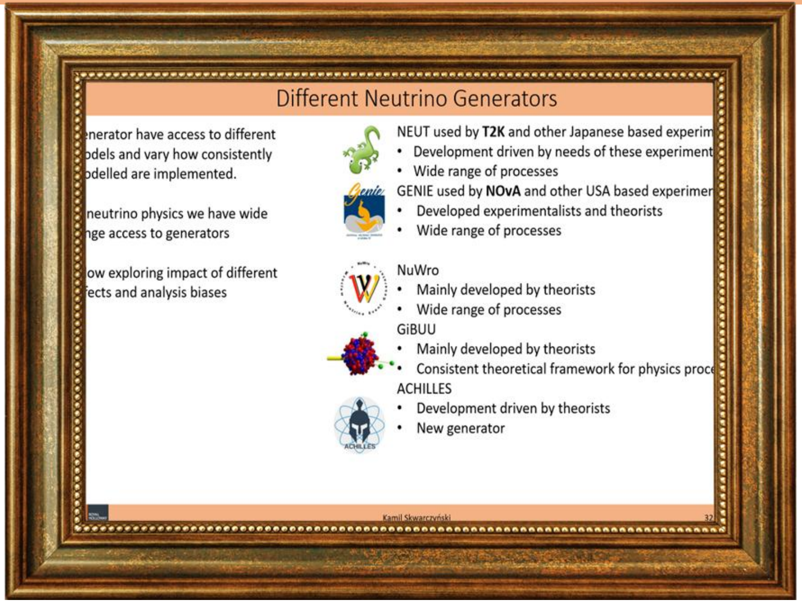




T2K and NOvA uses different neutrino generators and different models and interaction uncertainties.

Direct correlation of models impossible ☹

Exception ν_μ / ν_e and $\bar{\nu}_\mu / \bar{\nu}_e$ cross-section uncertainties, treatment is identical (large $\boldsymbol{\delta_{CP}}$ impact)



Impact of Correlations – Nightmare Studies

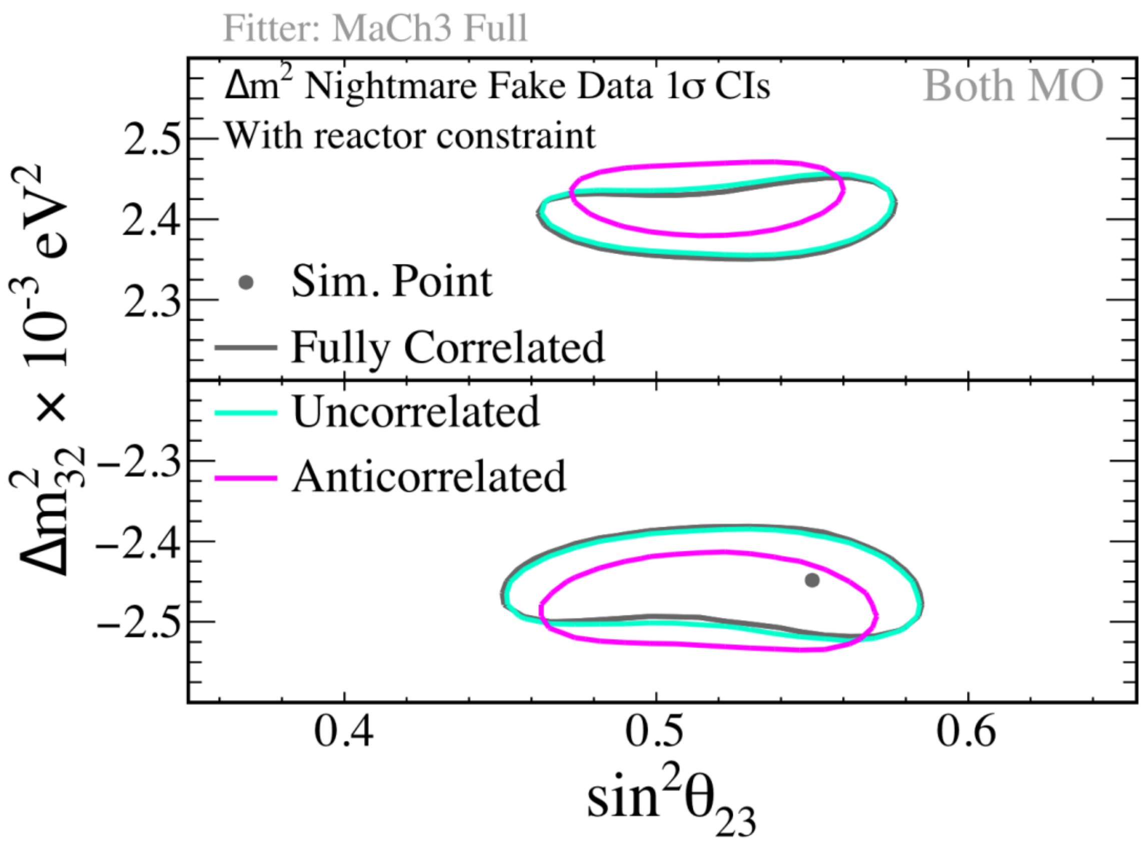
T2K and NOvA uses different neutrino generators and different models and interaction uncertainties.

Direct correlation of models impossible ☹

Exception ν_μ / ν_e and $\bar{\nu}_\mu / \bar{\nu}_e$ cross-section uncertainties, treatment is identical (large $\boldsymbol{\delta_{CP}}$ impact)

Fabricated parameters for each experiment to simulate a fully correlated bias for Δm^2_{32} or $\sin^2\theta_{23}$

- Keeping the parameters either fully correlated, uncorrelated, or fully anti-correlated in the fit
- Uncorrelated and correlated (to follow simulated bias) agree well while incorrectly correlating systematics leads to biases
- Impact of correlations merits further investigation for future analyses with increased statistics

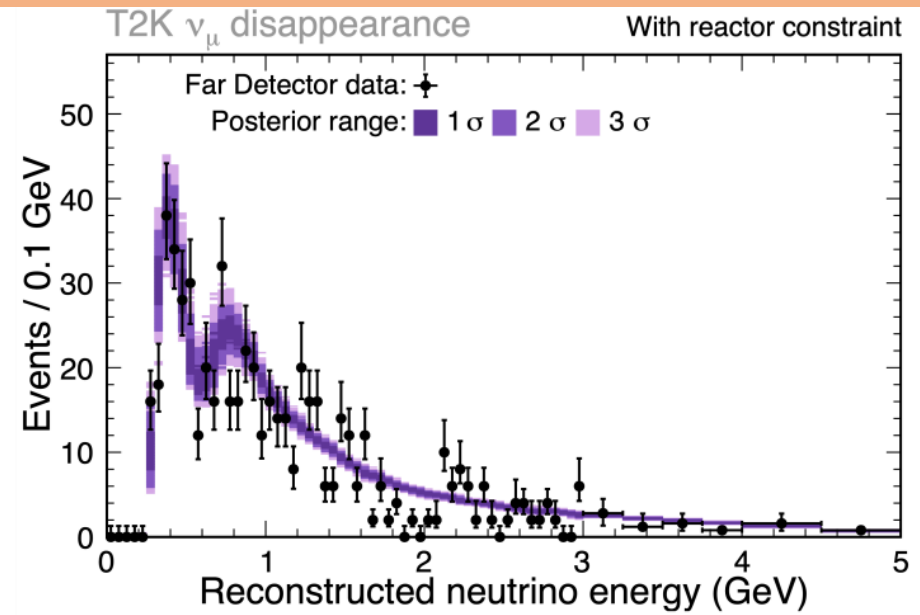


Epilogue: All Comes Together

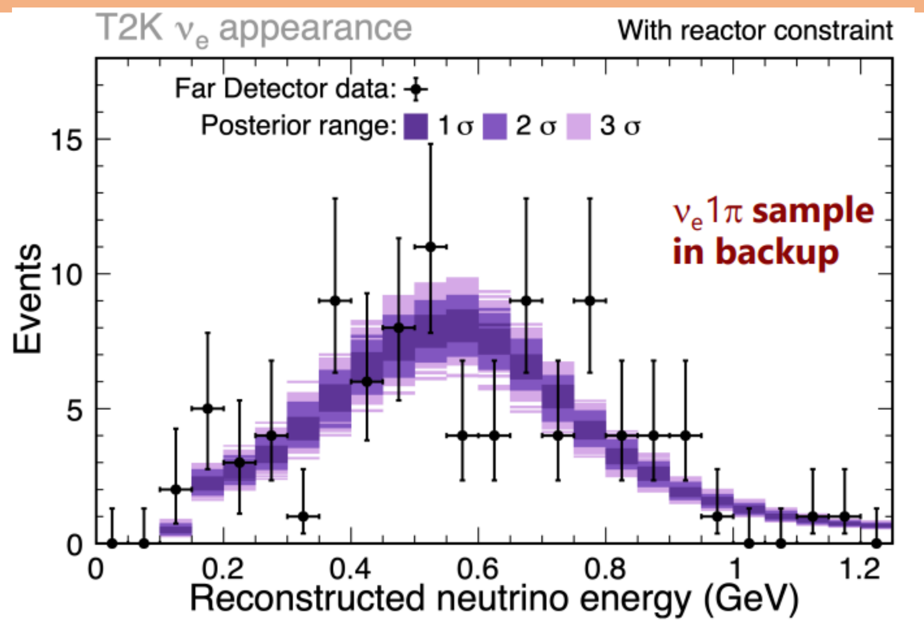
Summary

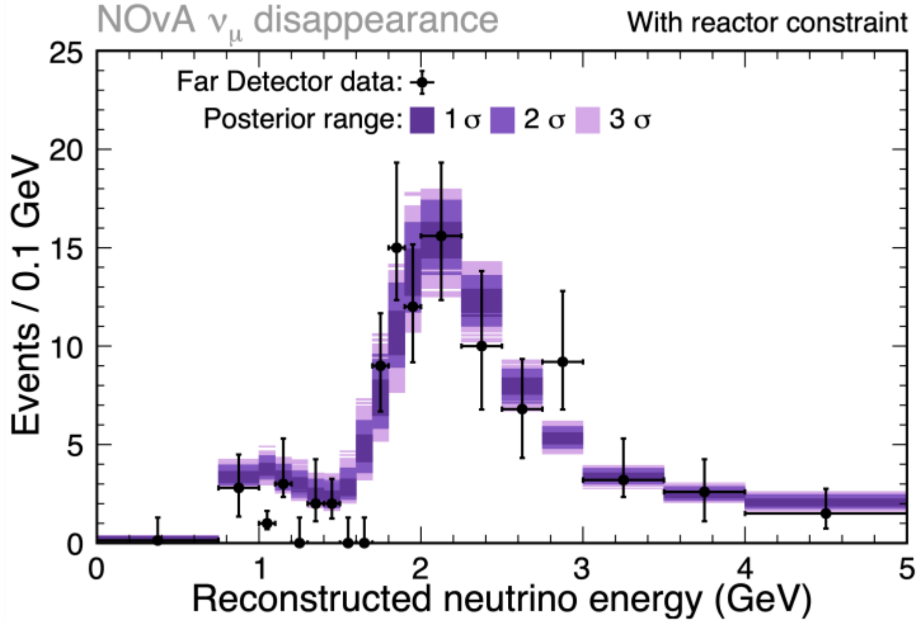
- To measure ν oscillation one need only energy
- We can measure Energy using products of ν interaction
- Modelling of interactions is difficult ☹
- Using e/ν scattering to develop better models
- Near detectors are used for ν scattering and error reduction
- T2K+NOvA performer several simulated data studies all successful below threshold

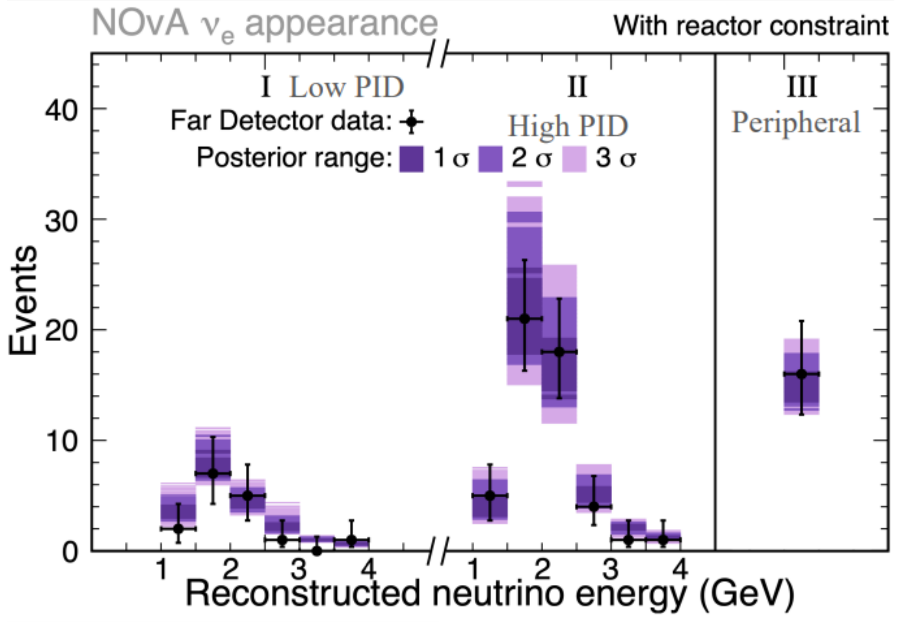
FD Data Samples



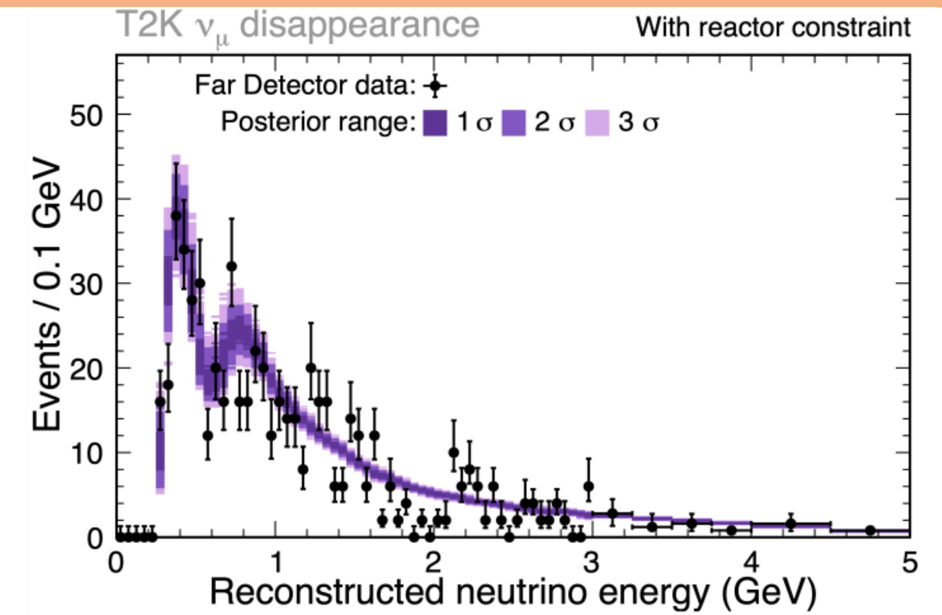
Good agreement between data and MC for FD samples at T2K and NOvA

