To CCQE and Beyond

Neutrino oscillations, neutrino-nucleus interactions, nuclear effects and the latest cross section measurements

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Overview

- Neutrino oscillations and long-baseline experiments
- Why care about neutrino interactions?
- Neutrino nucleus cross-section challenges and measurements
- Conclusions

Neutrino Oscillations

PMNS mixing matrix

- Neutrinos are produced linear combinations of mass/energy eigenstates

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

- Time evolution: flavour content "oscillates" in L(distance)/E(neutrino)

$$\begin{aligned} P(\nu_\alpha \to \nu_\beta) = \quad & \delta_{\alpha\beta} \\ & -4\Sigma_{i>j} \Re(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2[1.27 \Delta m^2_{ij} (L/E)] \\ & +2\Sigma_{i>j} \Im(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin [2.54 \Delta m^2_{ij} (L/E)] \end{aligned}$$

- Can parameterise neutrino oscillations as:
  - Two mass differences ($\Delta m^2_{21}, \Delta m^2_{32}$)
  - Three rotation angles ($\theta_{12}, \theta_{13}, \theta_{23}$)
  - One CP-violating phase (δ_{CP})

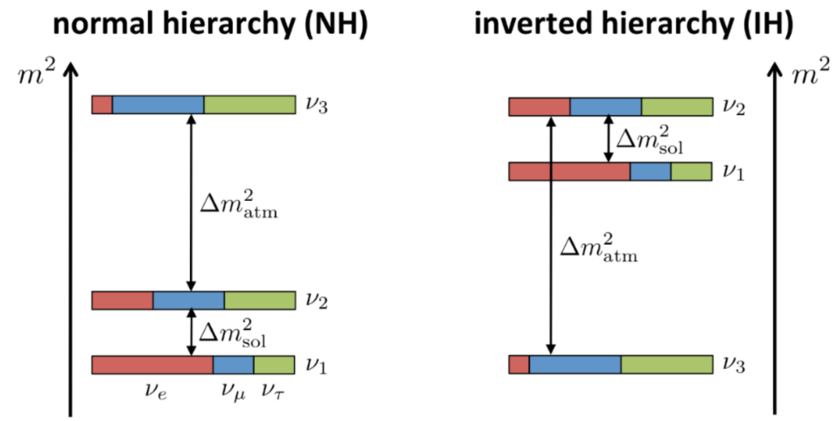
Oscillations perturbed in matter
→ sensitive to sign of mass splitting

$$U = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{+i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}$$

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

Physics Goals

- What is the neutrino mass ordering?
- Is CP violated in the lepton sector?
- Is θ_{23} mixing maximal ($\theta_{23} = 45°$)?
- Are there more than three neutrinos?



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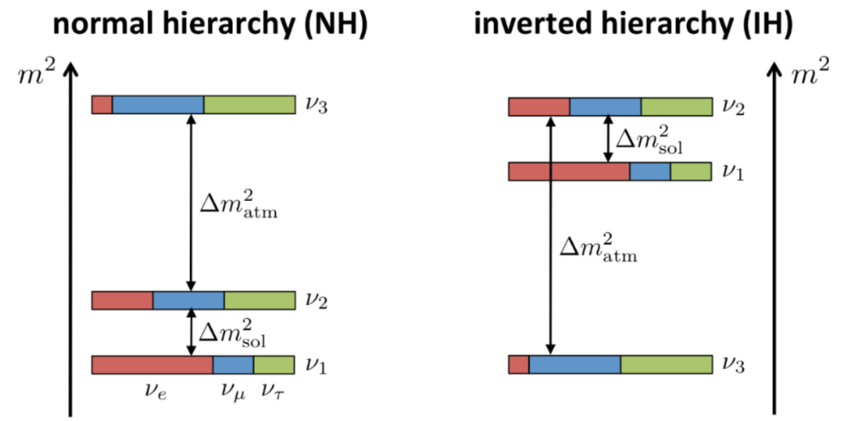

Accelerator-based experiments

- Produce beam of $\nu_\mu/\bar{\nu}_\mu$

Then after some distance …

- Measure $\nu_\mu/\bar{\nu}_\mu$ **disappearance**
  - $|\Delta m^2_{32}|, \sin^2(2\theta_{23})$
- Measure $\nu_e/\bar{\nu}_e$ **appearance**
  - θ_{13}, δ_{CP}, mass ordering

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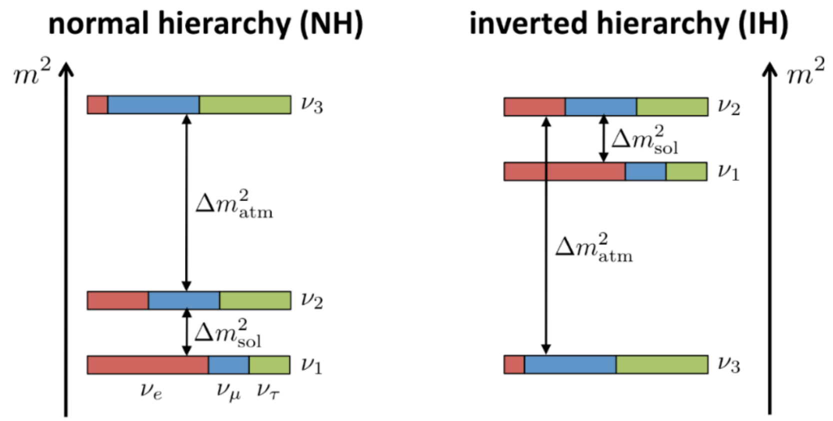

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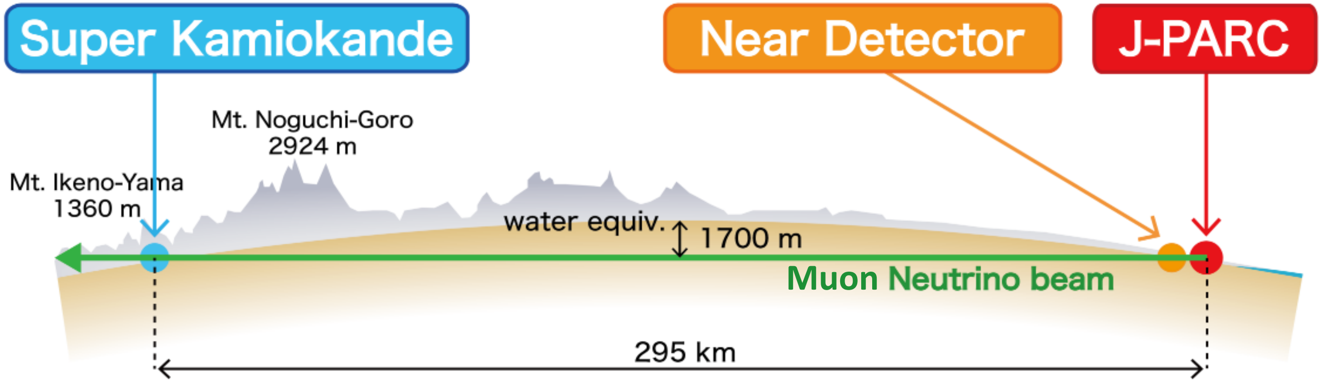
- Current experiments:
  - T2K, NOvA
- The future:
  - T2HK, DUNE, ESSnuSB

The T2K Experiment

0.6 GeV peak energy

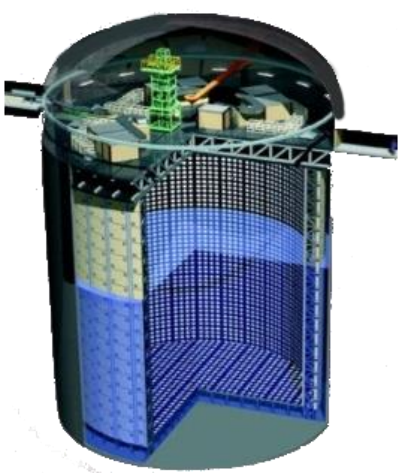


2.5° off-axis

Use off-axis beam to give a narrow neutrino energy spread

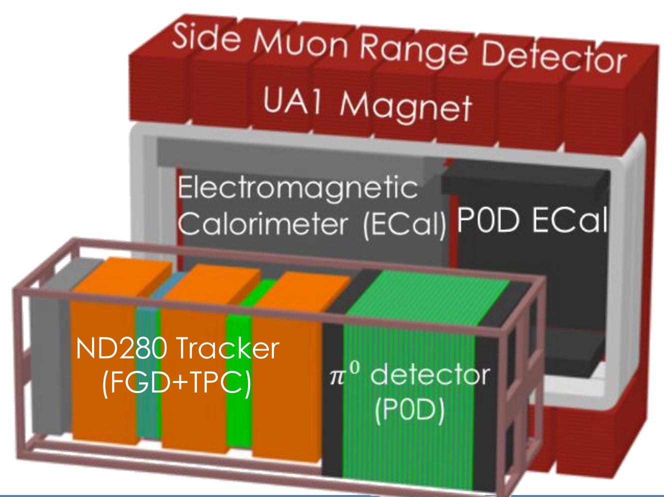
Far Detector (Off-Axis)

Super-Kamiokande

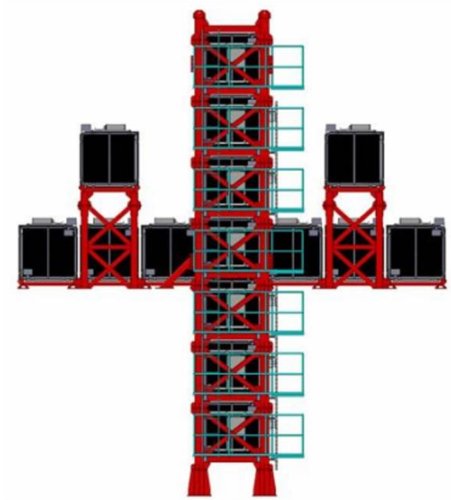


Near Detectors

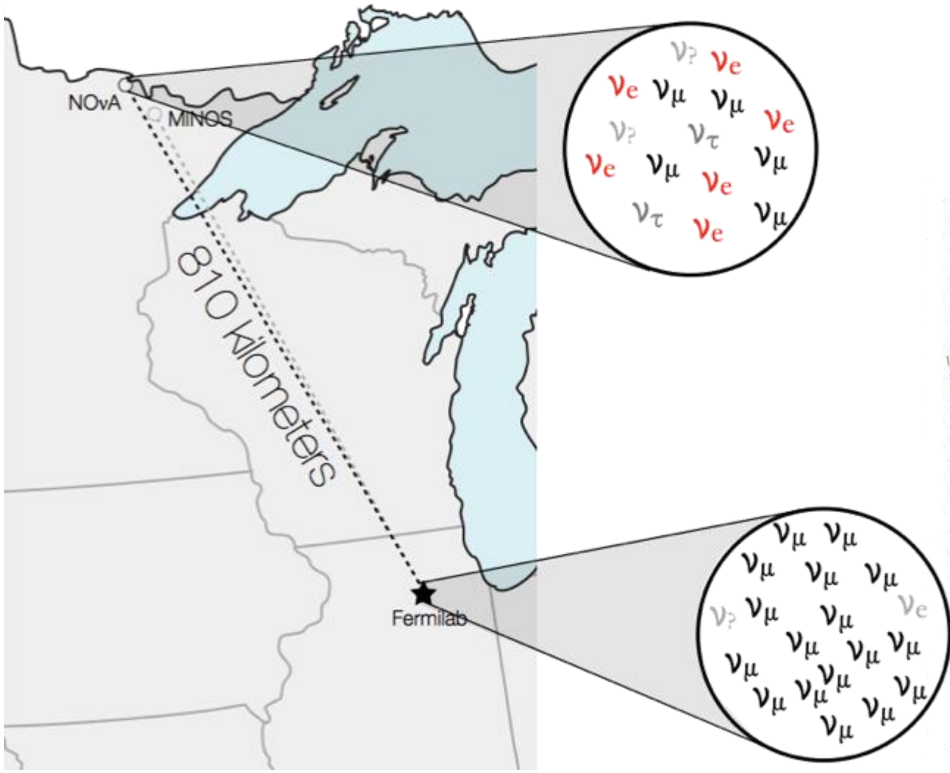
Off-Axis: ND280



On-Axis: INGRID

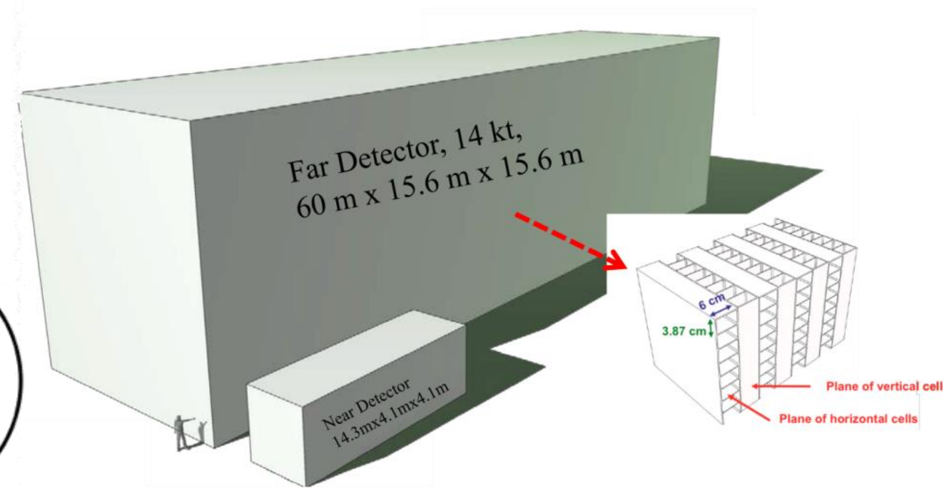


The NOvA Experiment



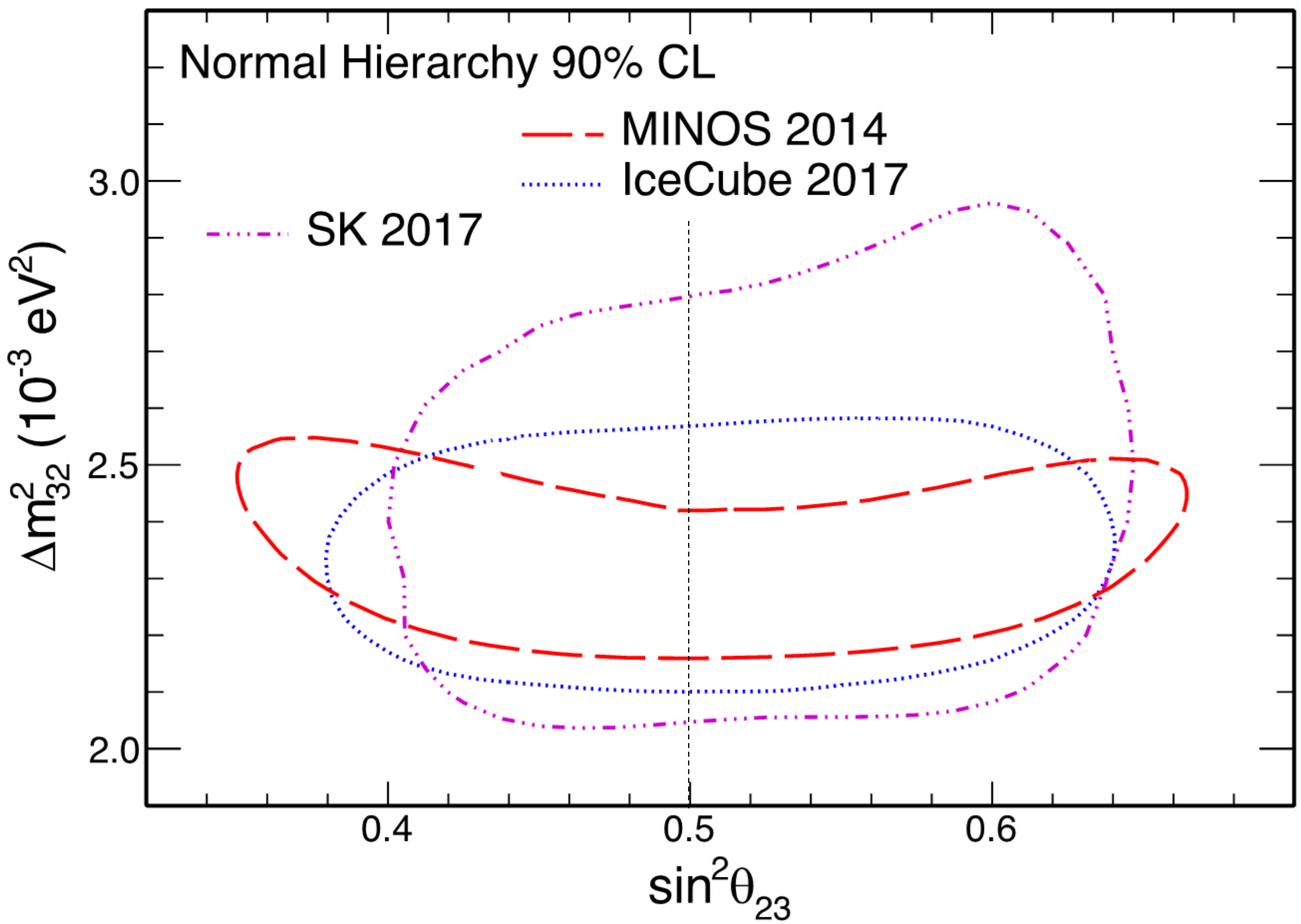
1.9 GeV peak energy

14 mrad off-axis



- Functionally identical near and far scintillator detectors
  - Cancellation of some systematic errors
- Very long baseline gives good sensitivity to mass hierarchy

