Neutrino interaction uncertainties in long-baseline oscillation experiments

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Talks this afternoon

- This afternoon we will hear talks from experiments on their experience with systematic uncertainties, especially due to neutrino cross sections:
  - **DUNE** analysis & systematics
  - **Hyper-K** systematics
  - **MicroBooNE** analysis & systematics
  - Coffee-related systematics
  - **T2K** neutrino interaction uncertainties
  - **NOvA** systematics
  - **MINERvA** interaction modeling uncertainties
- Goal of this talk is to introduce the topic of cross section uncertainties and why they matter

Generic neutrino oscillation measurement

Neutrino source

ν_μ

Far detector at distance **L**

ν_e

1) Measure flux, $\Phi(E_\nu)$ of ν_e at far detector at distance **L**
2) Compare to predicted flux $\Phi(E_\nu)$ of ν_μ at neutrino source
3) Party

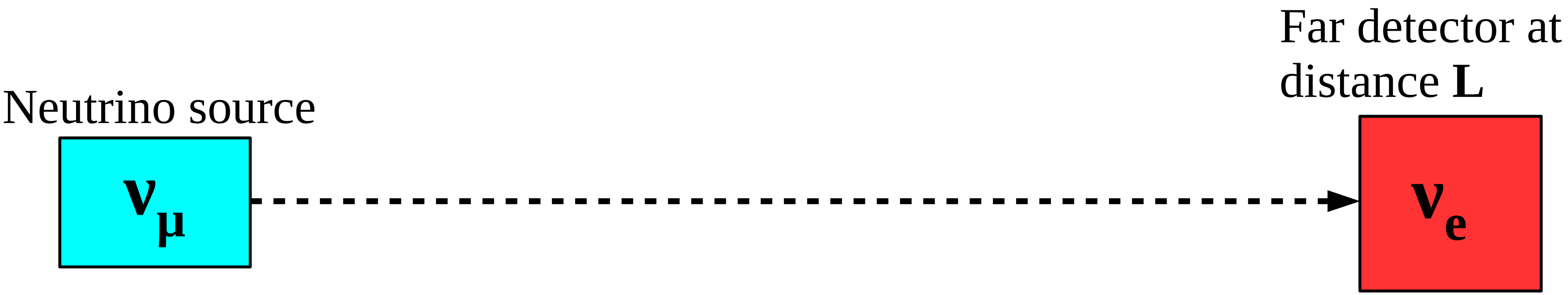
$$P(\nu_\mu \to \nu_e) = \frac{\Phi_{\nu_e}(E_\nu, L)}{\Phi_{\nu_\mu}(E_\nu, 0)}$$

Generic neutrino oscillation measurement

1) Measure reconstructed energy spectrum at far detector
2) Use models to infer ν_e flux at far detector
3) Much less fun party where you are worried about all the mistakes that might be in your models

$$N_{\nu_e}^{far}(E_{reco}) = \int \Phi_{\nu_e}(E_\nu, L) \times \sigma_{\nu_e}(E_\nu) \times \epsilon^{far}(E_\nu) \times \mathbf{D}_{\nu_e}^{far}(E_\nu \to E_{reco}) dE_\nu$$

Generic neutrino oscillation measurement



Neutrino source

ν_μ

Far detector at distance **L**

ν_e

To get flux $\Phi(E_\nu)$, you must first understand

1) ν_e-nucleus cross sections as a function of E_ν

$$N^{far}_{\nu_e}(E_{reco}) = \int \Phi_{\nu_e}(E_\nu, L) \times \sigma_{\nu_e}(E_\nu) \times \epsilon^{far}(E_\nu) \times \mathbf{D}^{far}_{\nu_e}(E_\nu \rightarrow E_{reco}) dE_\nu$$

Generic neutrino oscillation measurement

Far detector at distance **L**

Neutrino source

ν_μ

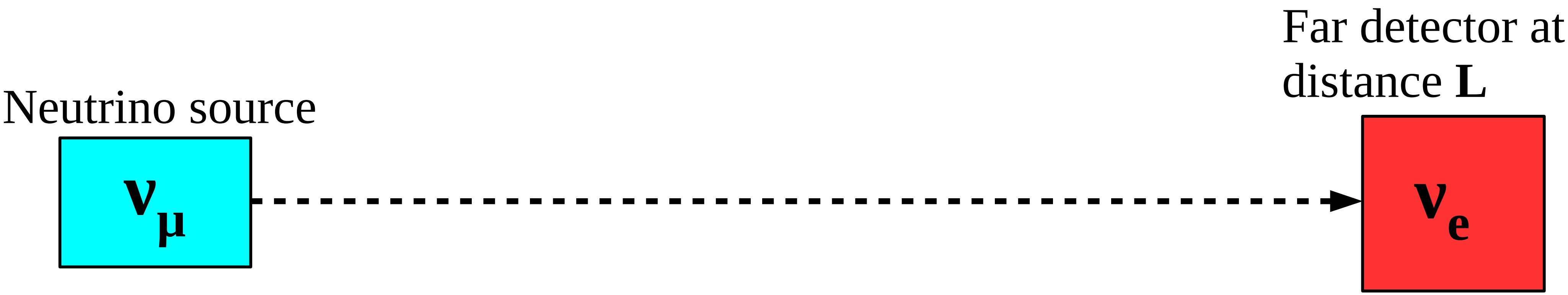
ν_e

To get flux $\Phi(E_\nu)$, you must first understand

1) ν_e-nucleus cross sections as a function of E_ν
2) Detector acceptance

$$N^{far}_{\nu_e}(E_{reco}) = \int \Phi_{\nu_e}(E_\nu, L) \times \sigma_{\nu_e}(E_\nu) \times \epsilon^{far}(E_\nu) \times \mathbf{D}^{far}_{\nu_e}(E_\nu \rightarrow E_{reco}) dE_\nu$$

Generic neutrino oscillation measurement



Neutrino source

ν_μ

Far detector at distance **L**

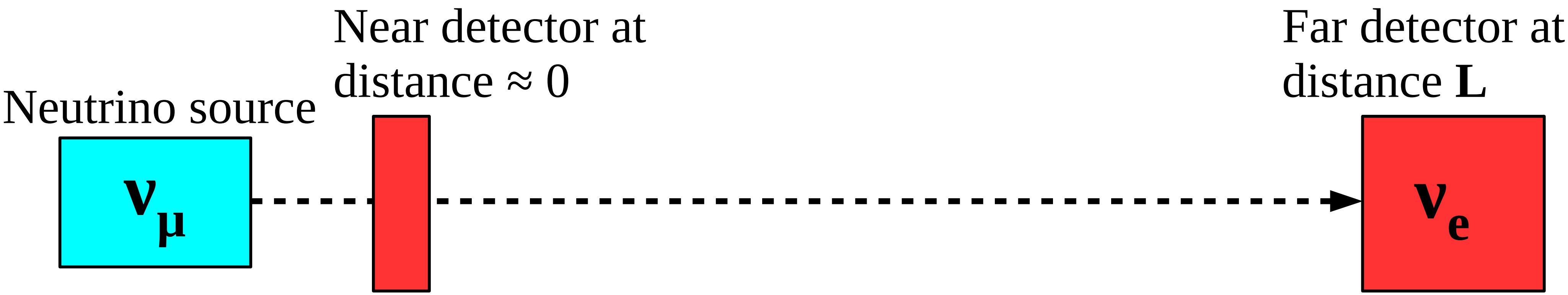
ν_e

To get flux $\Phi(E_\nu)$, you must first understand

1) ν_e-nucleus cross sections as a function of E_ν
2) Detector acceptance
3) Relationship between E_ν and your detector observable

$$N_{\nu_e}^{far}(E_{reco}) = \int \Phi_{\nu_e}(E_\nu, L) \times \sigma_{\nu_e}(E_\nu) \times \epsilon^{far}(E_\nu) \times \mathbf{D}_{\nu_e}^{far}(E_\nu \to E_{reco}) dE_\nu$$

But I have a near detector! Do I really need to worry about this?



