Modelling Neutrino Interactions for the T2K experiment

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For The T2K Collaboration

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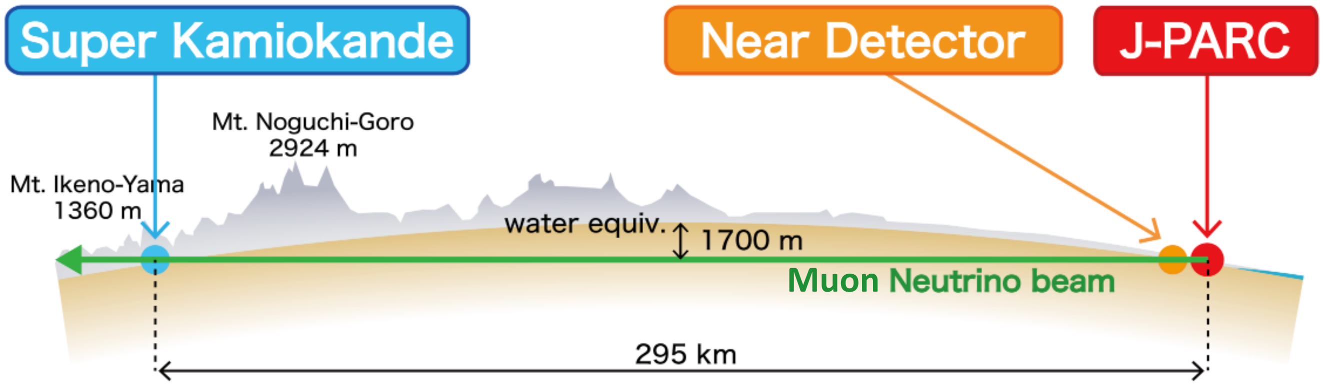
NuFACT 2022

Outline

- Why should T2K care about modelling neutrino interactions?
- The T2K uncertainty model for neutrino interactions
- Robustness checks of T2K analyses
- Summary

The T2K Experiment



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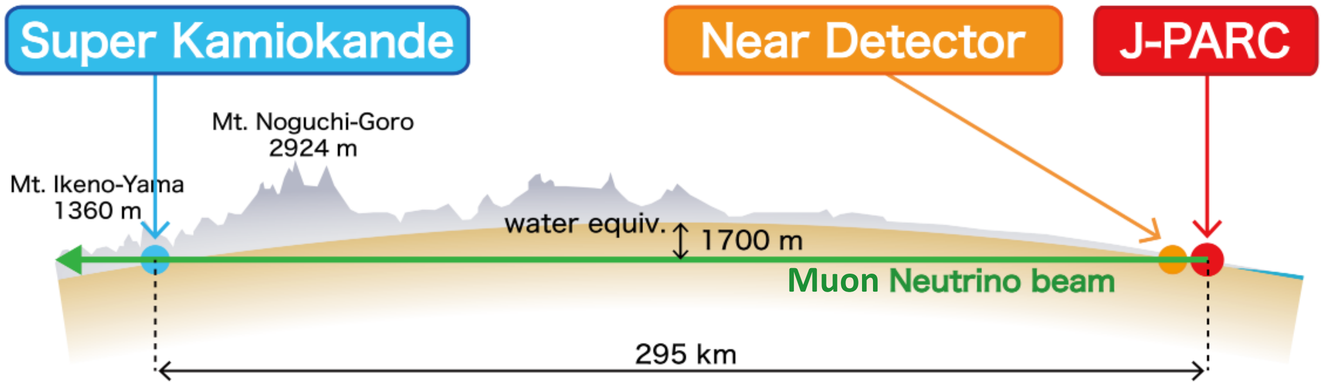