The Latest Results



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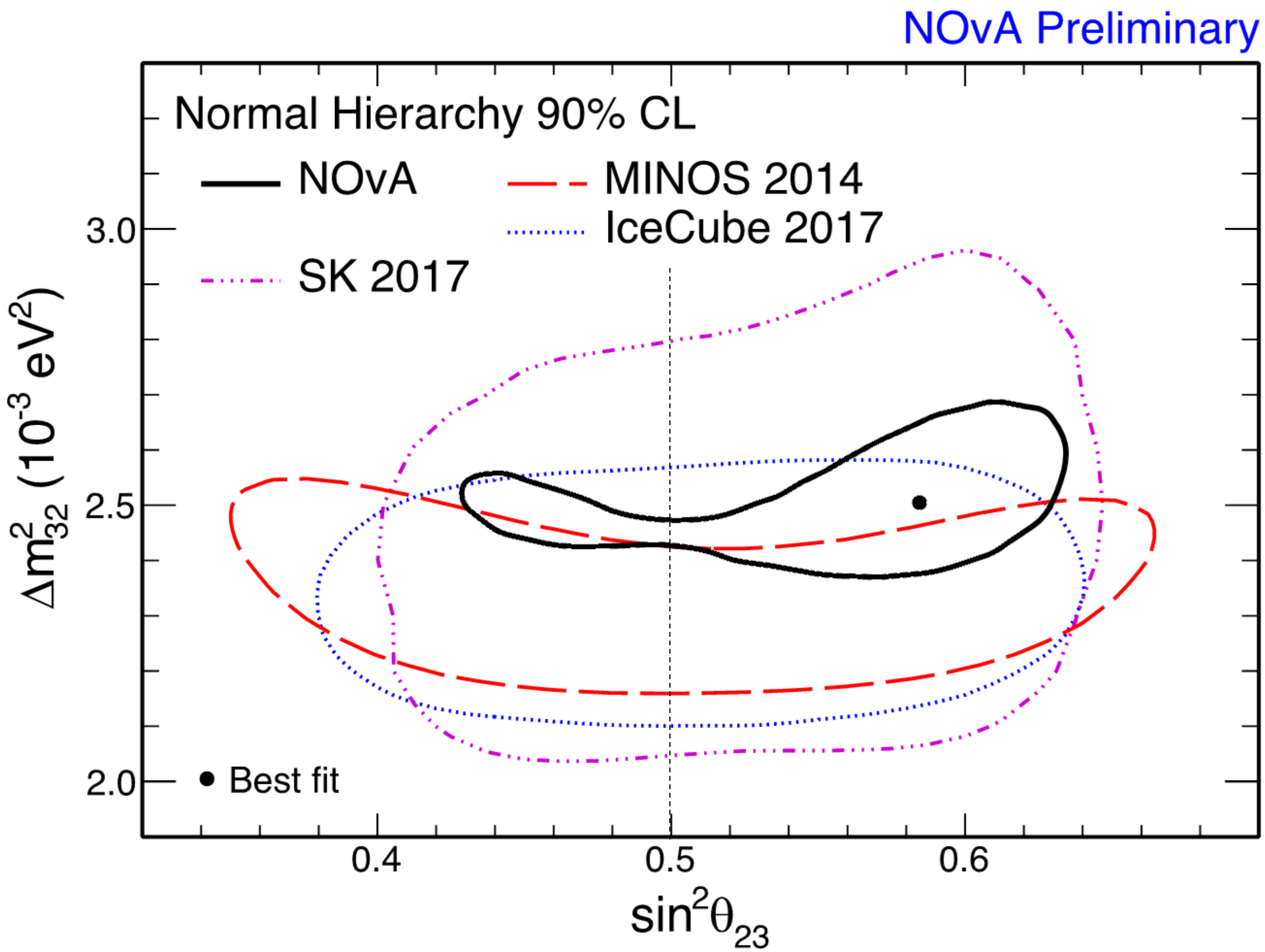

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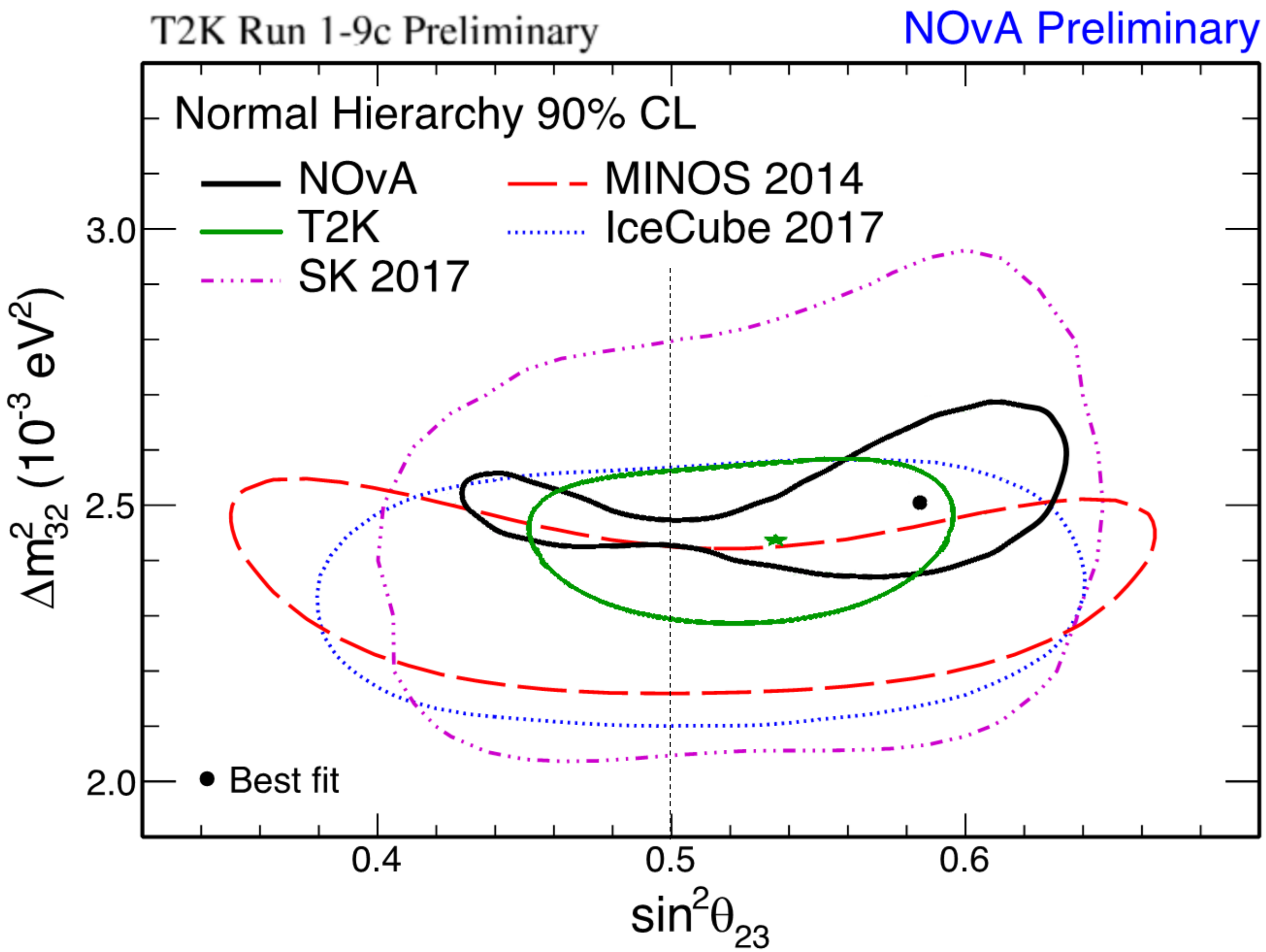

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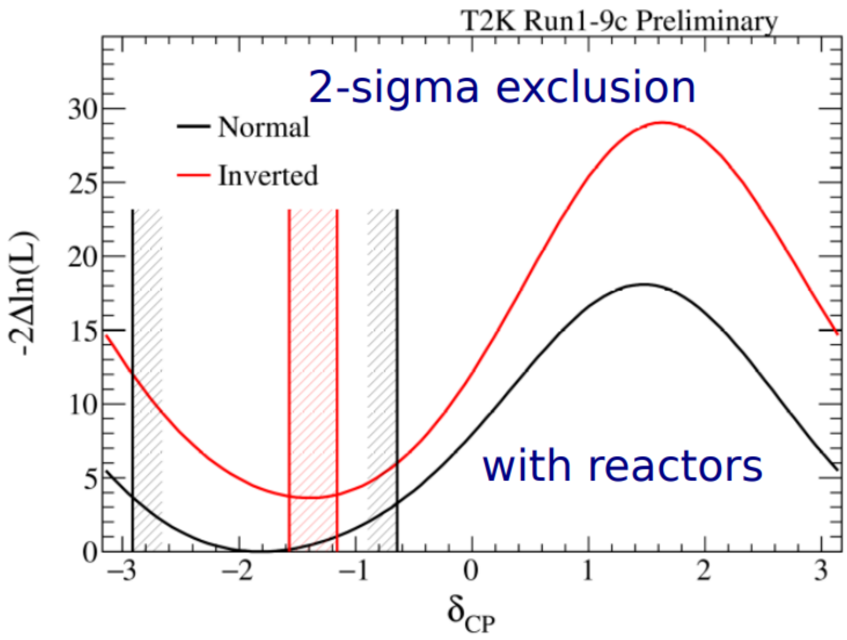
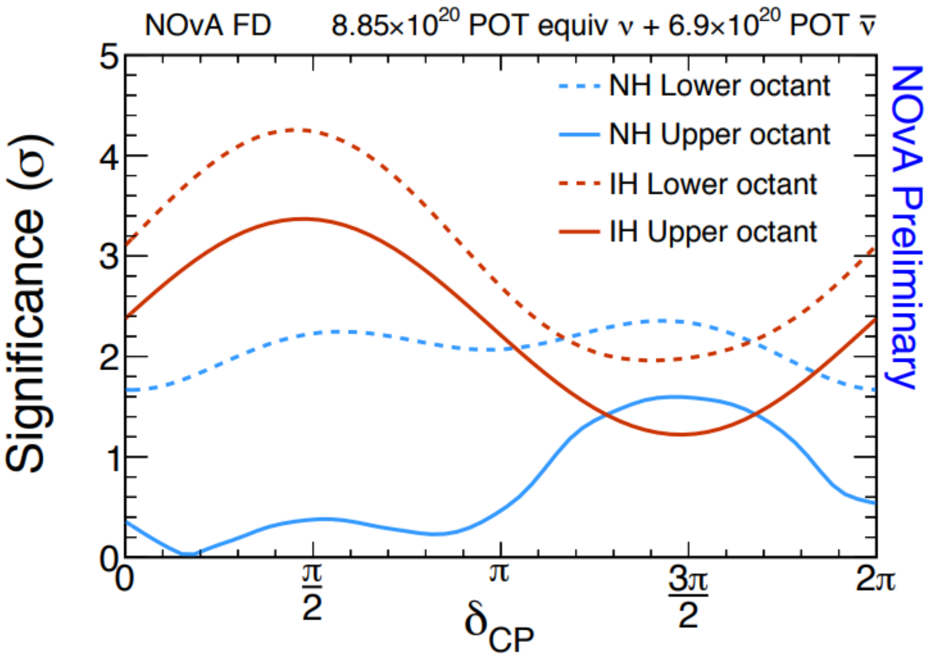




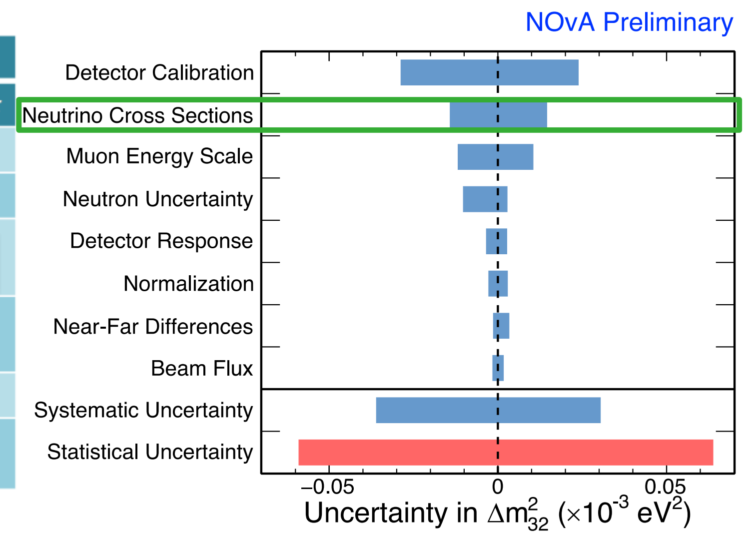
- Can begin to measure δ_{CP} - CP-violating phase in neutrino mixing
- T2K and NOvA measurements are (currently) consistent
- T2K excludes $\delta_{CP} = 0, \pi$ (CP-conserving) at 2σ (for the normal mass hierarchy)
- Both prefer normal mass ordering (NH)

Why can't we do better?

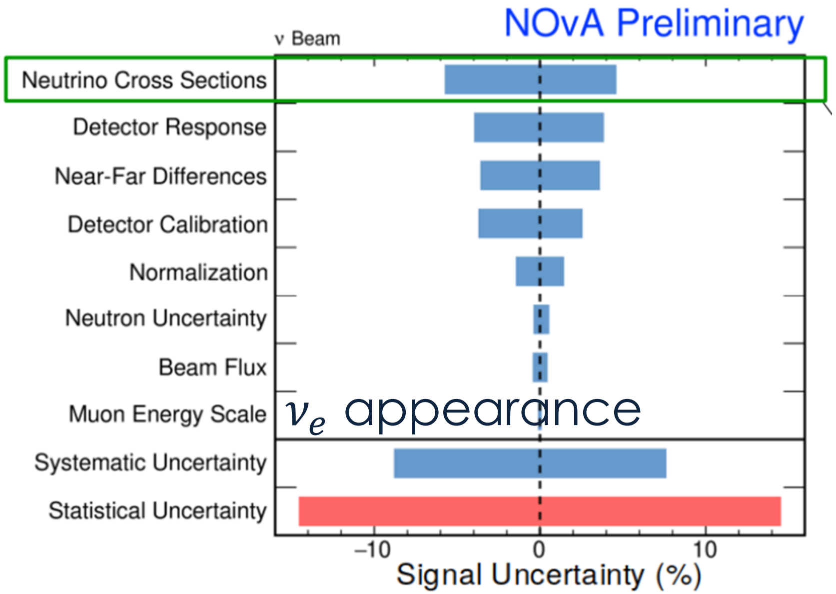
T2K

% Errors on Predicted Event Rates

Error Source	1Ring μ-like		1Ring e-like		
	ν mode	$\bar{\nu}$ mode	ν mode	$\bar{\nu}$ mode	ν mode+1π
SK detector	1.9	1.5	3.0	4.2	16.7
SK FSI+SI+PN	2.2	2.0	3.0	2.3	11.4
ND280 constrained flux & cross section	3.2	2.7	3.2	2.9	4.1
$\sigma(\nu_e)/\sigma(\nu_\mu)$, $\sigma(\bar{\nu}_e)/\sigma(\bar{\nu}_\mu)$	< 0.05	< 0.05	2.6	1.5	2.6
Neutral Currents	0.3	0.3	1.1	2.6	1.0
Total	4.4	3.8	6.1	6.5	20.9



- Current measurements are statistics limited, but not for long …
- Most worrying systematics related to **neutrino-nucleus interactions**
- Essential total systematic uncertainty <3% for DUNE/T2HK



Overview

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$$N_{pred}(E_\nu^{reco}) = \Phi(E_\nu^{true}) \boxed{\sigma(E_\nu^{true})} \boxed{P(\alpha \to \beta, E_\nu^{true})} \epsilon(E_\nu^{true}) \boxed{S(E_\nu^{true}, E_\nu^{reco})}$$

$N_{pred}(E_\nu^{reco})$ = Expected number of events

$\Phi(E_\nu^{true})$ = Neutrino flux

$\boxed{\sigma(E_\nu^{true}) = \text{Interaction cross sections}}$

$\boxed{P(\alpha \to \beta, E_\nu^{true}) = \text{Oscillation probability}}$

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$S(E_\nu^{true}, E_\nu^{reco})$ = Smearing matrix

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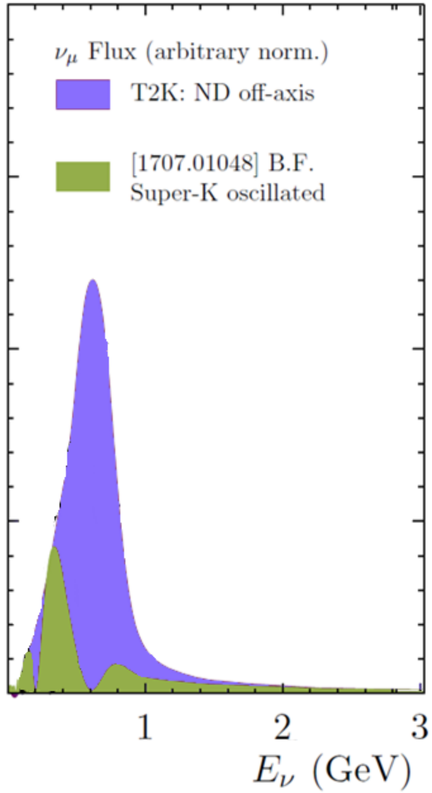
- Near / far ratios don't fully cancel this:
  - Dramatic change in E_ν distribution
  - Different ND/FD design, acceptance



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- Near / far ratios don't fully cancel this:
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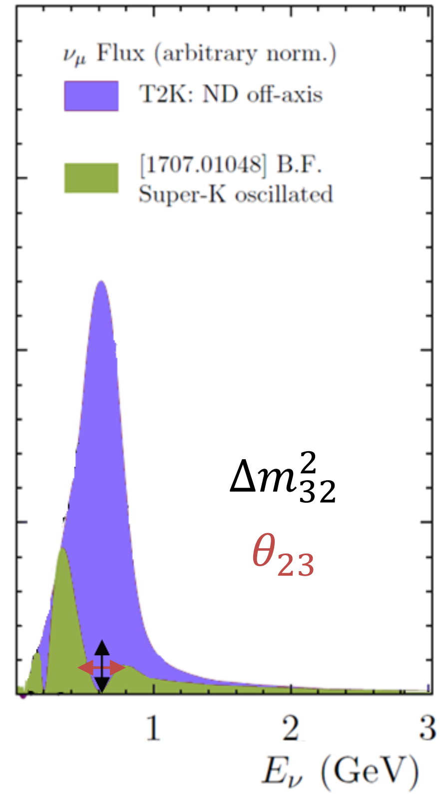
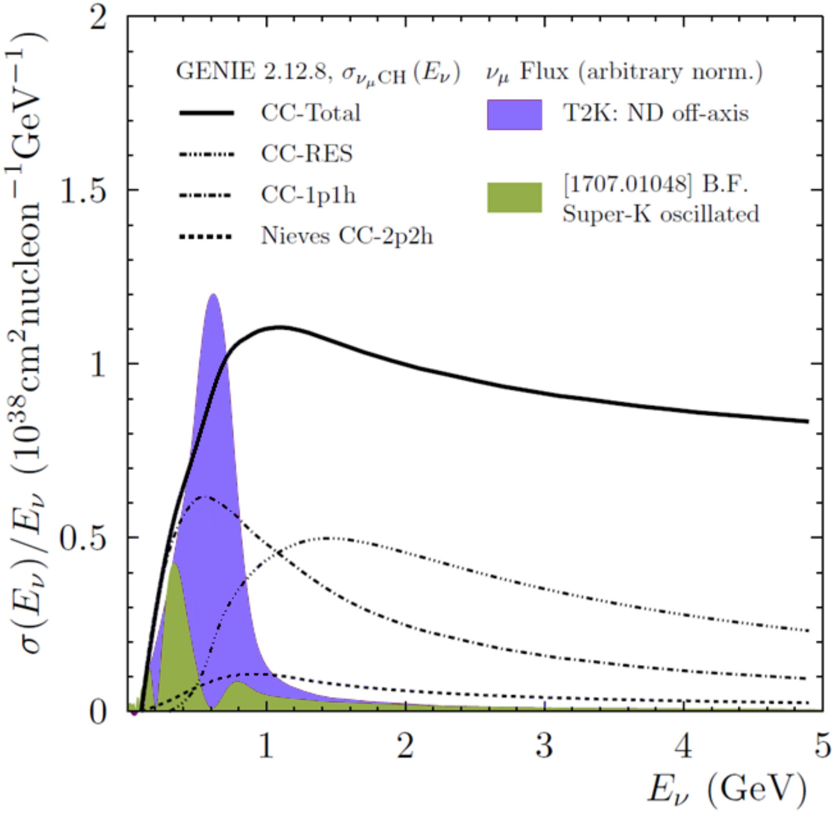
- Not just counting experiments: Require a model to relate E_ν^{reco} to E_ν^{true}