Neutrino source

Near detector at
distance ≈ 0

Far detector at
distance **L**

$\boldsymbol{\nu_\mu}$

$\boldsymbol{\nu_e}$

$$\frac{N_{\nu_e}^{far}(E_{reco}) = \int \Phi_{\nu_e}(E_\nu, L) \times \sigma_{\nu_e}(E_\nu) \times \epsilon^{far}(E_\nu) \times \mathbf{D}_{\nu_e}^{far}(E_\nu \rightarrow E_{reco}) dE_\nu}{N_{\nu_\mu}^{near}(E_{reco}) = \int \Phi_{\nu_\mu}(E_\nu, 0) \times \sigma_{\nu_\mu}(E_\nu) \times \epsilon^{near}(E_\nu) \times \mathbf{D}_{\nu_\mu}^{near}(E_\nu \rightarrow E_{reco}) dE_\nu}$$

The near detector is very important, and greatly reduces the effect of uncertain flux and cross section

But many important effects do **not** cancel in a FD/ND ratio

Differences are corrected using a model

$$\frac{N_{\nu_e}^{far}(E_{reco}) = \int \Phi_{\nu_e}(E_\nu, L) \times \sigma_{\nu_e}(E_\nu) \times \epsilon^{far}(E_\nu) \times \mathbf{D}_{\nu_e}^{far}(E_\nu \rightarrow E_{reco}) dE_\nu}{N_{\nu_\mu}^{near}(E_{reco}) = \int \Phi_{\nu_\mu}(E_\nu, 0) \times \sigma_{\nu_\mu}(E_\nu) \times \epsilon^{near}(E_\nu) \times \mathbf{D}_{\nu_\mu}^{near}(E_\nu \rightarrow E_{reco}) dE_\nu}$$

- Extrapolation from near detector measurement to far detector prediction is done with a model, which is tuned to external data
- Cross section uncertainties can be reduced by
  - Putting better, more complete models into event generators
  - Making more/better measurements of neutrino cross sections

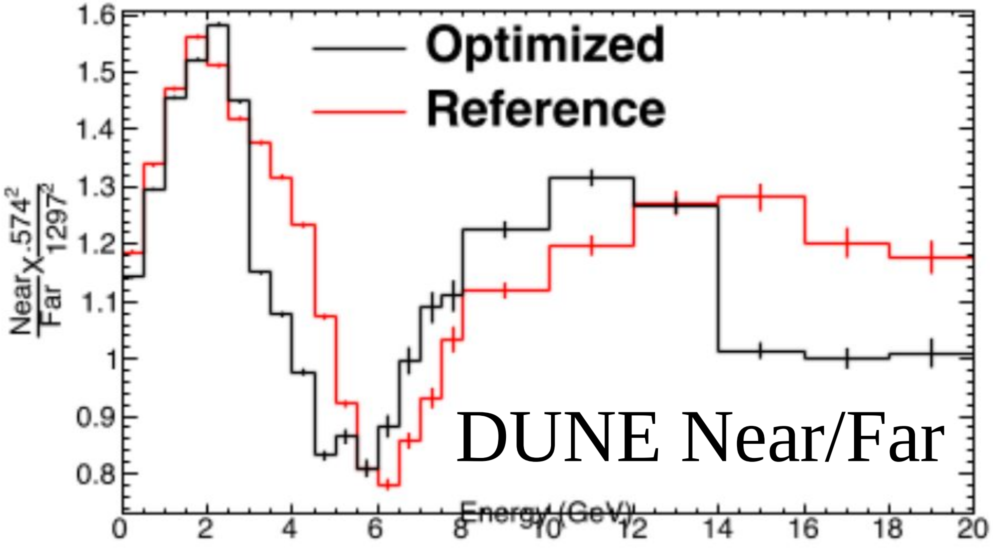
Genie

UNIVERSAL NEUTRINO GENERATOR & GLOBAL FIT

Near vs. Far flux differences

$$\frac{N^{far}_{\nu_e}(E_{reco}) = \int \boxed{\Phi_{\nu_e}(E_\nu, L)} \times \sigma_{\nu_e}(E_\nu) \times \epsilon^{far}(E_\nu) \times \mathbf{D}^{far}_{\nu_e}(E_\nu \rightarrow E_{reco}) dE_\nu}{N^{near}_{\nu_\mu}(E_{reco}) = \int \boxed{\Phi_{\nu_\mu}(E_\nu, 0)} \times \sigma_{\nu_\mu}(E_\nu) \times \epsilon^{near}(E_\nu) \times \mathbf{D}^{near}_{\nu_\mu}(E_\nu \rightarrow E_{reco}) dE_\nu}$$

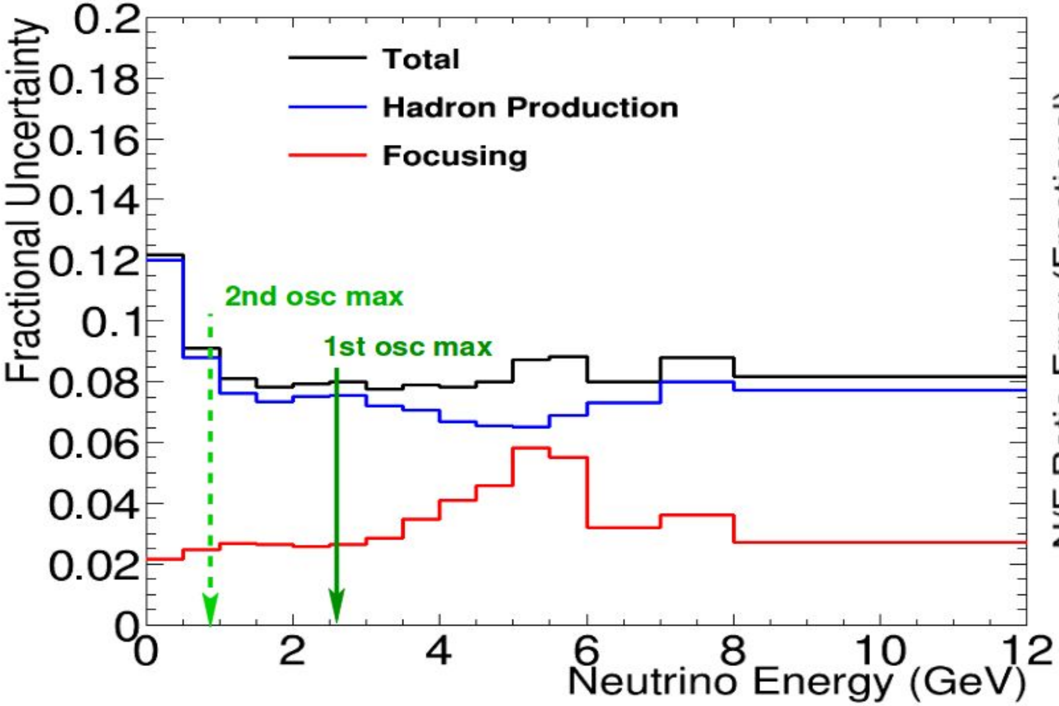
- Solid angle effects introduce significant differences in the flux at the near and far detectors
- Affects energy dependence of the rest of the equation
- And that's without taking oscillations into account



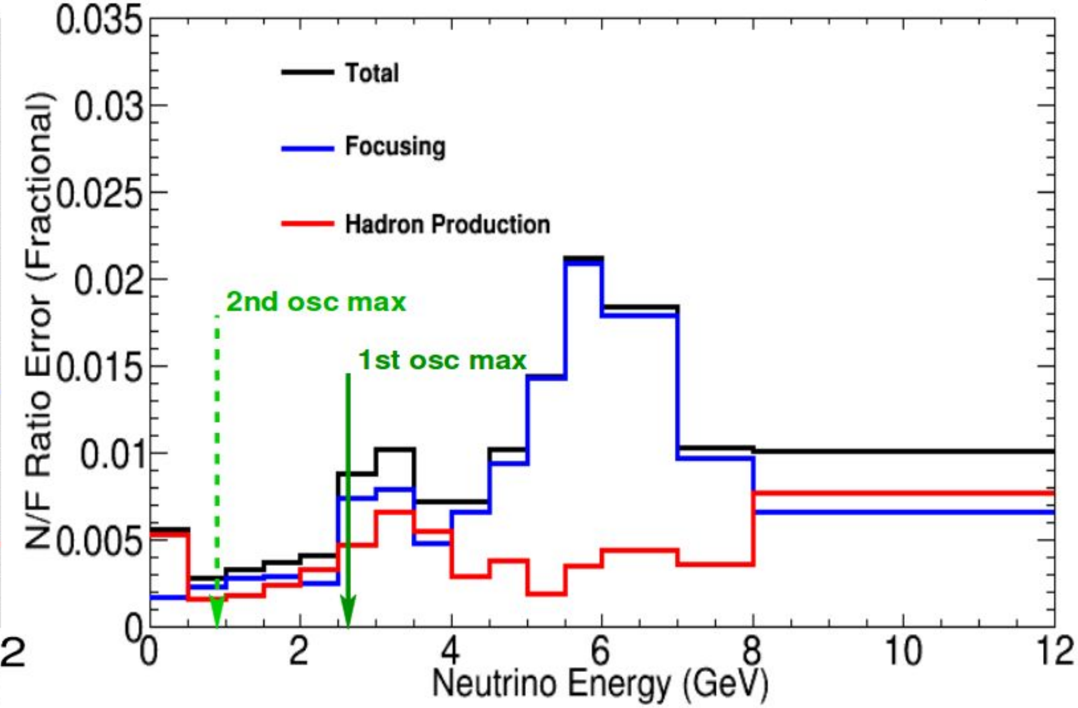
For DUNE, ND/FD flux differences have ~0.3-0.8% uncertainty

$$\frac{N_{\nu_e}^{far}(E_{reco}) = \int \boxed{\Phi_{\nu_e}(E_\nu, L)} \times \sigma_{\nu_e}(E_\nu) \times \epsilon^{far}(E_\nu) \times \mathbf{D}_{\nu_e}^{far}(E_\nu \rightarrow E_{reco}) dE_\nu}{N_{\nu_\mu}^{near}(E_{reco}) = \int \boxed{\Phi_{\nu_\mu}(E_\nu, 0)} \times \sigma_{\nu_\mu}(E_\nu) \times \epsilon^{near}(E_\nu) \times \mathbf{D}_{\nu_\mu}^{near}(E_\nu \rightarrow E_{reco}) dE_\nu}$$