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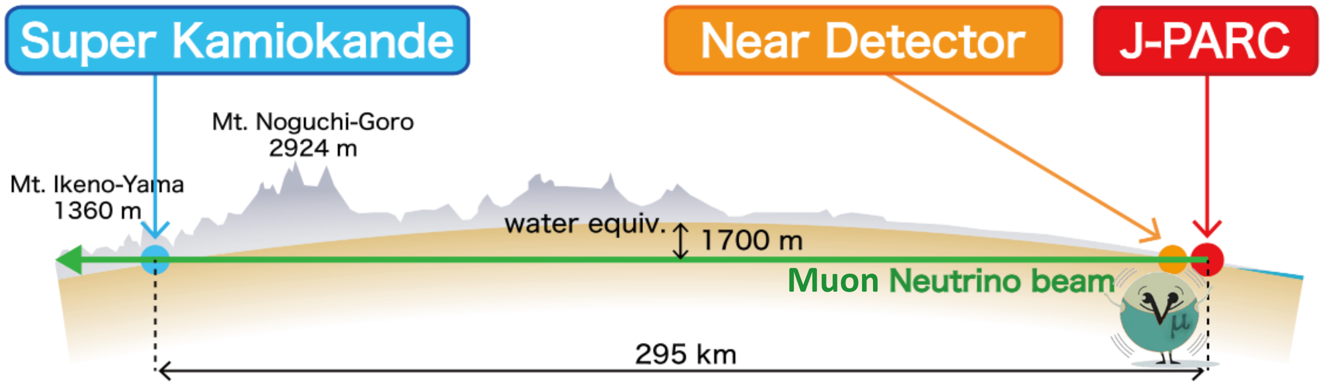
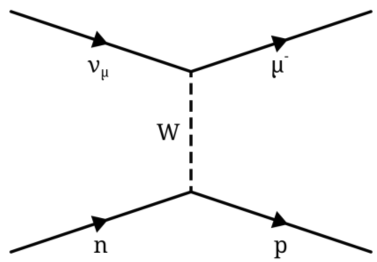
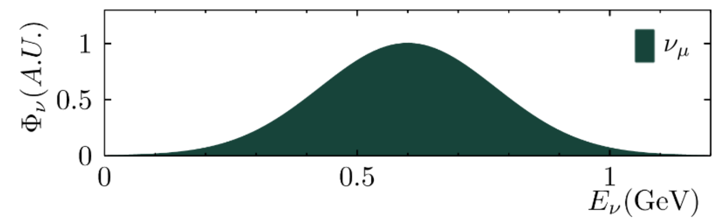






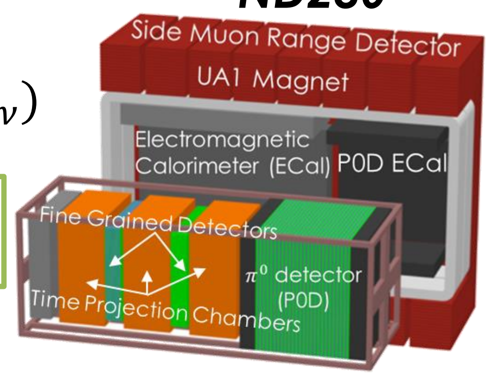
$$N_\mu(E_\nu) = \sigma(E_\nu)\Phi_\nu(E_\nu)\epsilon(E_\nu)$$

Interaction cross section

Neutrino flux

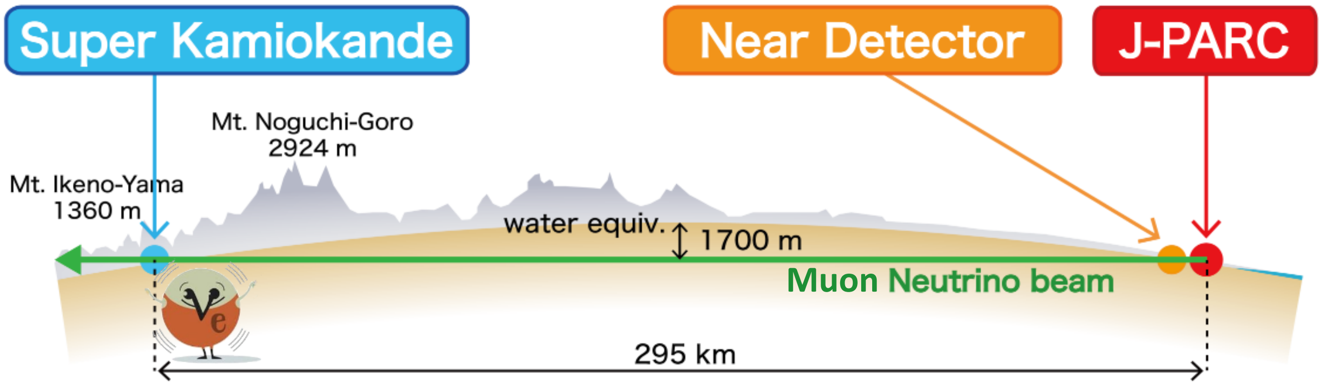
Detector effects

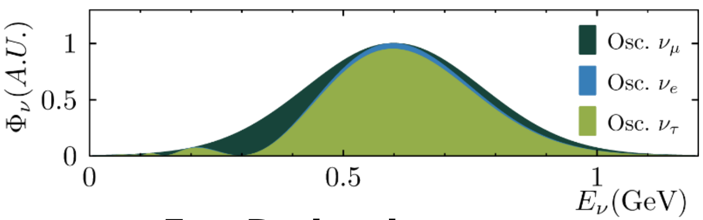
Near Detector
ND280



(Mostly Hydrocarbon Scintillator)