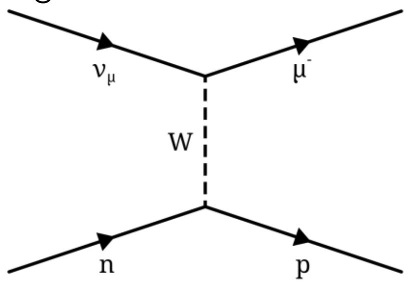


Neutrino Interactions at T2K



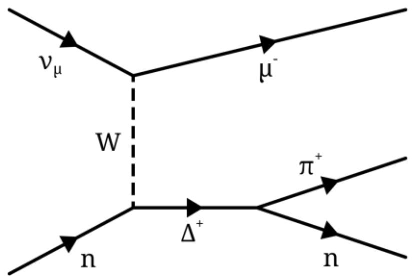
CCQE (1p1h)

(Charged-Current Quasi-Elastic)



CCRES

(Charged-Current Resonant)



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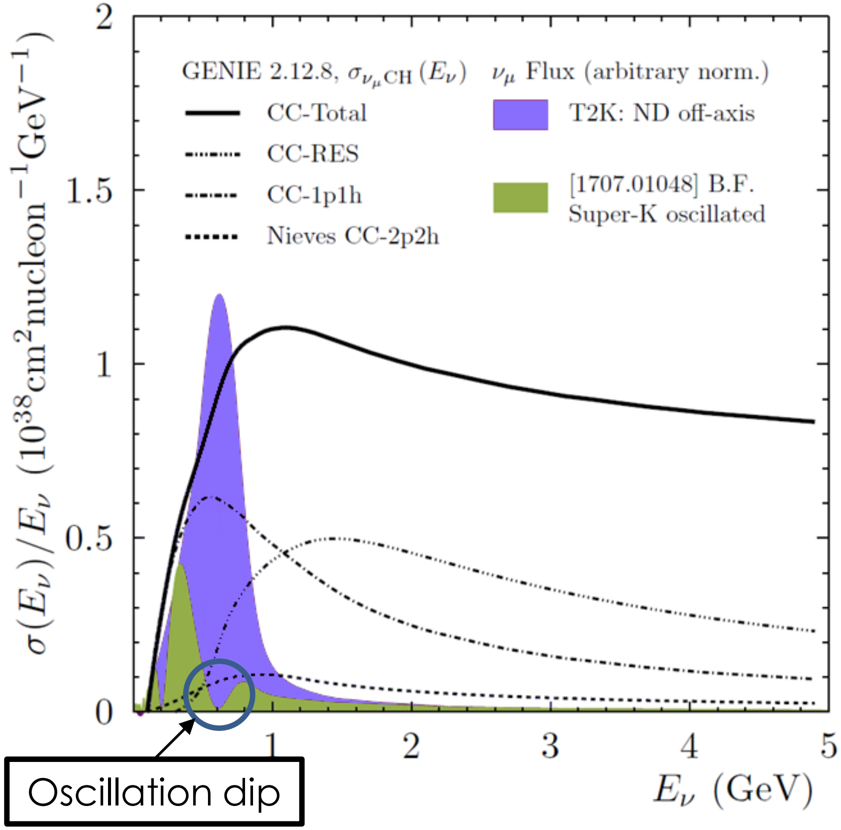

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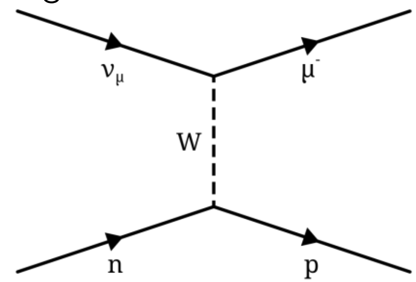

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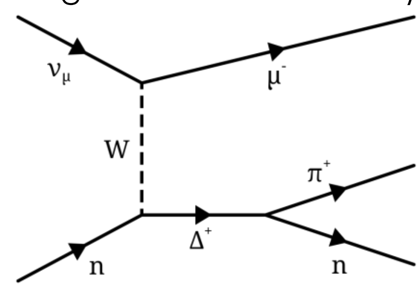
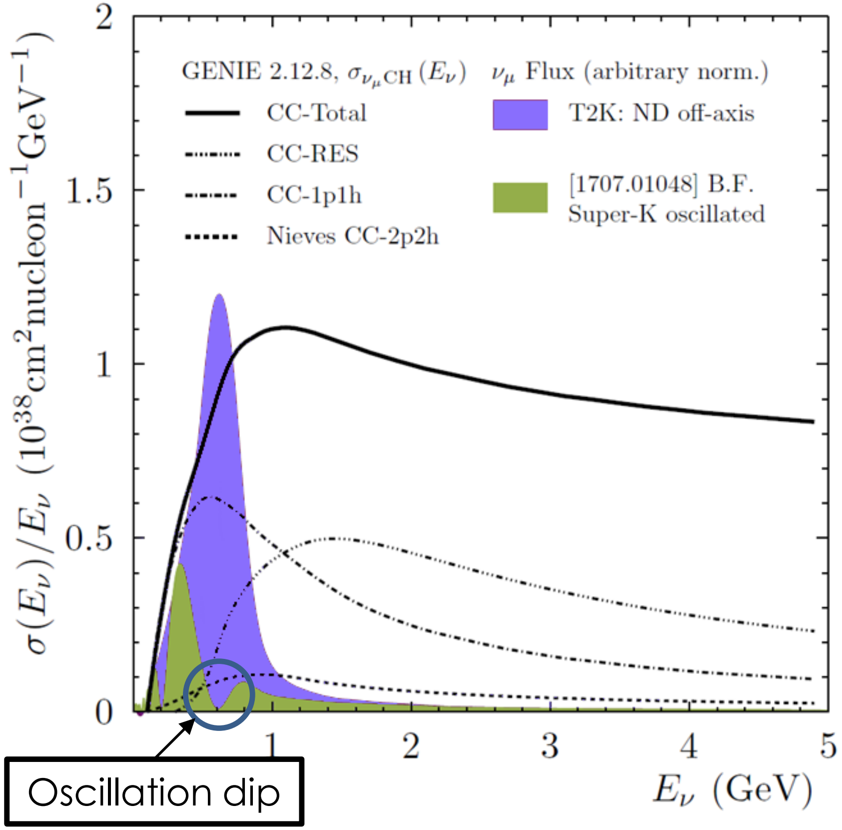


- Reconstruct neutrino energy from muon kinematics in CC pionless events at SK

$$E_\nu^{reco} = \frac{m_p^2 - m_n^2 - m_\mu^2 + 2m_n E_\mu}{2(m_n - E_\mu + p_\mu \cos(\theta_\mu))}$$

- Assume **stationary target** and **CCQE scattering** …

Neutrino Interactions at T2K



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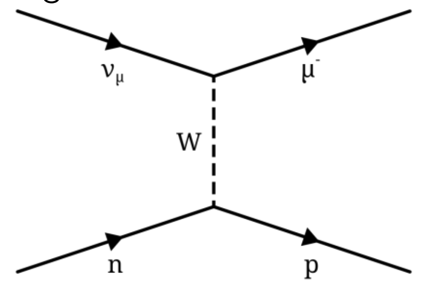

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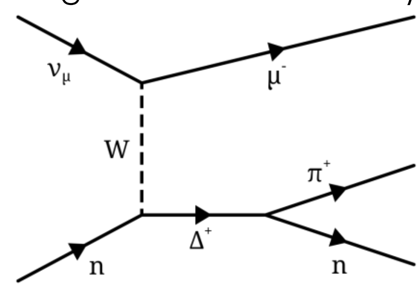
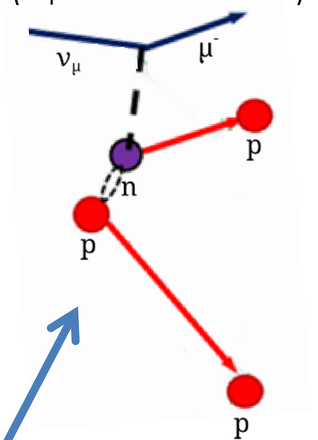
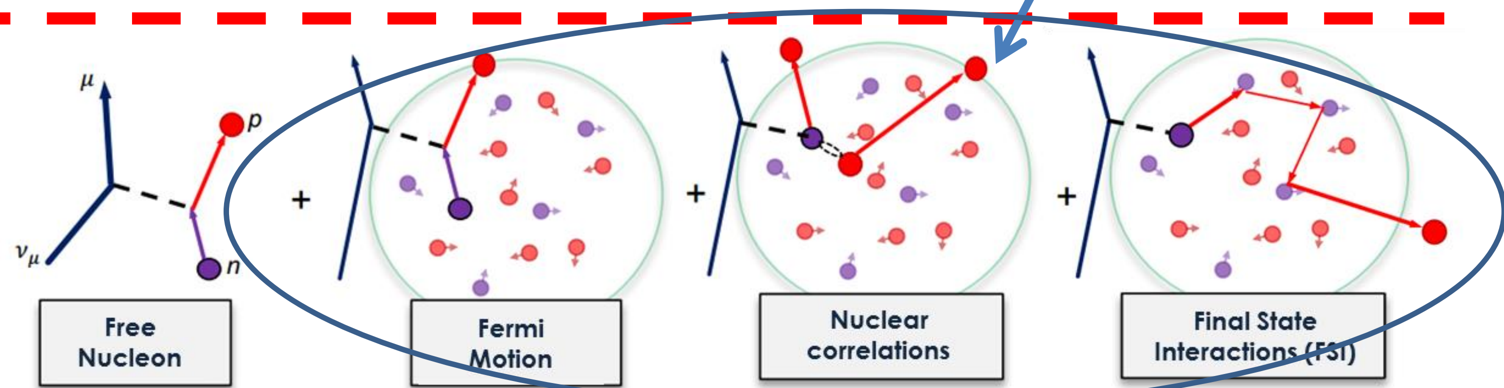


2p2h

(2 particle – 2 hole)



Nuclear Effects



Neutrino Interactions at T2K

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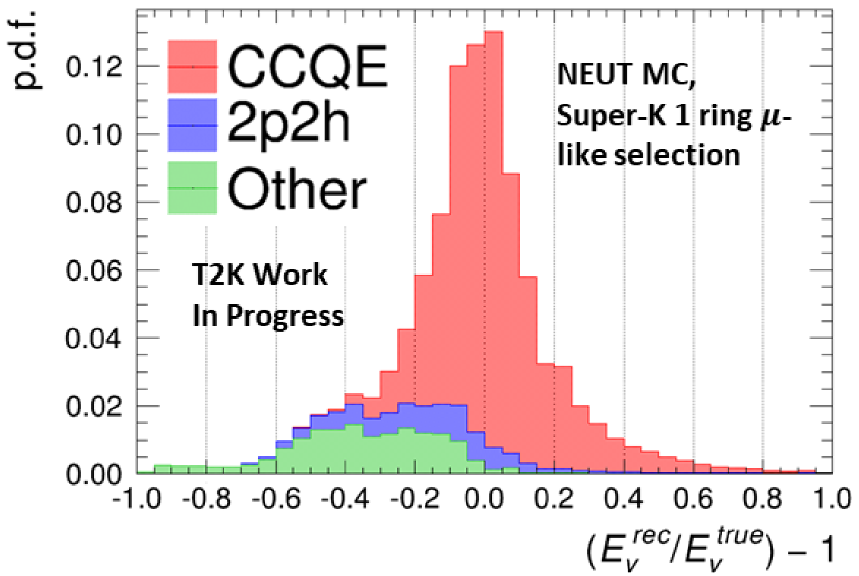
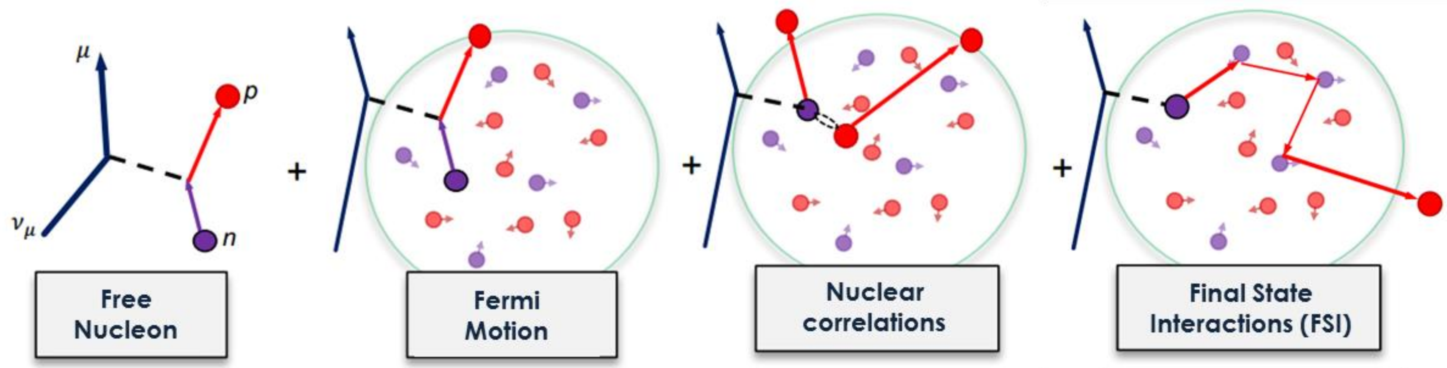
Bias due to:
- **Fermi motion** in the initial nuclear state
- Nucleon-nucleon **correlations**
- Pion absorption **FSI** → CCnonQE events



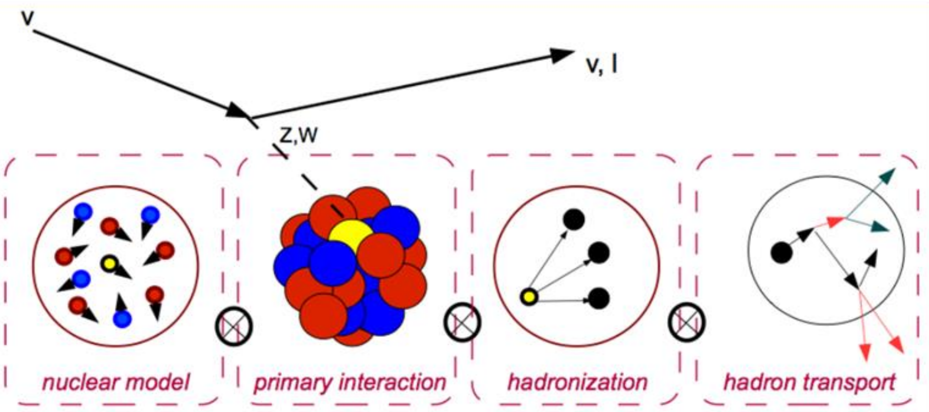
- Correct for bias using models …

Nuclear Effects



Modelling neutrino interactions

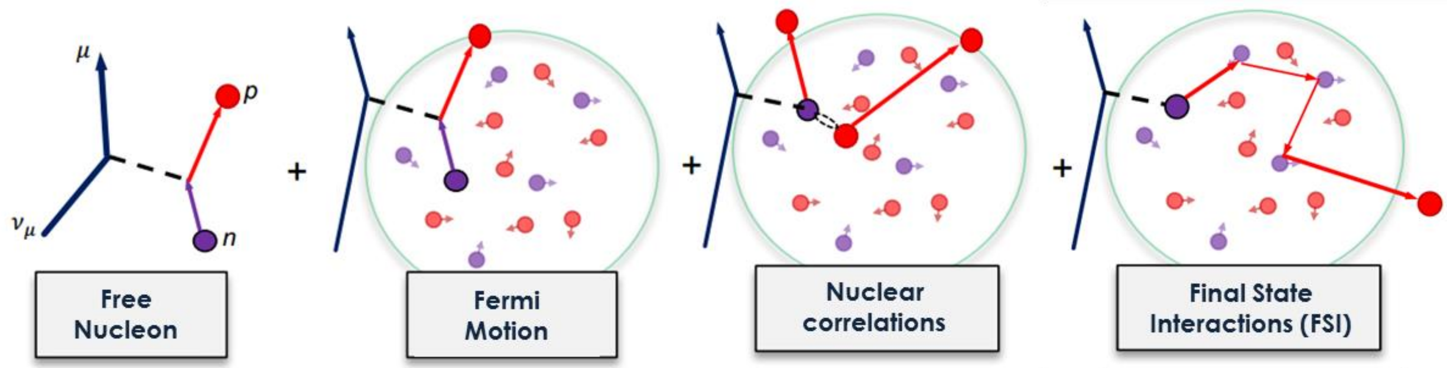
- Use **Monte-Carlo event generators** with **inclusive models** built from old bubble chamber and e^- scattering data.
- Predicting hadron kinematics *properly* requires **semi-inclusive** interaction models.
  - These don't really exist
  - Those that do are too slow
- Instead we introduce ad-hoc semi-classical models …
- Even the inclusive models struggle beyond the QE region → **large systematics**



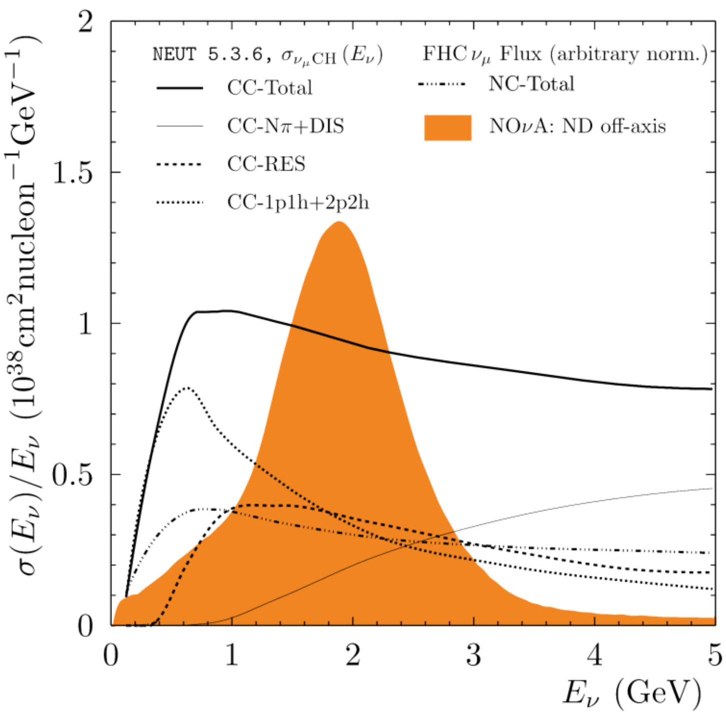
We use an inclusive ($\frac{d\sigma_{CCQE}}{dp_\mu d\cos\theta_\mu}$) model for this.

