Neutrino-nucleus interaction uncertainties in the oscillation measurements

NuWro Workshop – Wroclow December 2117

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Flux and cross-section

We measure flux and xsec at the ND and *we use our models to extrapolate* at the far detector, like a ratio measurement convoluted to resolution:

predicted number of neutrino interactions at the FD (w/o oscillations)

detector resolution ($E^{reco} \leftrightarrow E^{vis}$)

$$\frac{N^{FD}_{\nu_{\alpha'}}(E^{reco}_{\nu})}{N^{ND}_{\nu_{\alpha}}(E^{reco}_{\nu})} \approx \frac{\int\int P_{\nu_\alpha\to\nu_{\alpha'}}(E_\nu)\times\varphi^{FD}_{\nu_{\alpha'}}(E_\nu)\sigma^{FD}_{\nu_{\alpha'}}(E_\nu)\times\epsilon^{ND}(E_\nu)\,p^{FD}(E_\nu)\times R_{FD}(E^{reco}_\nu-E^{vis}_\nu)}{\int\int \varphi^{ND}_{\nu_\alpha}(E_\nu)\sigma^{ND}_{\nu_\alpha}(E_\nu)\times\epsilon^{FD}(E_\nu)\,p^{ND}(E_\nu)\times R_{ND}(E^{reco}_\nu-E^{vis}_\nu)}\,F_{theo}(E^{vis}_\nu-E_\nu)\,dE^{vis}_\nu\,dE$$

what we measure

oscillation probability

predicted number of neutrino interactions at the ND

efficiency corrections

background corrections

nuclear theoretical effects ($E^{vis} \leftrightarrow E^{true}$)

These depends on the technology (and size) of ND and FD and are (partially) evaluated from MC

- The most complicated part is :

1) **We measure rate of events in a given energy range** and the neutrino energy spectrum is different at ND (before oscillation) and at the FD (after oscillation)
→ so we measure the xsec and flux at a given energy and we need to extrapolate to a different energy

2) flux and xsec extrapolation from ND to FD are different → we need to separately estimate flux and xsec at the ND

But **we measure only the product of the two = rate of events** (strong anti-correlation between them)

Statistics

D.Hadley NuFact2117

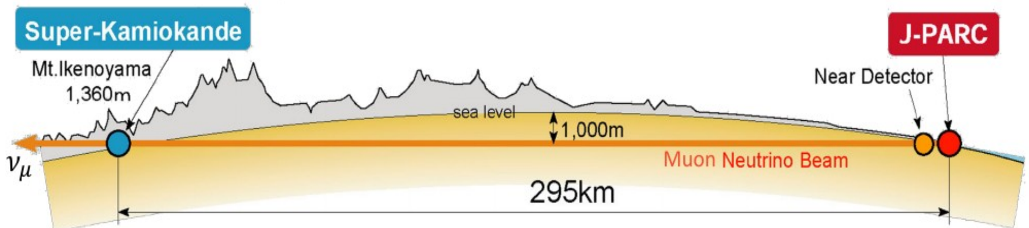
Experiment	$\nu_e + \bar{\nu}_e$	$1/\sqrt{N}$	Ref.
T2K (current)	74 + 7	12% + 40%	2.2×10^{21} POT
NOvA (current)	33	17%	FERMILAB-PUB-17-065-ND
NOvA (projected)	110 + 50	10% + 14%	arXiv:1409.7469 [hep-ex]
T2K-I (projected)	150 + 50	8% + 14%	7.8×10^{21} POT, arXiv:1409.7469 [hep-ex]
T2K-II	470 + 130	5% + 9%	20×10^{21} POT, arXiv1607.08004 [hep-ex]
T2HK	2900 + 2700	2% + 2%	10 yrs 2-tank staged KEK Preprint 2016-21
DUNE	1200 + 350	3% + 5%	3.5+3.5 yrs x 40kt @ 1.07 MW arXiv:1512.06148 [physics.ins-det]

Today stat error ~ 15%

Next generation experiments ~ few 10^3 events → need systematics <2%

T2K: Tokai (JPARC) to Kamioka (SuperKamiokande)

Long baseline (295 km) neutrino oscillation experiment with off-axis technique:

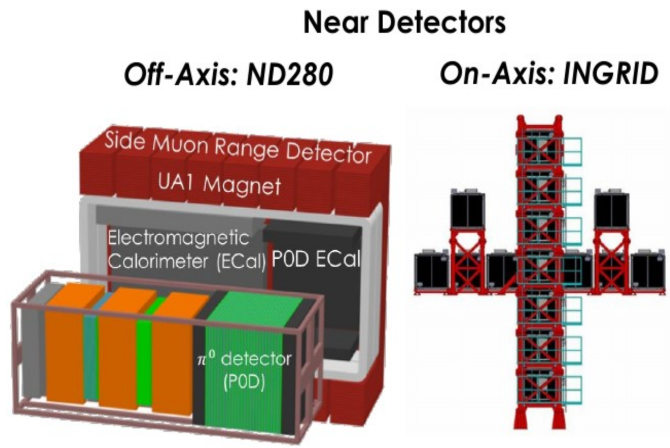


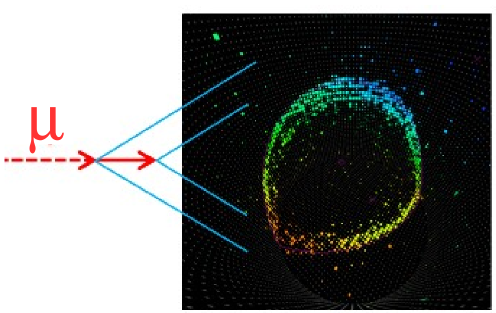
Near Detectors:

On-axis:
iron/CH scintillator
monitoring of beam angle and position

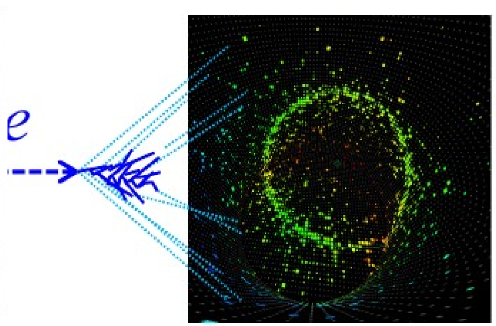
Off-axis:
full tracking and particle reconstruction in near detectors
(magnetized TPC!)

Far Detector:
huge water cherenkov detector (50 kTon) with optimal μ/e identification to distinguish ν_e, ν_μ

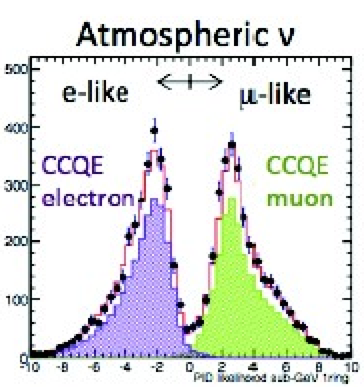




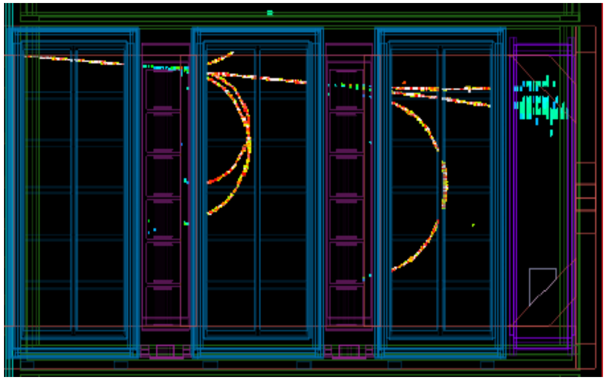
clear ring



fuzzy ring



1% mis-id



What do we measure?