DUNE ND flux uncertainty



DUNE ND/FD flux uncertainty



Near and far cross section differences

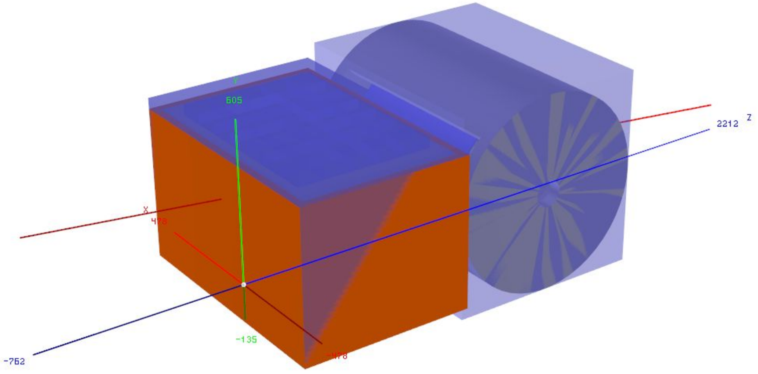
$$\frac{N^{far}_{\nu_e}(E_{reco}) = \int \Phi_{\nu_e}(E_\nu, L) \times \boxed{\sigma_{\nu_e}(E_\nu)} \times \epsilon^{far}(E_\nu) \times \mathbf{D}^{far}_{\nu_e}(E_\nu \rightarrow E_{reco}) dE_\nu}{N^{near}_{\nu_\mu}(E_{reco}) = \int \Phi_{\nu_\mu}(E_\nu, 0) \times \boxed{\sigma_{\nu_\mu}(E_\nu)} \times \epsilon^{near}(E_\nu) \times \mathbf{D}^{near}_{\nu_\mu}(E_\nu \rightarrow E_{reco}) dE_\nu}$$

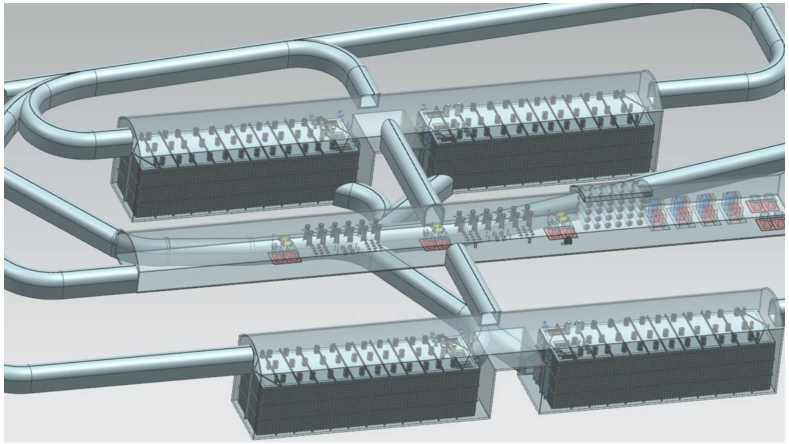
- For a ν_e appearance measurement, ND is sensitive to ν_μ cross sections while FD is sensitive to ν_e cross sections
- Differences in lepton mass lead to different allowed phase space for ν_μ CC and ν_e CC interactions – the cross section in the additional ν_e CC phase space is completely unconstrained by ND data
- ND and FD may have different target material (i.e. T2K FGD), and measure cross sections on different nuclei

Acceptance differences

$$\frac{N_{\nu_e}^{far}(E_{reco}) = \int \Phi_{\nu_e}(E_\nu, L) \times \sigma_{\nu_e}(E_\nu) \times \boxed{\epsilon^{far}(E_\nu)} \times \mathbf{D}_{\nu_e}^{far}(E_\nu \rightarrow E_{reco}) dE_\nu}{N_{\nu_\mu}^{near}(E_{reco}) = \int \Phi_{\nu_\mu}(E_\nu, 0) \times \sigma_{\nu_\mu}(E_\nu) \times \boxed{\epsilon^{near}(E_\nu)} \times \mathbf{D}_{\nu_\mu}^{near}(E_\nu \rightarrow E_{reco}) dE_\nu}$$

- Does ND cover same phase space as FD?
- Especially important when ND cannot be “functionally identical” to FD, i.e. T2K, DUNE





Reconstructing neutrino energy: CCQE hypothesis

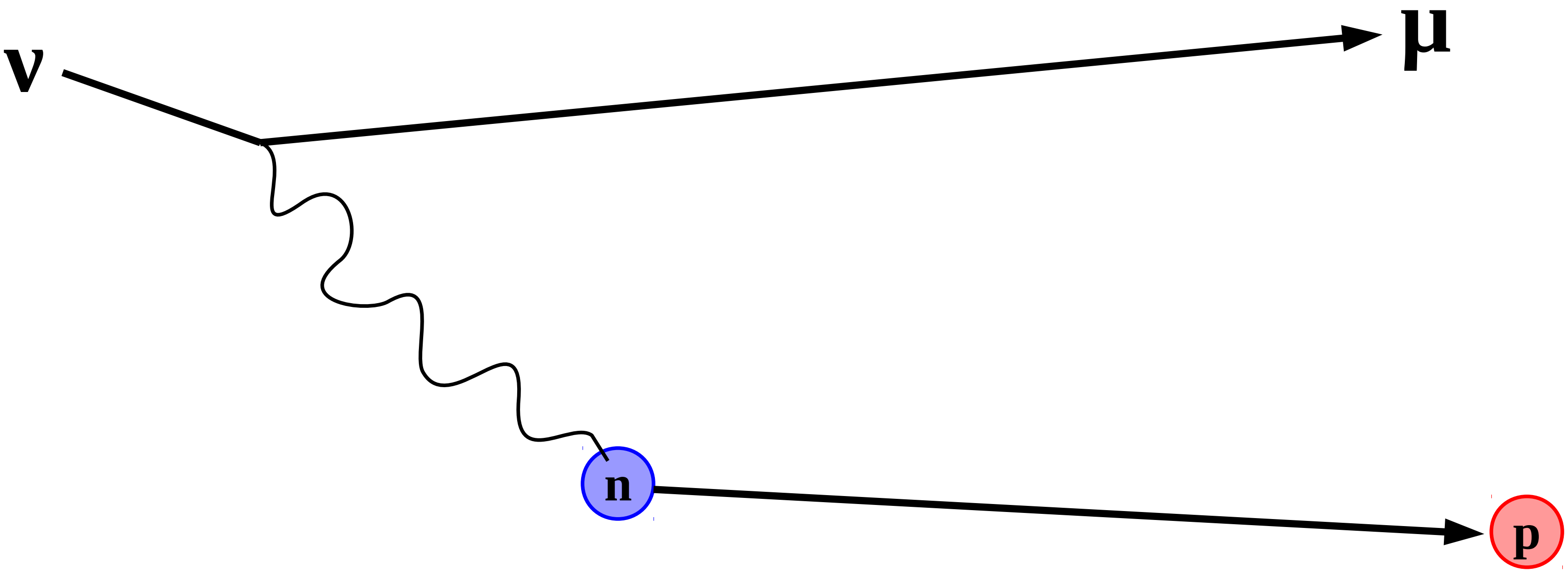
$$\frac{N^{far}_{\nu_e}(E_{reco}) = \int \Phi_{\nu_e}(E_\nu, L) \times \sigma_{\nu_e}(E_\nu) \times \epsilon^{far}(E_\nu) \times \boxed{\mathbf{D}^{far}_{\nu_e}(E_\nu \rightarrow E_{reco})} dE_\nu}{N^{near}_{\nu_\mu}(E_{reco}) = \int \Phi_{\nu_\mu}(E_\nu, 0) \times \sigma_{\nu_\mu}(E_\nu) \times \epsilon^{near}(E_\nu) \times \boxed{\mathbf{D}^{near}_{\nu_\mu}(E_\nu \rightarrow E_{reco})} dE_\nu}$$