The rest is *ad-hoc* nuclear / FSI models.

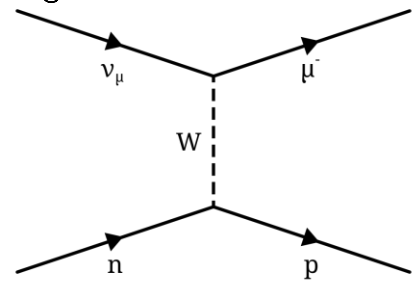
Nuclear Effects



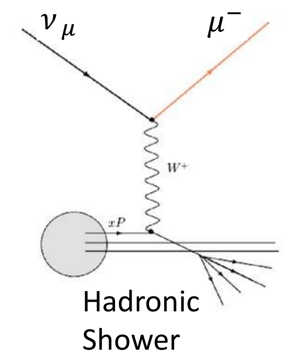
Neutrino Interactions at NOvA



CCQE (1p1h)
(Charged-Current Quasi-Elastic)



CCDIS
(Deep Inelastic Scattering)



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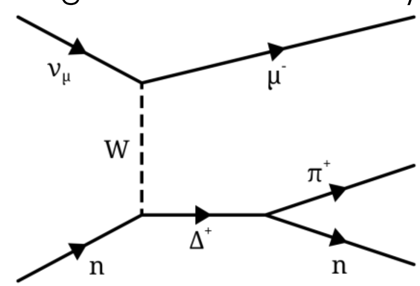
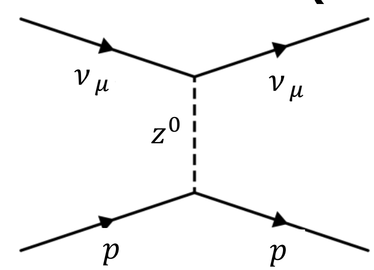
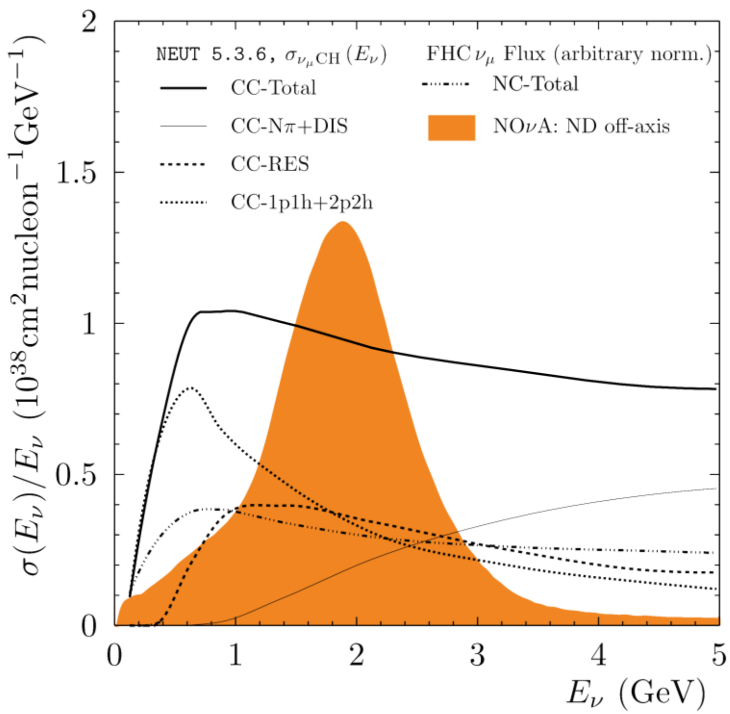


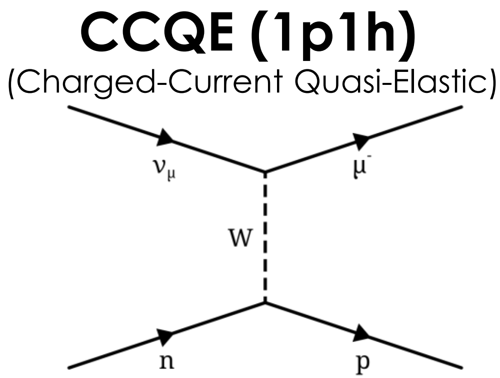
Neutral Current (NC)

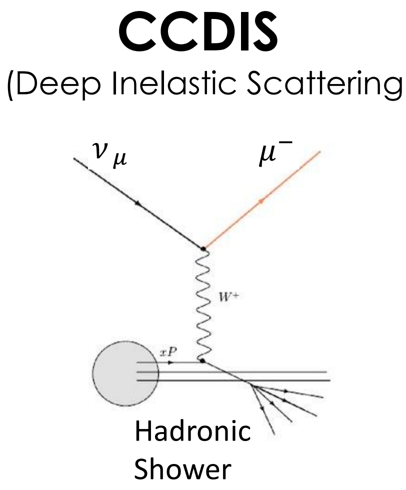


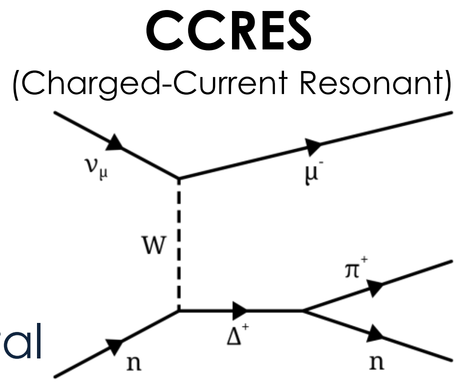
- NOvAs higher energy beam means most interactions are not CCQE
- DIS interactions become important
- T2K method of reconstructing neutrino energy will not work

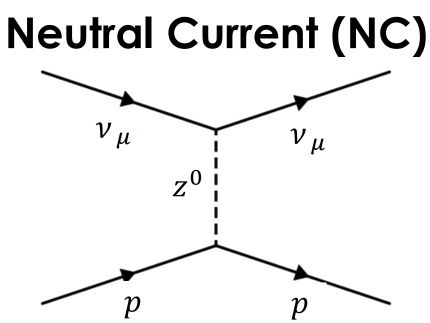
Neutrino Interactions at NOvA









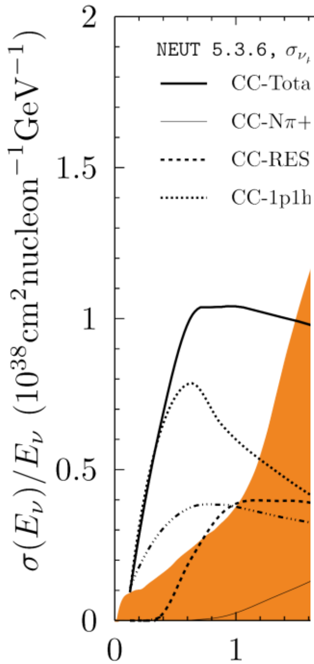


- Reconstruct neutrino energy from total energy deposited in the detector
- Misses most **neutrons** …

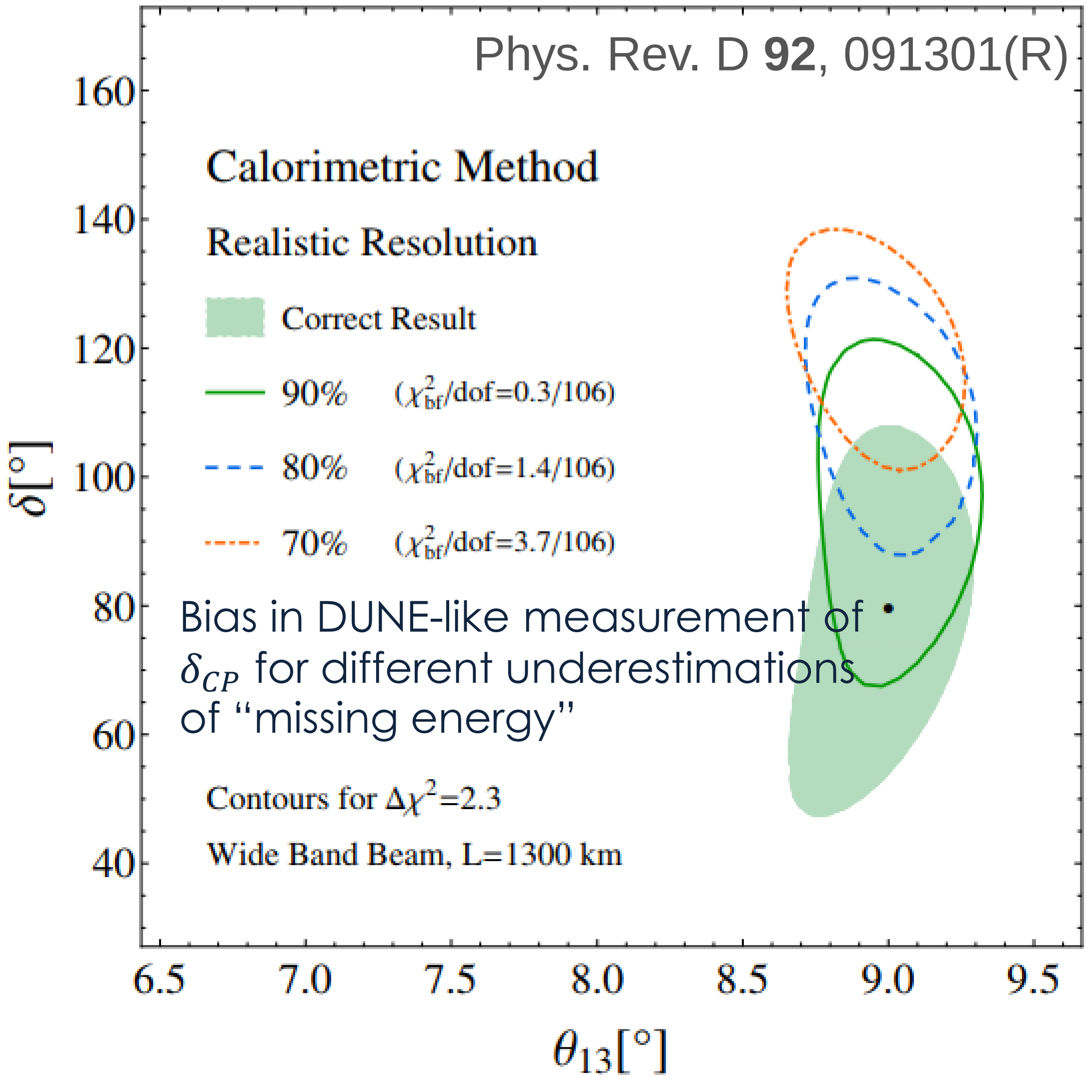
- **Rely on models** to tell us about neutrons:
  - Number of np, nn, pp initial state pairs in 2p2h
  - Neutrons produced through FSI
  - Neutron energy fraction in RES or DIS events

- **Large systematics**

Neutrino Interactions at NOvA



CCQE (1p1h)



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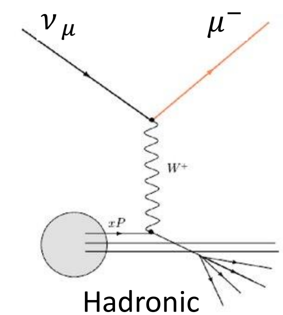
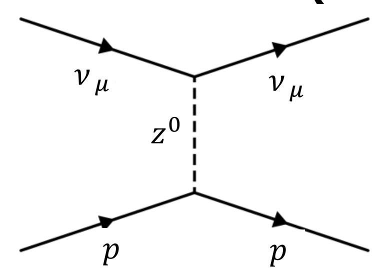


Neutral Current (NC)



- Reconstruc… energy dep…
- Misses most … bout neutrons:
  - … ial state pairs in 2p2h
  - … ugh FSI
  - … in RES or DIS events
    - **Large sy…**

Neutrino interactions and OA

- Future precision measurements of neutrino oscillations require **few-% systematics**
- Need to understand neutrino interactions to interpret the **event rate at the FD** and to **reconstruct neutrino energy**
- We rely on ***ad-hoc* models** of poorly understood nuclear physics to do this → **dominant systematics** (too large)

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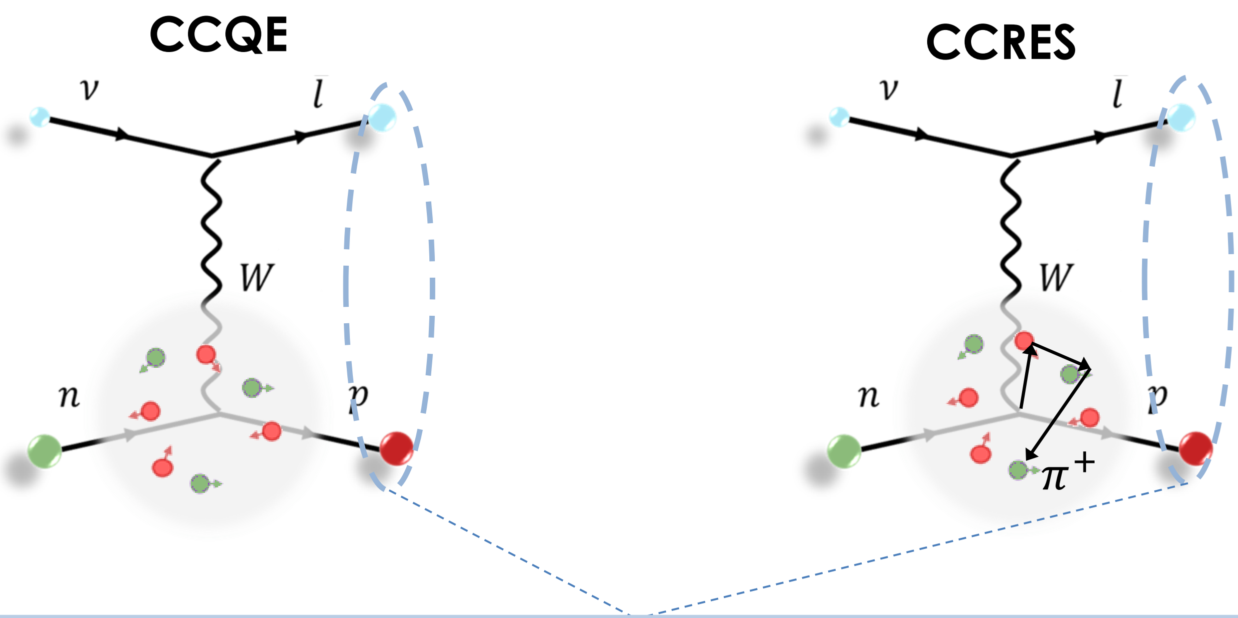
Overview

- Neutrino oscillations and long-baseline experiments
- Why care about neutrino interactions?
- Neutrino nucleus cross-section challenges and measurements
- Conclusions

What can't we measure

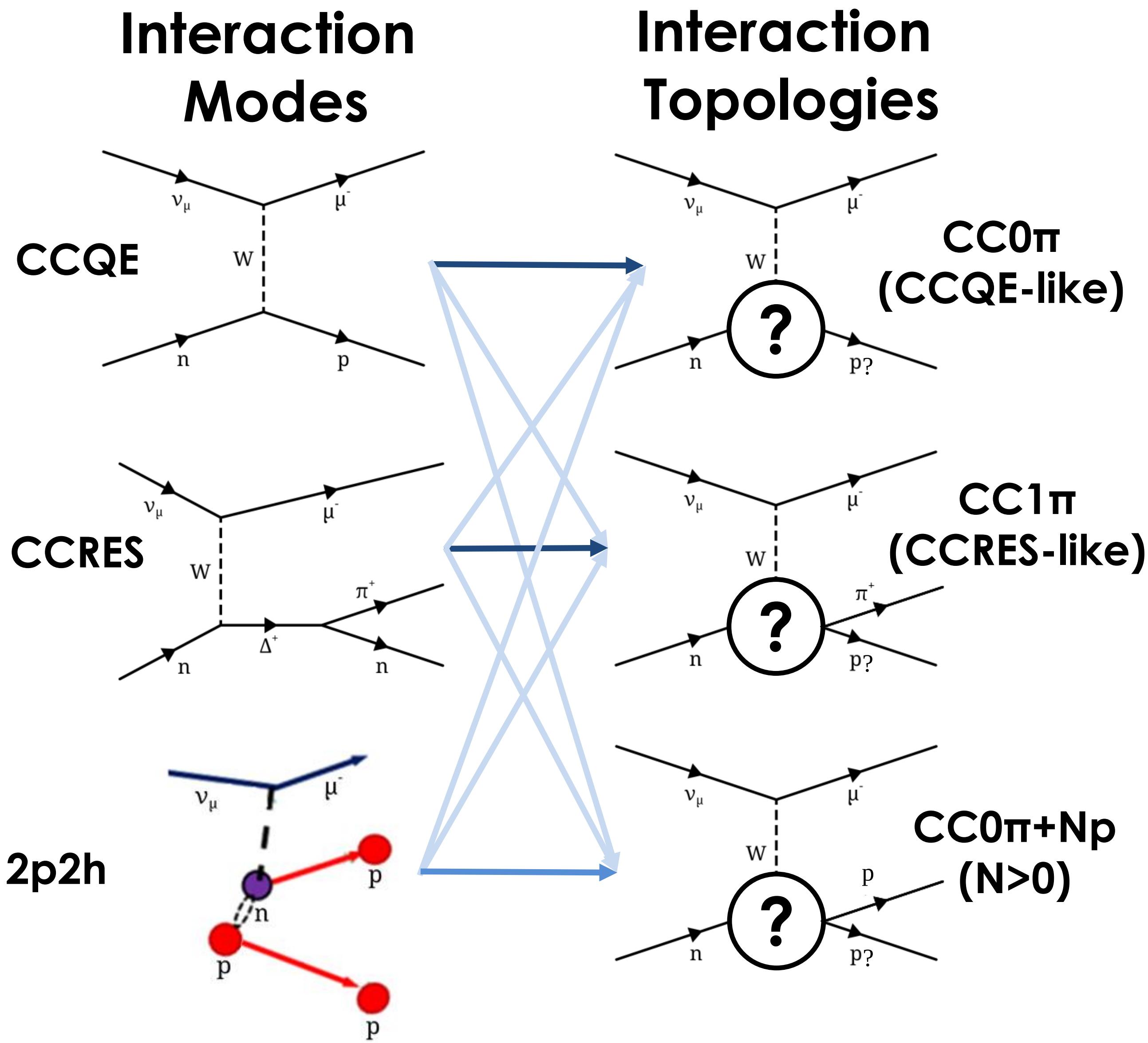
- Naively it would be great to measure $\sigma_{CCQE}(E_\nu), \sigma_{2p2h}(E_\nu), \sigma_{Oth}(E_\nu)$
- Why not?