- **Super-Kamiokande:**
  - signal CCQE-only identified as events with only 1-ring from the lepton (proton is below Cherencov threshold)

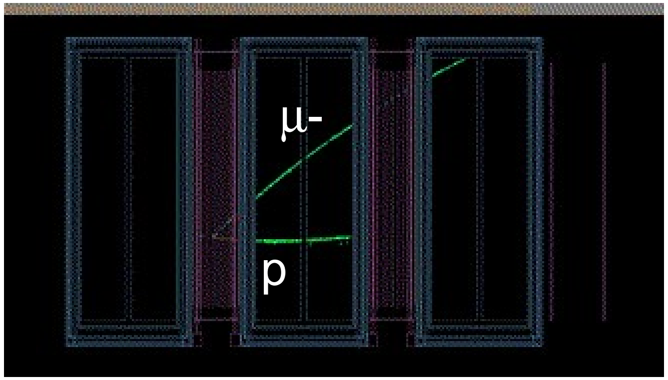
  → reconstruction of lepton 4-momentum from Cherenkov ring (and μ/e separation)

  E_ν estimated from lepton kinematics using nuclear models

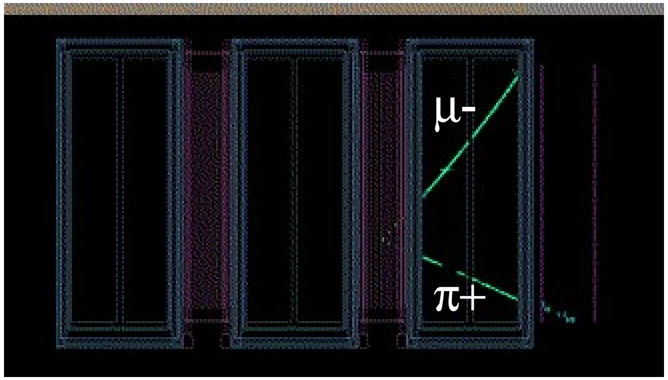
  - charged pions rejected if above Cherencov threshold (2-rings events) or by looking at Michel electron.
  - neutral pions ($\pi^0 \rightarrow \gamma\gamma$) give 2-rings

- **ND280 near detector (magnetized):**

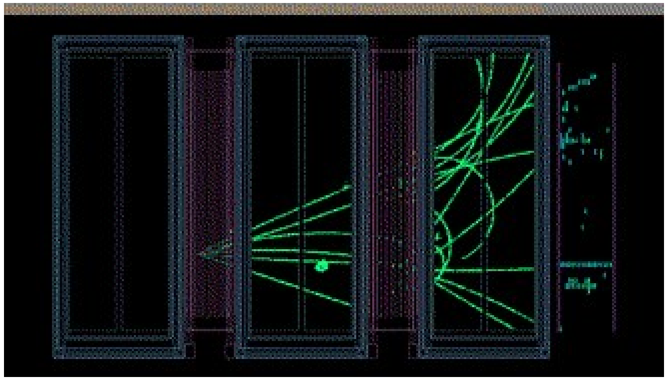
4-momenta, charge reconstruction for all particles reaching the TPC and particle ID to separate the interaction channels:



CCQE event with proton > 500 MeV

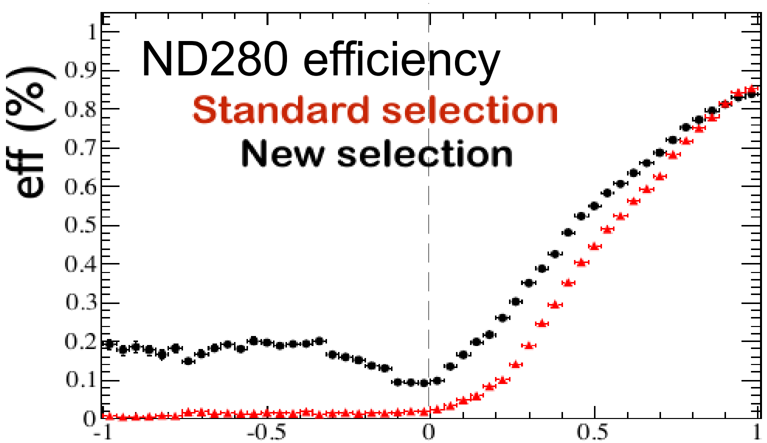


CC1π+: particle ID (p vs μ,π vs e) with dE/dx in TPC

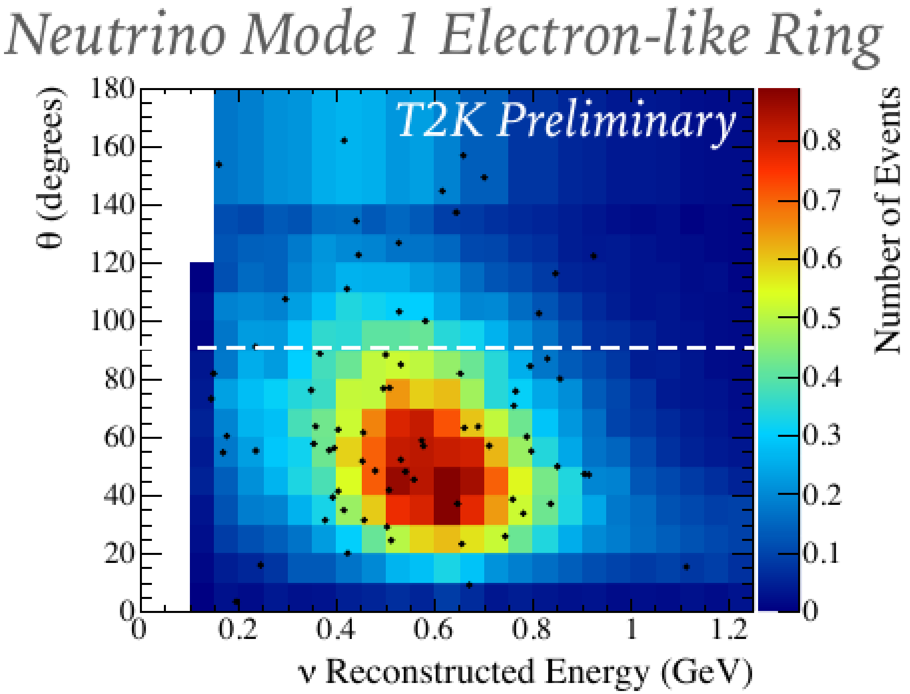


DIS event

Angular acceptance

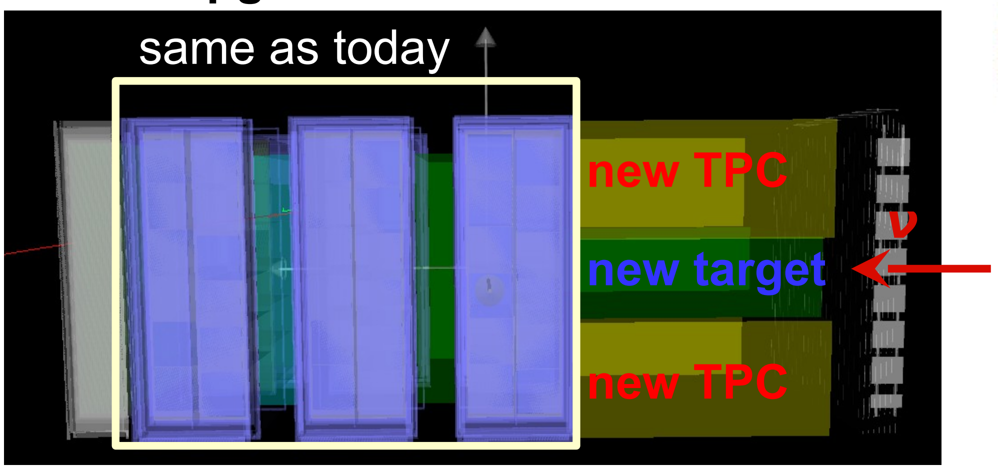


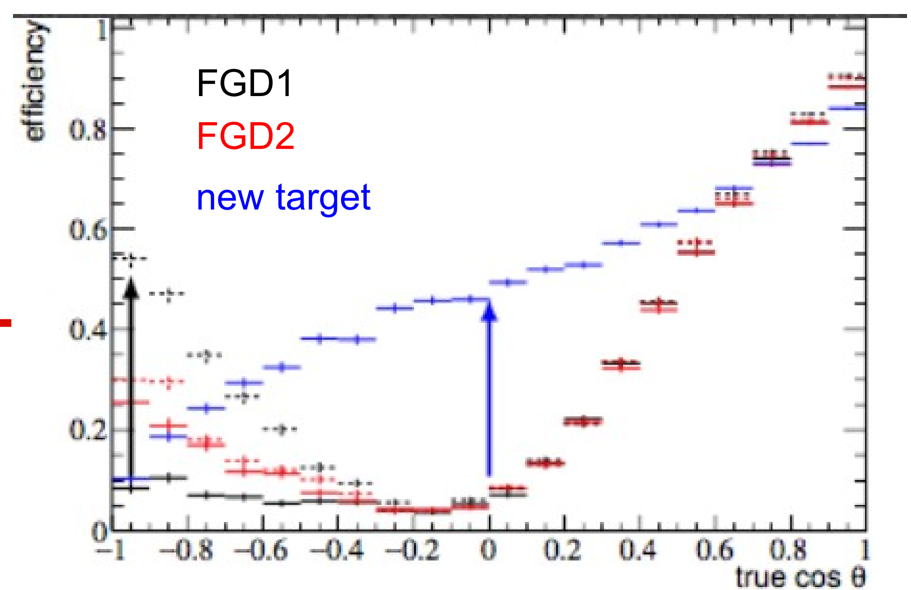
SuperKamiokande events



- **T2K-2: new horizontal target and TPCs to enlarge high angle acceptance**

ND280 Upgrade

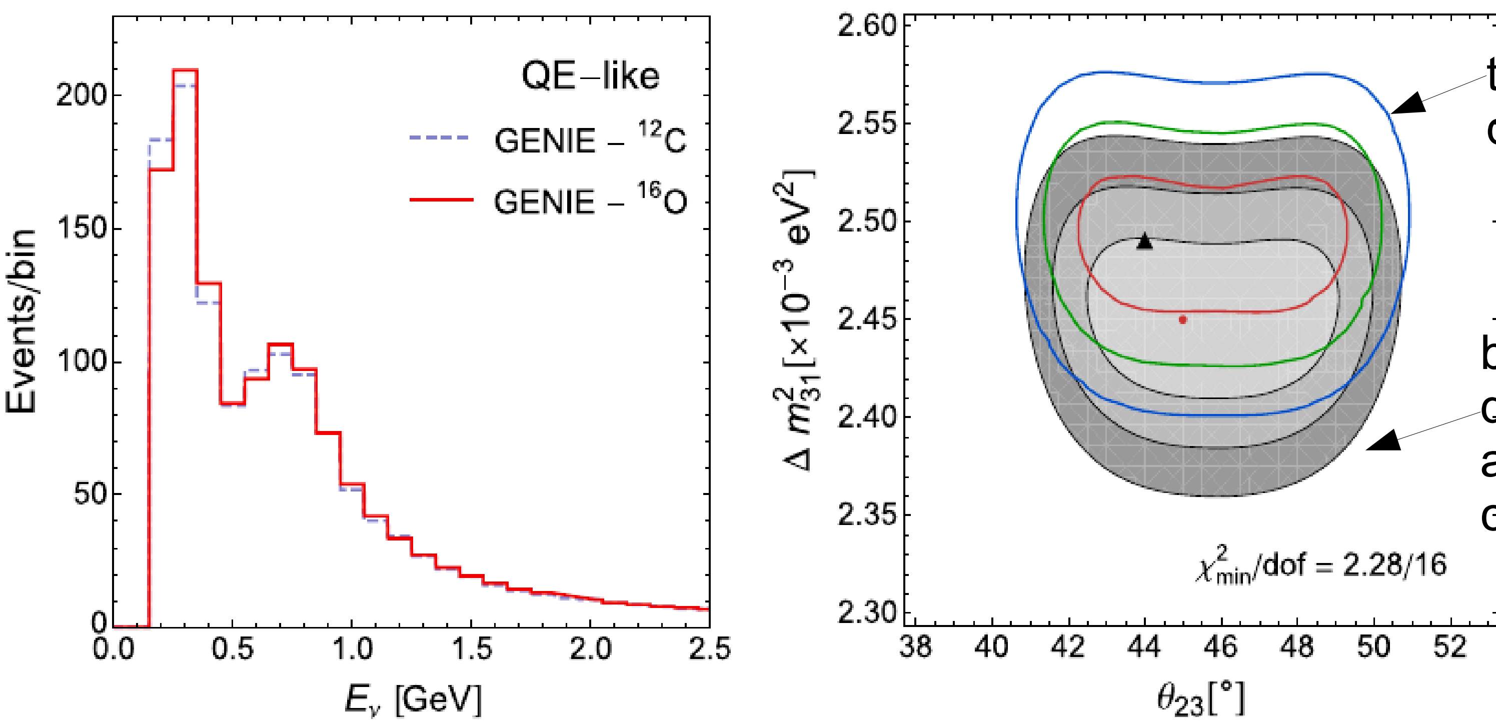




Multiple targets (C,O) at ND and FD

Phenomenological study **neglecting the difference between nuclear model in Carbon and Oxygen:**

J. Phys. G: Nucl. Part. Phys. **44** (2017) 054001 A M Ankowski and C Mariani



Treatment of multiple targets

- **Part of ND280 data are on Carbon while SK is on Water**, we need to know how the cross-section change as a function of A (nucleus size)

  We rely on the **model (NEUT MC) to predict the cross-section on C and O** and when there are effects not well known, we introduce free parameters in the fit

- All the 'physics' is in the estimation of the **correlation between the C and O parameters:**

- if we assume to know perfectly how to extrapolate from C to O, then we have one single parameter for C and O

- if we don't know at all, then two uncorrelated parameters for C and O (we kill our sensitivity because is like using only FGD2 water data for ND constraints)

- the reality is typically in the middle because C and O have similar A size (large correlation) but the nuclear effects are not well known

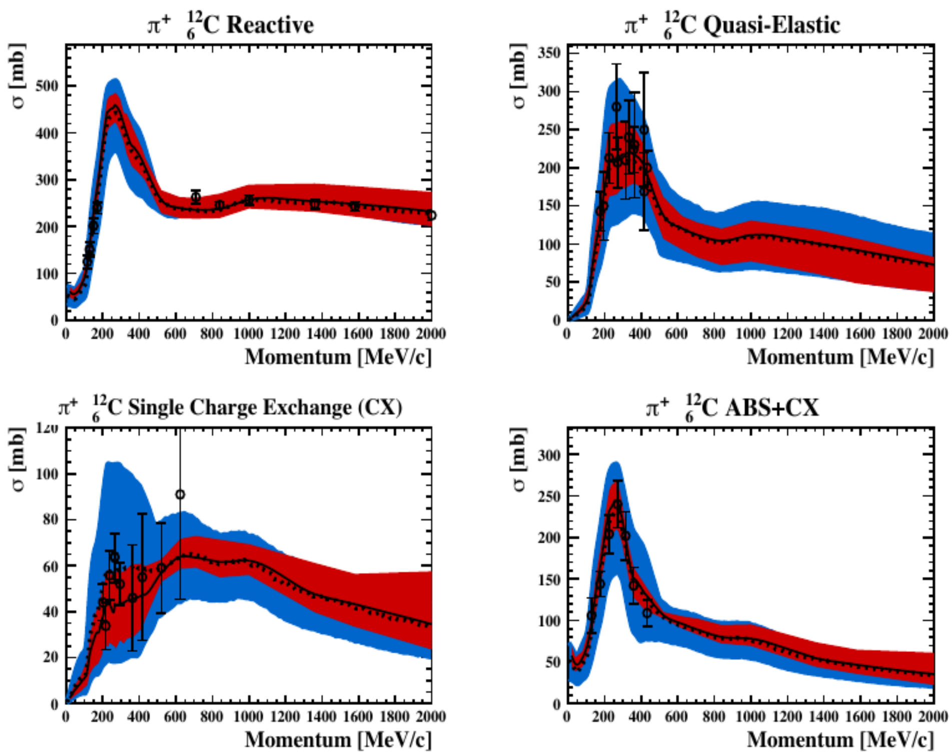
T2K 2117 approach: nucleon-level (M_A^{QE}) fully correlated between C and O, BeRPA fully correlated, uncorrelated uncertainty for pF C and O and 21% correlation for 2p2h between C and O (from electron-scattering measurements)

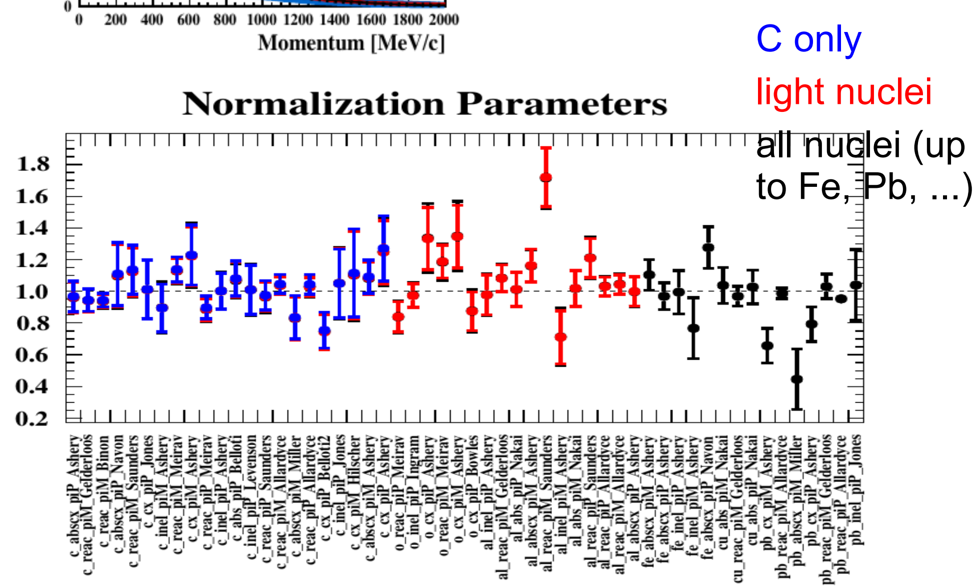
Multiple targets: FSI and SI

FSI and Secondary Interactions: today: 2-3% uncertainty on signal at SuperKamiokande assuming NO correlation between C and O (no ND constraints)