- T2K, T2HK: quasi-elastic assumption from lepton kinematics only

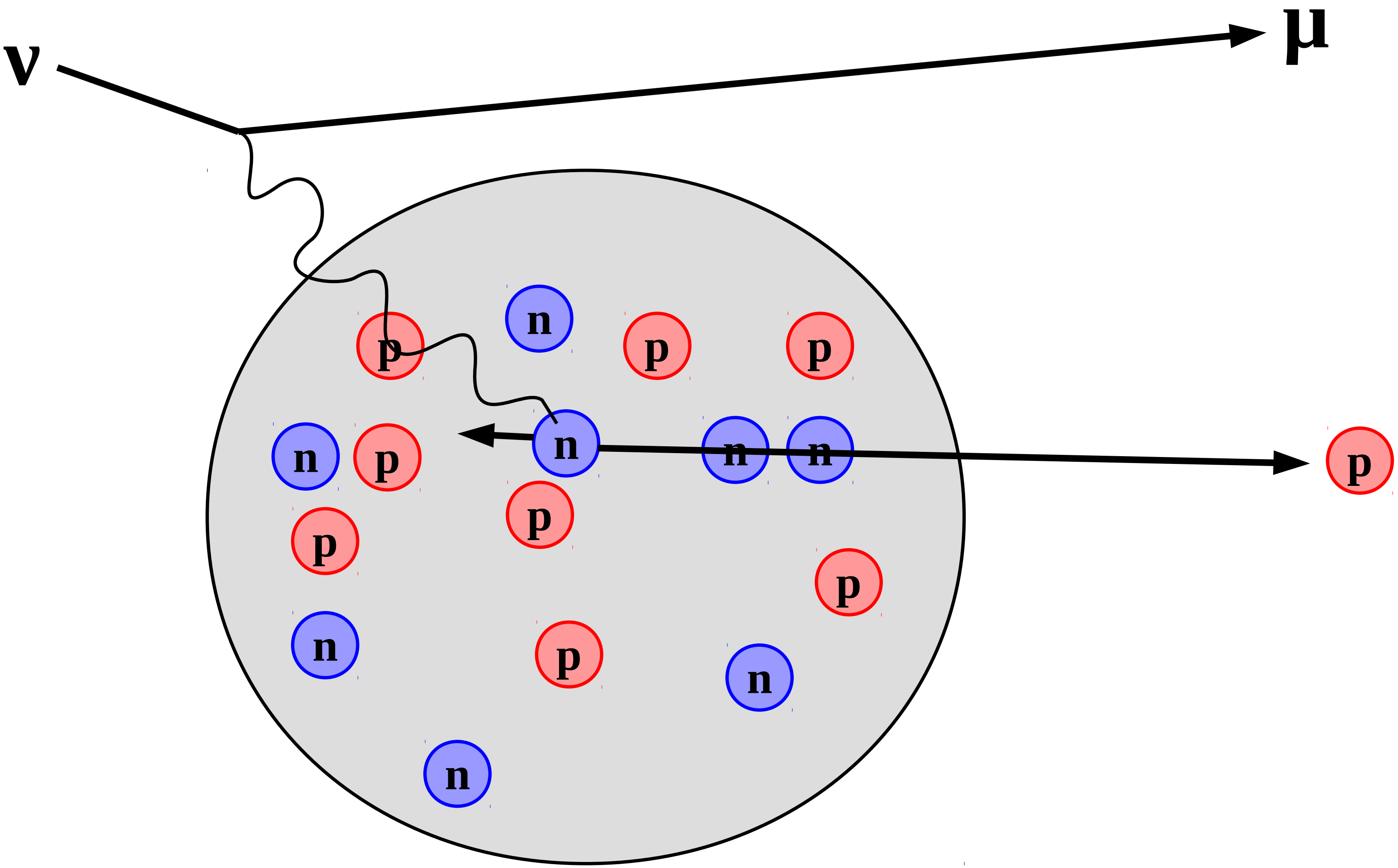
$$E^{rec}_\nu = \frac{m_f^2 - (m_i')^2 - m_l^2 + 2m_i' E_l}{2(m_i' - E_l + p_l \cos\theta_l)}$$

- m_f, m_i final and initial nucleon masses $m_i' = m_i - E_B$
- Depends on “removal energy” E_B
- Incorrect when interaction isn't CCQE 1p1h νn → μp

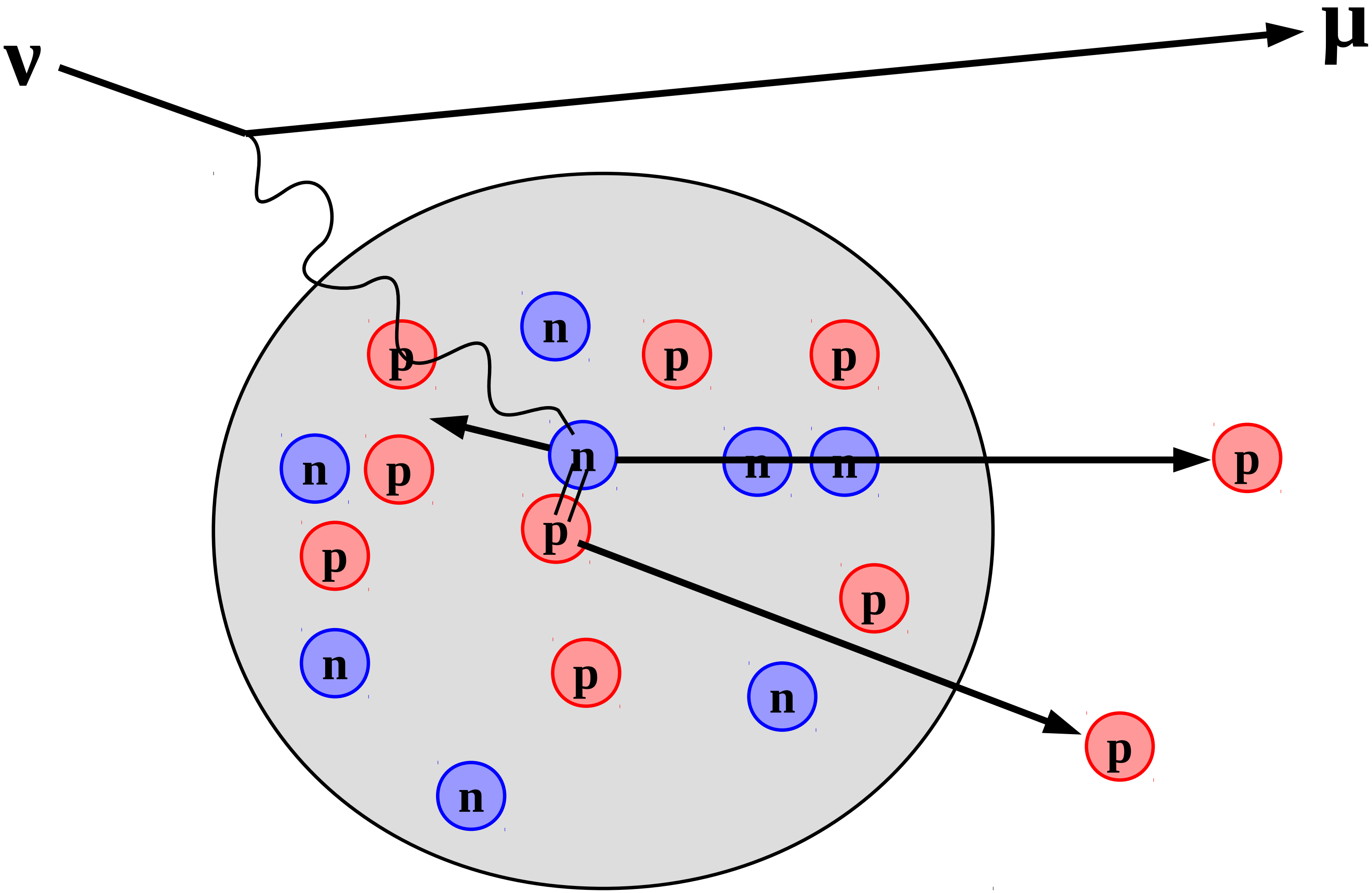
CCQE hypothesis is correct for free nucleon target at rest