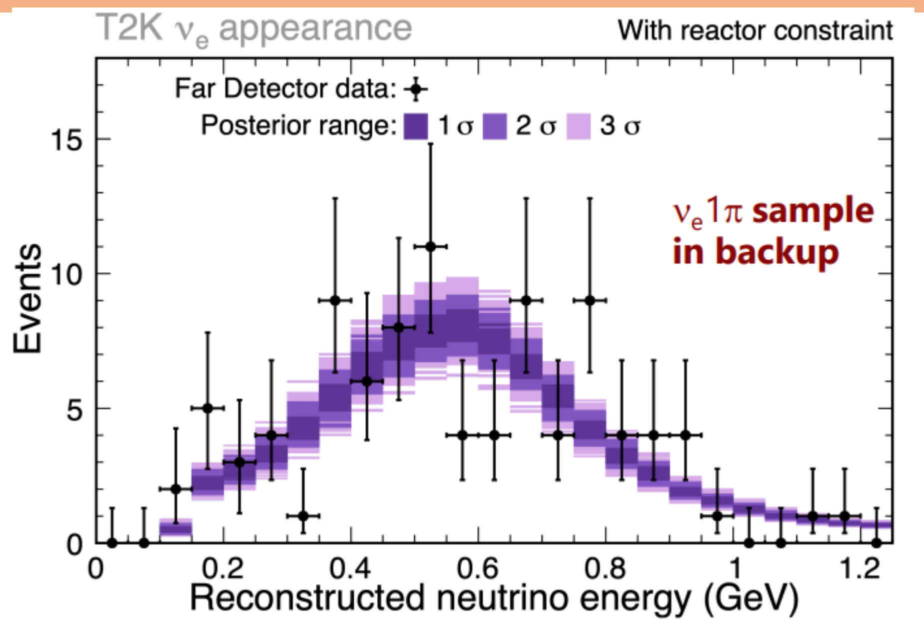






FD Data Samples





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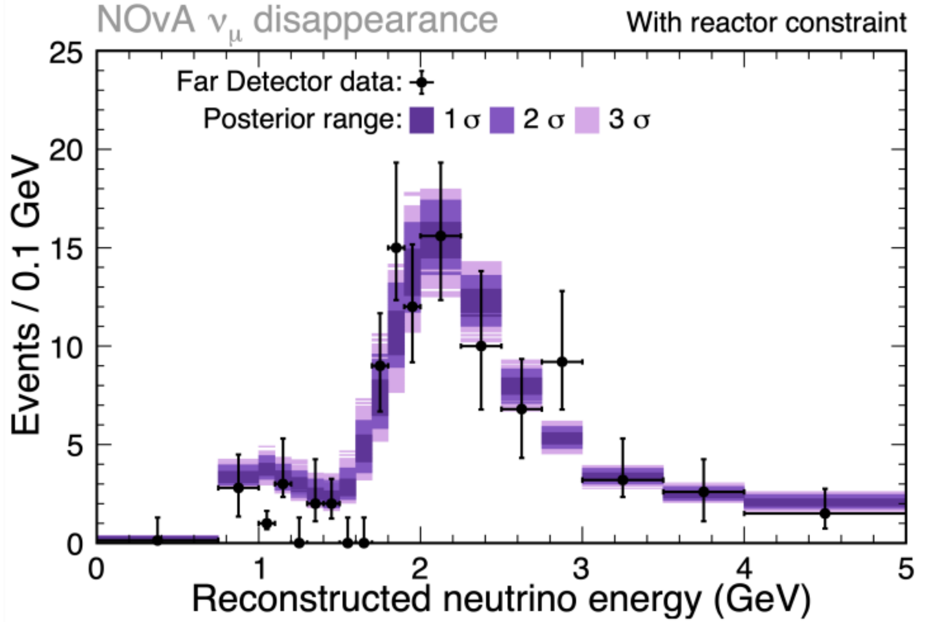
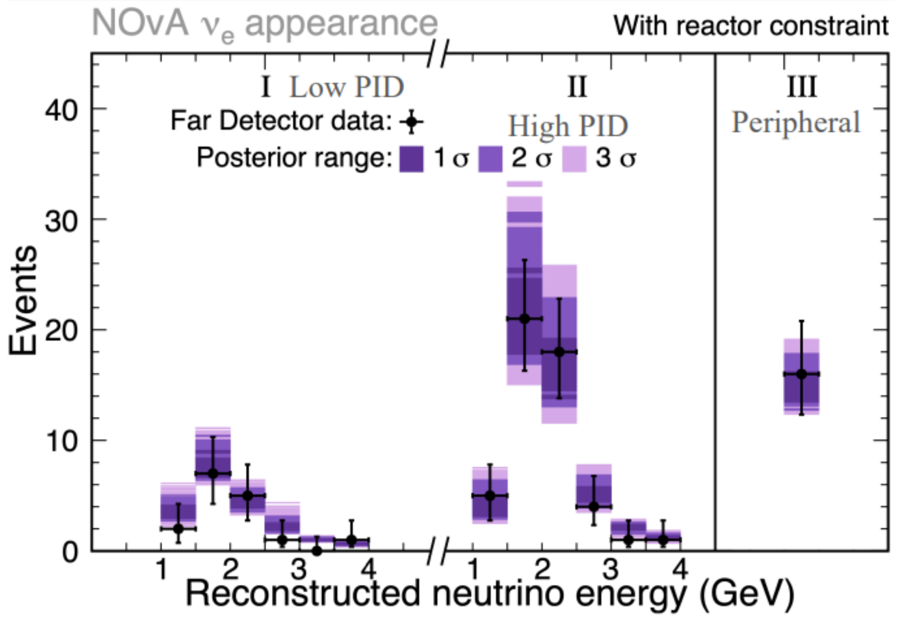


Channel	NOvA	T2K	Total
ν_e	82	$94_{(\nu_e)}$ $14_{(\nu_e 1\pi)}$	**190**
$\bar{\nu}_e$	33	16	**49**
ν_μ	211	318	**529**
$\bar{\nu}_\mu$	105	137	**242**



Jarlskog and CP Violation

Appearance channel

$$P(\nu_\mu \to \nu_e),\ P(\bar{\nu}_\mu \to \bar{\nu}_e) \approx \sin^2(2\theta_{13})\sin^2(\theta_{23})\sin^2\left(\frac{1.27\Delta m^2_{32}L}{E}\right) \mp \frac{1.27\Delta m^2_{21}L}{E} 8 J_{CP} \sin^2\left(\frac{1.27\Delta m^2_{32}L}{E}\right)$$

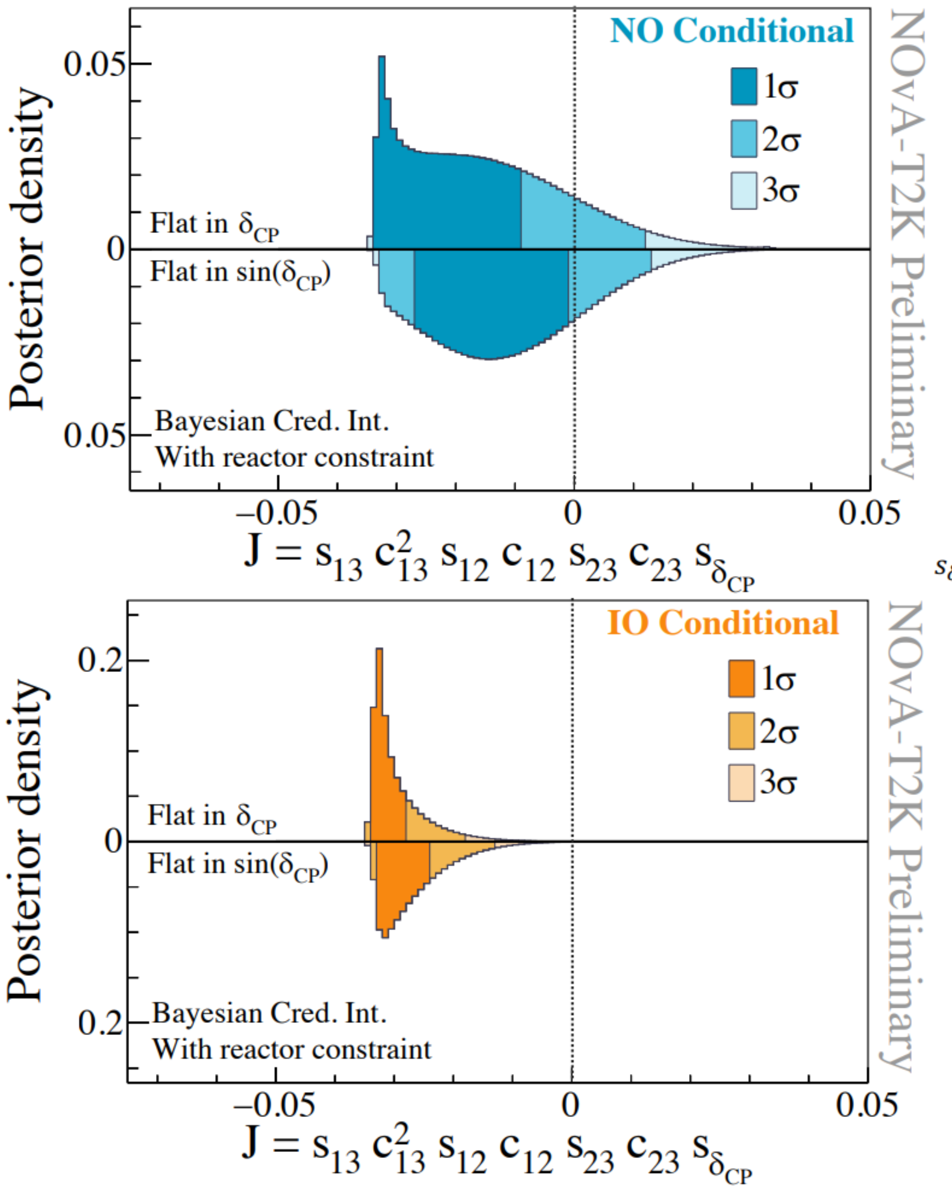
Jarlskog-invariant is a parameterization independent way to measure CP violation.

J = 0: CP-Conservation

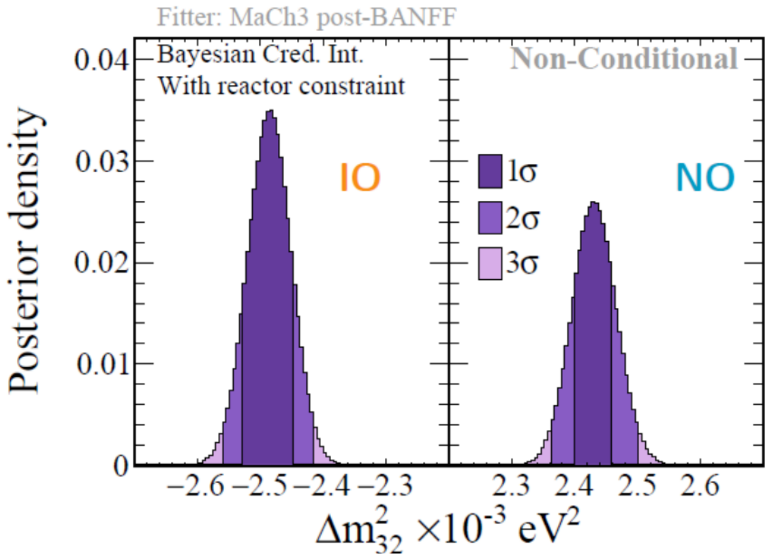
J != 0: CP-Violation

For Normal Ordering, a considerably wider range of probable values for J

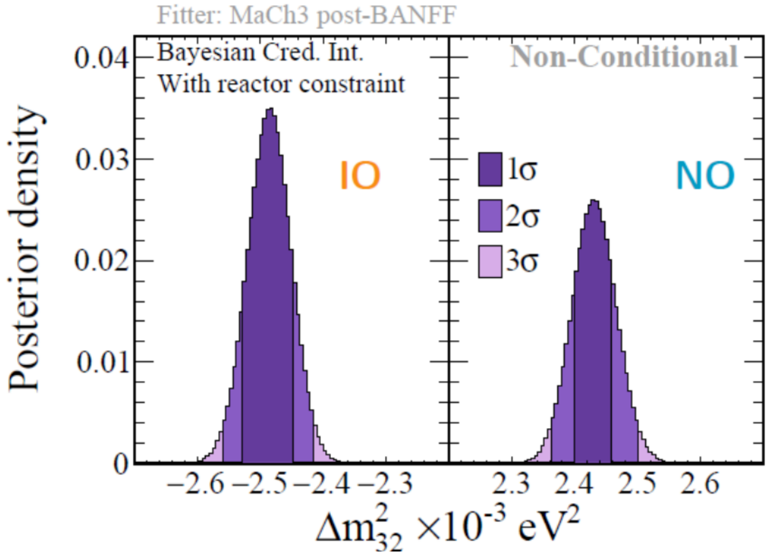
J = 0 lies outside the 3sigma interval for the Inverted Ordering



$c_{ij} = \cos\theta_{ij}$
$s_{ij} = \sin\theta_{ij}$
$s_{\delta_{CP}} = \sin\delta_{CP}$