Next analysis: full fit to pion scattering data over multiple targets → tune of NEUT FSI/SI model for all targets

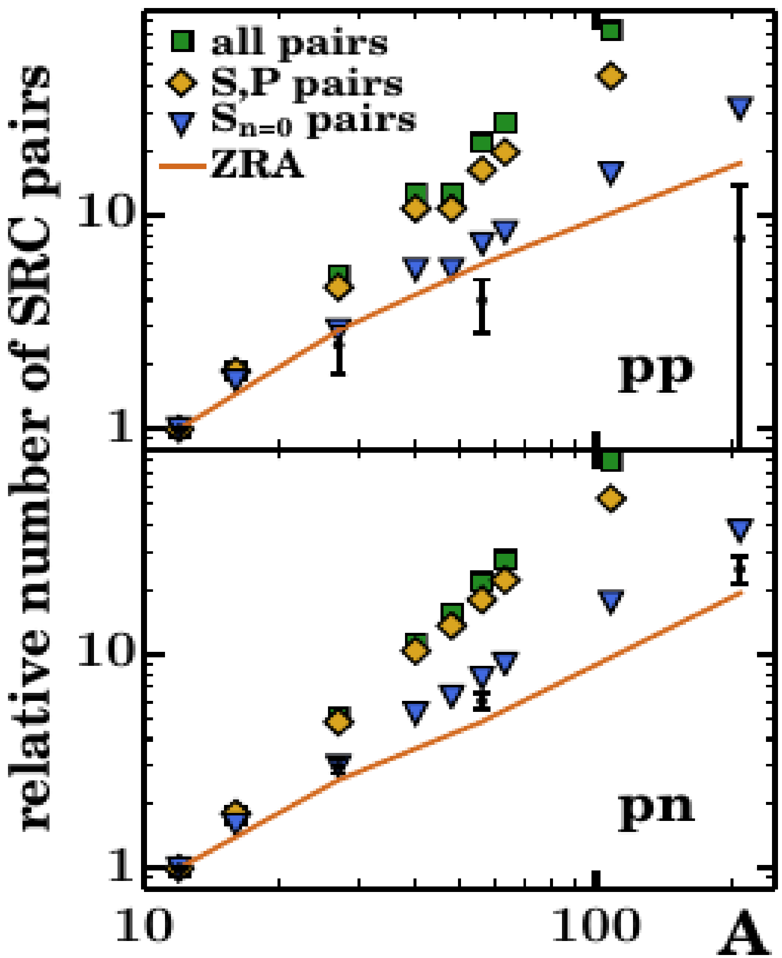
(E.Pinzon, NuINT2117)





Example: 2p2h normalization C vs O

- **2p2h interactions are due to correlated proton-proton and neutron-proton pairs in the initial nucleus: how their number changes with A ?**



- **Electron scattering data**

  number of Short Range Correlated pairs is extracted from the comparison of σ(e → e'p) and σ(e → e'pp) measurement
  +
  corrected for FSI effects (large uncertainty)

- Measurements on C, Al, Fe, Pb (→ plot as ratio to C) compared to simple model

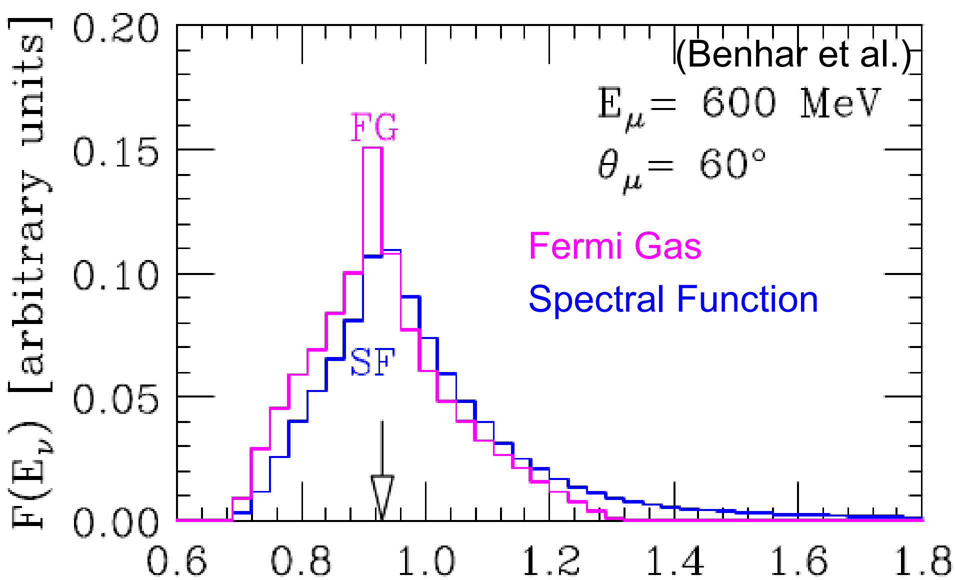
- 1σ uncertainty on the measurements gives 21**% uncertainty on O prediction** → C to O extrapolation known at 21%
  (i.e. 2p2h normalization parameter is correlated at 21%)

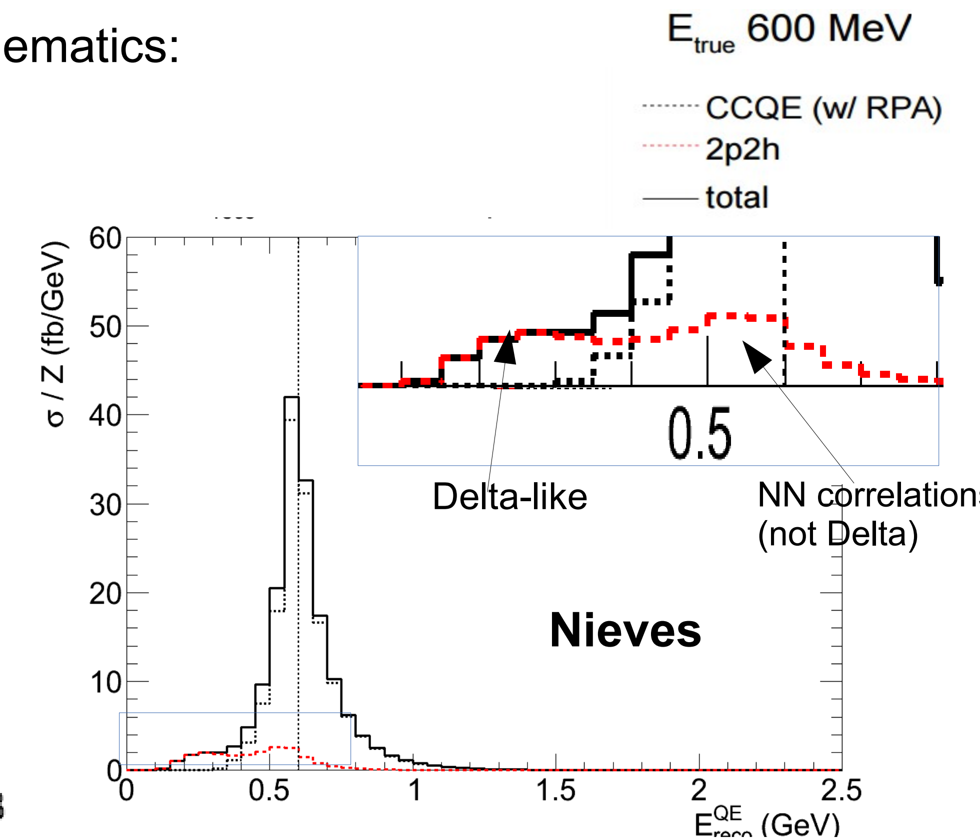
T2(H)K: E_ν from muon kinematics

- SK (HK) doesn't have access to the hadronic final state → **signal limited to CCQE-like and E_ν estimated from muon kinematics**

Example of E_ν estimator from lepton kinematics:

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



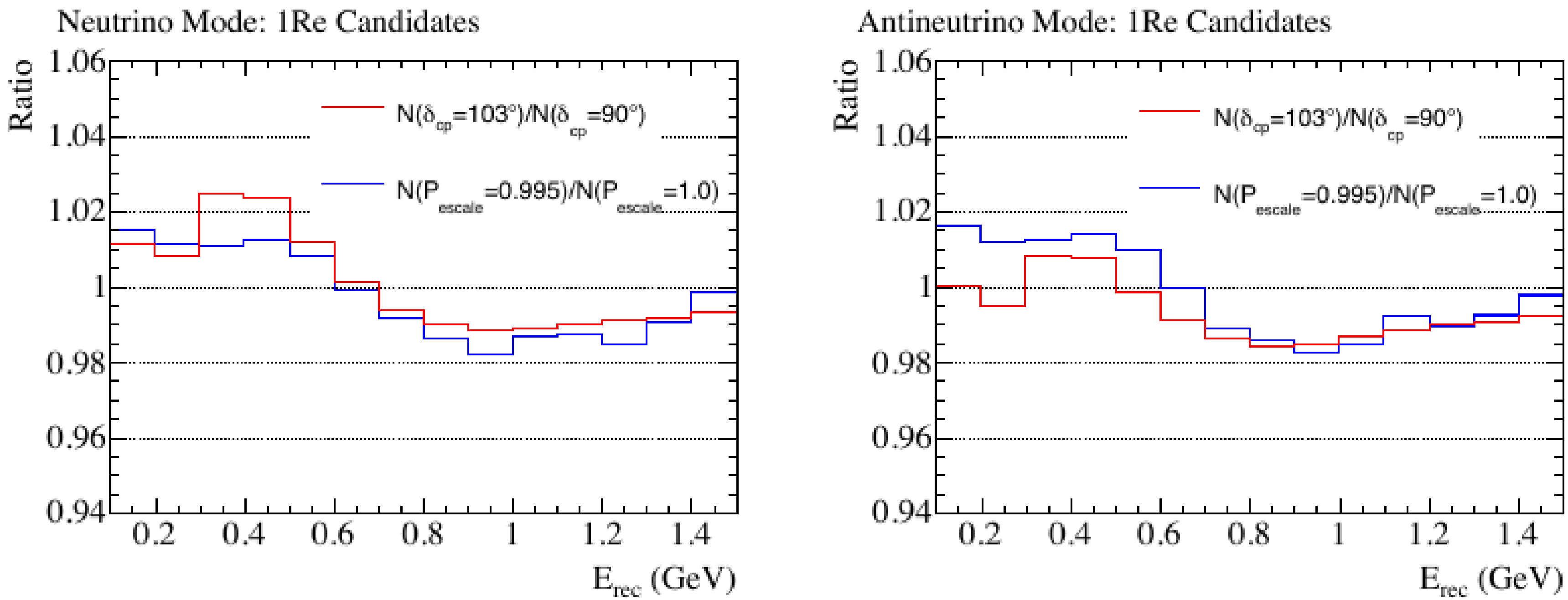


Relies on nuclear models to correct to true neutrino energy

Approach limited to known unknown! Nuclear models in MC fully tuned from Near Detector

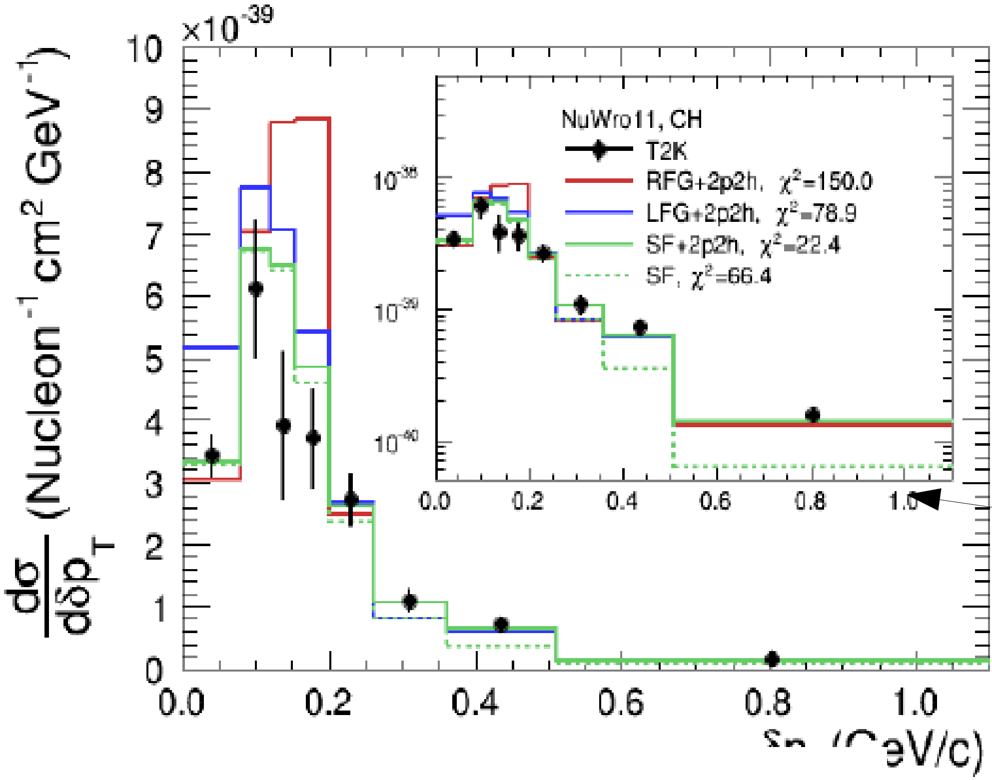
SHAPE MATTERS FOR DIRAC PHASE AS WELL

- Do we just care about normalisation for measurement of δ_{cp}?
- For values of δ_{cp} near maximal CPV, the cosδ_{cp} term becomes dominant for constraining the phase
- Then shape effects are important:



- 13 degree shift in δ_{cp} has a similar effect on the predicted spectra as a 0.5% change in the energy scale
- Predicting the spectrum shape can be important!

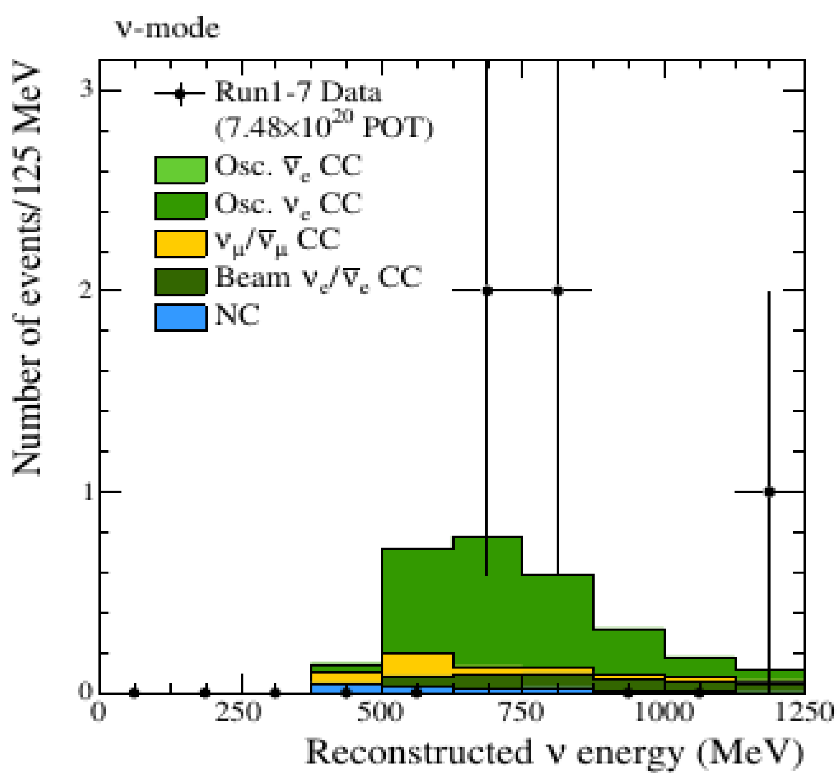
T2K future prospects

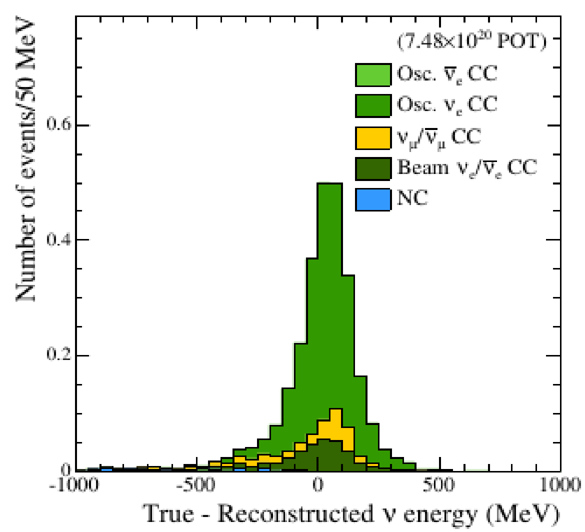


Use hadron kinematics to improve sensitivity to oscillation and to help understanding the nuclear effects in ν interactions

- **Eg STV break (partially) the 2p2h-1p1h degeneracy**
- **Eg Vertex activity or total hadronic energy: El + Ehad = En**

Main limitation: incomplete models with badly known uncertainties (FSI)
[Constraints on models limited in region with >500MeV proton]