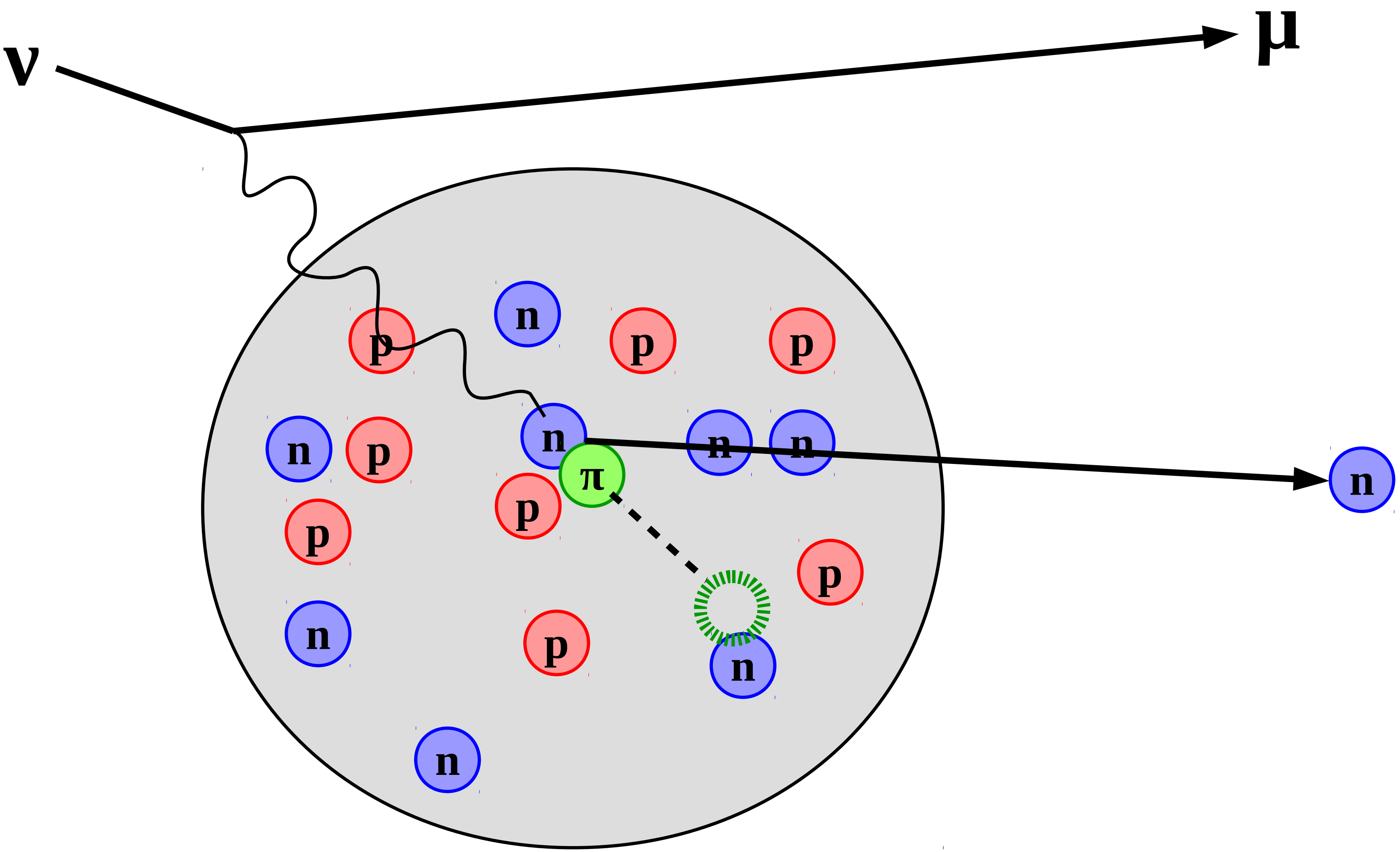
Reconstructed neutrino energy is smeared by Fermi motion



Reconstructed neutrino energy is smeared by 2p2h interactions

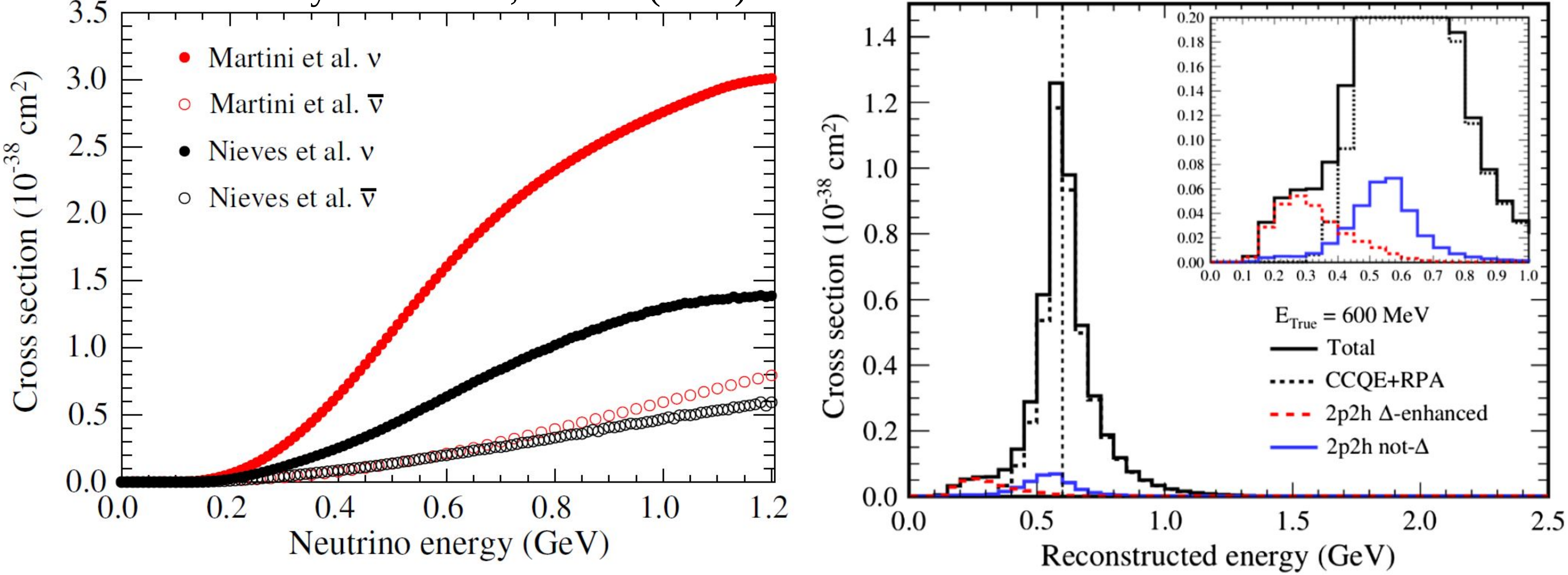


Pion production, FSI



T2K 2p2h predictions and energy reconstruction

T2K: Phys. Rev. D 96, 092006 (2017)



- 2p2h processes give low-side tail on reconstructed energy spectrum
- Pion production + absorption also gives low-side tail

Reconstructing neutrino energy calorimetrically

$$\frac{N^{far}_{\nu_e}(E_{reco}) = \int \Phi_{\nu_e}(E_\nu, L)\times\sigma_{\nu_e}(E_\nu)\times\epsilon^{far}(E_\nu)\times \boxed{\mathbf{D}^{far}_{\nu_e}(E_\nu \to E_{reco})}dE_\nu}{N^{near}_{\nu_\mu}(E_{reco}) = \int \Phi_{\nu_\mu}(E_\nu, 0)\times\sigma_{\nu_\mu}(E_\nu)\times\epsilon^{near}(E_\nu)\times \boxed{\mathbf{D}^{near}_{\nu_\mu}(E_\nu \to E_{reco})}dE_\nu}$$

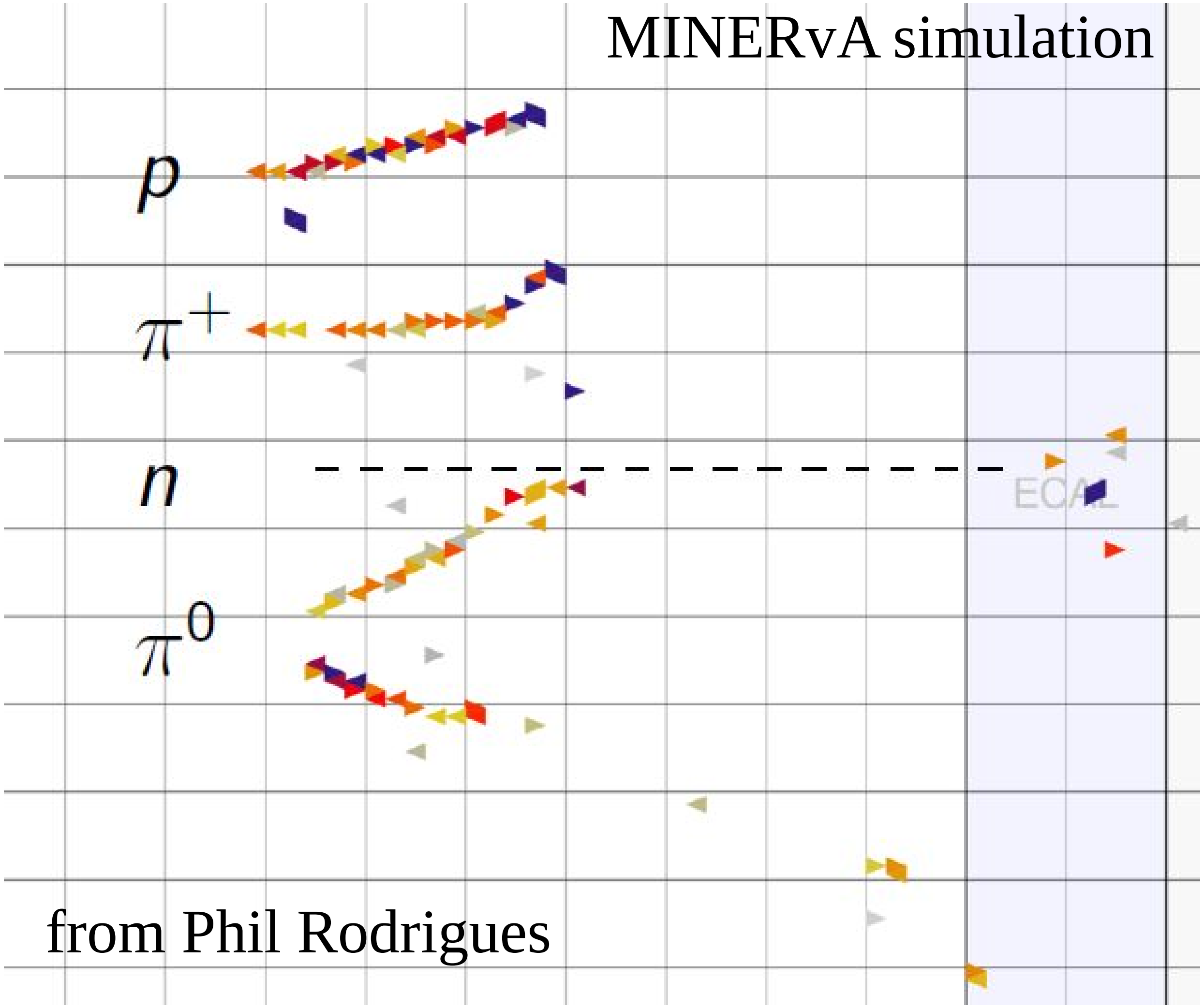
- NOvA, DUNE: calorimetric hadronic energy