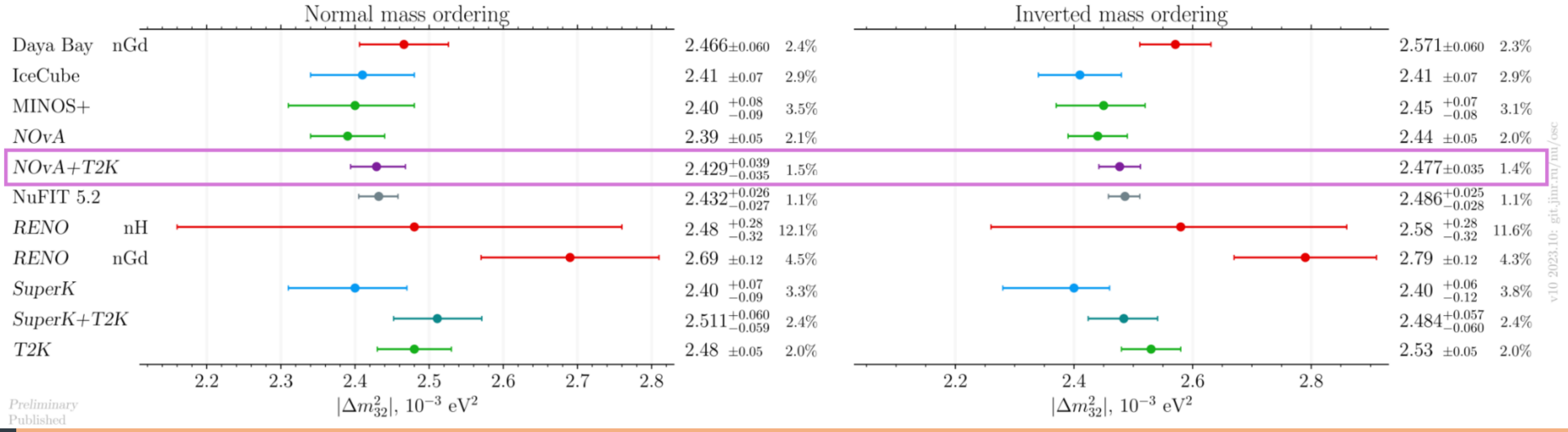


Mild preference for inverted ordering



Mild preference for inverted ordering

Smallest uncertainty in Δm2 32 < 2 %



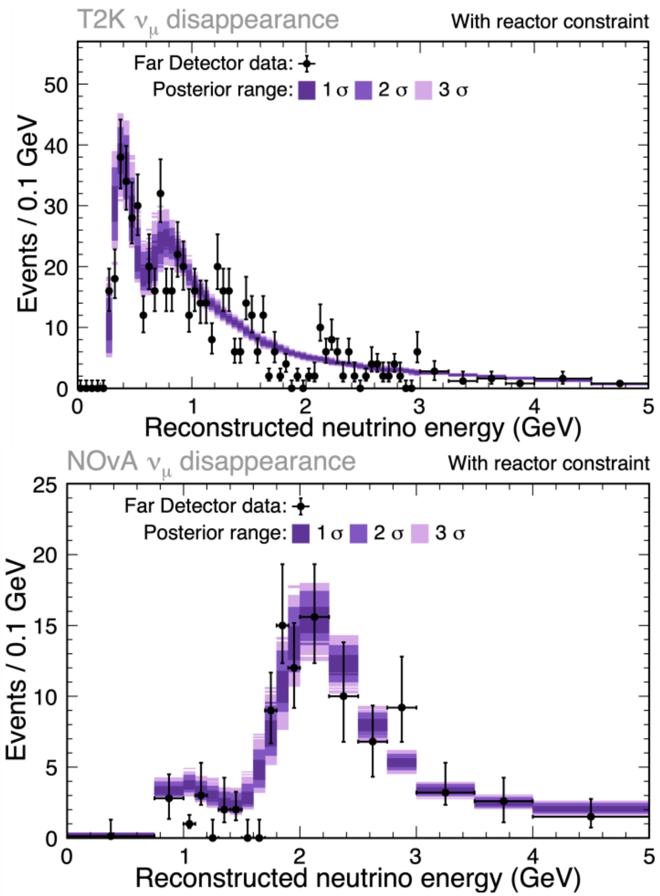
Bonus: Looking Beyond

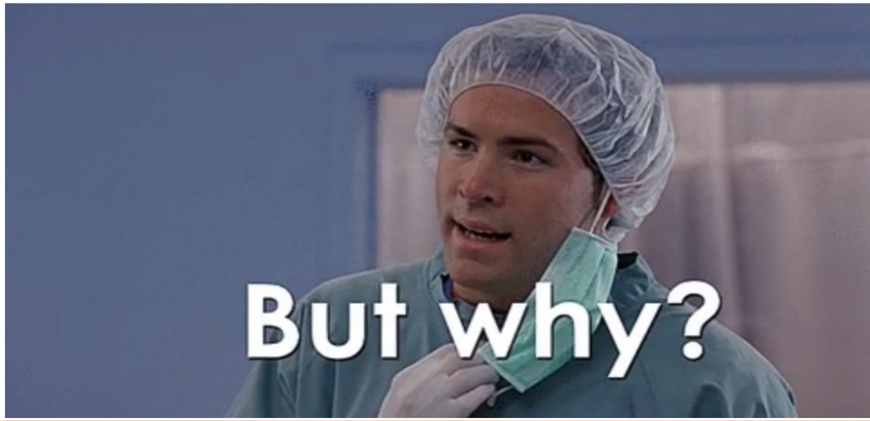
Summary

- To measure ν oscillation one need only energy
- We can measure Energy using products of ν interaction
- Modelling of interactions is difficult ☹
- Using e/ν scattering to develop better models
- Near detectors are used for ν scattering and error reduction
- T2K+NOvA performed several simulated data studies all successful below threshold
- T2K+NOvA performed measurement of mass ordering parameter

One Step Back

Some may ask why I focused so much on modelling uncertainties if we have huge statistical error.

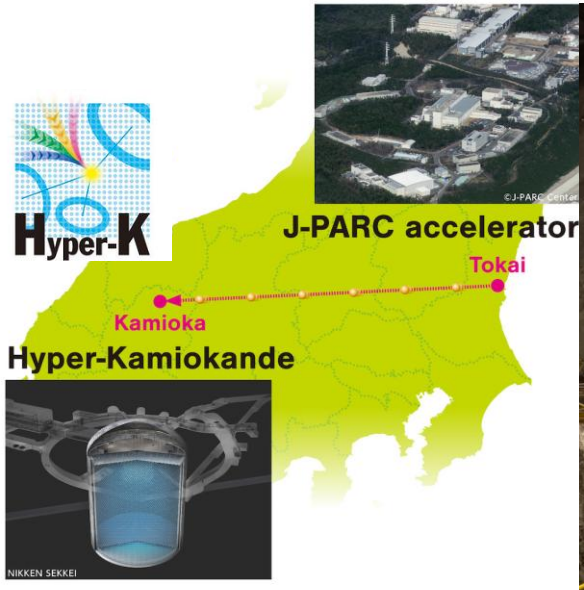


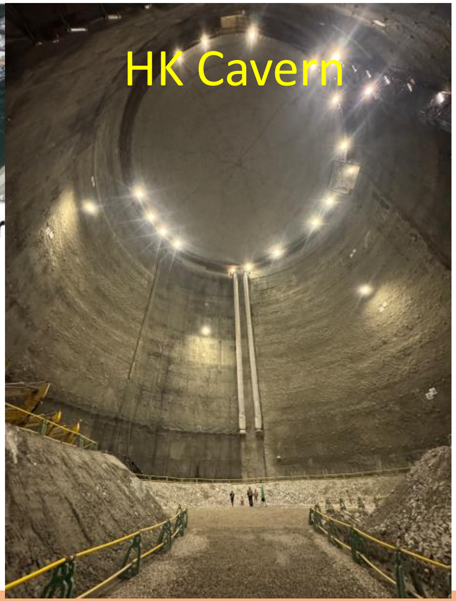


Hyper Kamiokande

Current experiment will be replaced with new much larger at scale.

Successor of T2K will be Hyper-Kamiokande (Japan)



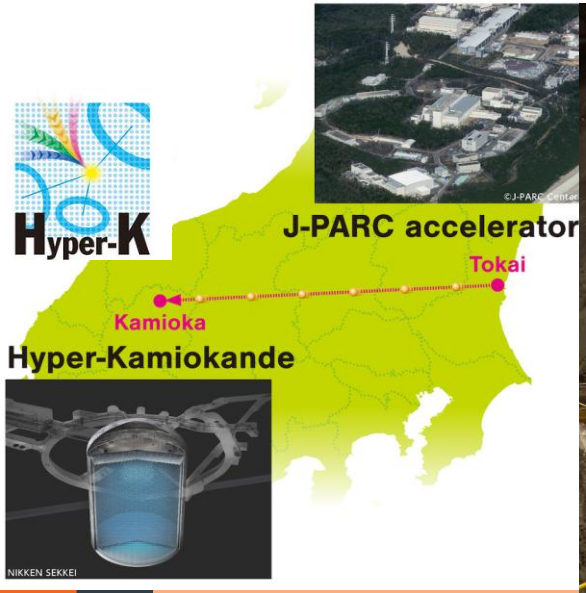


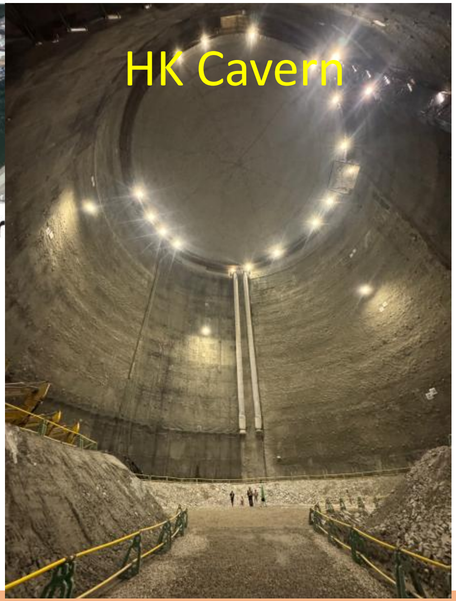
Hyper Kamiokande and DUNE

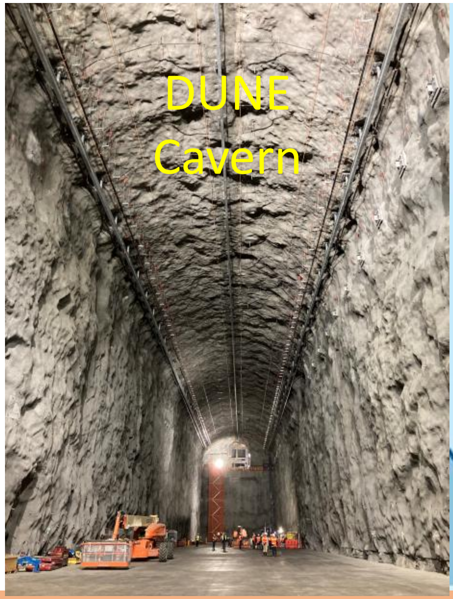
Current experiment will be replaced with new much larger at scale.

Successor of T2K will be Hyper-Kamiokande (Japan)

Successor to NOvA will be DUNE (USA).





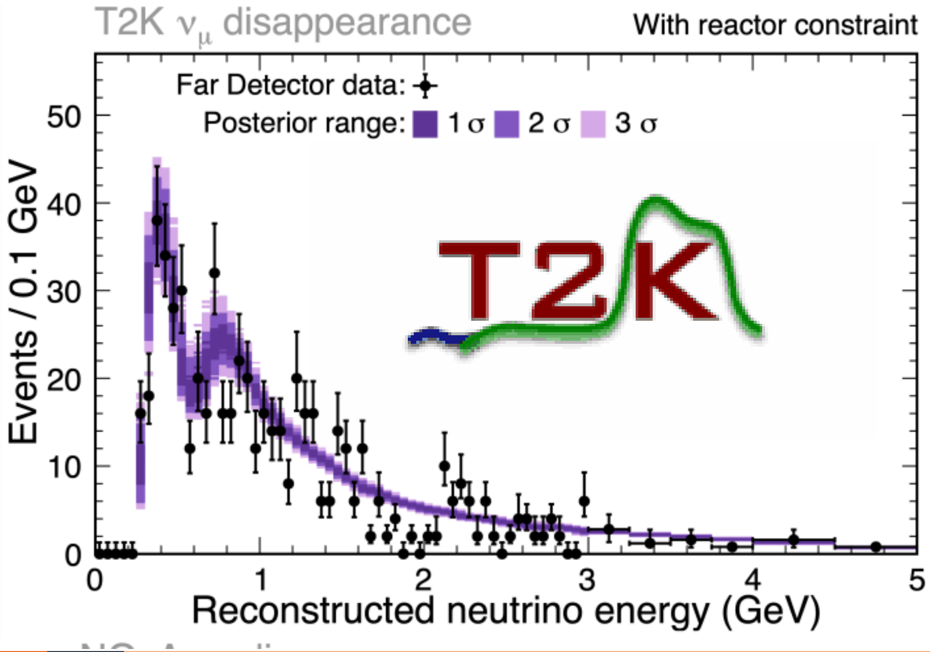


New experiment can expect thousand of events.

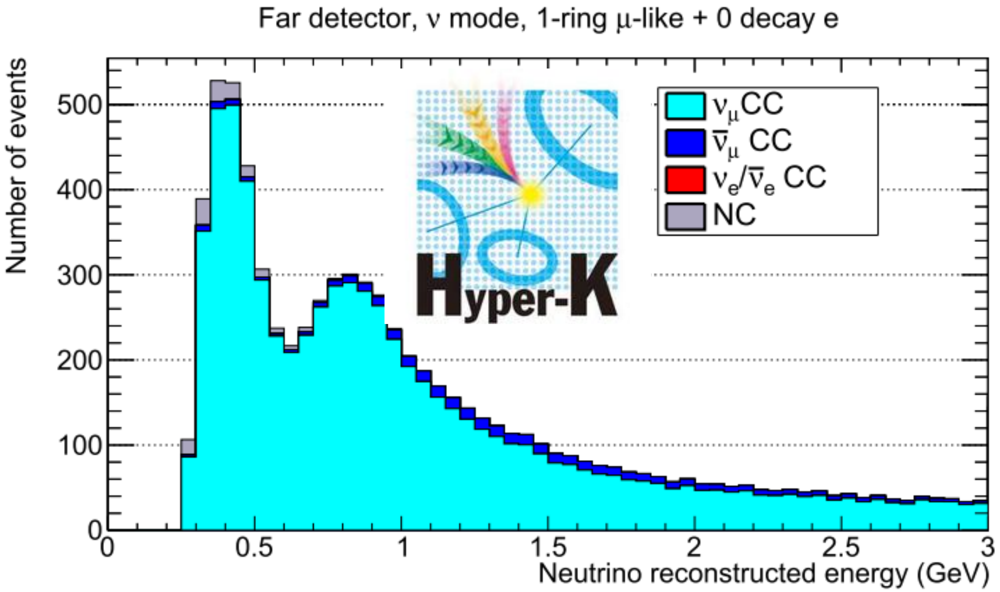
With such high number of events stat error will be much lower.