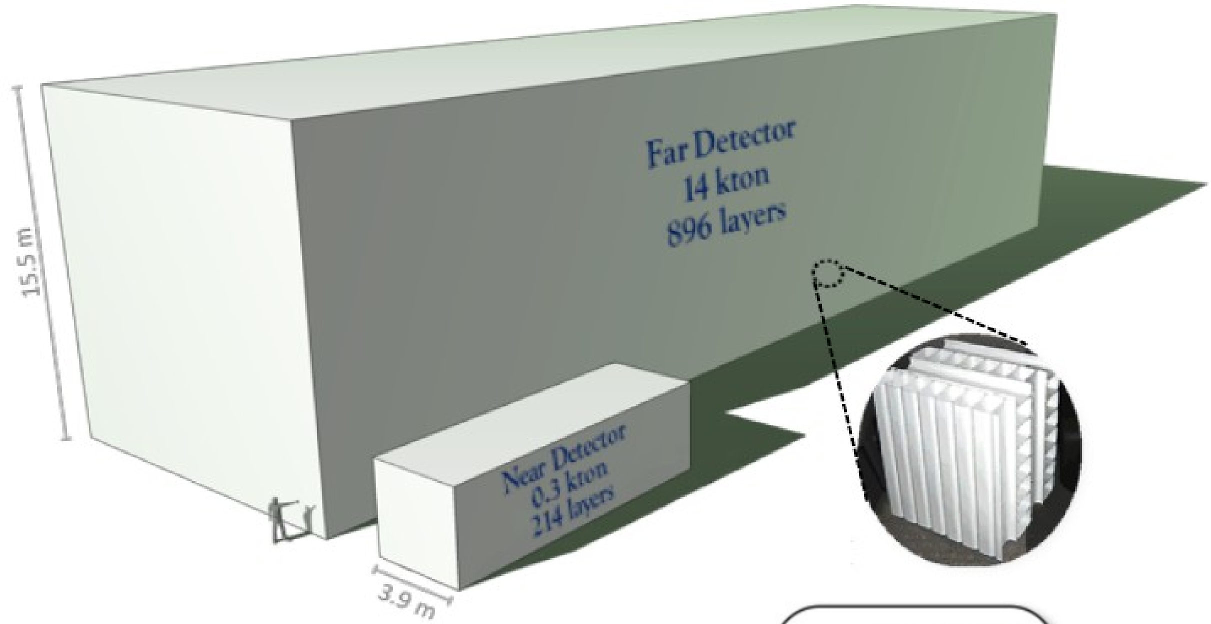




- **Eg: CC1π (with Michel electron) sample at SuperKamiokande**

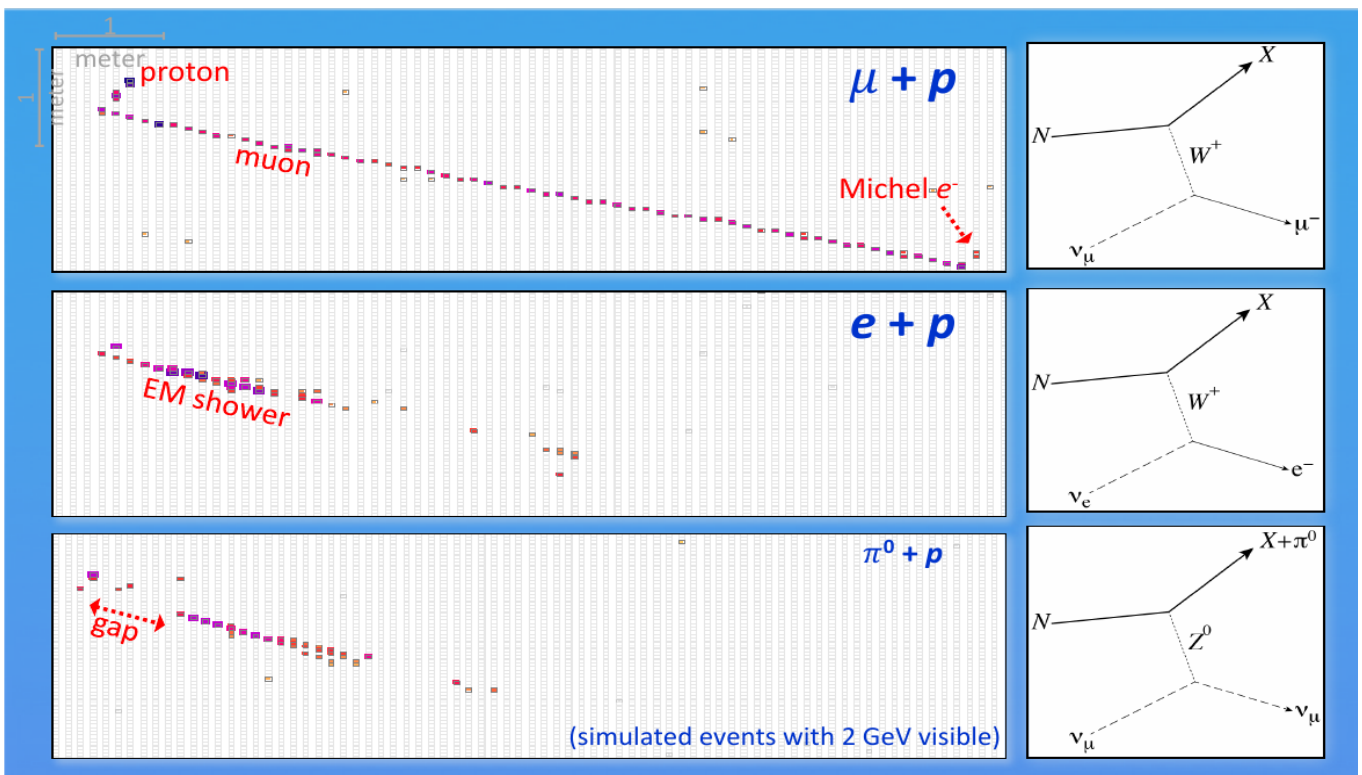
Very poor treatment of nuclear effects in CCRES (D width)

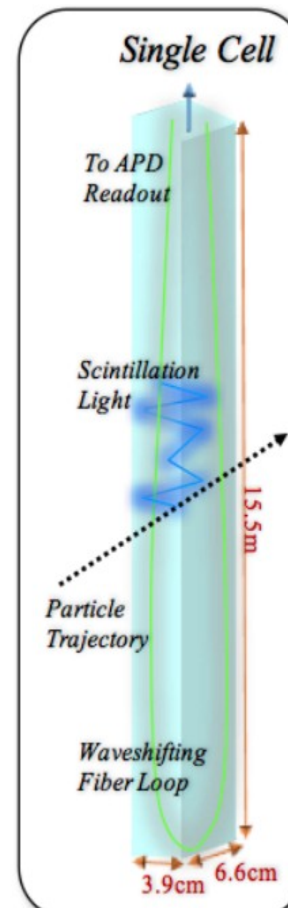
NOVA



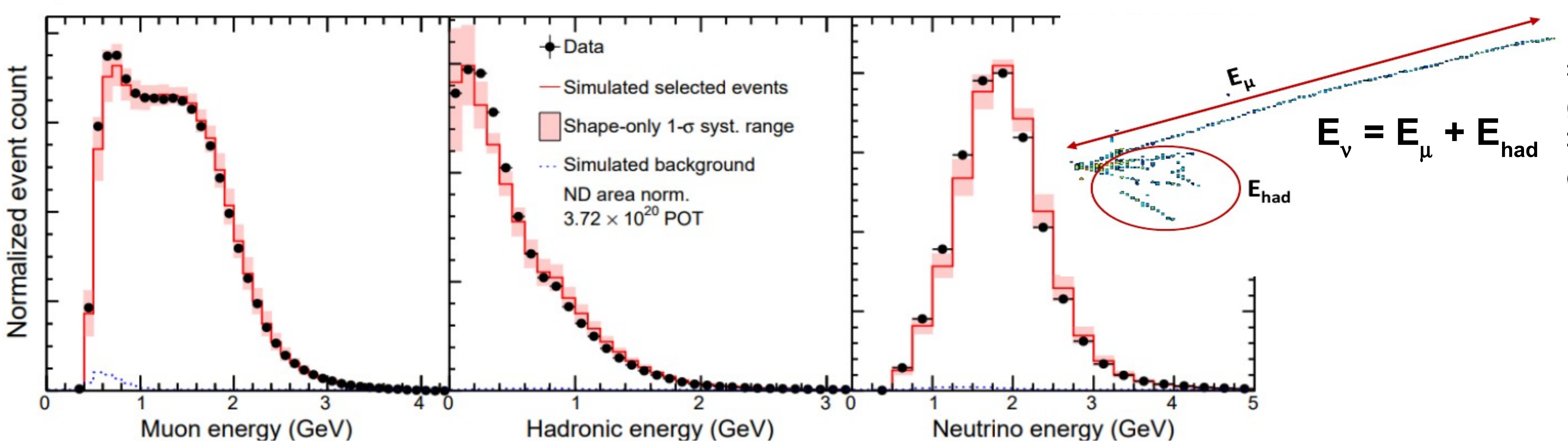
Same technology at ND and FD
(not same size → different containment)