$$E_{reco} = E_{lep} + E_{had}$$

- Sensitive to makeup of hadronic final state
- Neutrons generally not detected, lead to missing hadronic energy

Detectors respond differently to different particles

- p, $\pi^\pm$ → hadronic showers, maybe single tracks
- e, π^0 → EM showers
- Do you see pion masses?
- Do you see neutrons at all?



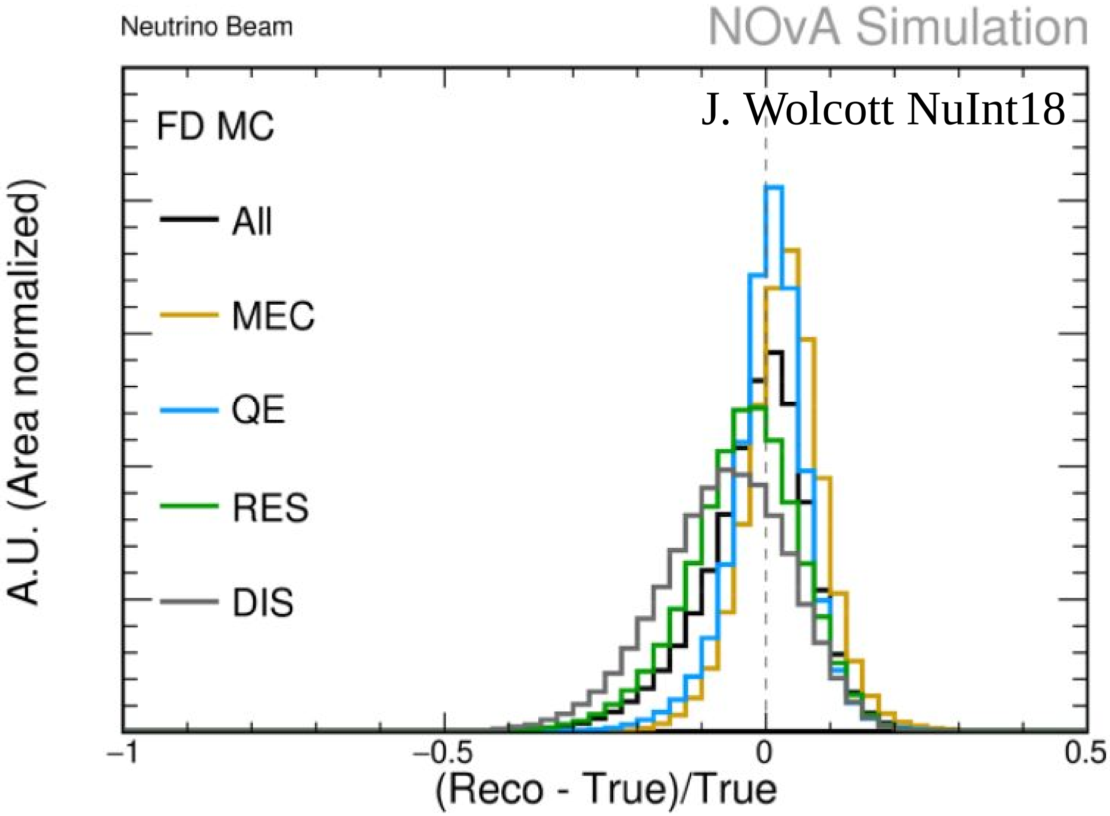
MINERvA simulation

from Phil Rodrigues

Even for calorimetric reco, energy smearing depends on final state

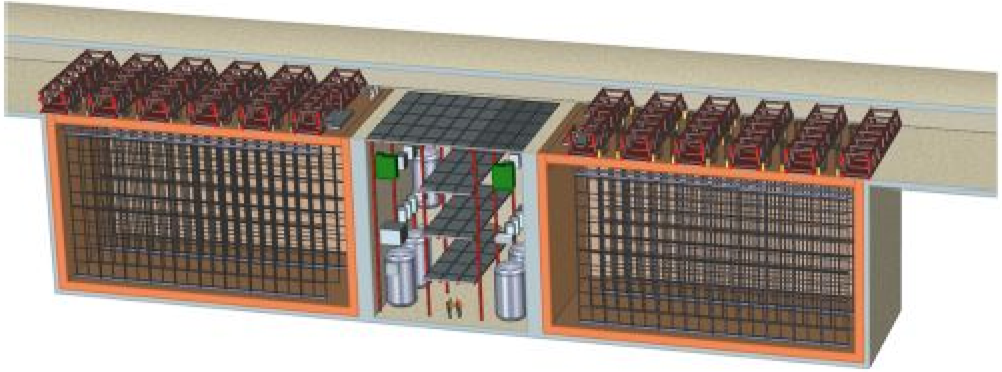
$$\frac{N^{far}_{\nu_e}(E_{reco}) = \int \Phi_{\nu_e}(E_\nu, L) \times \boxed{\sigma_{\nu_e}(E_\nu) \times \epsilon^{far}(E_\nu) \times \mathbf{D}^{far}_{\nu_e}(E_\nu \rightarrow E_{reco})} dE_\nu}{N^{near}_{\nu_\mu}(E_{reco}) = \int \Phi_{\nu_\mu}(E_\nu, 0) \times \boxed{\sigma_{\nu_\mu}(E_\nu) \times \epsilon^{near}(E_\nu) \times \mathbf{D}^{near}_{\nu_\mu}(E_\nu \rightarrow E_{reco})} dE_\nu}$$

- Example: NOvA simulated neutrino energy residual for different processes
- The relative mix of QE, 1π, DIS, etc. vs E_ν affects E_{reco}, even if uncertainty on total cross section is small