Final state interactions (FSI) can cause different interaction modes to have the same final state

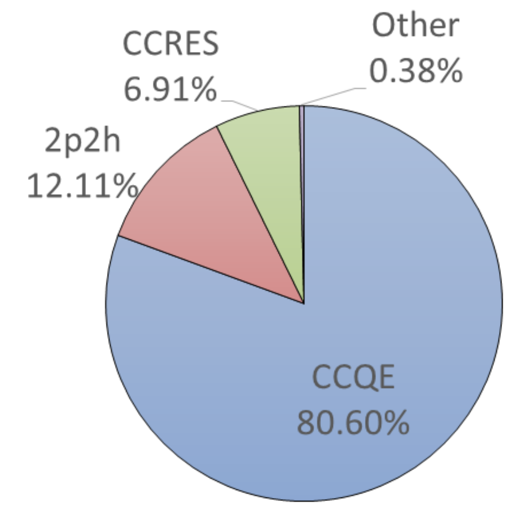
- Can't separate interaction modes on an event by event basis
- Entirely reliant on the input simulation to tell us contamination

What can we measure



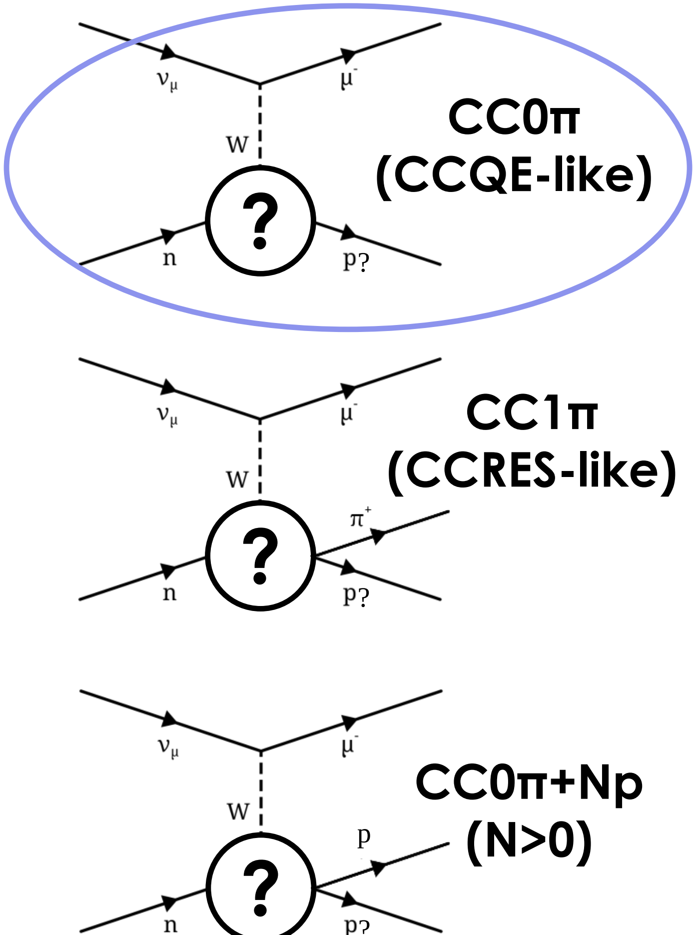
- Nuclear effects obfuscate interaction mode
- To minimise model dependence we measure interaction topologies

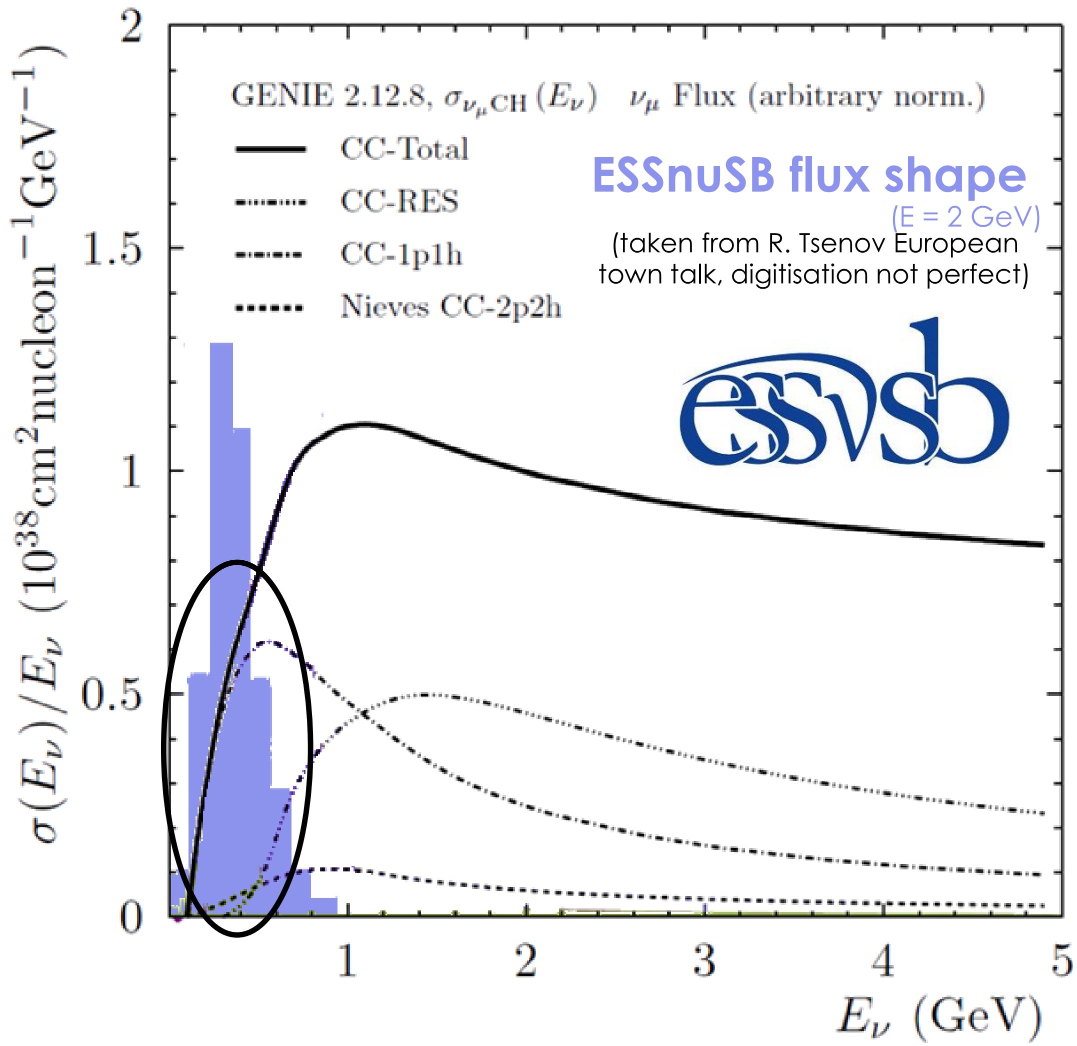
Interaction modes in CC0π topology at ND280:
(NEUT MC)



What can we measure

Interaction Topologies

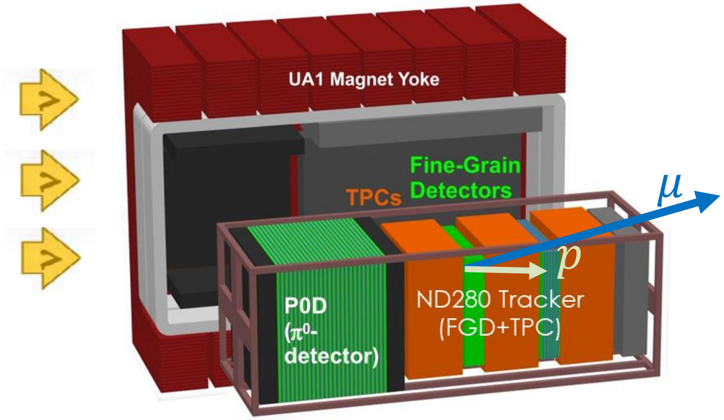




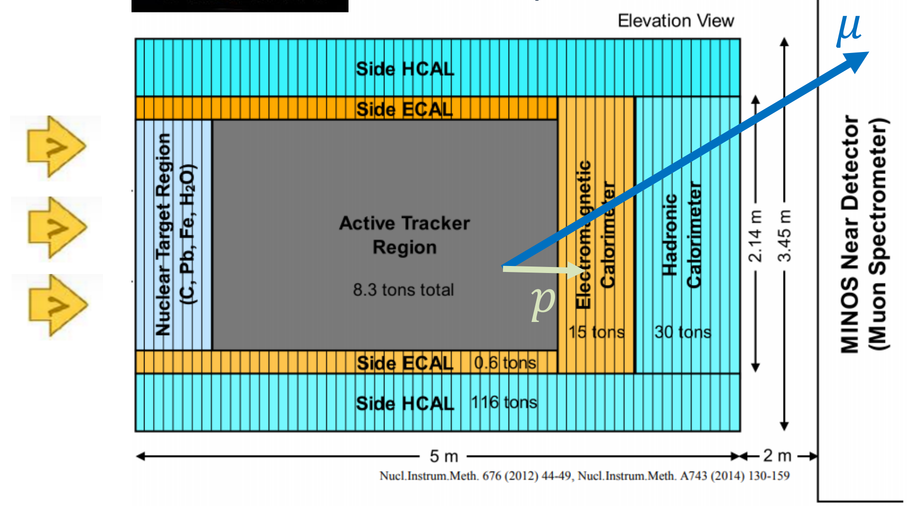
- Will focus on 0π / QE interactions
  – these are the most relevant to ESSnuSB

Who can do the measuring

T2K Near detectors (ND280+INGRID)
$E_\nu \approx 1$ GeV

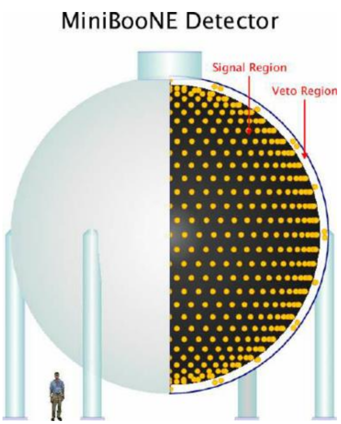


Purpose built neutrino interaction experiment
$E_\nu \approx 3$ GeV



Nucl.Instrum.Meth. 676 (2012) 44-49, Nucl.Instrum.Meth. A743 (2014) 130-159

Previous experiments:

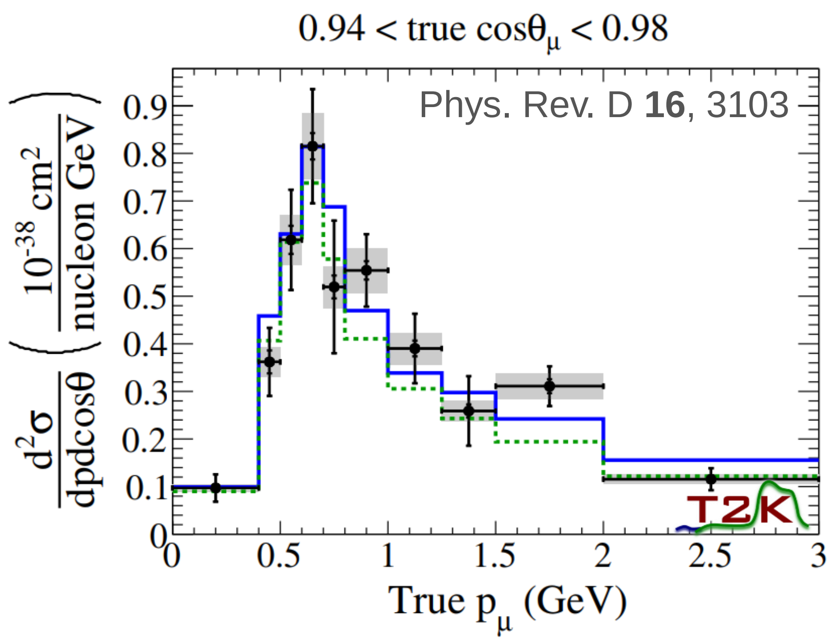


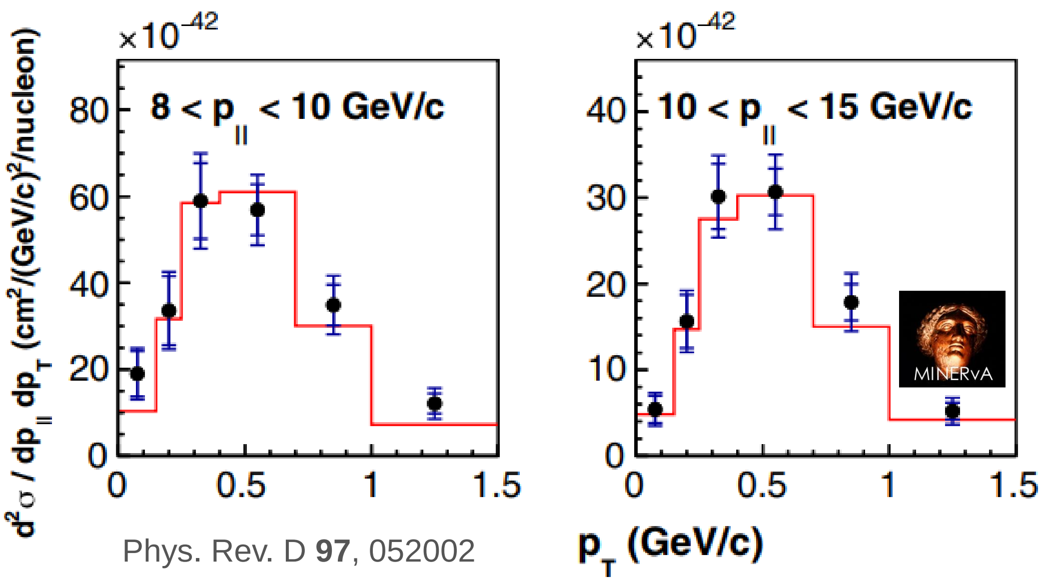
MiniBooNE measured many neutrino cross sections
$E_\nu \approx 1$ GeV

Old bubble chambers (ANL, BNL) provide the only light target (H_2,D_2) data: nuclear effect free!

CC0π measurements

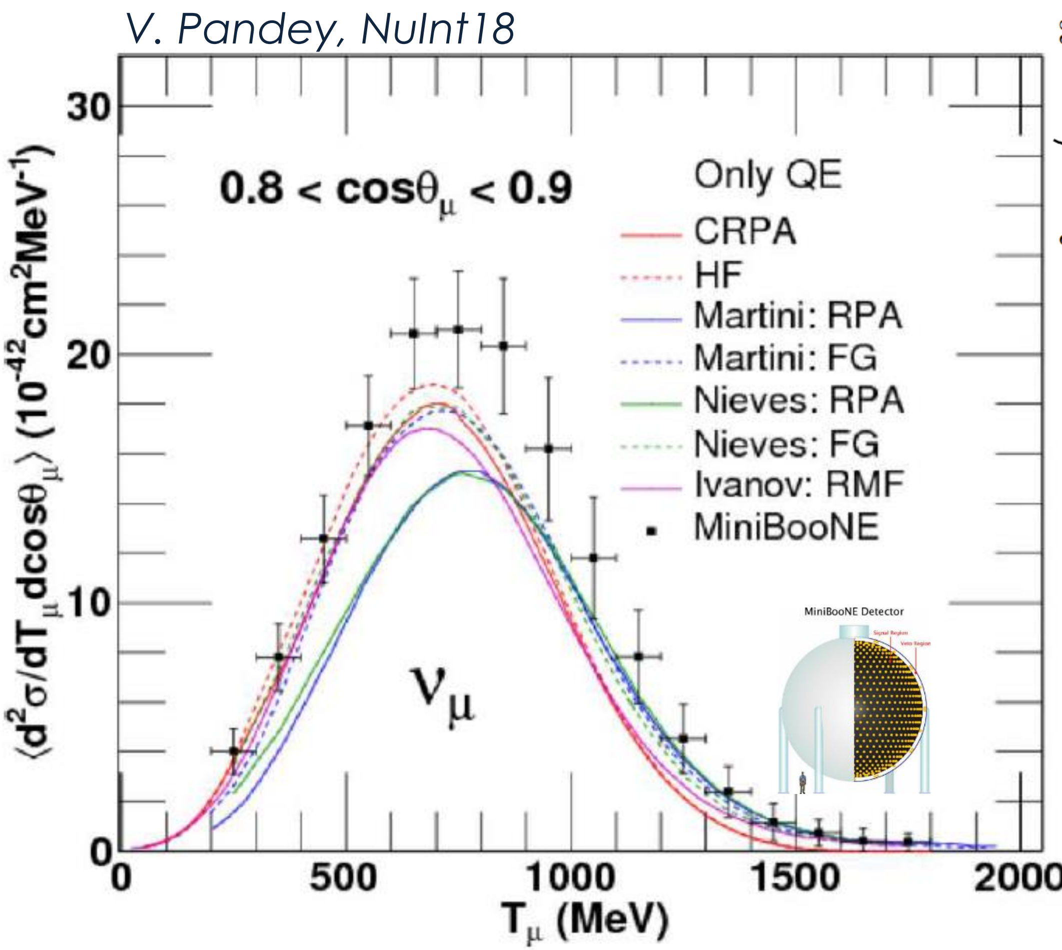
- Available models are able to reasonably well describe most T2K and MINERvA CC0π measurements of **lepton kinematics** on **CH targets**

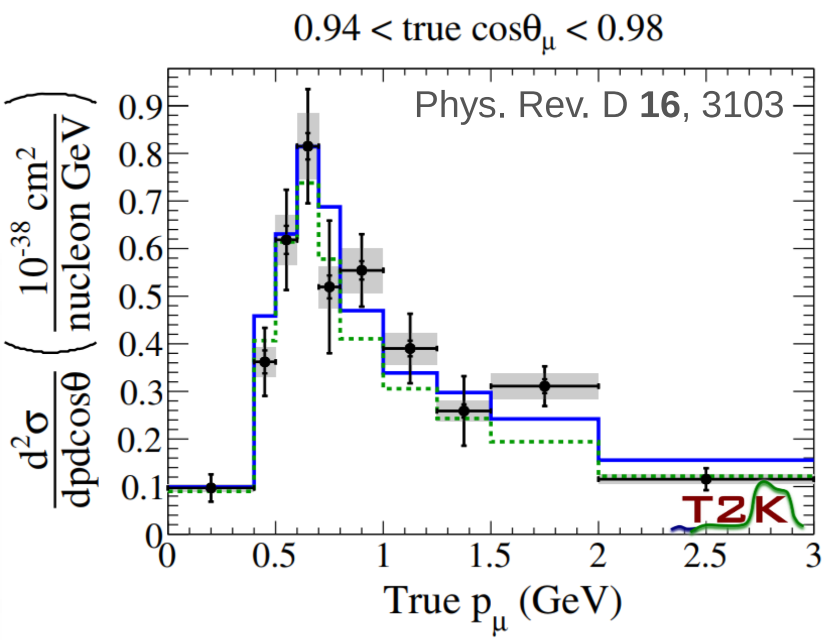




- However, **very different models** with different implications for oscillation analyses can **look very similar** in such measurements