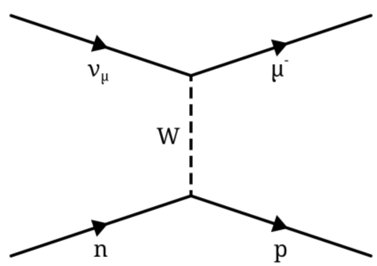
The T2K Experiment

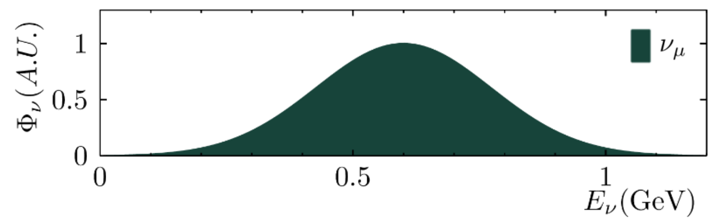




Far Detector

Super-Kamiokande





Near Detector

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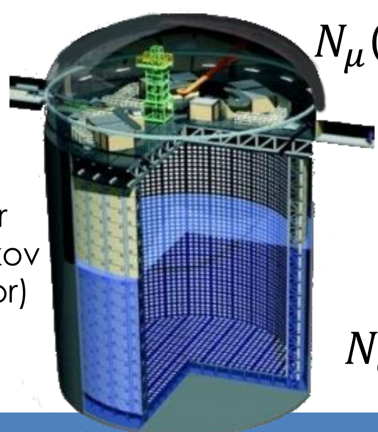


(Water Cherenkov Detector)

$$N_\mu(E_\nu) = P(\nu_\mu \to \nu_\mu)\sigma(E_\nu)\Phi_\nu(E_\nu)\epsilon(E_\nu)$$

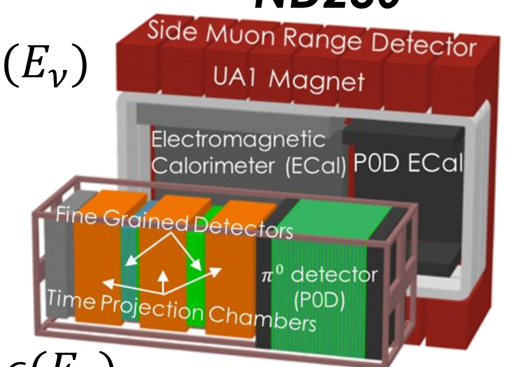
Oscillation probability

PMNS Mixing

δ_{CP} θ_{13}

Δm^2_{32} θ_{23}

$$N_e(E_\nu) = P(\nu_\mu \to \nu_e)\sigma(E_\nu)\Phi_\nu(E_\nu)\epsilon(E_\nu)$$



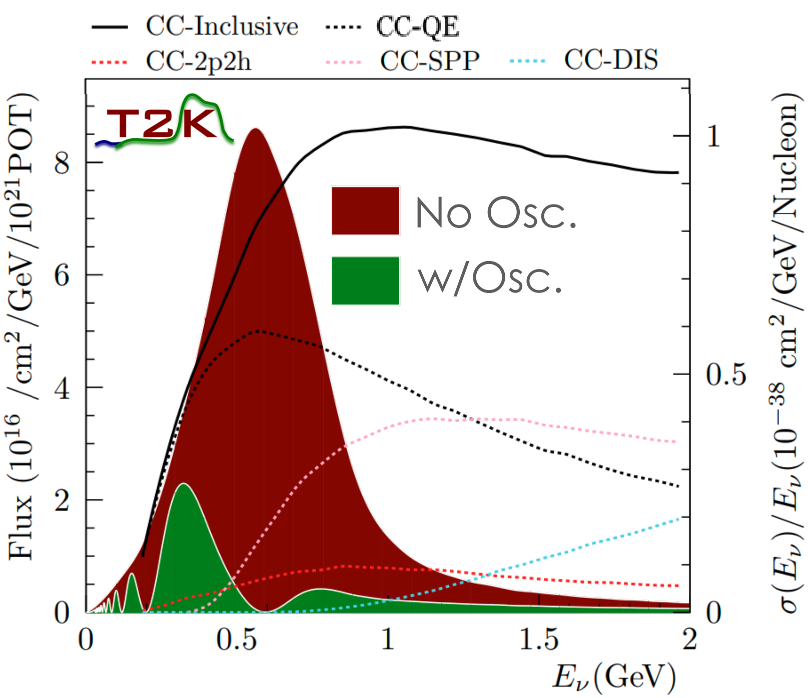
(Mostly Hydrocarbon Scintillator)