Thus, progress on modelling done in current experiments will directly transfer to future.

Around 500 events for this sample

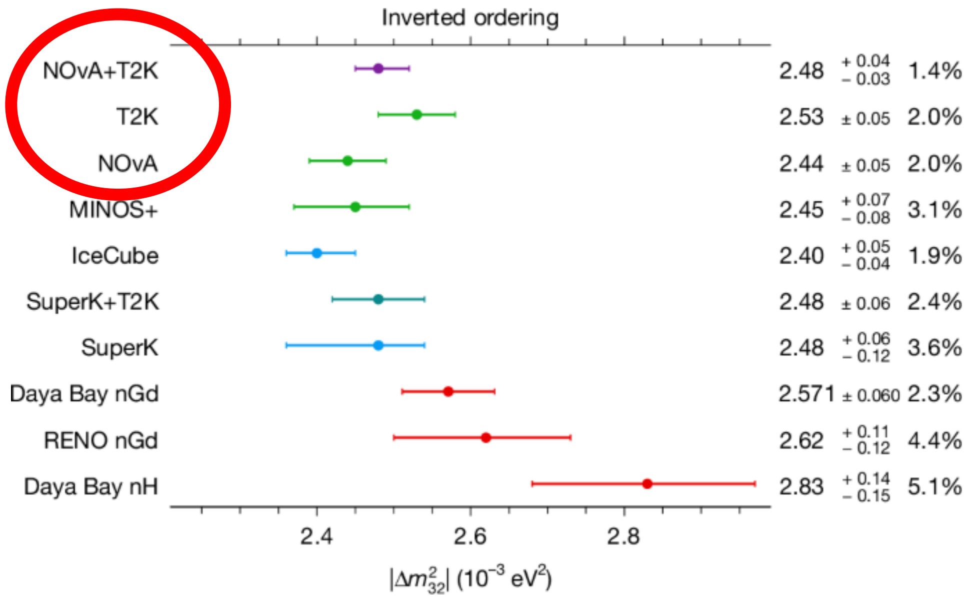


Around 9k events for this sample



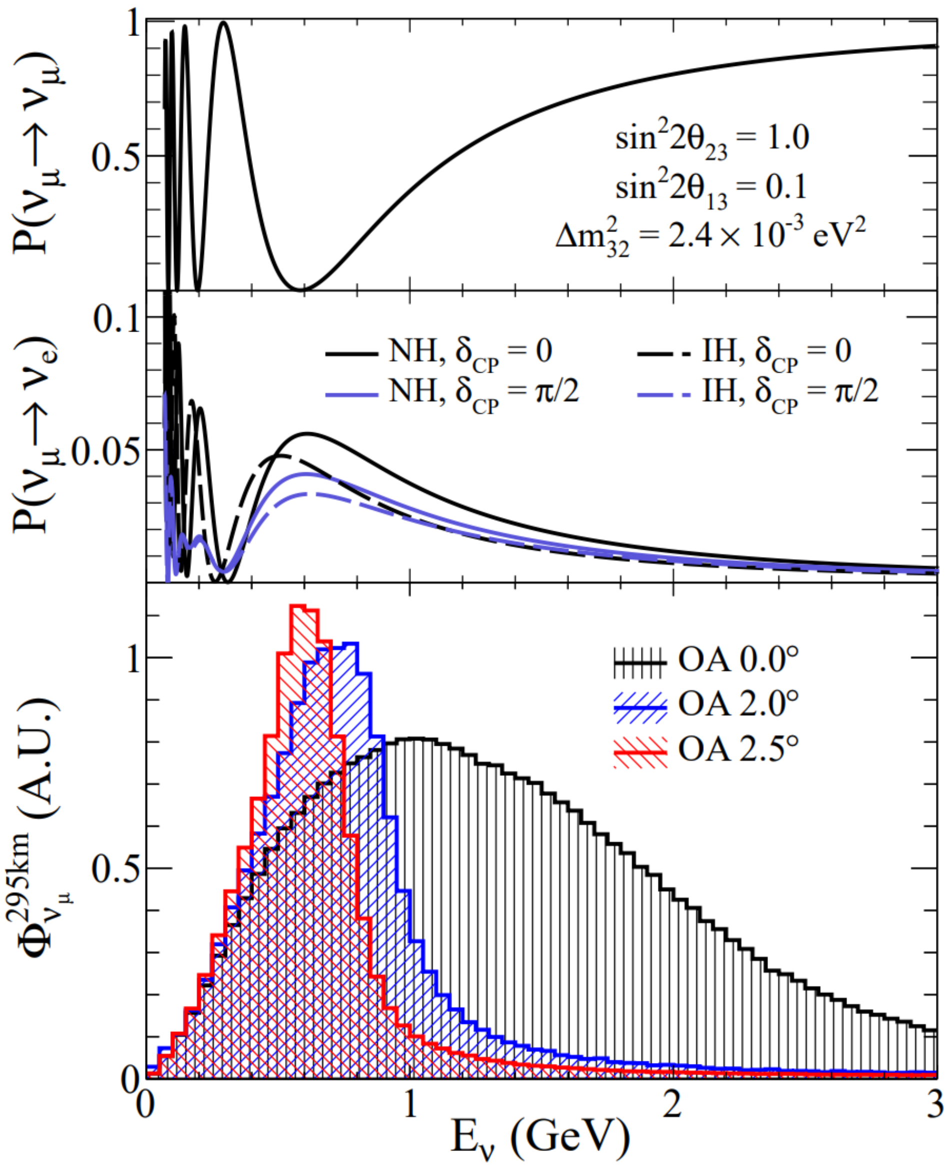
Summary

- To measure ν oscillation one need only energy
- We can measure Energy using products of ν interaction
- Modelling of interactions is difficult ☹
- Using e/ν scattering to develop better models
- Near detectors are used for ν scattering and error reduction
- T2K+NOvA performed several simulated data studies all successful below threshold
- T2K+NOvA performed measurement of mass ordering parameter
- Future Experiments like HK and DUNE will require more sophisticate modelling