CC0π measurements

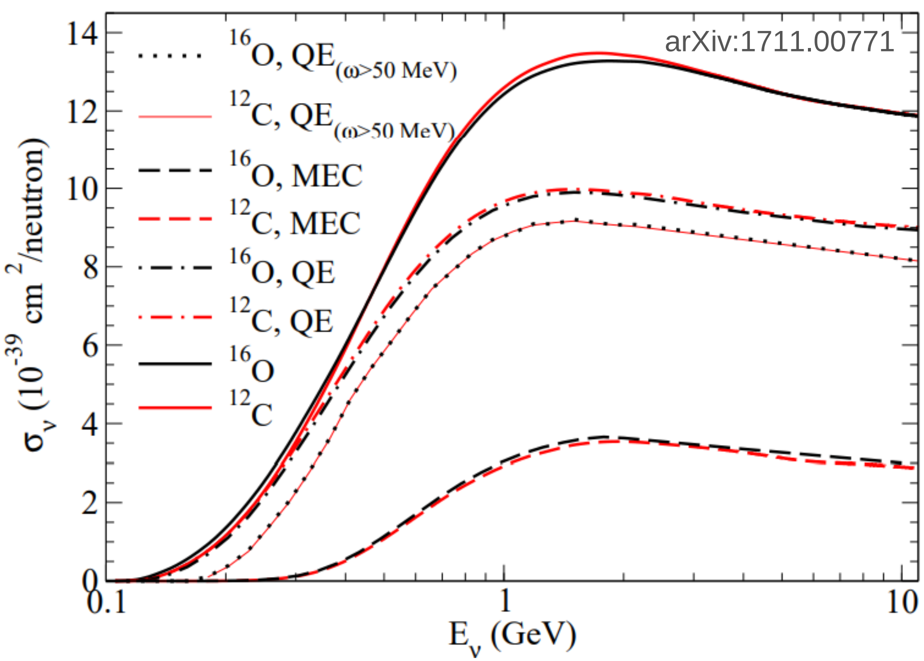


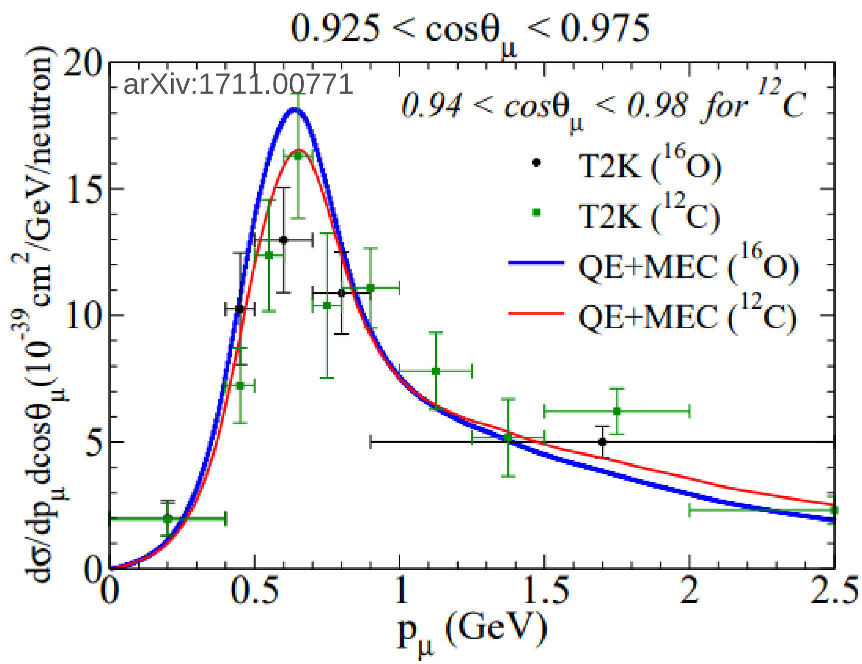


- However, **very different models** with different implications for oscillation analyses can **look very similar** in such measurements

C/O extrapolation

- Majority of our cross-section results come from CH scintillator targets
- T2K / ESS FD is water Cherenkov detector
- Latest theory predicts very little different between the targets, much smaller than experimental errors → small systematic
- Useful to continue to measure C/O to check theory, but not a major concern

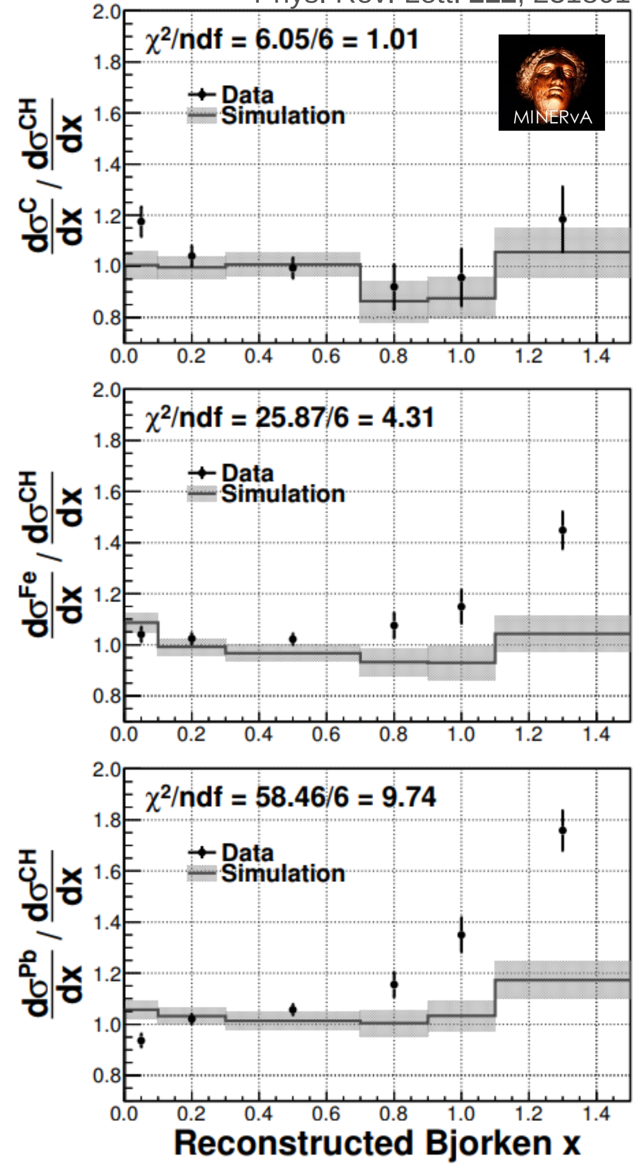




Beyond Hydrocarbon …

$$x = \frac{Q^2}{2M_N \nu}$$

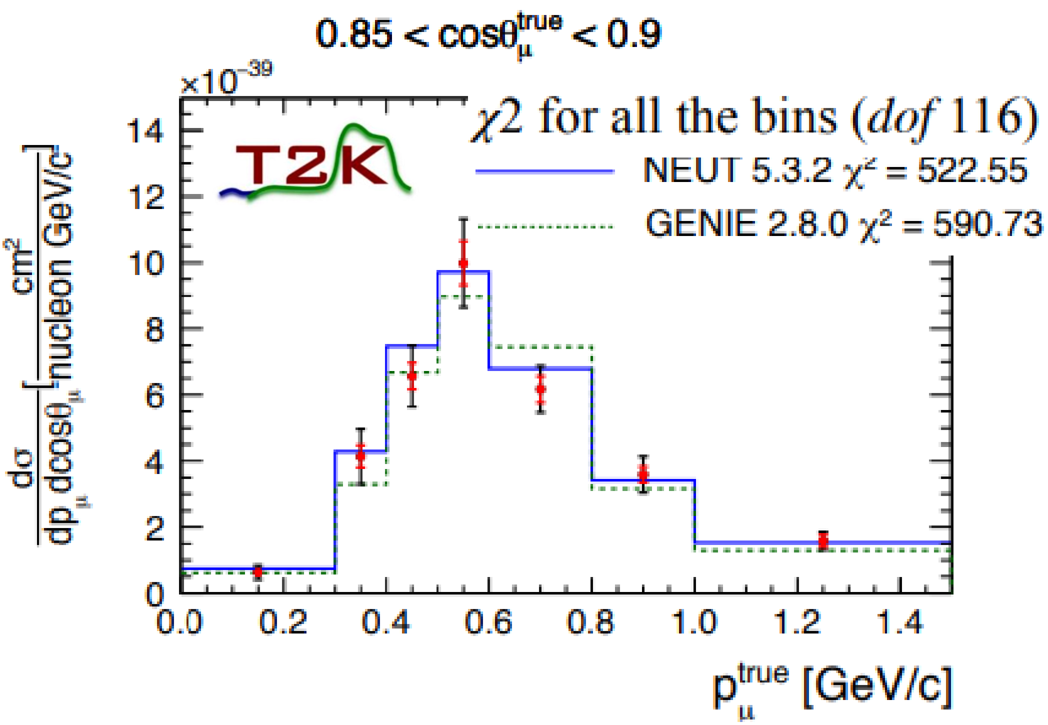
Phys. Rev. Lett. **112**, 231801

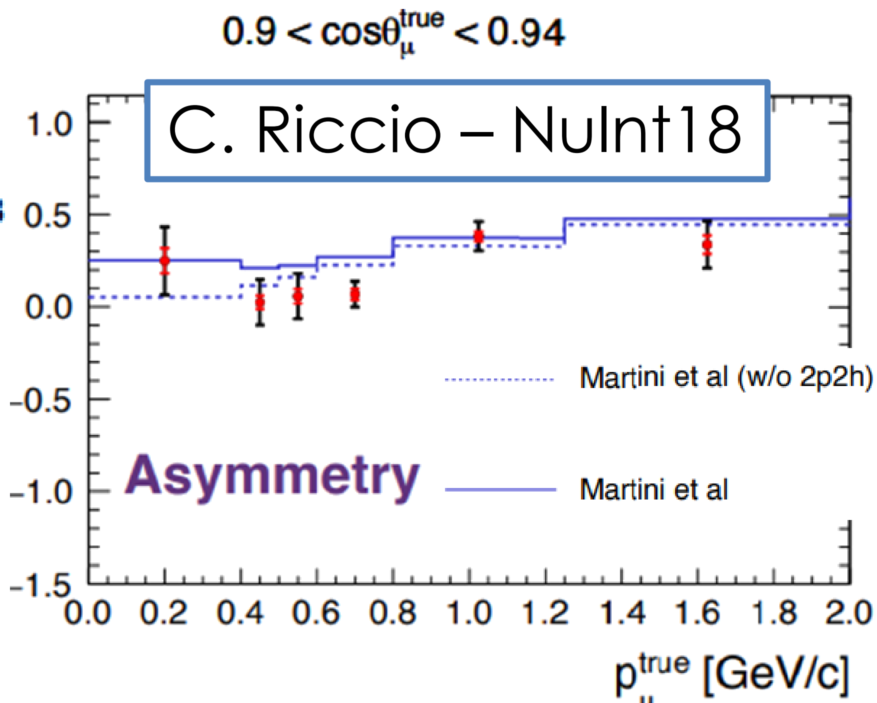


- MINERvA results show that our models do a poor job for much heavier targets
- It is critical for DUNE that we develop models to describe ^{40}Ar …
- MicroBooNE and SBN Fermilab program (^{40}Ar detectors) may help, but have a very different E_ν to DUNE (<1GeV vs 1-4GeV)

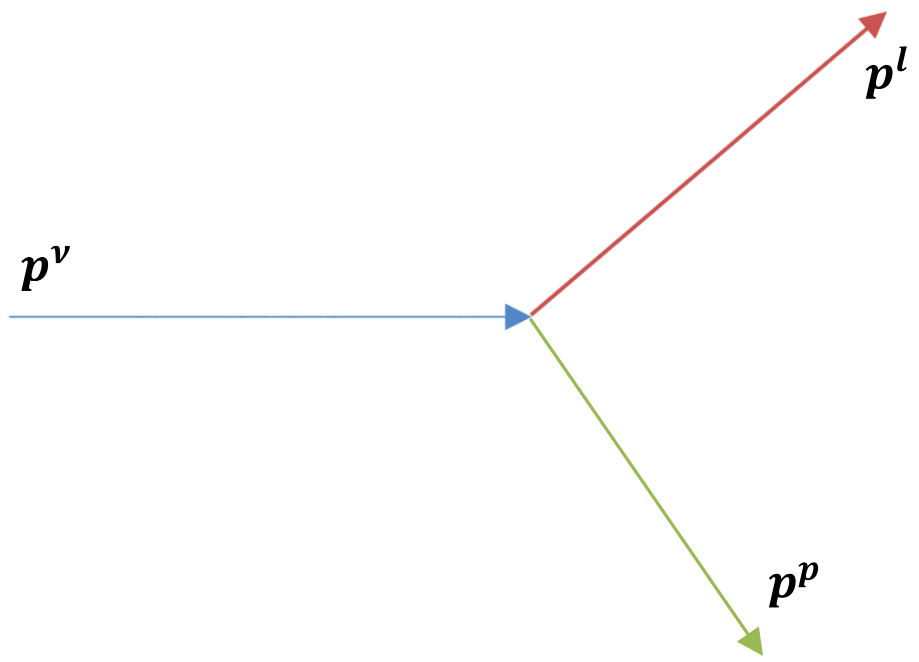
$\nu/\bar{\nu}$ differences

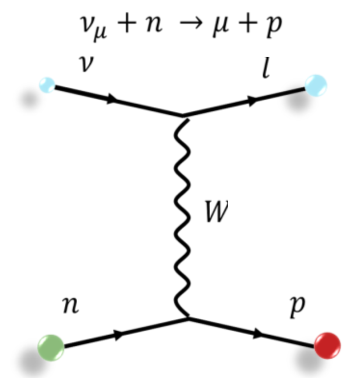
- Measuring CP-asymmetry depends on understanding $\nu/\bar{\nu}$ cross section ratio
- Few measurements of this exist, recent T2K measurement indicate issues with our models