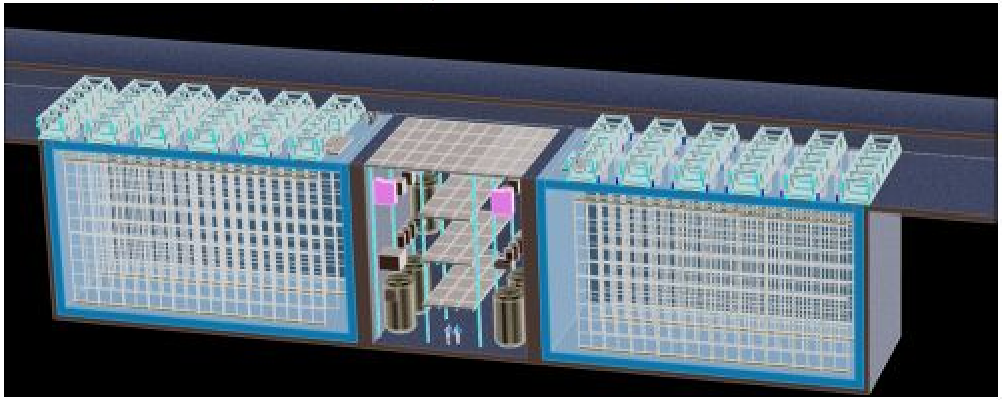


J. Wolcott NuInt18

Neutrons



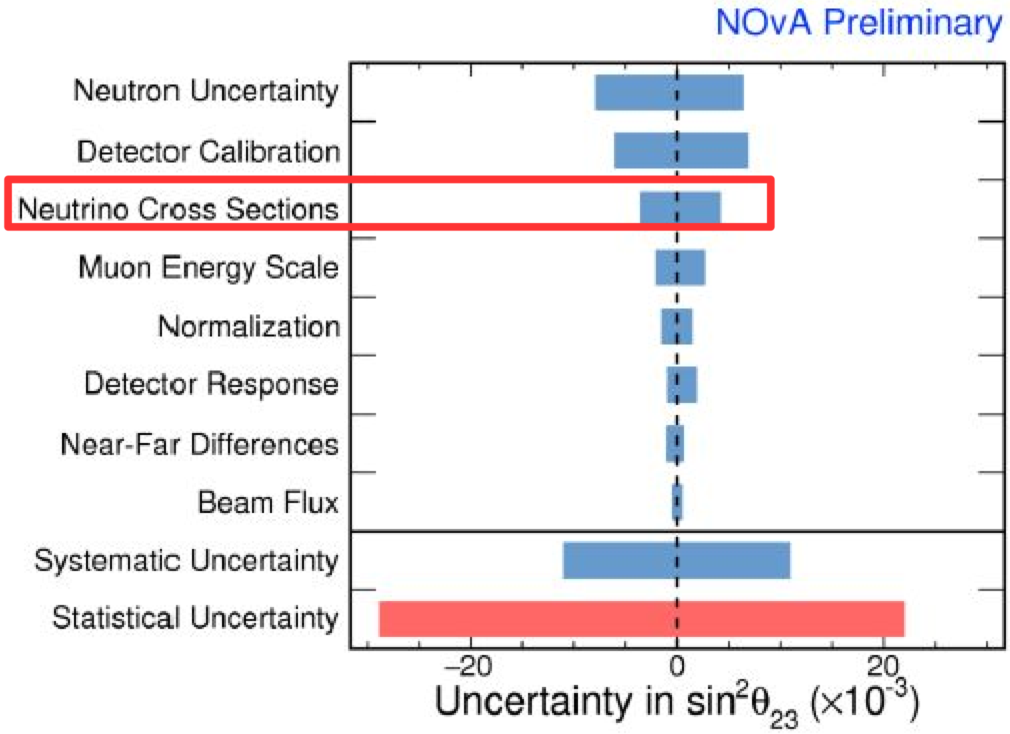
$P(\nu_\mu \rightarrow \nu_e)$

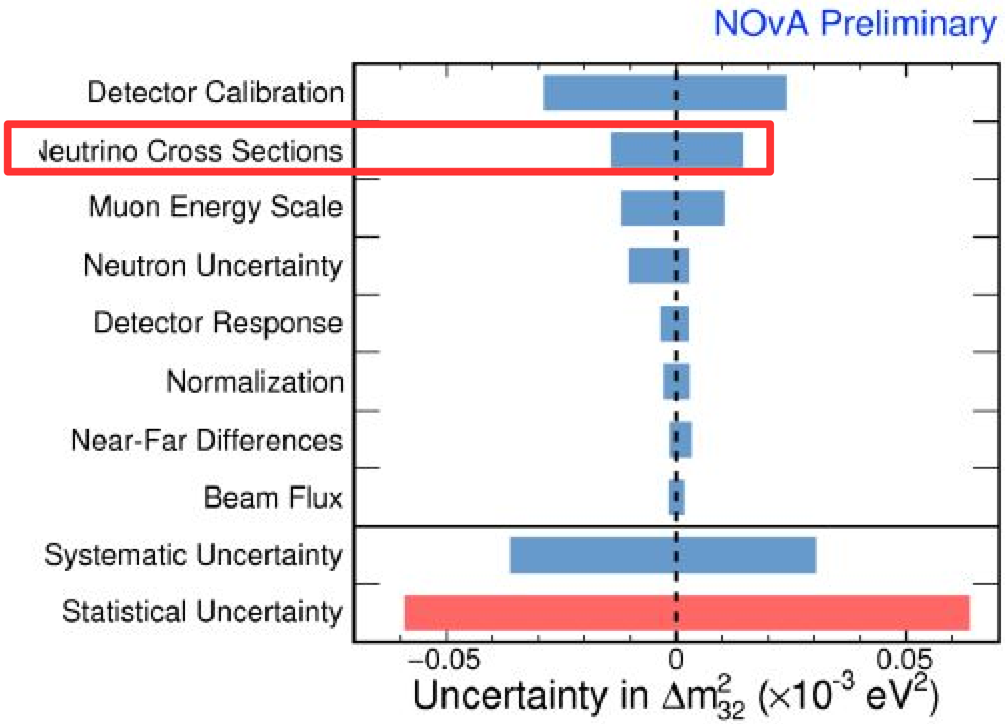


$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

- Ideally, we would measure antineutrino oscillations with an antidetector: $\nu\, n \rightarrow \mu^- p$ and $\bar{\nu}\, \bar{n} \rightarrow \mu^+ \bar{p}$
- I'm told this is not feasible
- Poor detector response to neutrons, combined with asymmetry in neutron production by neutrinos and antineutrinos, is scary for CP violation measurements
- Modeling neutron production is very important