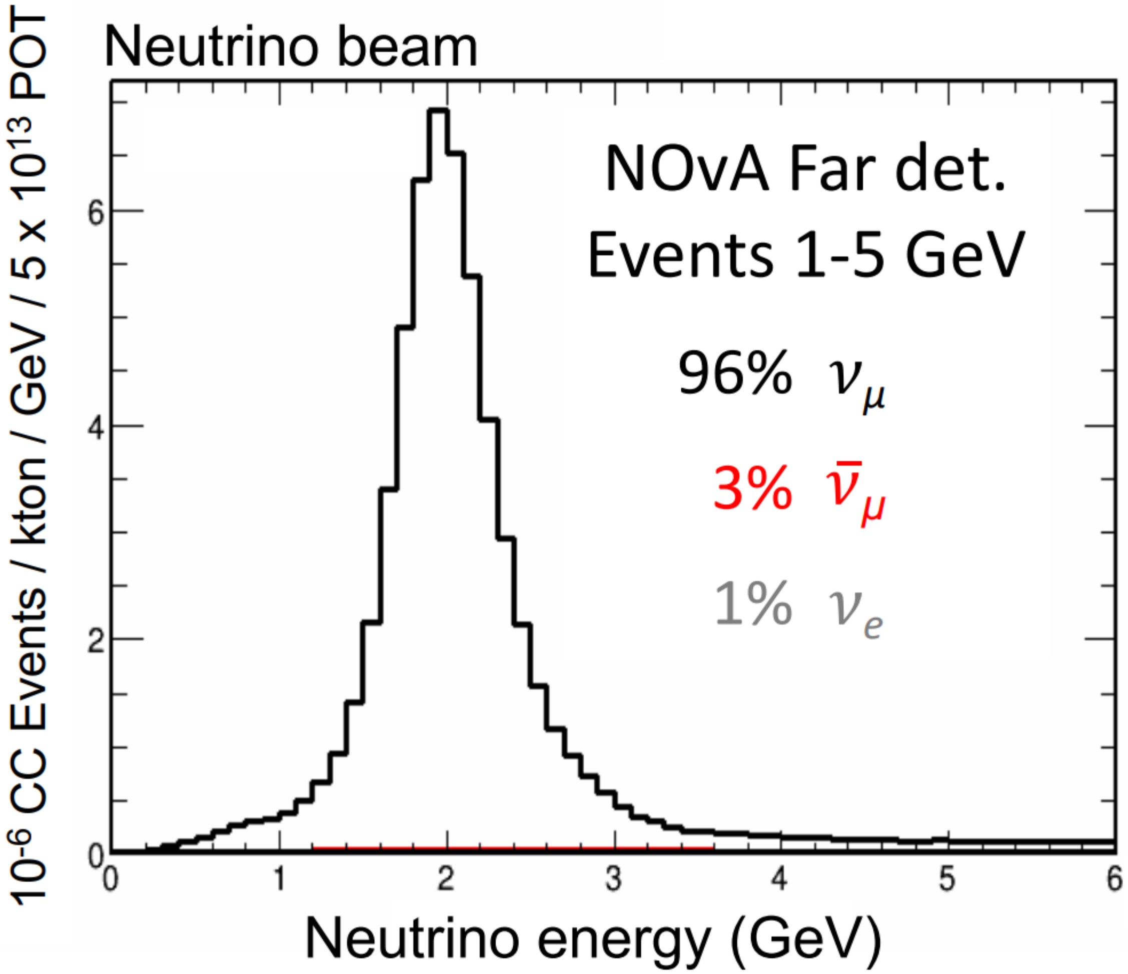


Backup

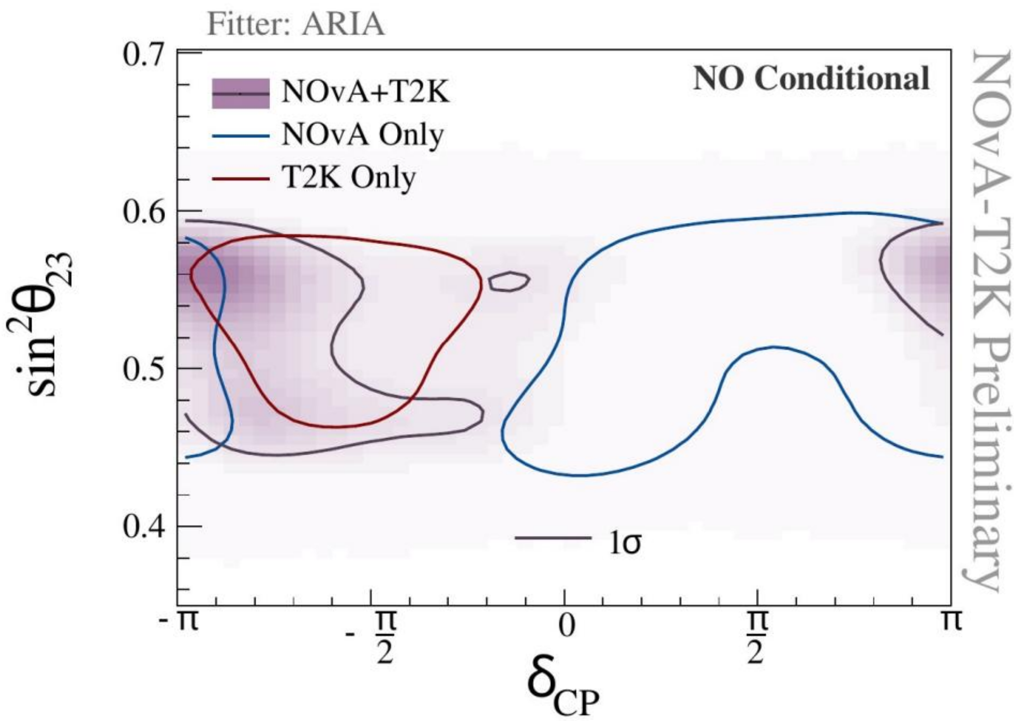
Flux

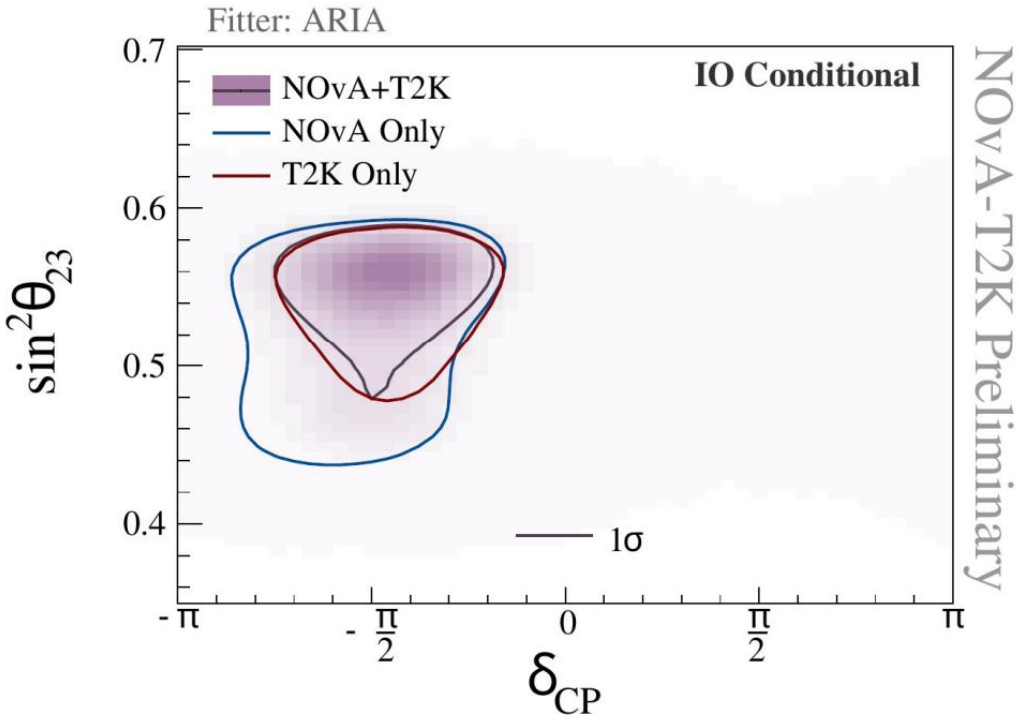


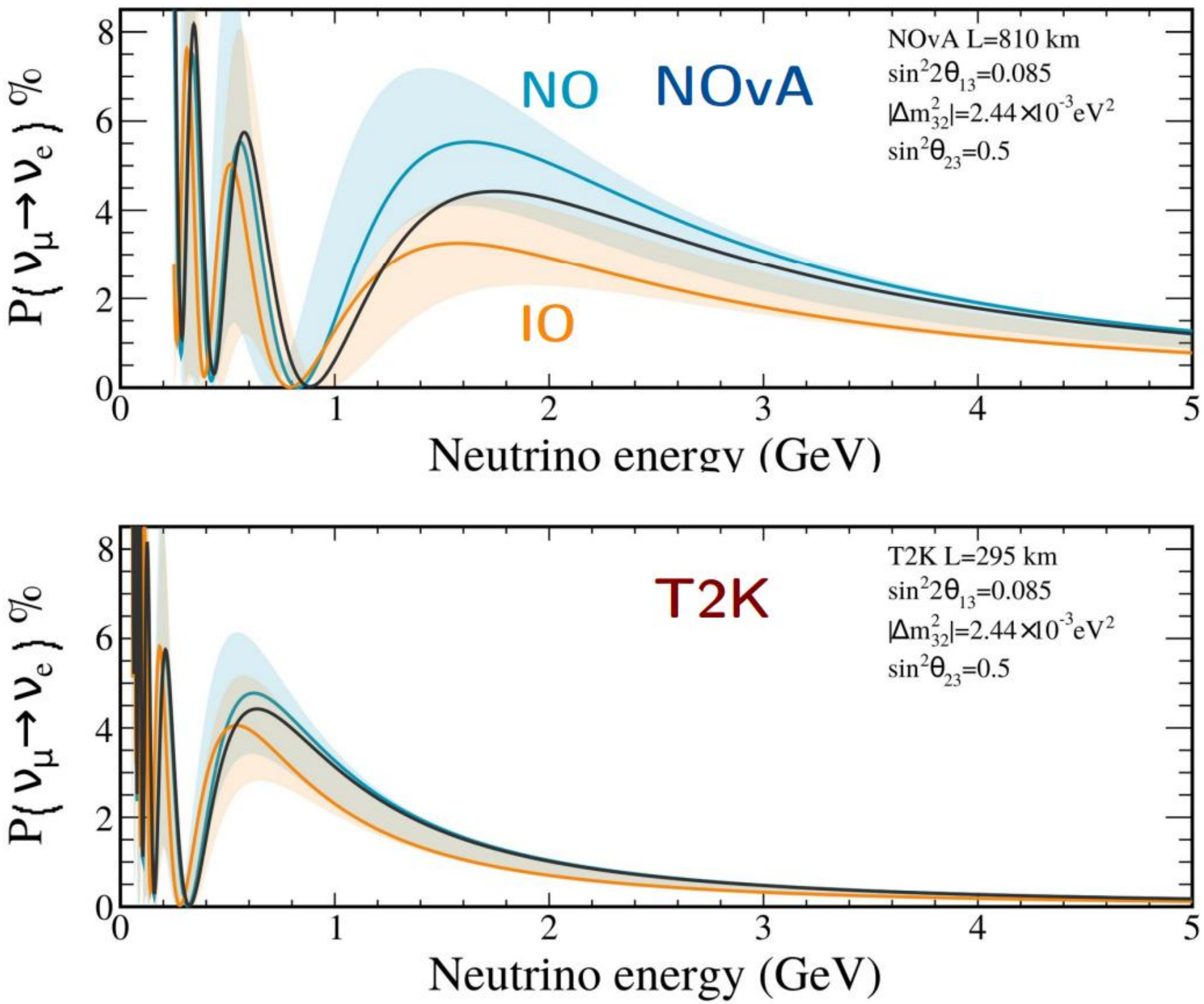
P(νμ → νμ)
sin²2θ23 = 1.0
sin²2θ13 = 0.1
Δm²32 = 2.4 × 10⁻³ eV²
P(νμ → νe)
NH, δCP = 0
NH, δCP = π/2
IH, δCP = 0
IH, δCP = π/2
Φ 295km νμ (A.U.)
OA 0.0°
OA 2.0°
OA 2.5°
Eν (GeV)



Neutrino beam
10⁻⁶ CC Events / kton / GeV / 5 x 10¹³ POT
NOvA Far det.
Events 1-5 GeV
96% νμ
3% ν̄μ
1% νe
Neutrino energy (GeV)

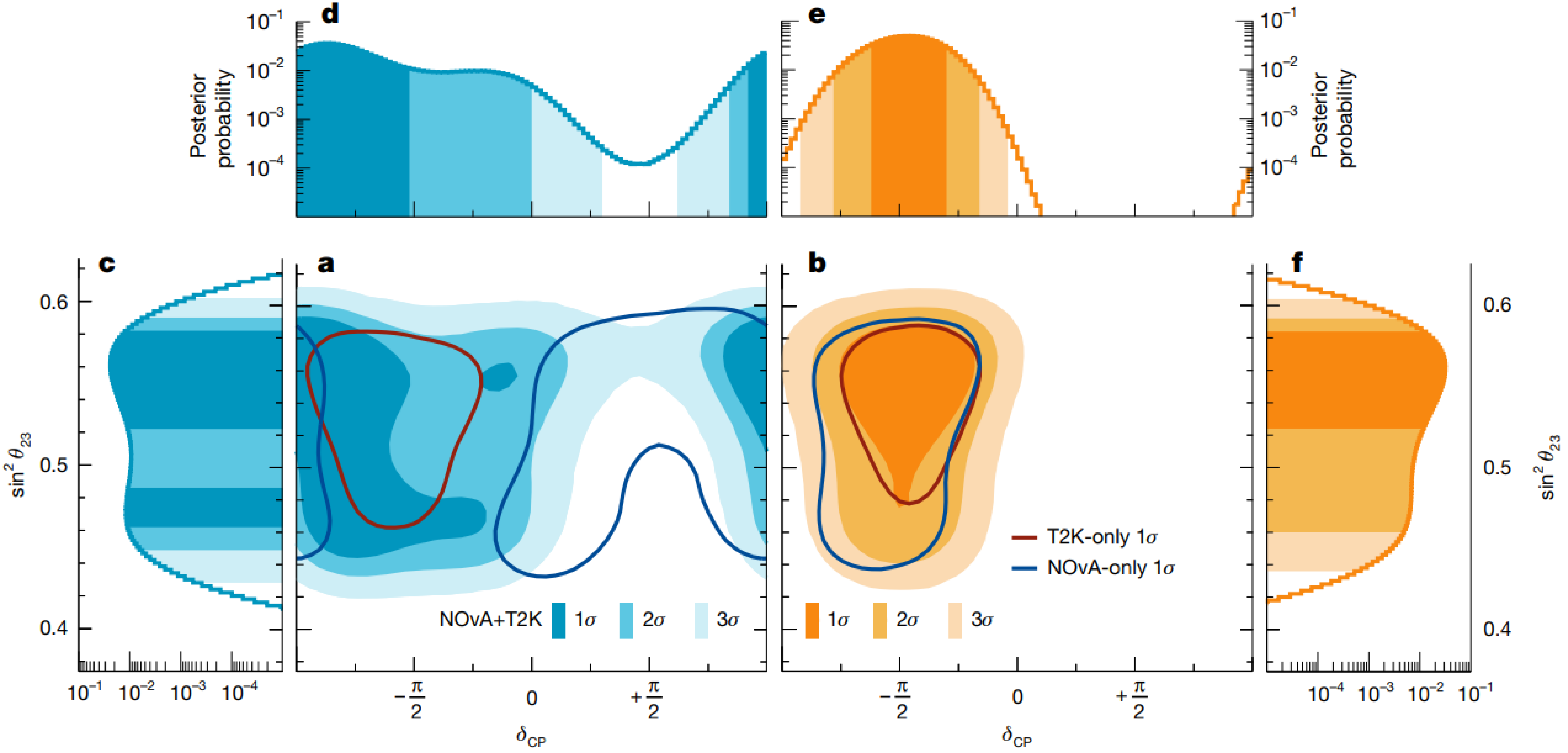

Fitter: ARIA
NO Conditional
NOvA+T2K
NOvA Only
T2K Only
1σ
NOvA-T2K Preliminary
sin²θ₂₃
δCP


Fitter: ARIA
IO Conditional
NOvA+T2K
NOvA Only
T2K Only
1σ
NOvA-T2K Preliminary
sin²θ₂₃
δCP



NO
NOvA
IO
NOvA L=810 km
$\sin^2 2\theta_{13}=0.085$
$|\Delta m^2_{32}|=2.44\times10^{-3}eV^2$
$\sin^2\theta_{23}=0.5$
$P(\nu_\mu \rightarrow \nu_e)$ %
Neutrino energy (GeV)
T2K
T2K L=295 km
$\sin^2 2\theta_{13}=0.085$
$|\Delta m^2_{32}|=2.44\times10^{-3}eV^2$
$\sin^2\theta_{23}=0.5$
$P(\nu_\mu \rightarrow \nu_e)$ %
Neutrino energy (GeV)