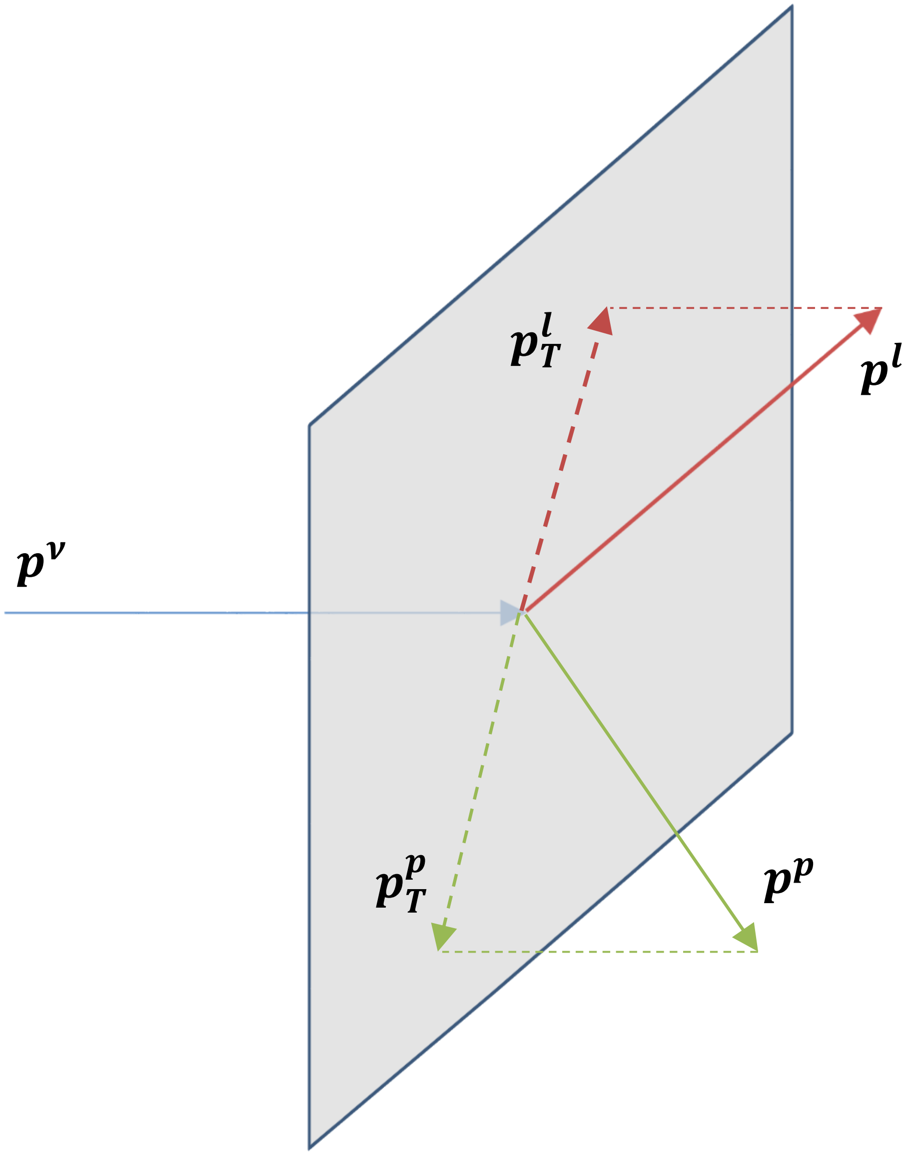
Single Transverse Variables

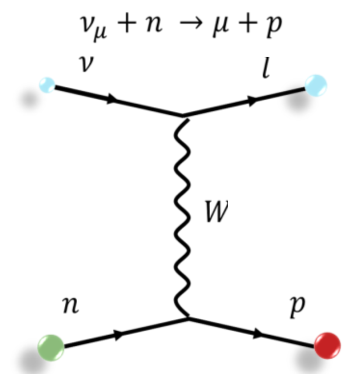




No nuclear Effects

Single Transverse Variables

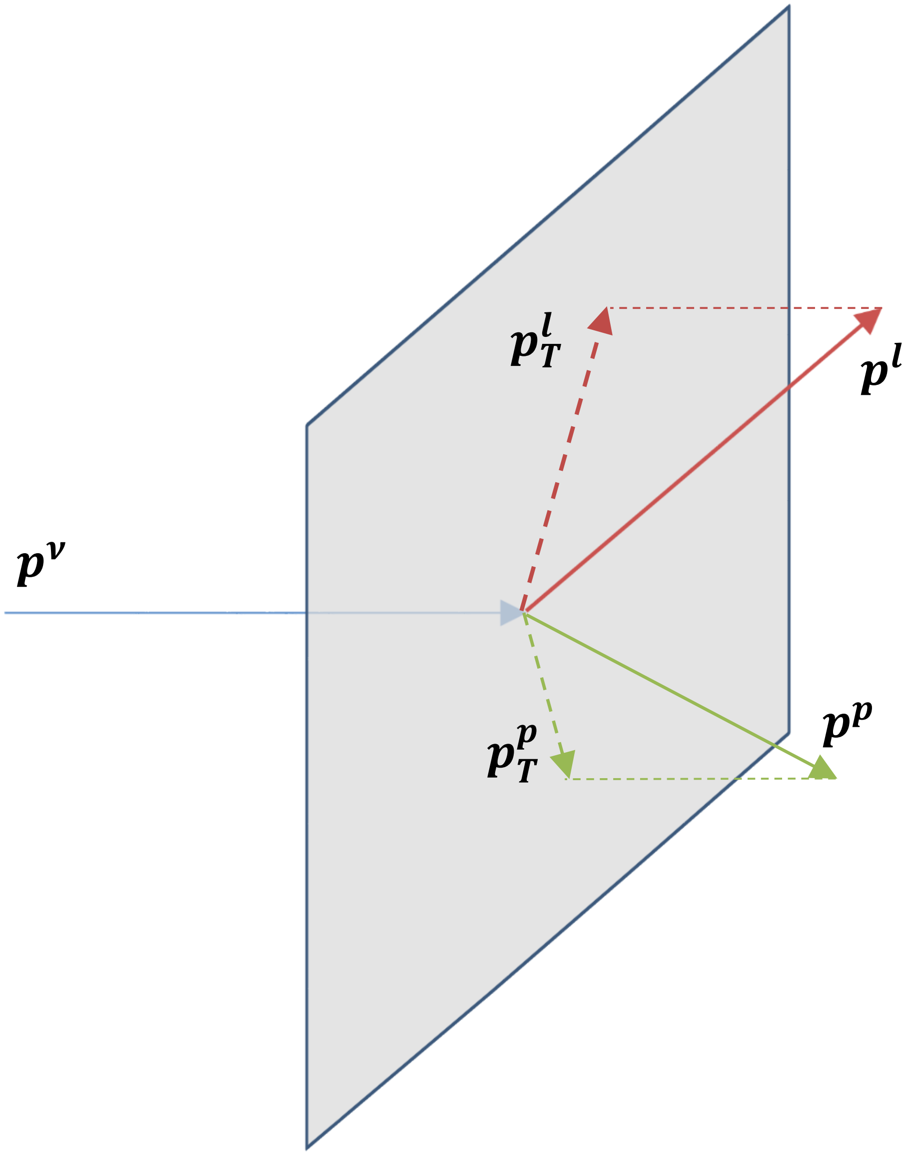


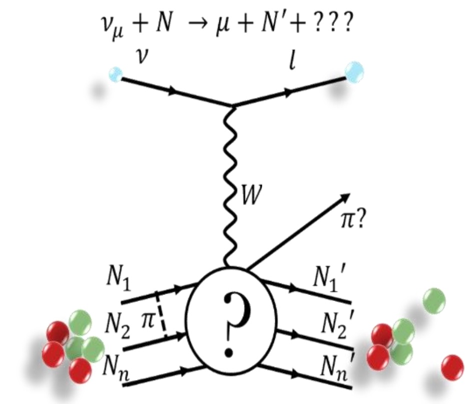


No nuclear Effects

$$p^l_T = -p^p_T$$

Single Transverse Variables



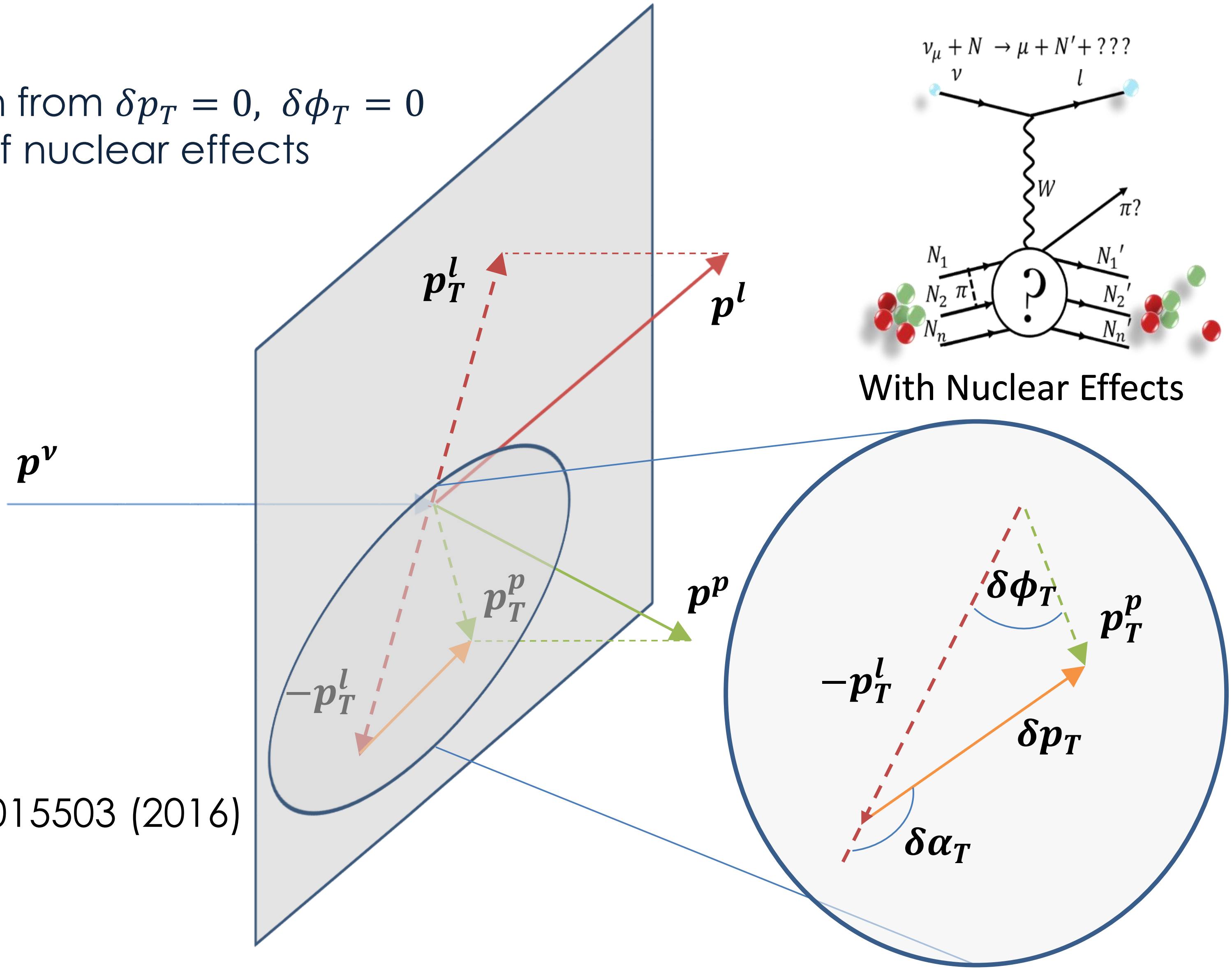


With Nuclear Effects

$$p_T^l \neq -p_T^p$$

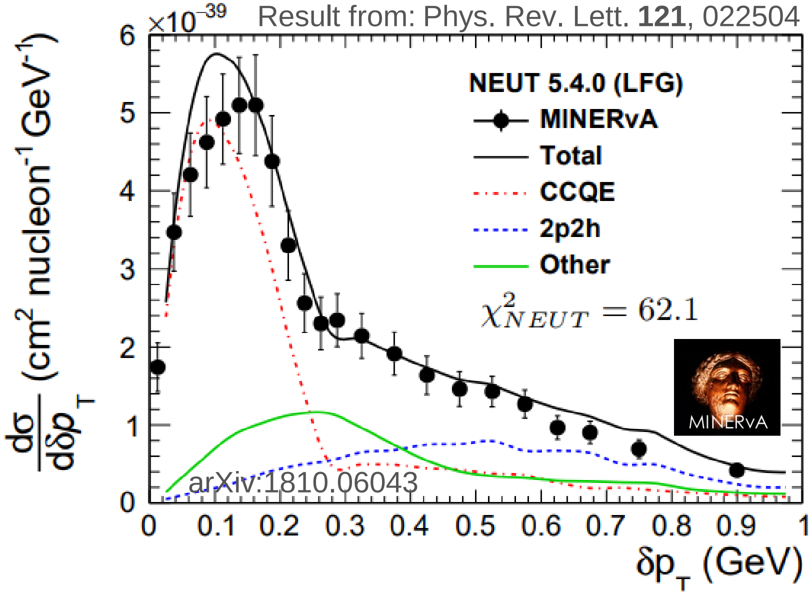
Single Transverse Variables

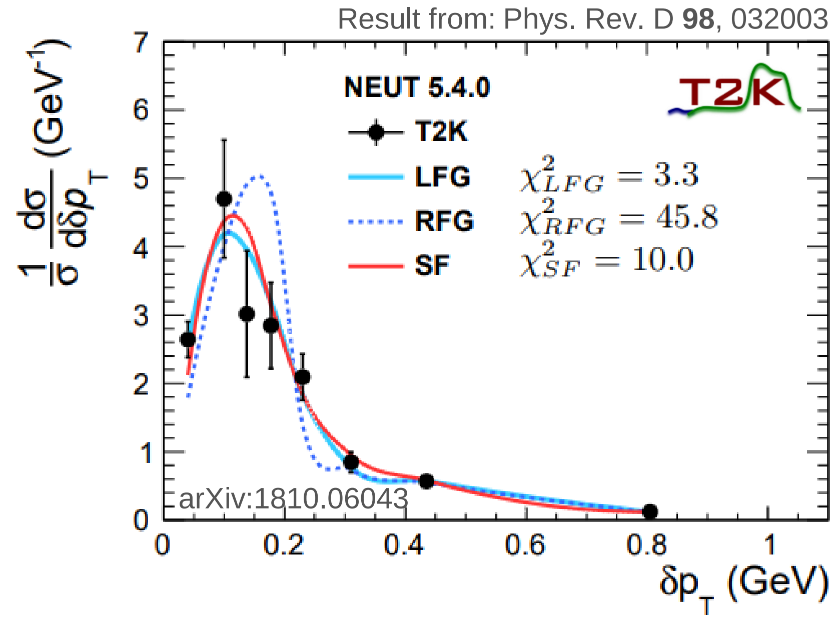
- Any deviation from $\delta p_T = 0,\ \delta\phi_T = 0$ is indicative of nuclear effects

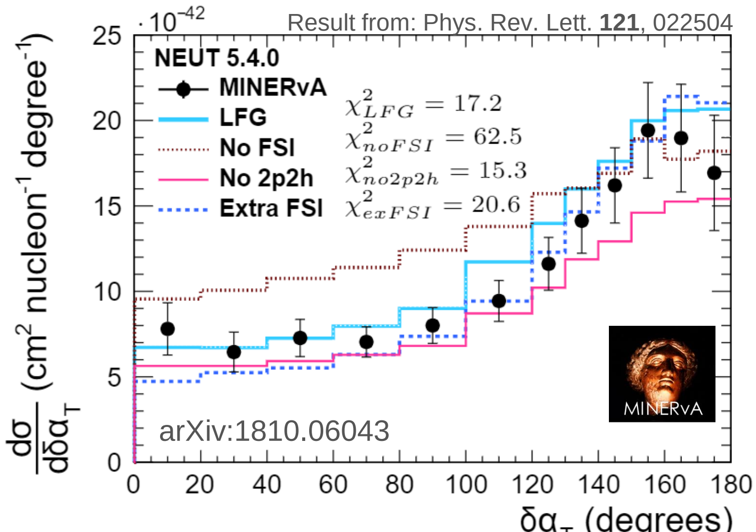


Phys. Rev. C **94**, 015503 (2016)

Single Transverse Measurements





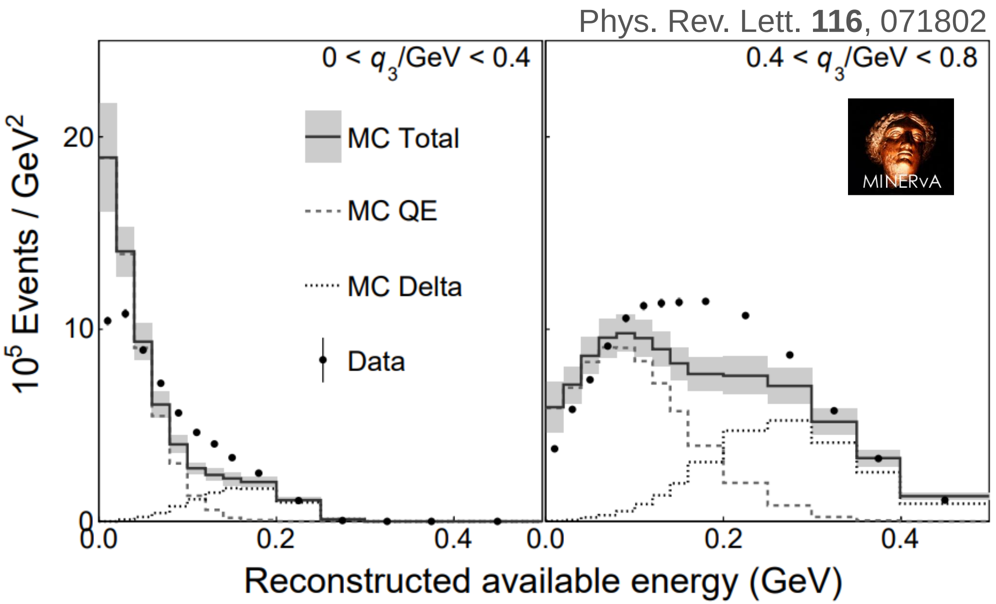


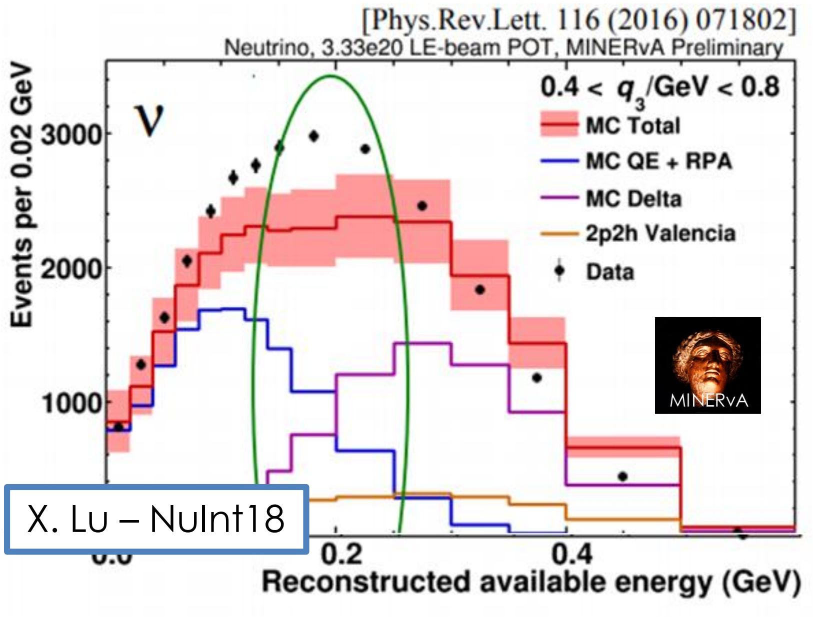
- Different parts of the STV are sensitive to different nuclear effects
- Can begin to see where our models do well and where they fail
- Clearly the models need work …

Also see: Phys. Rev. C **98**, 045502

Calorimetric measurements

- Use measurements of calorimetric energy to estimate energy and momentum transfer of an interaction (like we have in e^- scattering)
- Separates QE, 2p2h and RES (Delta) contributions
- Models show a clear deficit, particularly in 2p2h enhanced regions





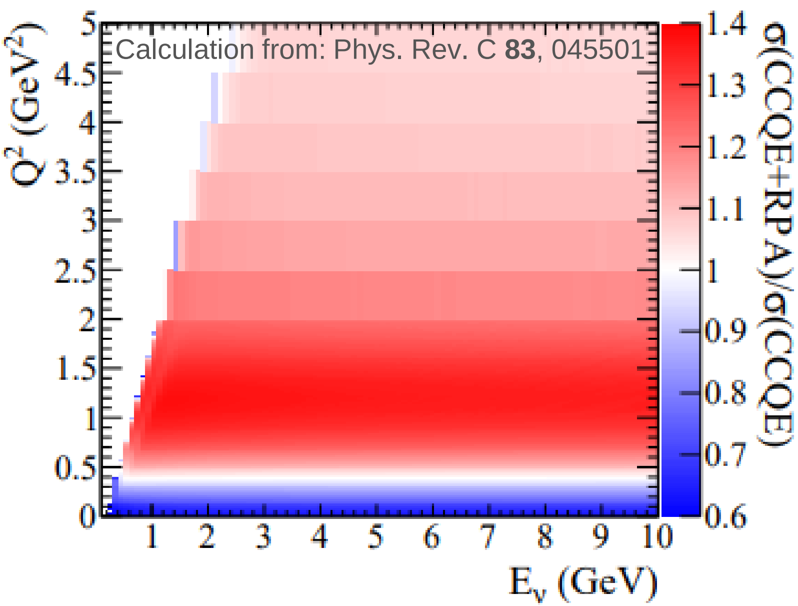
Low energy CC0π

- At low energies, longer wavelength propagator means "long-range correlations" between nucleons become more important
  - **Potentially very important for ESSnuSB!**

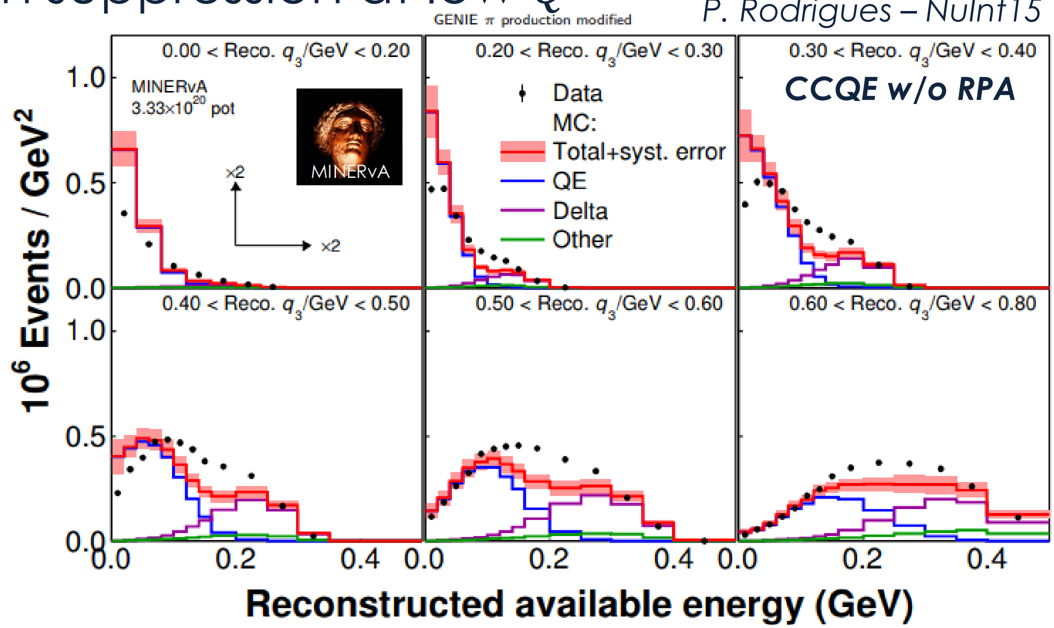
- Whole nucleus becomes excited by interaction – energy transfer distributed across many nucleons