Neutrino Interactions at T2K

$$N_\ell(E_\nu) = P\big(\nu_\mu \to \nu_\ell\big)(E_\nu)\ \sigma(E_\nu)\ \Phi_\nu(E_\nu)\ \epsilon(E_\nu)$$

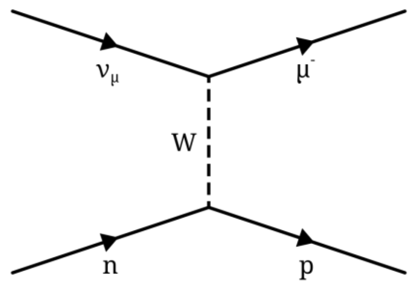
$N_\ell(\mathrm{E}_\nu)$ = Event rate
$P(\nu_{\ell'} \to \nu_\ell)(E_\nu)$ = Oscillation probability

$\Phi_\nu(\mathrm{E}_\nu)$ = Neutrino flux
$\epsilon(E_\nu)$ = Detector efficiency
$\sigma_\ell(E_\nu)$ = Interaction cross section



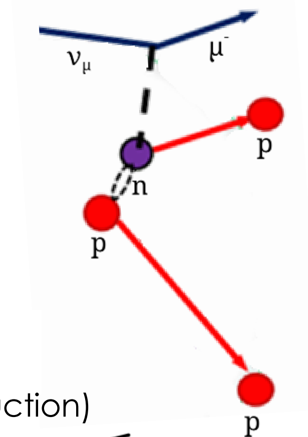
CC-QE

(Charged-Current Quasi-Elastic)



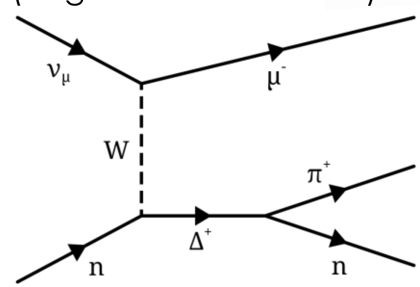
CC-2p2h

(2 particle, 2 hole)



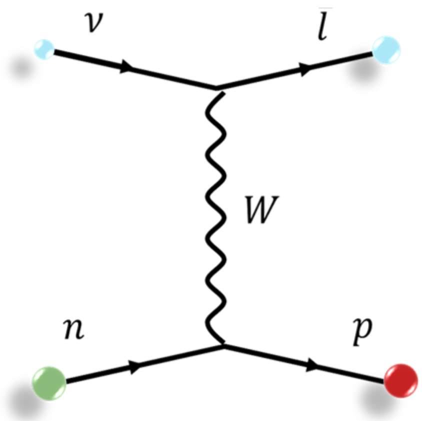
CC-SPP

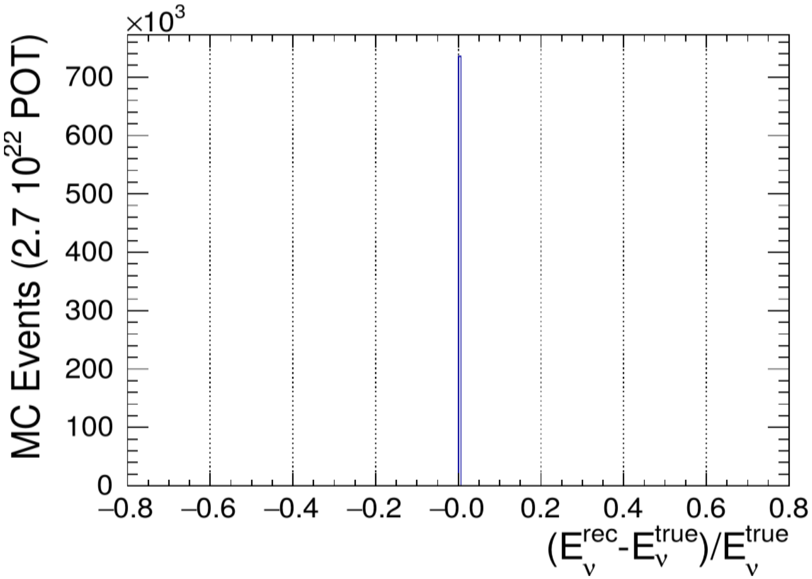
(Single Pion Production)