Joint Distribution

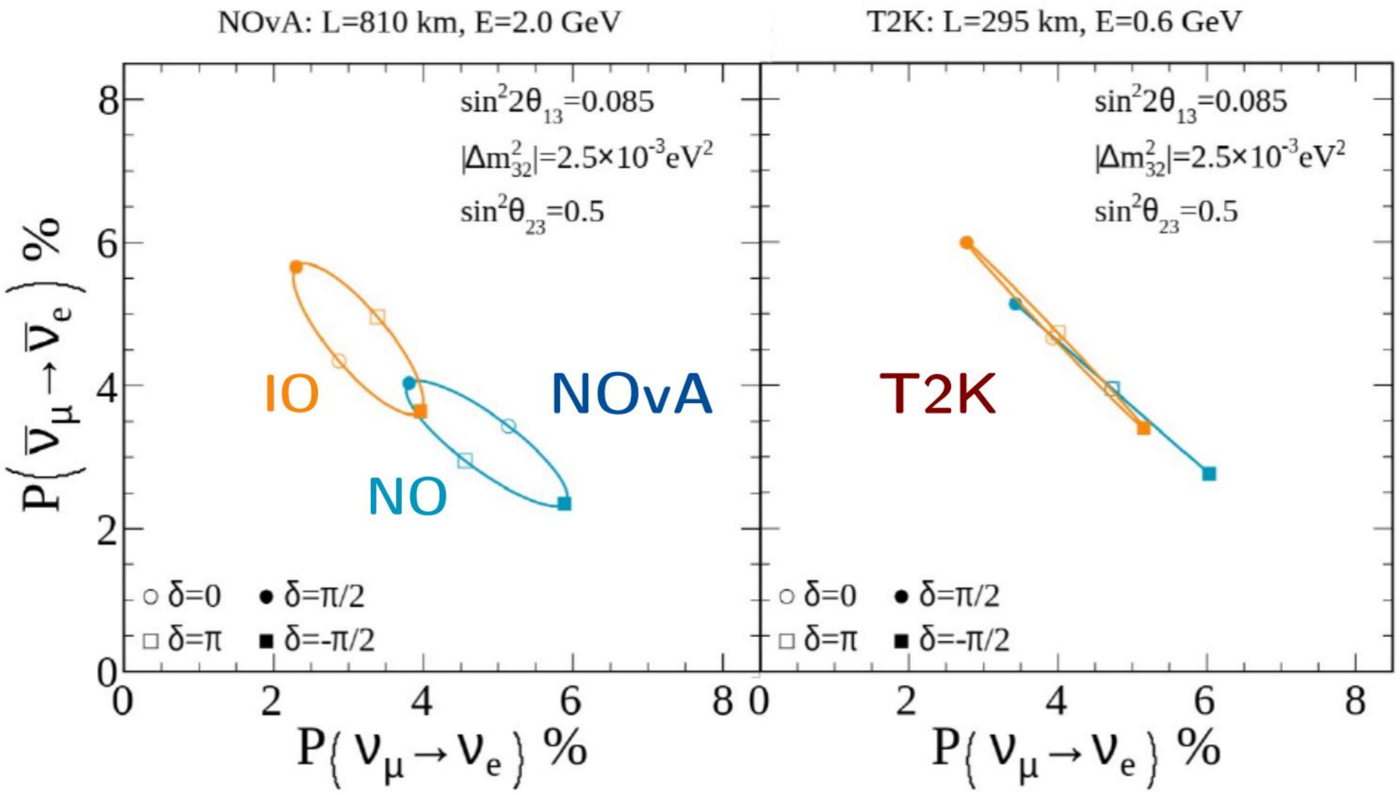


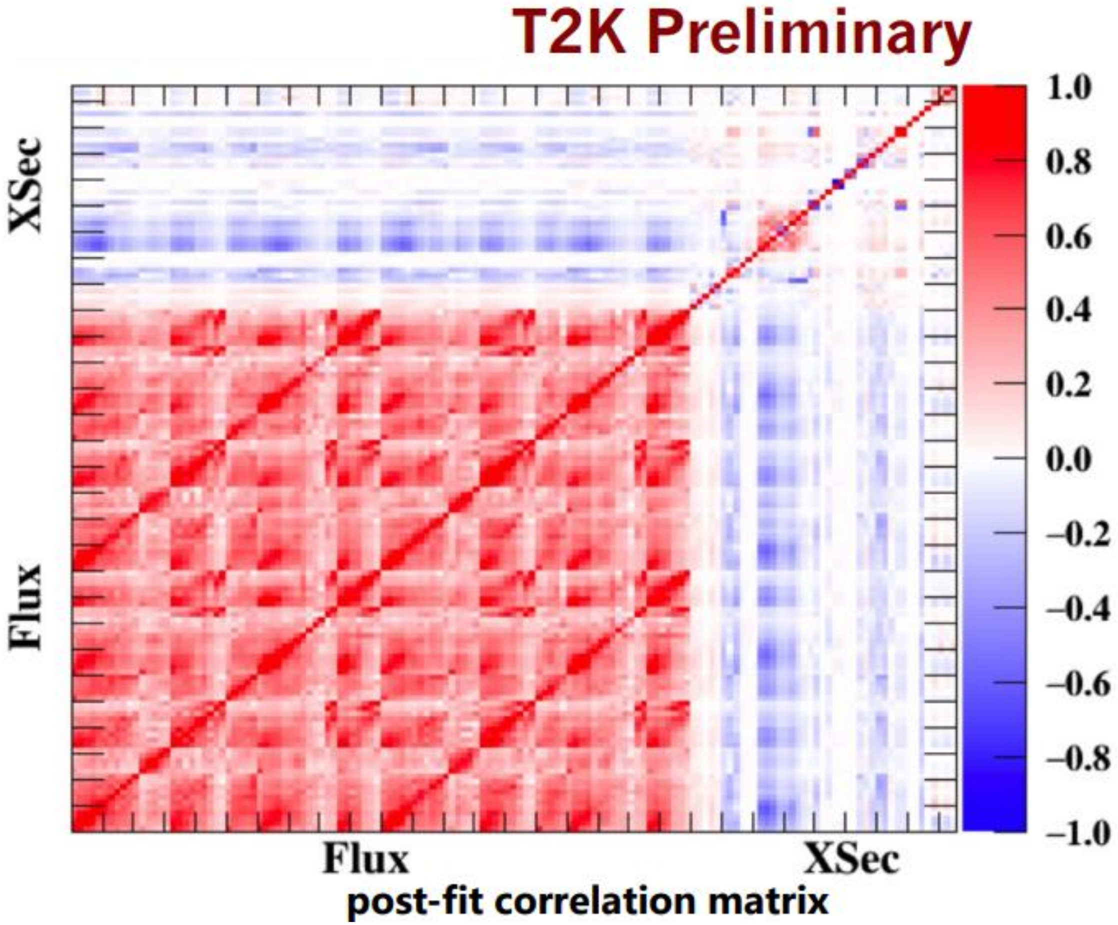
NOvA:

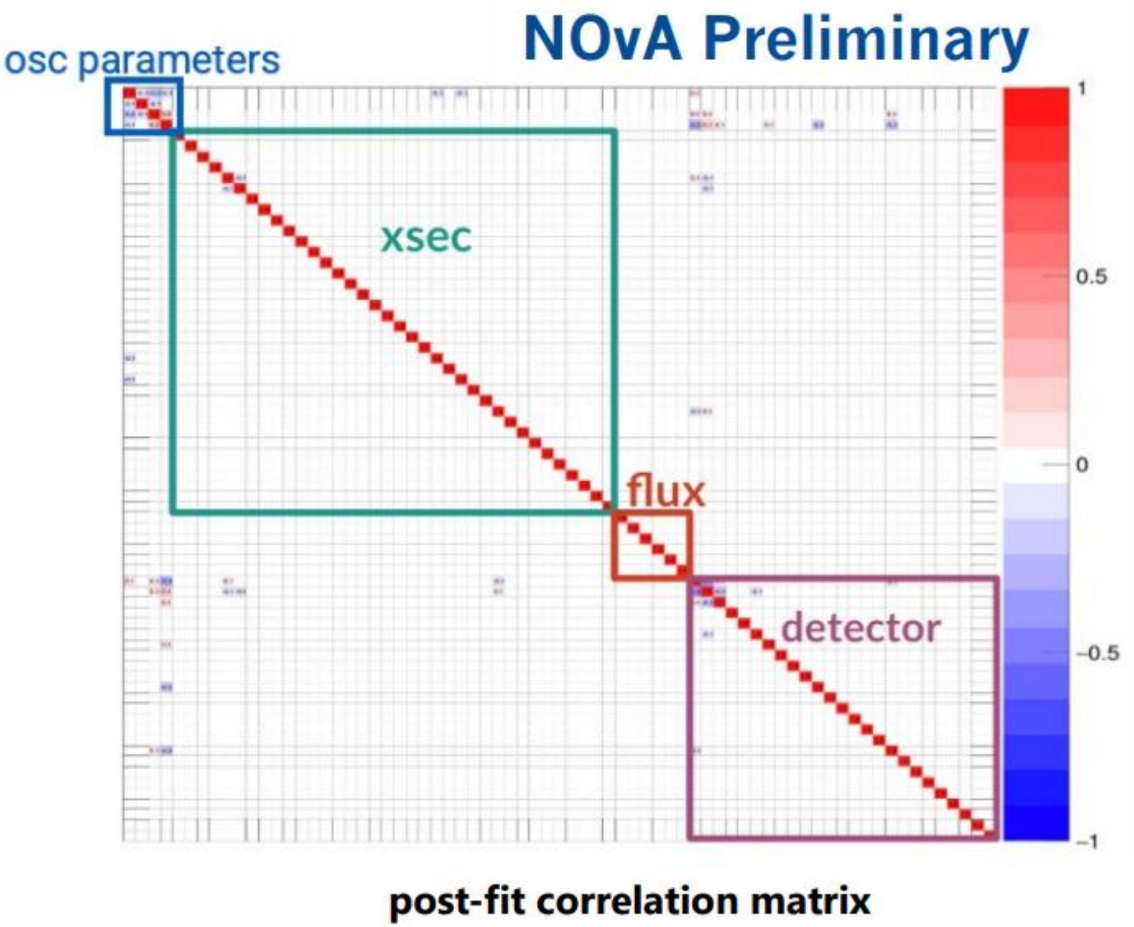
- Better mass ordering sensitivity
- Degenerate for around $\delta_{CP} = \pi/2$ and $-\pi/2$ (CPV)

T2K:

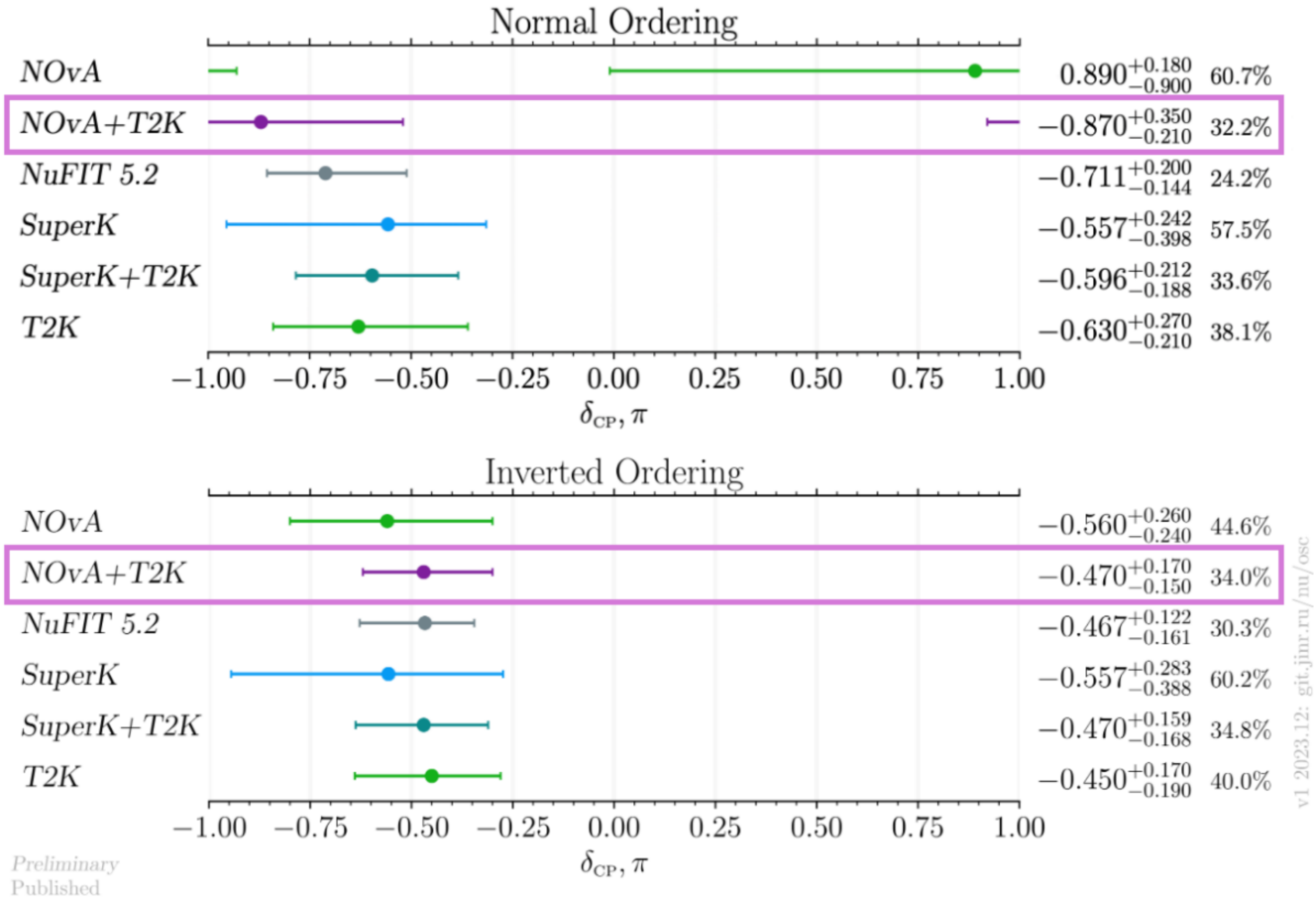
- Better δ_{CP} sensitivity
- Degenerate for around $\delta_{CP} = 0$ and π (no-CPV)



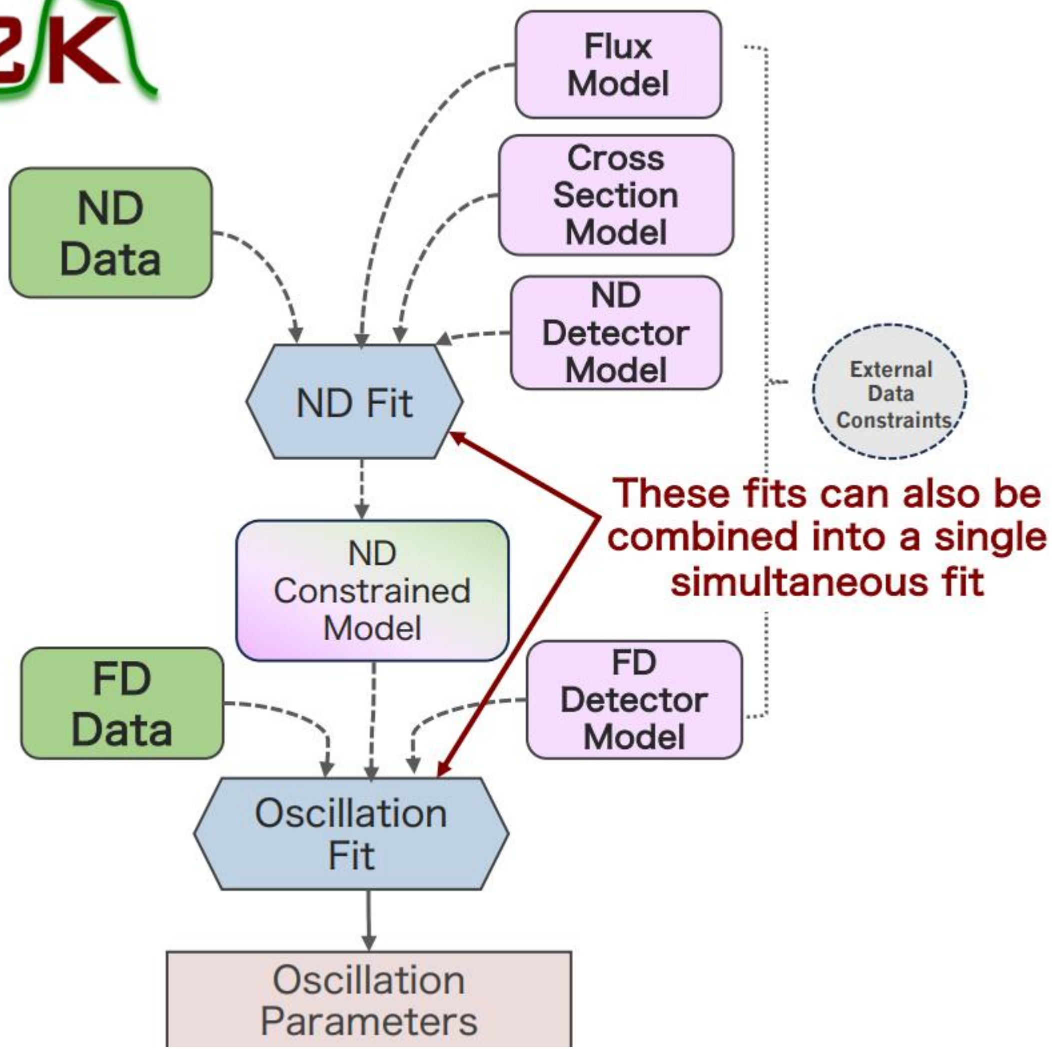

T2K Preliminary
XSec
Flux
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8
−1.0
Flux
XSec
post-fit correlation matrix