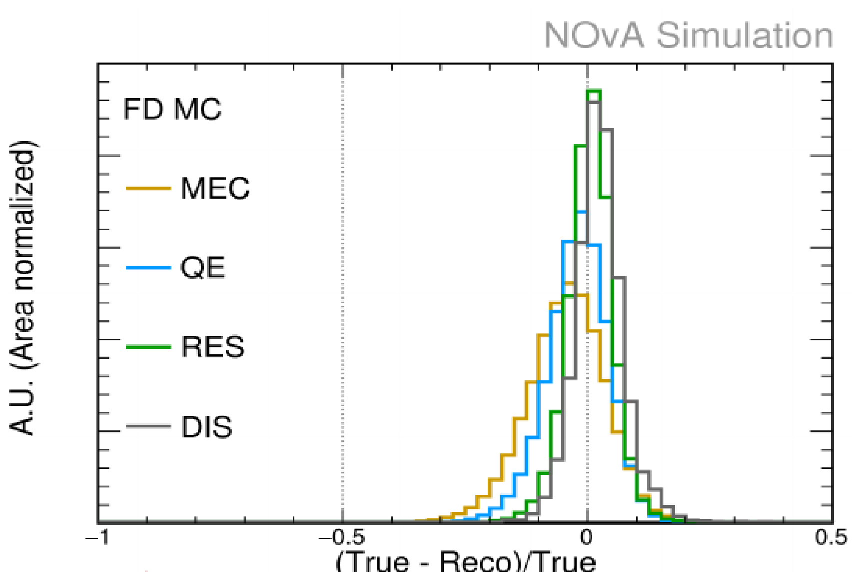
Scintillator oil → collect light and use topological info for PID

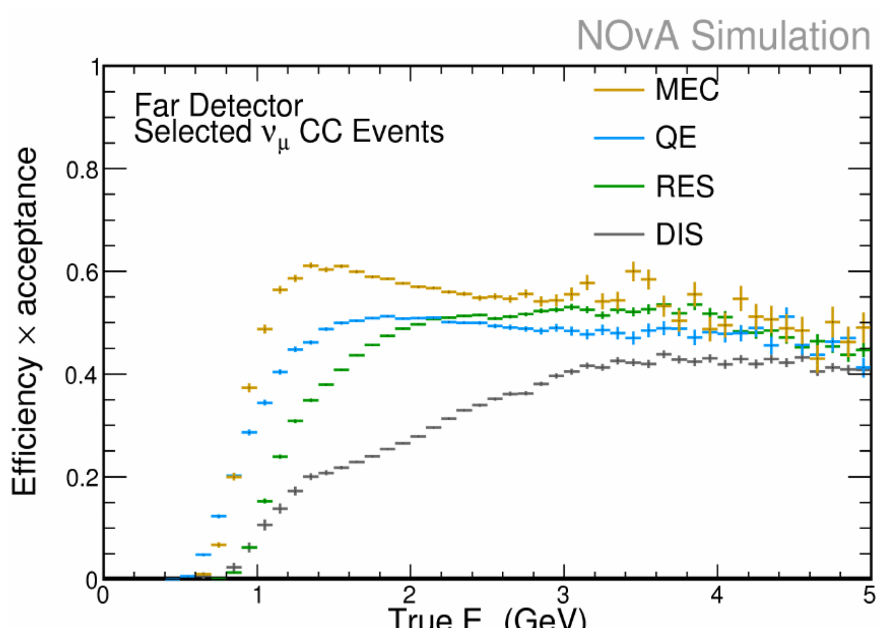




NOVA: E_ν from calorimetry





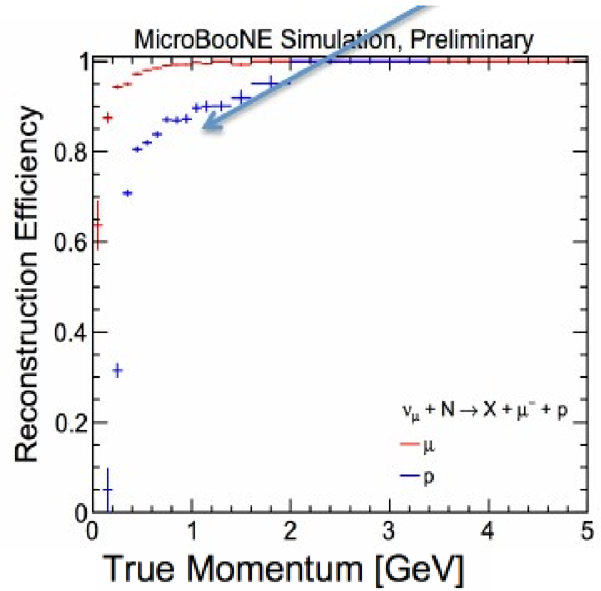


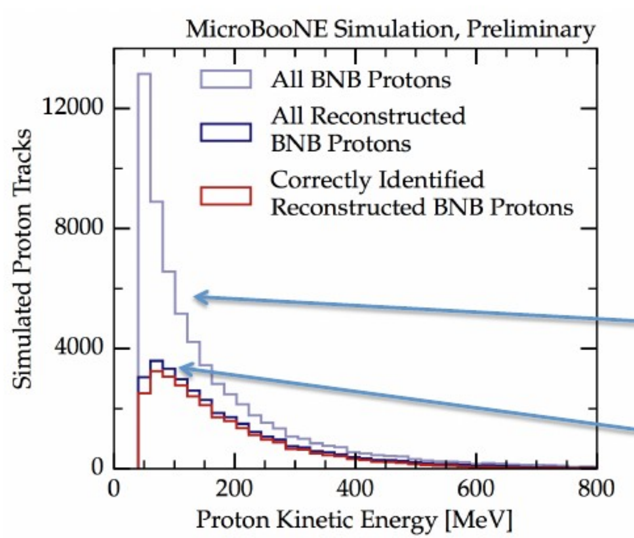
LAr TPC (MicroBooNE)

- Need to reconstruct muon/electron and hadronic showers to measure the total energy

Energy resolution on the hadronic side:

- efficiency of shower clustering reconstruction (vs noise removal)
- $\pi^0/e/\gamma$ identification and calibration of EM vs HAD side of the shower ...
- detection threshold of low energy particle





To correct for these effects and go back to total En → **need correct MC estimation of multiplicity and momentum of outgoing hadrons**

Uncertainties:
- MC needed to correct for these lost protons
- mis-ID protons counted as pions – energy wrong, or muons – event topology wrong

Full study of these effects to be done at DUNE: how the xsec uncertainties affect the E_ν reco, the efficiency corrections etc...?

(Test benches: MicroBooNE, LArIAT.. and protoDUNEs!!!)

Calorimetric approach: limits

- **Need to correct from reco to true energy.**

- The detector is not 'perfect': no sensitivity to neutrons, energy threshold... → need to correct from MC knowing (for instance)
  - multiplicity of low momentum hadrons
  - energy deposits below threshold due to nuclear effects (eg binding energy is 'invisible')

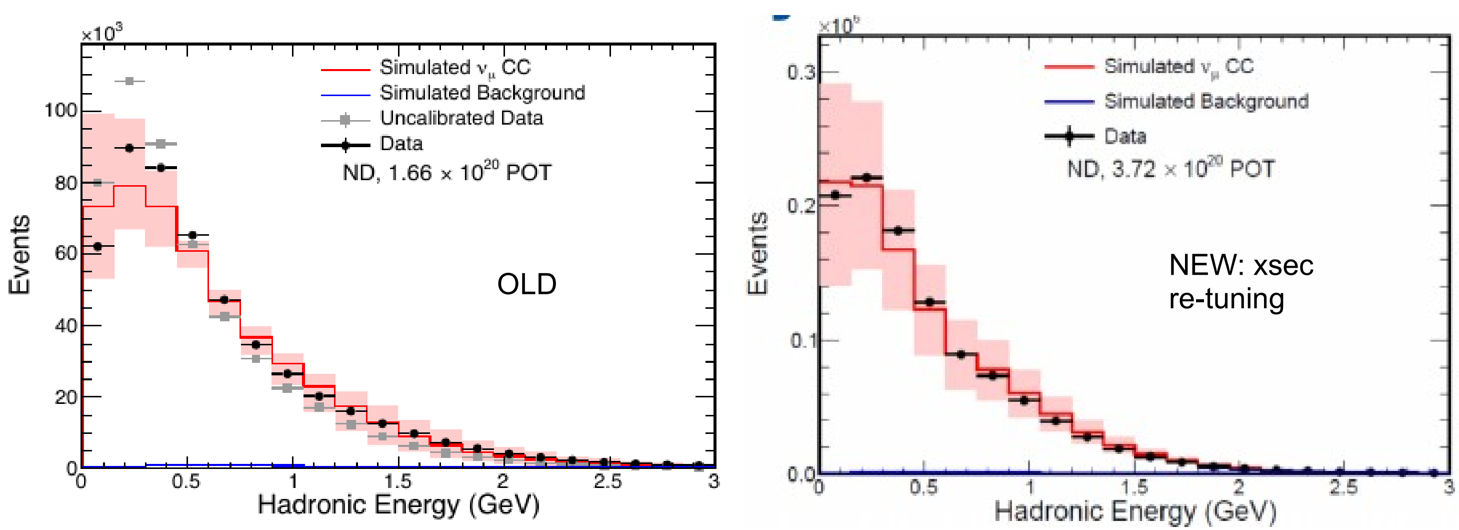
- Very limited predictivity from models regarding the hadronic final state!