NOvA cross section uncertainties for ν_μ disappearance

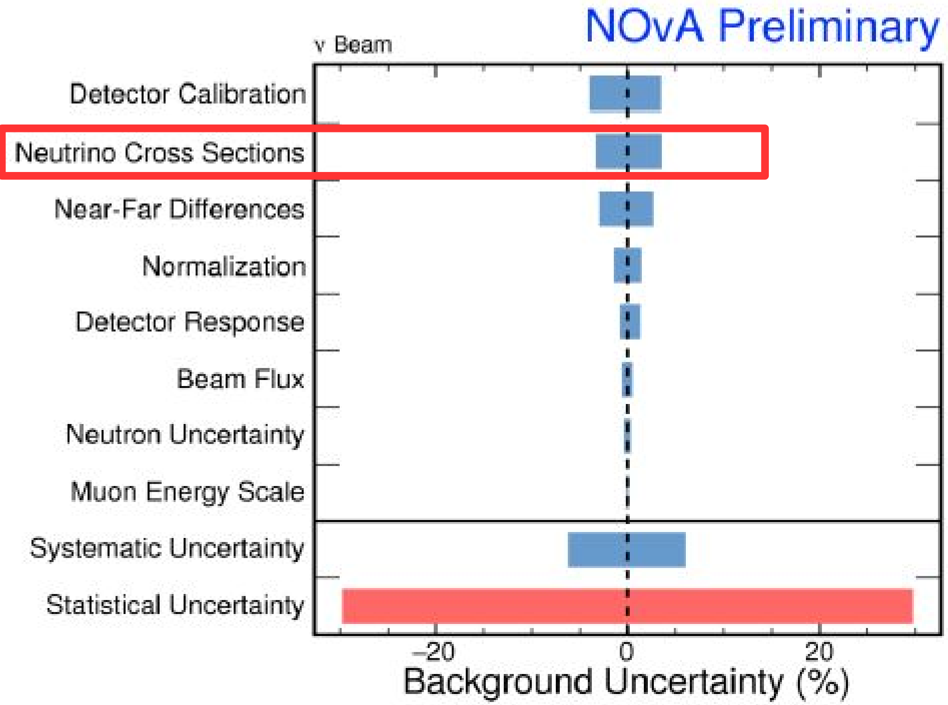


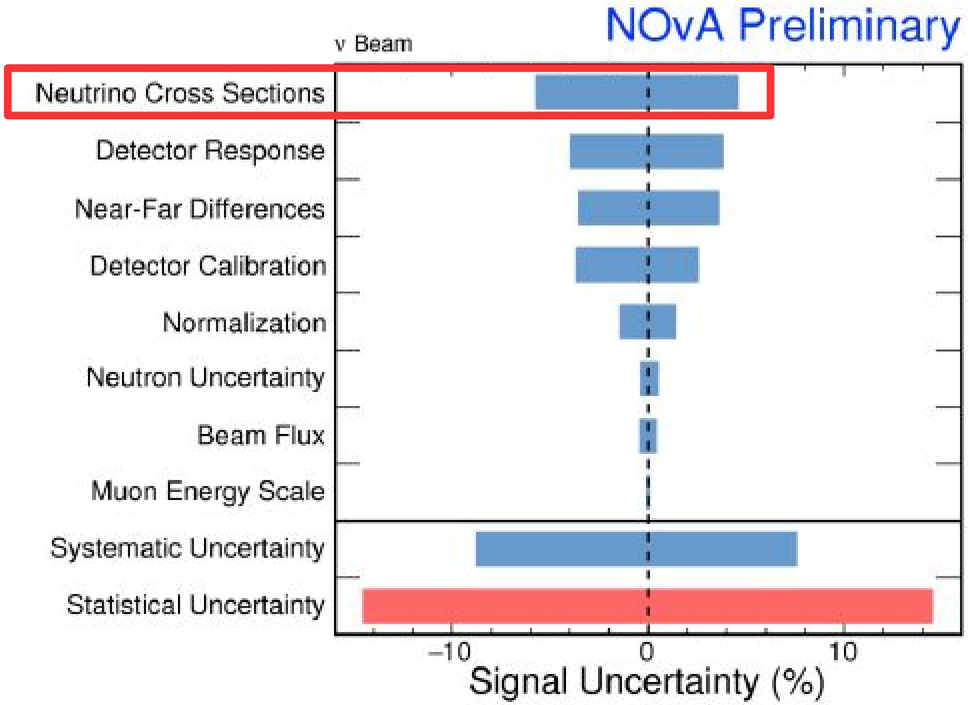


G. Pawlowski talk Friday

- Still statistically limited
- Cross sections among the leading uncertainties

NOvA cross section uncertainties for ν_e appearance



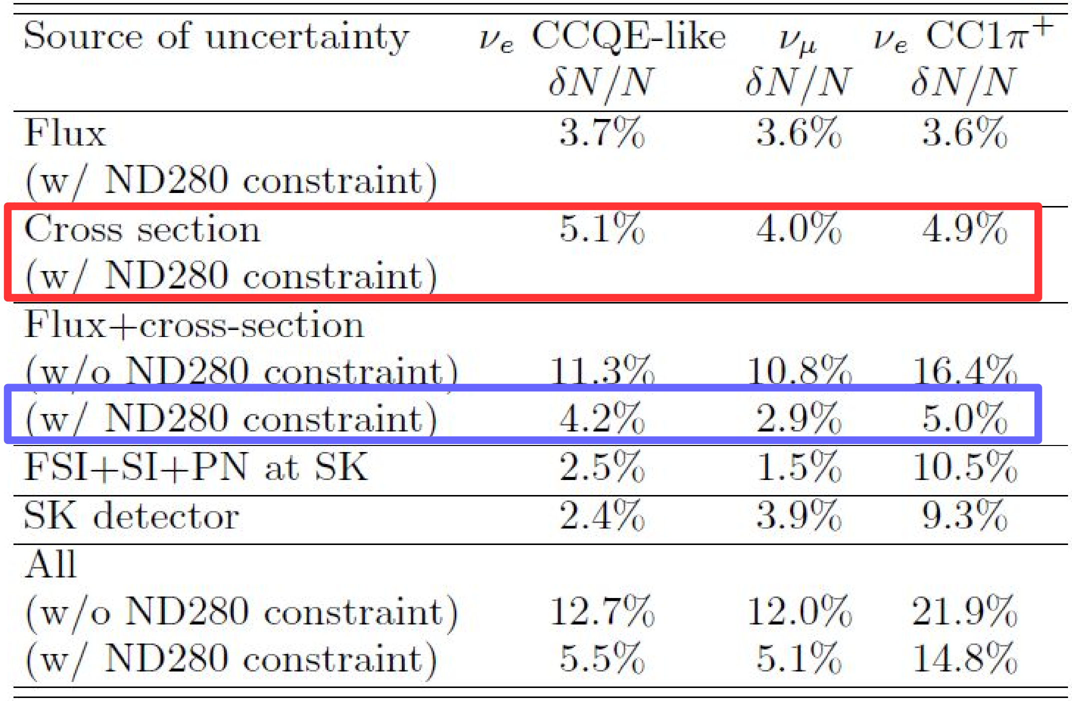


G. Pawlowski talk Friday

- Still statistically limited
- Cross sections among the leading uncertainties

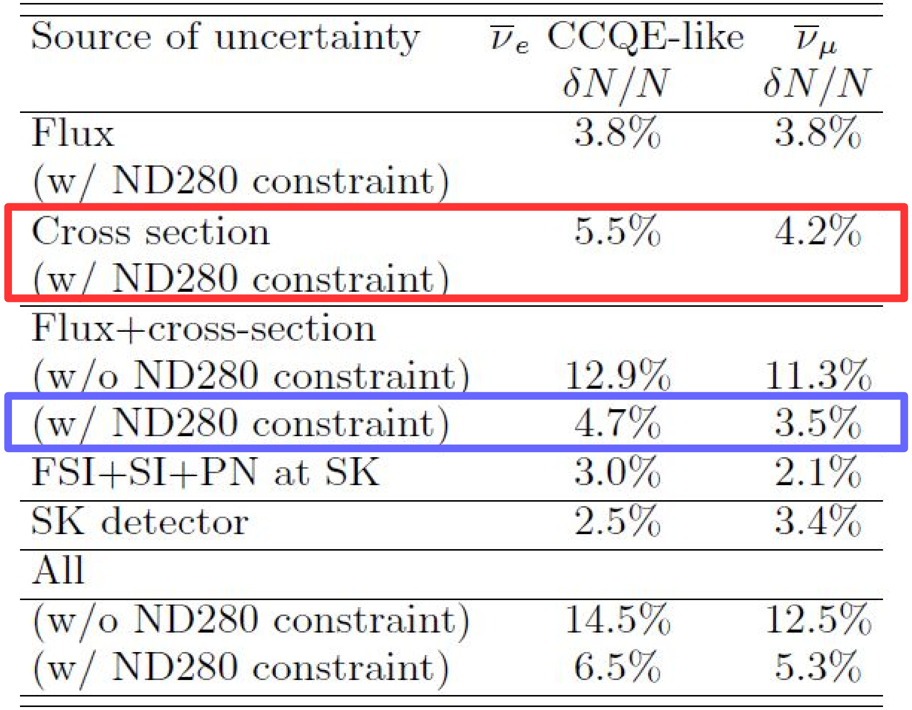
T2K cross section uncertainties

T2K: Phys. Rev. D 96, 092006 (2017)



Source of uncertainty	ν_e CCQE-like $\delta N/N$	ν_μ $\delta N/N$	ν_e CC1π^+ $\delta N/N$
Flux (w/ ND280 constraint)	3.7%	3.6%	3.6%
Cross section (w/ ND280 constraint)	5.1%	4.0%	4.9%
Flux+cross-section			
(w/o ND280 constraint)	11.3%	10.8%	16.4%
(w/ ND280 constraint)	4.2%	2.9%	5.0%
FSI+SI+PN at SK	2.5%	1.5%	10.5%
SK detector	2.4%	3.9%	9.3%
All			
(w/o ND280 constraint)	12.7%	12.0%	21.9%
(w/ ND280 constraint)	5.5%	5.1%	14.8%

ν



Source of uncertainty	$\overline{\nu}_e$ CCQE-like $\delta N/N$	$\overline{\nu}_\mu$ $\delta N/N$
Flux (w/ ND280 constraint)	3.8%	3.8%
Cross section (w/ ND280 constraint)	5.5%	4.2%
Flux+cross-section		
(w/o ND280 constraint)	12.9%	11.3%
(w/ ND280 constraint)	4.7%	3.5%
FSI+SI+PN at SK	3.0%	2.1%
SK detector	2.5%	3.4%
All		
(w/o ND280 constraint)	14.5%	12.5%
(w/ ND280 constraint)	6.5%	5.3%

$\overline{\boldsymbol{\nu}}$

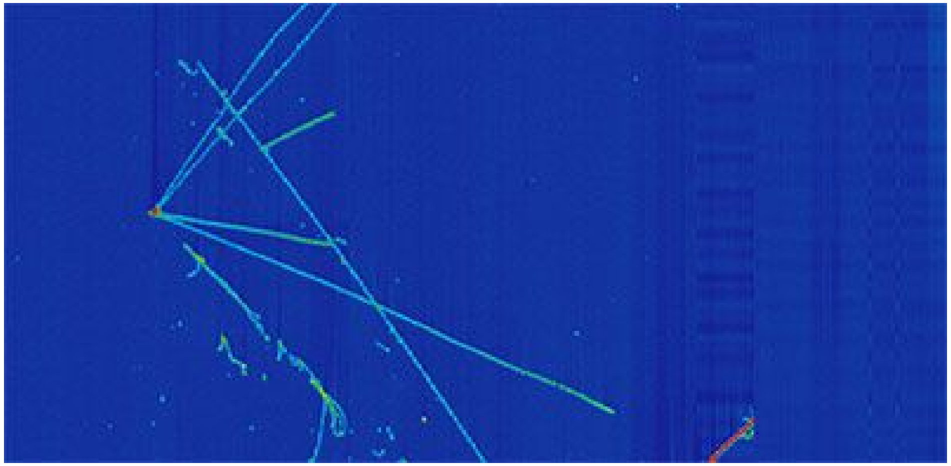
- Cross section uncertainties at the level of 5% after near detector constraint
- Due to anticorrelations, flux*XS has smaller uncertainty

Future: smaller statistical uncertainties

- Current “neutrino mode” event counts:
  - T2K: 90 ν_e candidates
  - NOvA: 58 ν_e candidates
- 10-15% statistical uncertainties
- Next generation: ~1000 ν_e candidates → few percent statistical uncertainty on ν_e rate
- Cross section systematics will become dominant if modeling and analysis is not improved

Future: argon

- Much of existing neutrino-nucleus cross section data is on carbon
- Not clear how those data constrain cross sections on Argon
- We need to make measurements on Argon



LAr neutrino interaction in MicroBooNE

Summary

- Neutrino interaction models affect predicted spectra in long-baseline oscillation experiments
- Uncertainties are significant, and only partially cancel with near detector inputs
- Next generation experiments will have high statistics → increased importance of cross section systematics