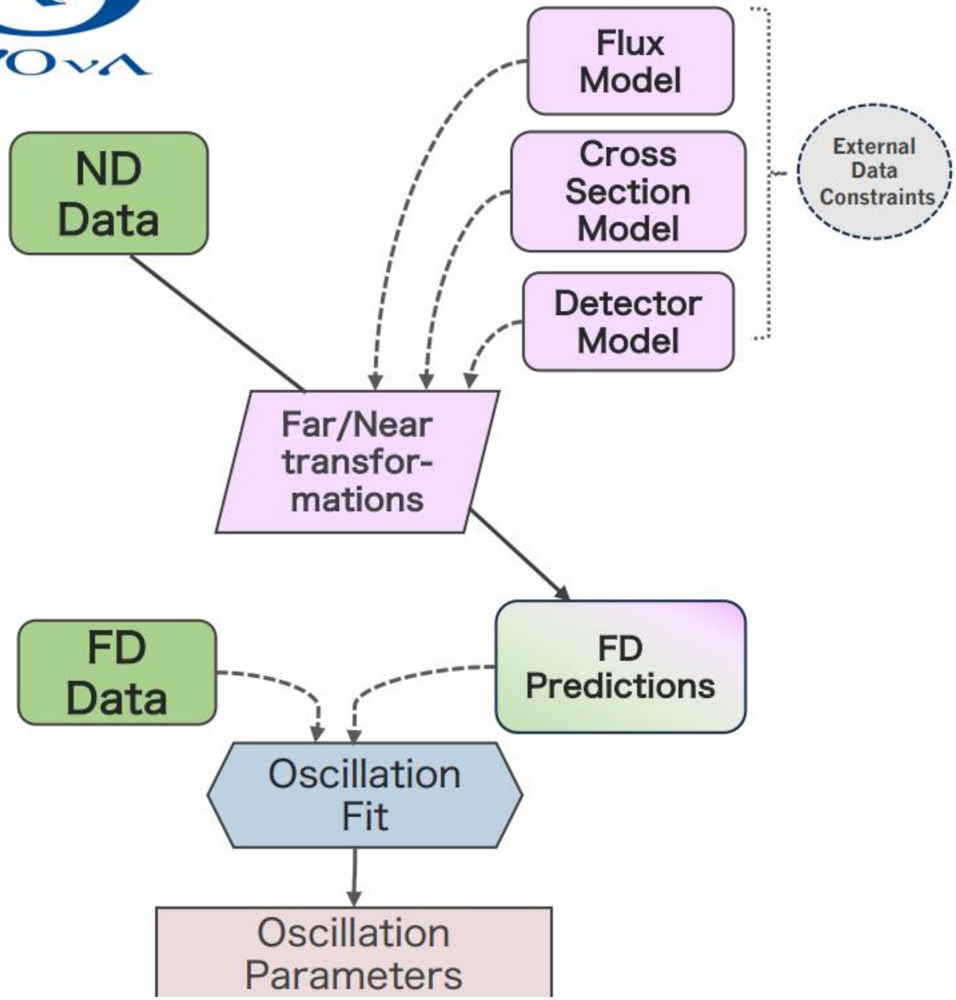

NOvA Preliminary
osc parameters
xsec
flux
detector
1
0.5
0
−0.5
−1
post-fit correlation matrix

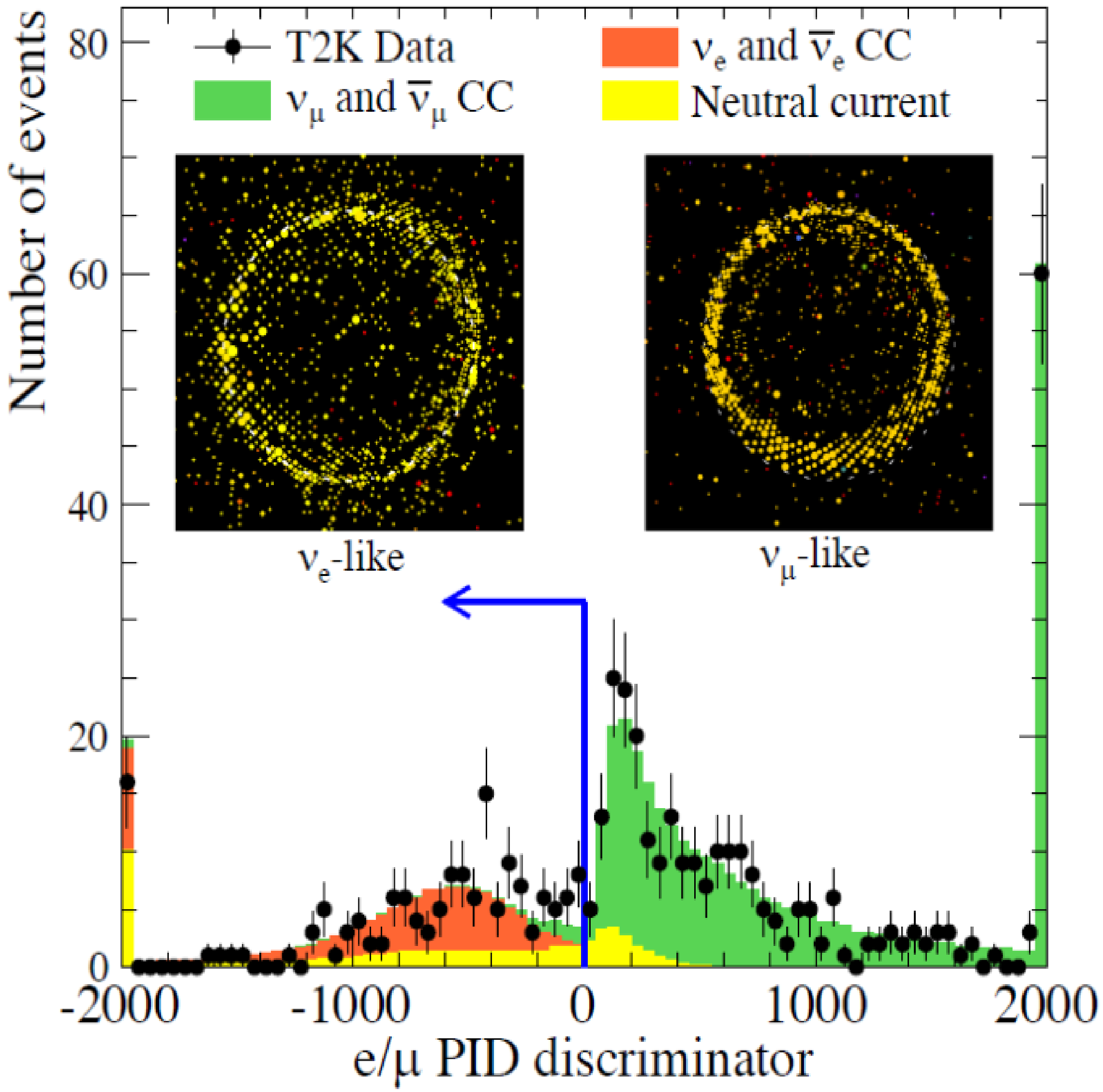
δCP global comparisons

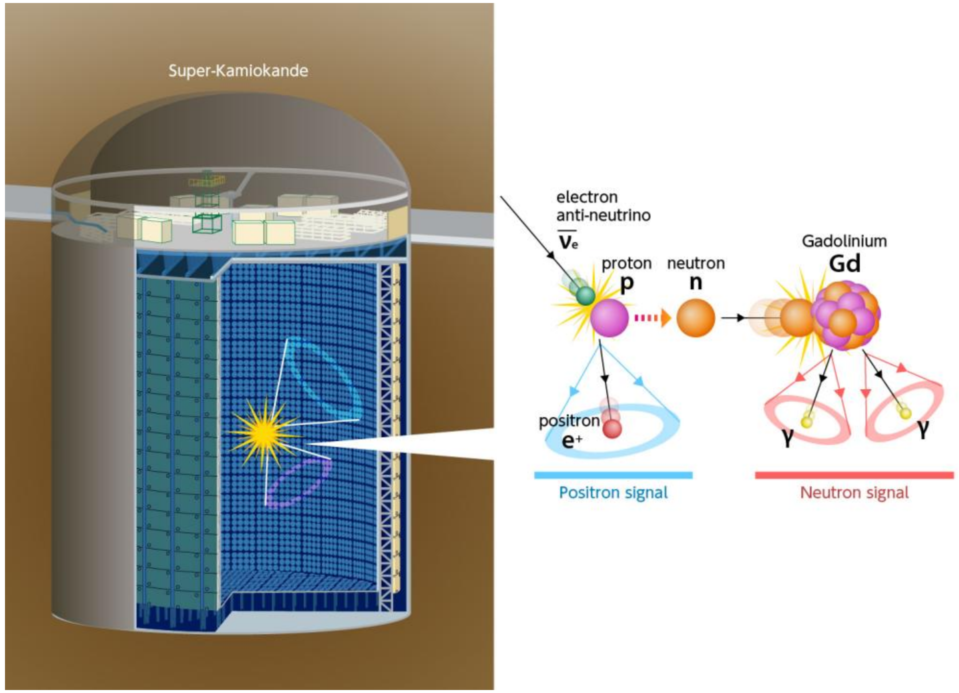


Analysis Flow

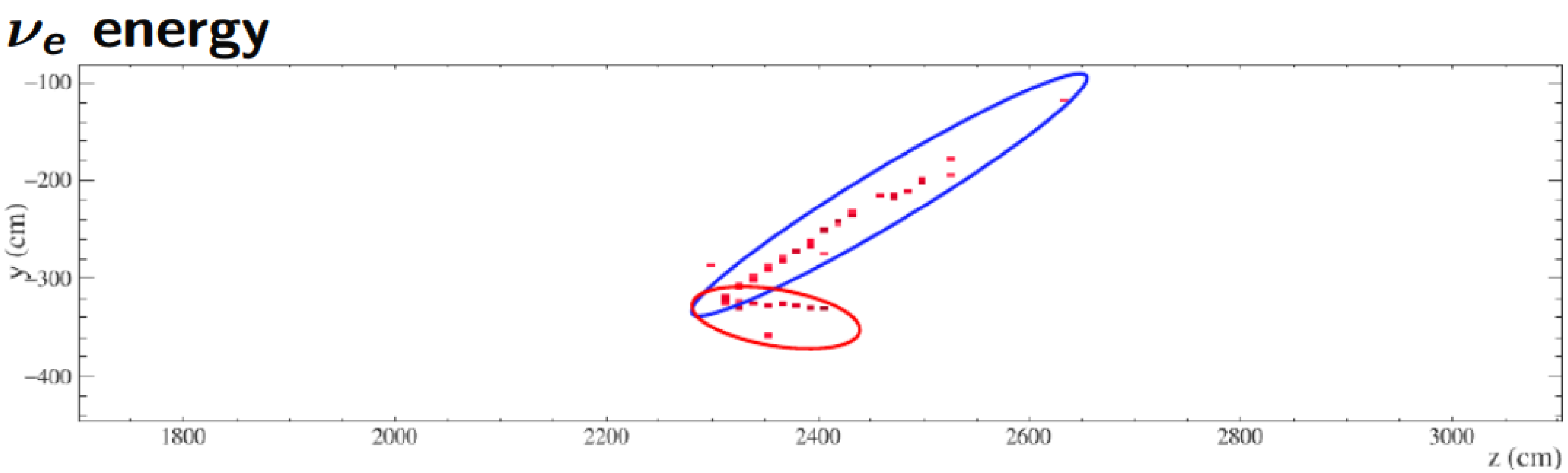




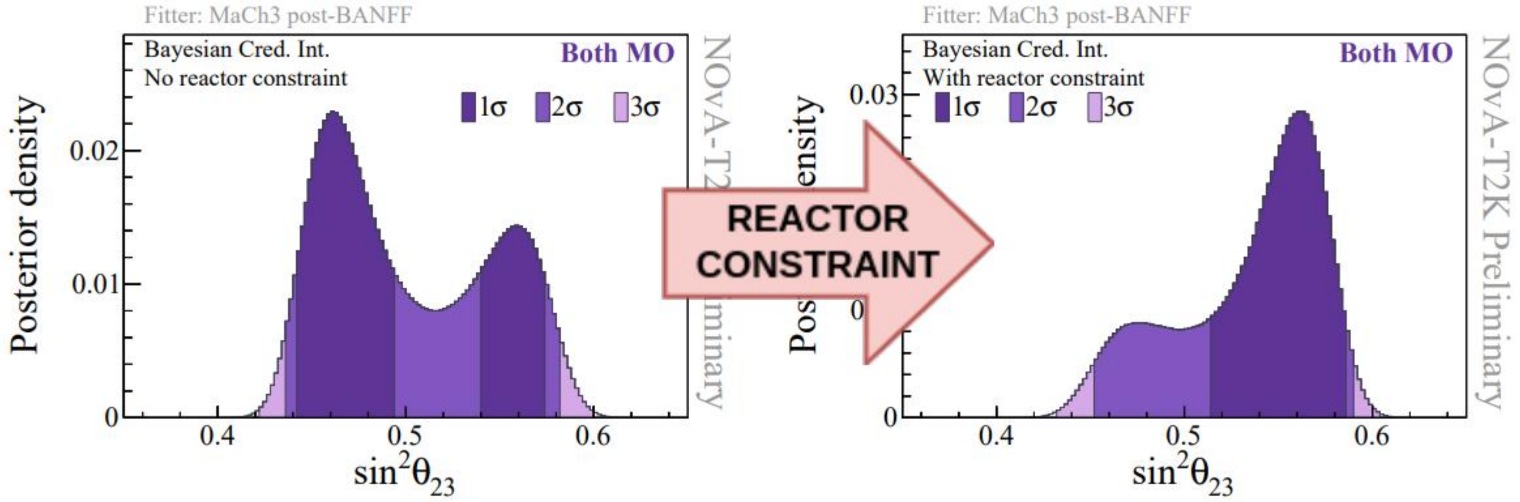

T2K Data
ν_e and $\bar{\nu}_e$ CC
ν_μ and $\bar{\nu}_\mu$ CC
Neutral current
ν_e-like
ν_μ-like
Number of events
e/μ PID discriminator

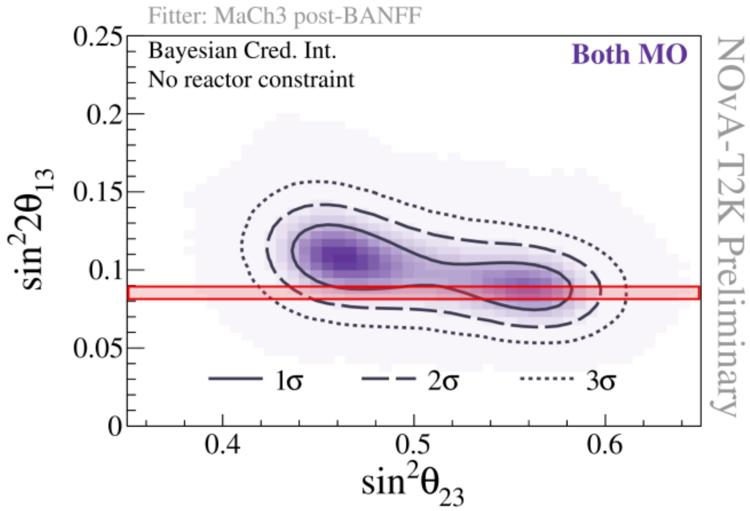

Super-Kamiokande
electron
anti-neutrino
$\bar{\nu}_e$
proton
p
neutron
n
Gadolinium
Gd
positron
e+
γ
γ
Positron signal
Neutron signal