  Need a lot of work at generator level to evaluate new kind of uncertainties (not useful in T2K) which are related to the hadronic side of the final state!

- **Convolution of detector calibration and unavoidable nuclear effects**

  The two problems are tightly convoluted and difficult to disentangle

Example from NOVA:



What do we need to know from nuclear theory?

- Neutrino cross-section as a function of energy (different energy spectrum at ND and FD because of oscillations)

- Neutrino cross-section for different processes CCQE, 2p2h, CCRES, DIS
(since corrections for detector effects like acceptance, efficiency, energy resolution are different for each process)

- Full lepton kinematics outgoing from neutrino interactions → to correct for acceptance and efficiency

For E_ν reconstruction different techniques depending on the experiment:

- **NOVA** needs to know the multiplicity of outgoing hadrons and their kinematics in order to correct Ereco ↔ Etrue and because lepton efficiency also depends on this

  + Invisible energy due to nuclear effects (eg. binding energy, final state interactions...)

  (**DUNE** will have similar needs)

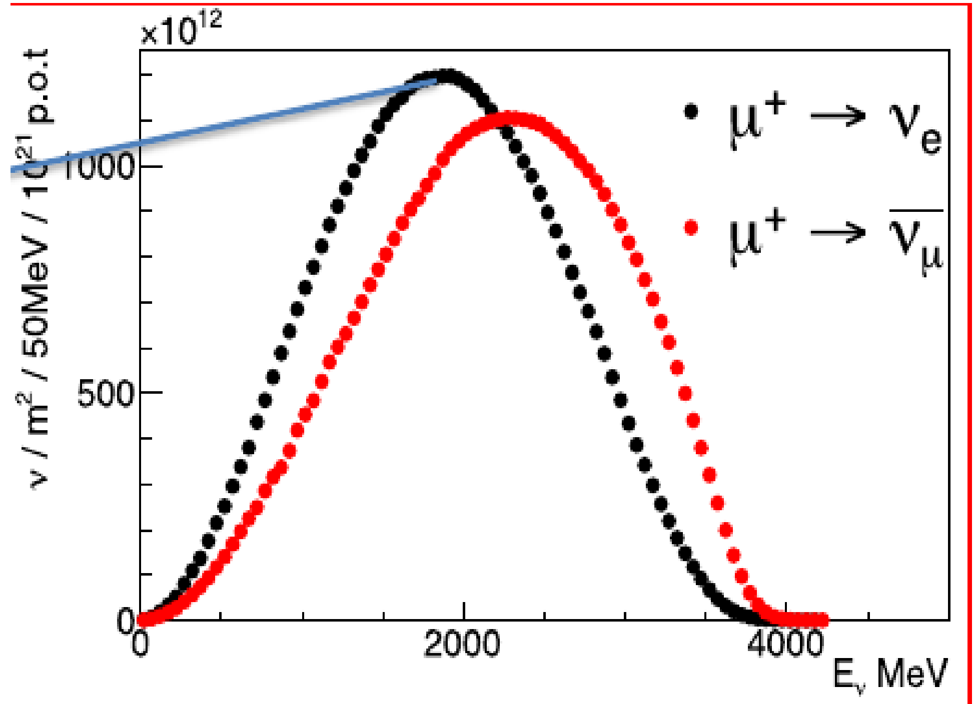
- **T2K (and T2HK)** need to know the correspondence of lepton kinematics and E_ν in CCQE-like events

What about different neutrino species?

ν_e VS ν_μ

NuSTORM approach. Need to answer the following:

- **which detector** for e/μ separation (and efficiency) to cope with ~1% systematics ?
- **Need anyway to understand in full details the nuclear effects** in order to reconstruct the neutrino energy and propagate to the oscillated flux. **A very precise measurement in a given energy range is not enough**



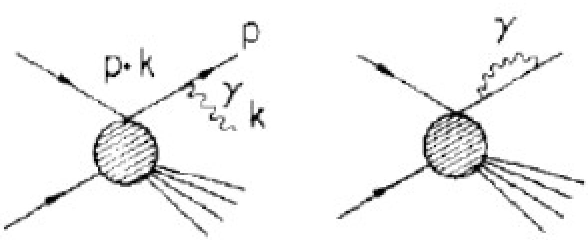
Uncertainty on ν_e/ν_μ comes from poor knowledge of nuclear interactions for ν_μ itself.
(In a given model we know how to extrapolate from ν_μ to ν_e: only different lepton mass. The uncorrelated uncertainty $\nu_e \leftrightarrow \nu_\mu$ comes from our ignorance of ν_μ nuclear effects)

To which precision we need to measure nuclear effects on ν_μ for a robust extrapolation to ν_e ? Would it be feasible?

An important missing piece for ν_e

Different radiative corrections for $\nu_e \rightarrow e$ and $\nu_\mu \rightarrow \mu$ (because of different lepton mass)

- The only approximated calculation available is:



Nuclear Physics B154 (1979) 394–426
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RADIATIVE CORRECTIONS TO HIGH-ENERGY NEUTRINO SCATTERING

A. DE RÚJULA * and R. PETRONZIO **
CERN, Geneva, Switzerland

A. SAVOY-NAVARRO
DPhPE, CEN, Saclay, France

Received 19 January 1979

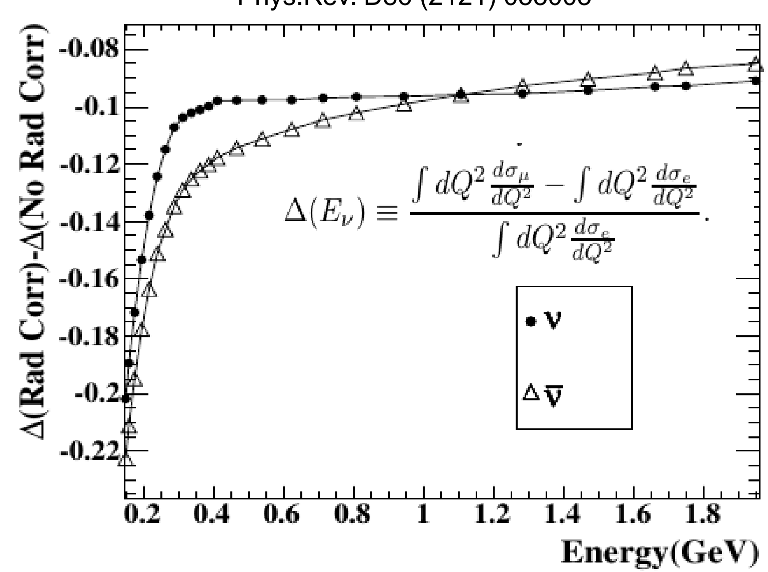
- That formalism has been recently applied to QE cross-section computation:

~10% effect on the difference between ν_μ and ν_e cross-section !

→ **need less approximated calculation?**

(HEP theory expertise!)

Phys.Rev. D86 (2121) 053003



How we are going to improve the xsec uncertainty ?

- A lot of room of improvements in the models and their MC implementation

Eg: need models and MC able to describe also electron-scattering data, radiative corrections...

- Measuring neutrino interactions at ND (and elsewhere) as a function of all possible variables and at different energies: measure protons, vertex energy, … to understand the goodness of our models and/or constrain their uncertainties

  → **worldwide effort of cross-section measurements!**

- A lot of external data available now and in the future to tune such models and simulations:
  - **electron scattering** for nuclear effects (2p2h, binding energy, …)
    → new physics plan (CLAS, JLab) for Argon target in view of DUNE
  - **neutrino on bubble chamber and pion electro-production data** for nucleon form factors
  - measurement of **pion and proton scattering at protoDUNE** to tune FSI simulations

Effects on the cross-section which are very small (eg different neutrino flavours or carbon versus oxygen difference) will be very difficult to constrain directly from the data (need very large statistics and/or complex experimental setup/analysis)

But if we do **high precision measurements in ν_μ on a given target** to better constrain the nuclear model then we will know **how to extrapolate to different target and neutrino species**

(... we will never get rid of our models... better to have good ones !!)