- Described by RPA – Random phase approximation

- Acts as a strong cross section suppression at low Q^2



P. Rodrigues – NuInt15



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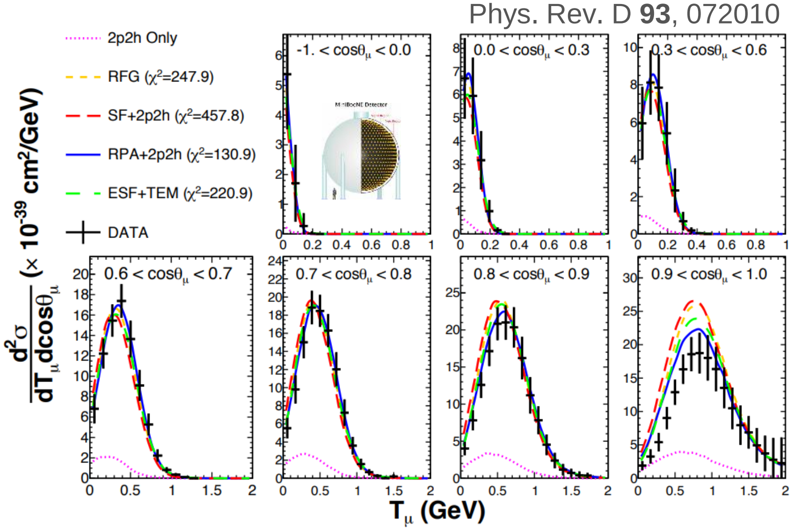
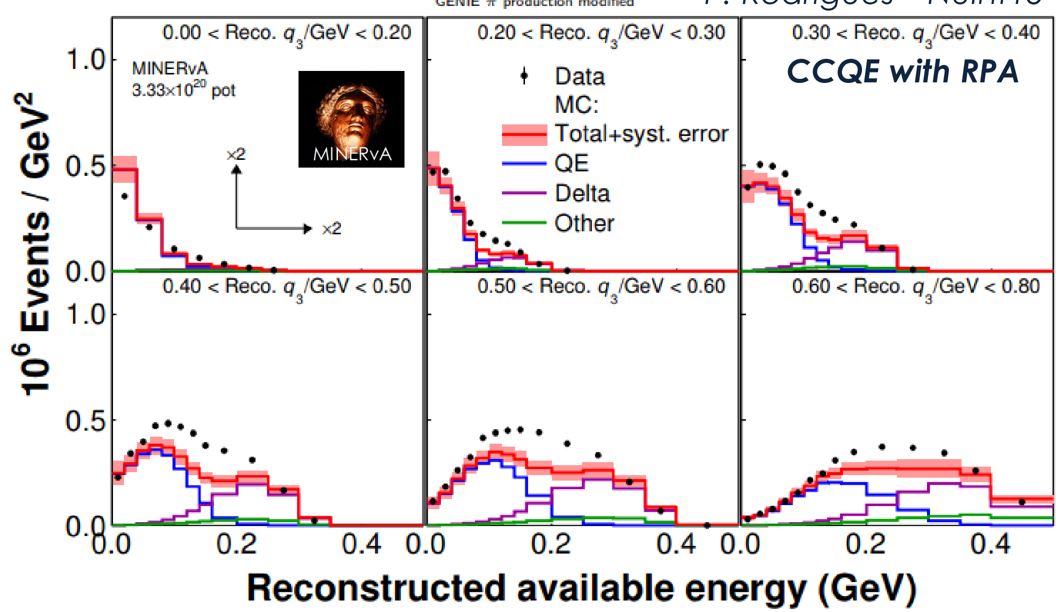
Phys. Rev. D **93**, 072010



GENIE π production modified

P. Rodrigues – NuInt15



Low energy CC0π

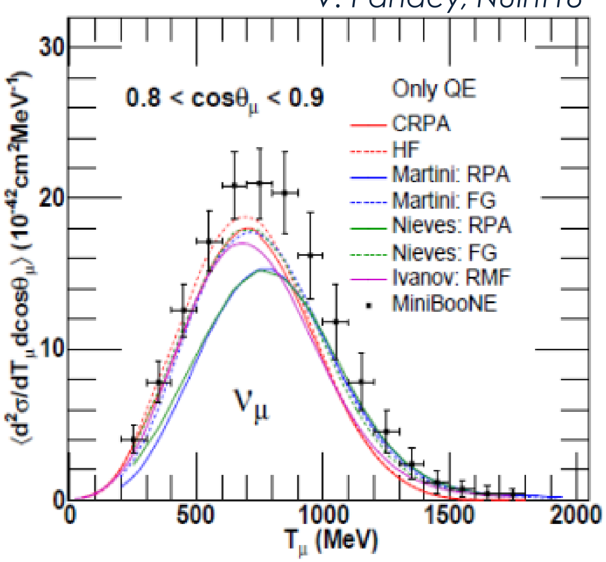
- Clearly required by MINERvA calorimetric results

- But the exact theoretical description is still uncertain:
  - Alternative theoretical approaches (e.g. HF-CRPA model)

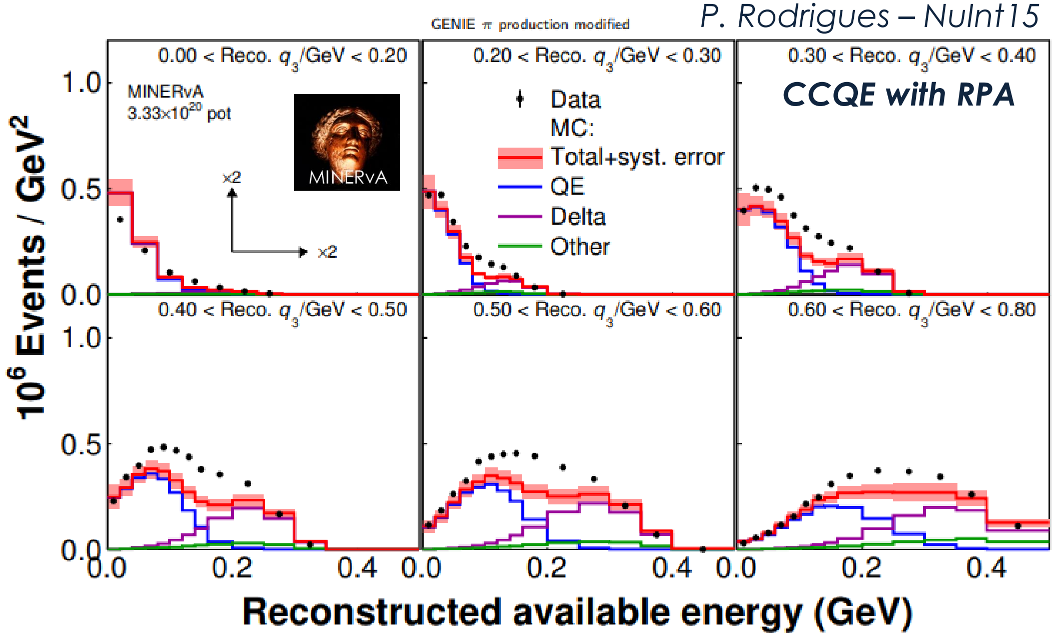
    Phys. Rev. C **83**, 045501, Phys. Rev. C **92**, 024606; Phys. Rev. C **65** 65025501; Phys. Rev. C **80**, 065501
  - Role of RPA less dramatic if nucleons properly bound?
  - Degeneracy with the rest of the nuclear model?

[U. Mosel ECT* workshop]

V. Pandey, NuInt18



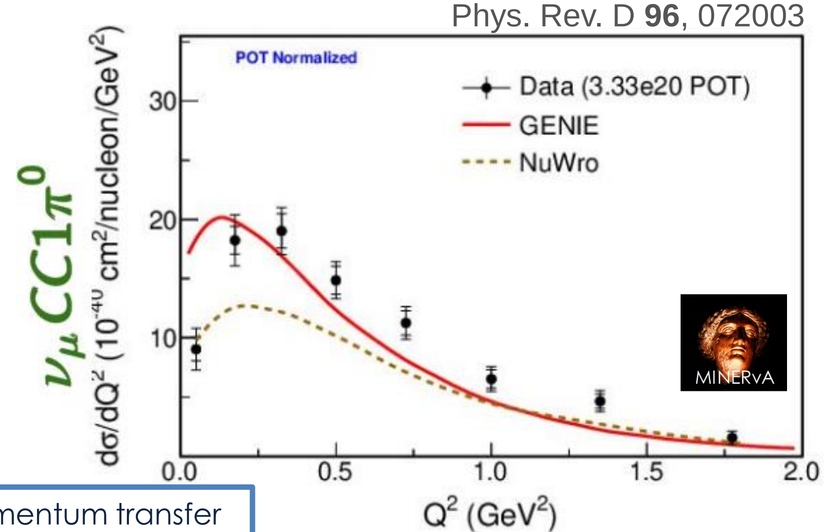
P. Rodrigues – NuInt15



CC1π measurements

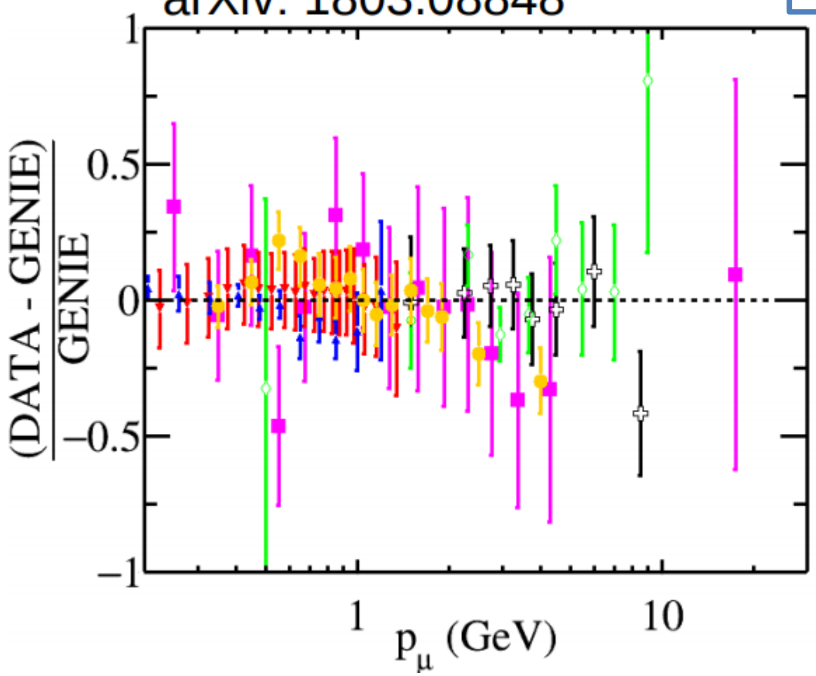
- Use a very simplistic inclusive model, many missing ingredients (few theoretical alternatives, but WIP)
- Seems able to describe muon kinematics, but not the pion's
- Gross overestimate at low Q^2

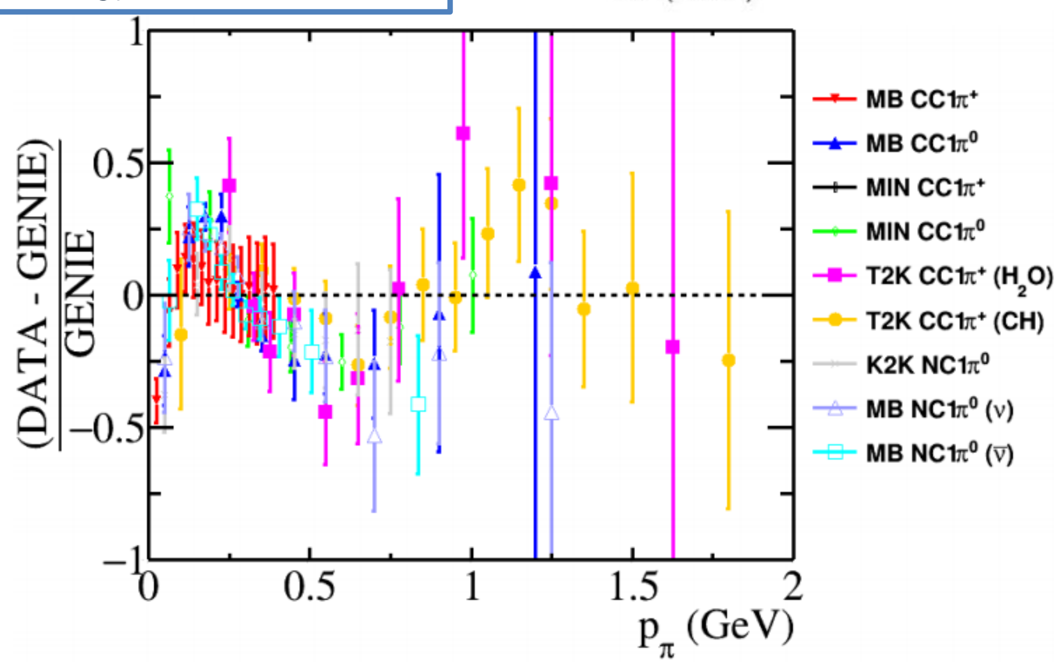
Phys. Rev. D **96**, 072003



Q^2: Energy-momentum transfer

arXiv: 1803.08848

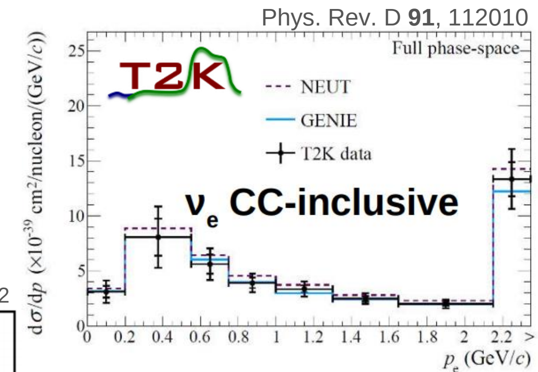


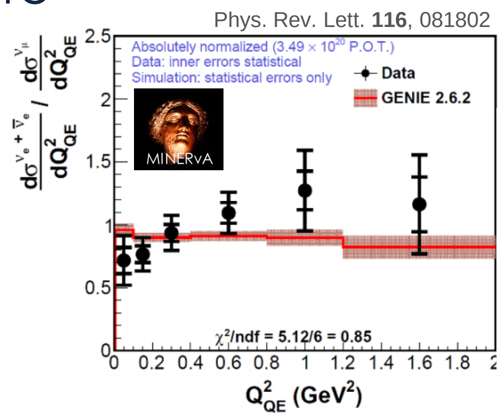


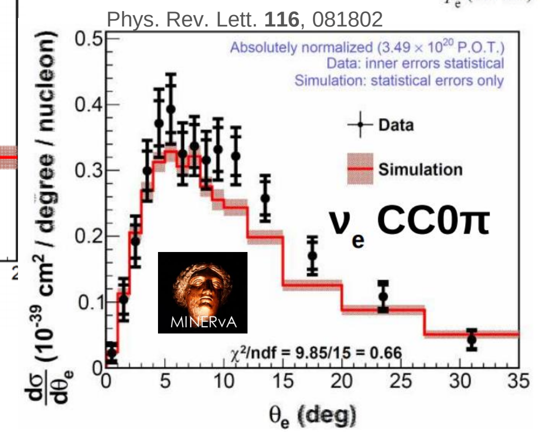
Further challenges

ν_e cross sections

- Use measurements of ν_μ at ND to constrain ν_e interactions at FD
- Important to understand the differences – T2K and MINERvA measure ν_e cross sections
- Oscillated ν_e flux is very small – challenging measurements

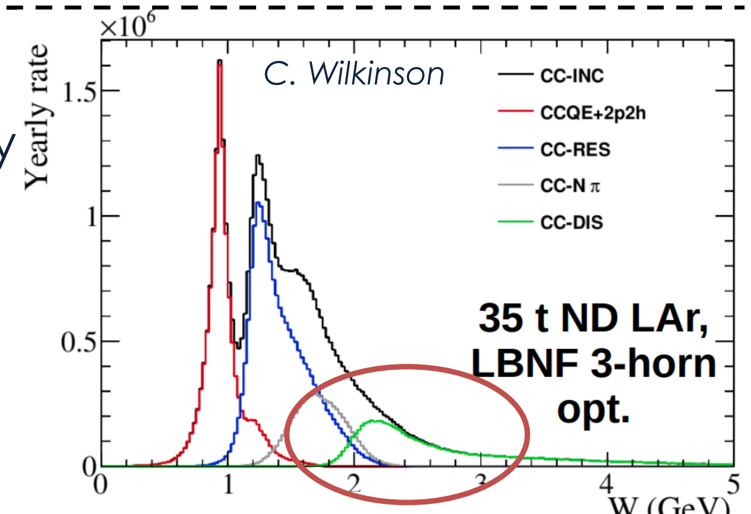






DIS-RES region

- Transition region between DIS and RES poorly modelled (stitching together models)
- Information on particle multiplicity limited to old bubble chamber data
- Critical region for DUNE (also partially NOvA)



Conclusions

- A precise understanding of neutrino-nucleus interactions is essential for precision measurements of neutrino oscillations
- Associated systematic uncertainties are either already dominant, or expected to become so soon
- T2K and MINERvA are making a variety of creative measurements of neutrino scattering cross sections …
- But our models are unable to describe the new data!
- essνsb will be dominated by ***better*** understood CC0π processes, but even these are not ***well*** understood
- New data from existing and future experiments may help, but model development is essential.

The way out?

Input from and collaboration with theorists is fundamental to overcoming these challenges

- Experiments have outstripped the over simplified models in generators.

NuInt 18 Experimental summary talk – K. McFarland

With every topic we find that the challenges can be met only with the active support and collaboration among specialists in strong interactions and electroweak physics that include theorists and experimentalists from both the nuclear and high energy physics communities.

NuSTEC White Paper (Prog.Part.Nucl.Phys. 100 (2018) 1-68)

- Apart from rigorous work, inspiration (and whining abilities ☺) (especially young) theorists need institutional support!

NuInt 18 Theoretical summary talk – V. Pandey

NEUTRINO 2018 cross-section talk - U. Mosel

- Precision era of neutrino physics requires more sophisticated generators and a dedicated joint effort in nuclear theory and generator development
- This joint effort has to be funded as integral part of experiments

Thank you for listening!