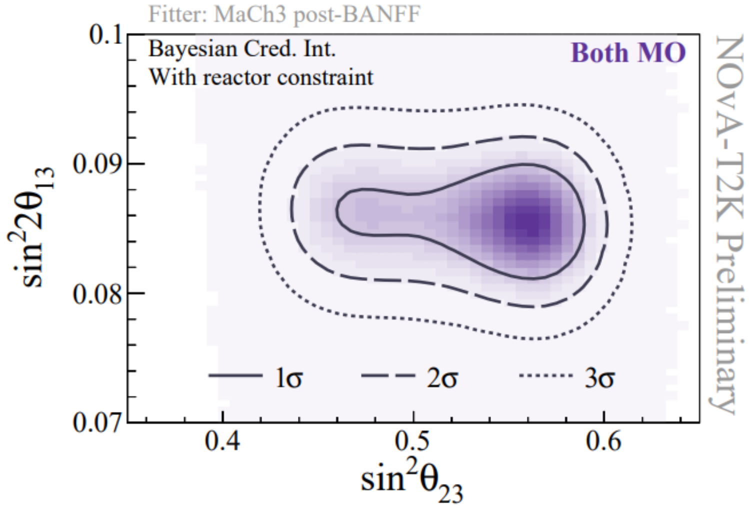
NOvA Em

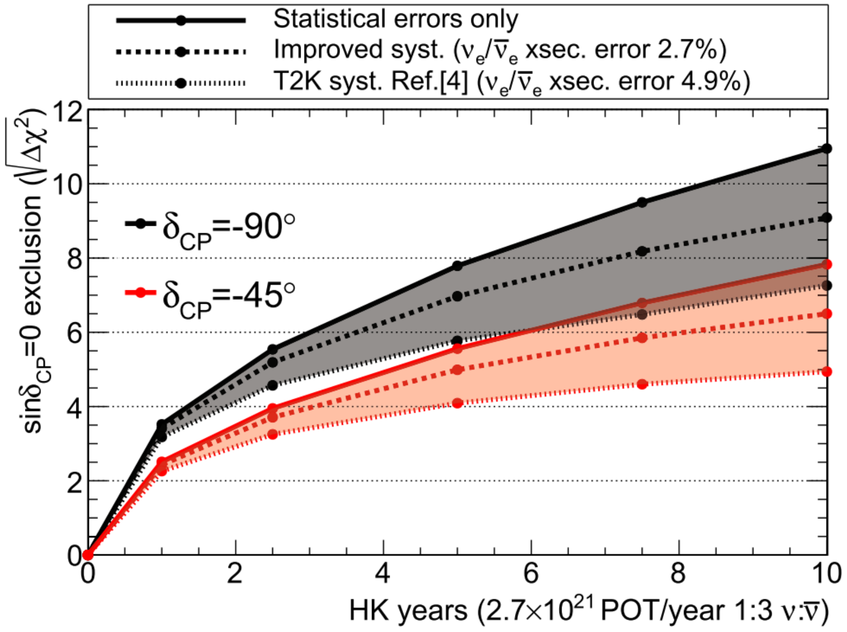


$E_{\nu_e} =$ quadratic function of E_{EM} and E_{had}


Fitter: MaCh3 post-BANFF
Bayesian Cred. Int.
No reactor constraint
Both MO
1σ 2σ 3σ
Posterior density
0.02
0.01
0
0.4 0.5 0.6
$\sin^2\theta_{23}$
NOvA-T2K Preliminary
REACTOR CONSTRAINT
Fitter: MaCh3 post-BANFF
Bayesian Cred. Int.
With reactor constraint
Both MO
1σ 2σ 3σ
0.03
0
0.4 0.5 0.6
$\sin^2\theta_{23}$
NOvA-T2K Preliminary


Fitter: MaCh3 post-BANFF
Bayesian Cred. Int.
No reactor constraint
Both MO
$\sin^2 2\theta_{13}$
0.25
0.2
0.15
0.1
0.05
0
1σ 2σ 3σ
0.4 0.5 0.6
$\sin^2\theta_{23}$
NOvA-T2K Preliminary


Fitter: MaCh3 post-BANFF
Bayesian Cred. Int.
With reactor constraint
Both MO
$\sin^2 2\theta_{13}$
0.1
0.09
0.08
0.07
1σ 2σ 3σ
0.4 0.5 0.6
$\sin^2\theta_{23}$
NOvA-T2K Preliminary



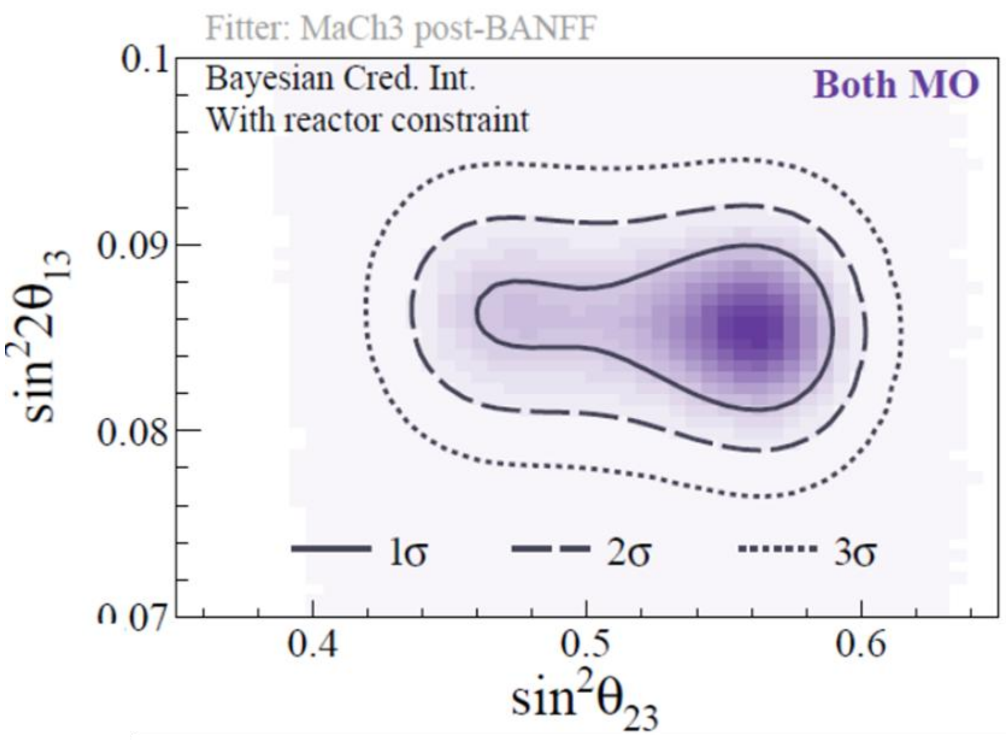
In the case of maximal CPV, δC P = −π/2, Hyper-Kamiokande reaches a definitive 5σ discovery in less than three years.

even with a very conservative assumption on the systematic uncertainties Hyper-Kamiokande will reach 5σ sensitivity in less than 6 years.

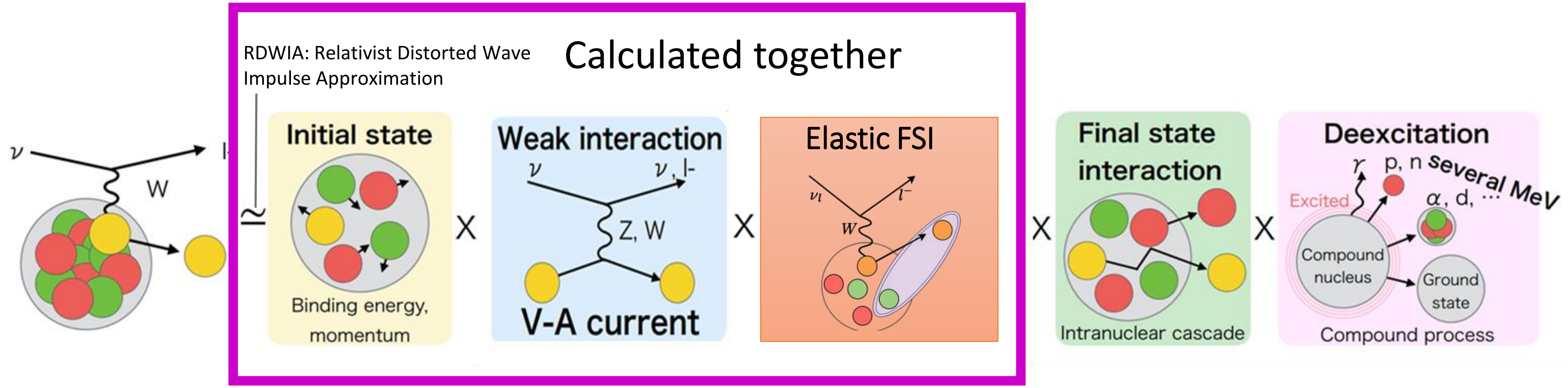
If we consider the degenerate case of δC P = −π/2 and inverted ordering and the Hyper-Kamiokande sensitivity to MO using atmospheric and beam data, the CPV discovery would be delayed to 6 years also in the case of improved systematic uncertainties.

- Bayes factor of 3.6 for upper octant preference (modest) with RC

- Very weak preference for IO, Bayes factor 1.3

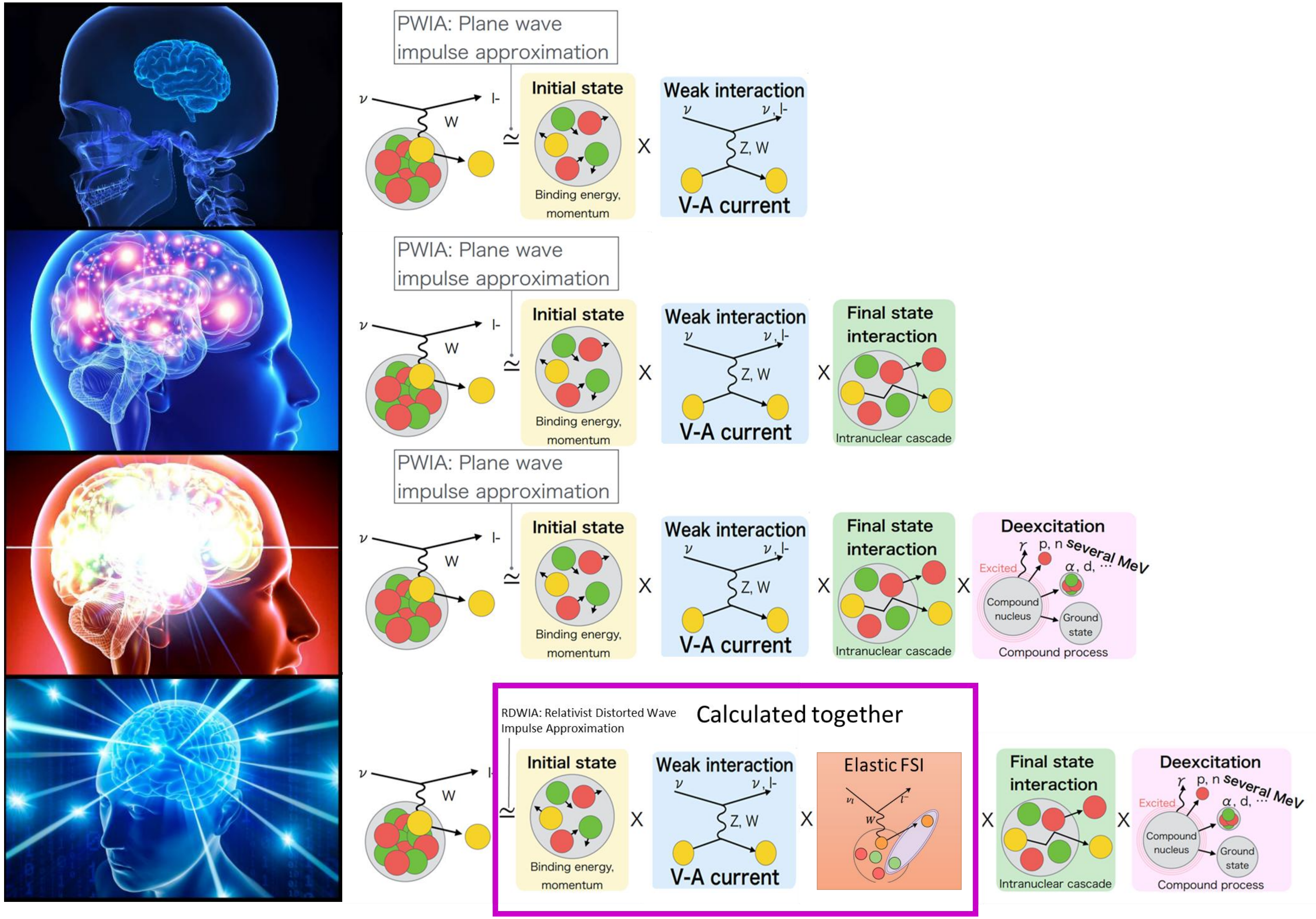


Graph


RDWIA: Relativist Distorted Wave Impulse Approximation
Calculated together
ν
l-
W
≃
Initial state
Binding energy, momentum
X
Weak interaction
ν
ν, l-
Z, W
V-A current
X
Elastic FSI
W
X
Final state interaction
Intranuclear cascade
X
Deexcitation
γ
p, n
several MeV
Excited
α, d, …
Compound nucleus
Ground state
Compound process

Meme


RFG
SF
EDRMF
rEDAIC
EDRMF
rEDAIC
Look what they need to
mimic a fraction of our power



PWIA: Plane wave impulse approximation
Initial state
Binding energy, momentum
Weak interaction
Z, W
V-A current
Final state interaction
Intranuclear cascade
Deexcitation
Several MeV
Excited
Compound nucleus
Ground state
Compound process
RDWIA: Relativist Distorted Wave Impulse Approximation
Calculated together
Elastic FSI