Neutrino Energy Reconstruction

CCQE (1p1h)





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

Proxy for E_ν from lepton kinematics is exact only for **CCQE elastic scattering** off a **stationary nucleon**

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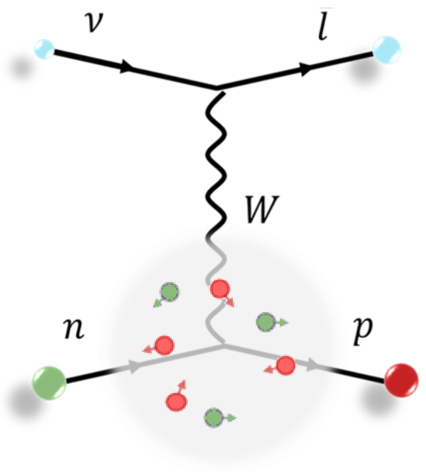

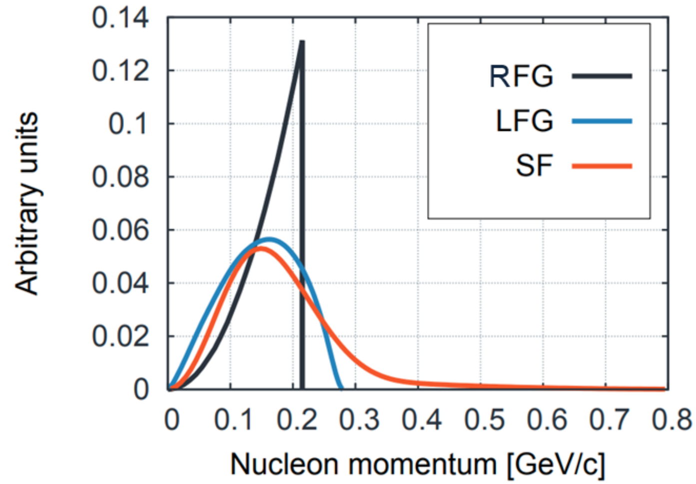

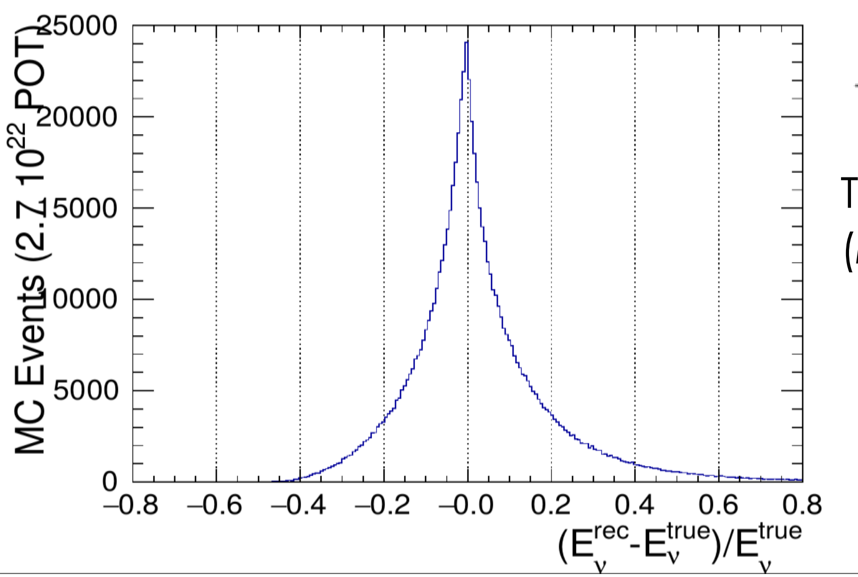

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The motion of the nucleons inside the nucleus (*Fermi motion*) causes a **smearing** on E_ν

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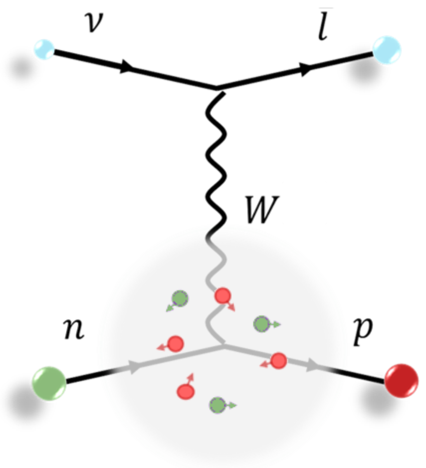
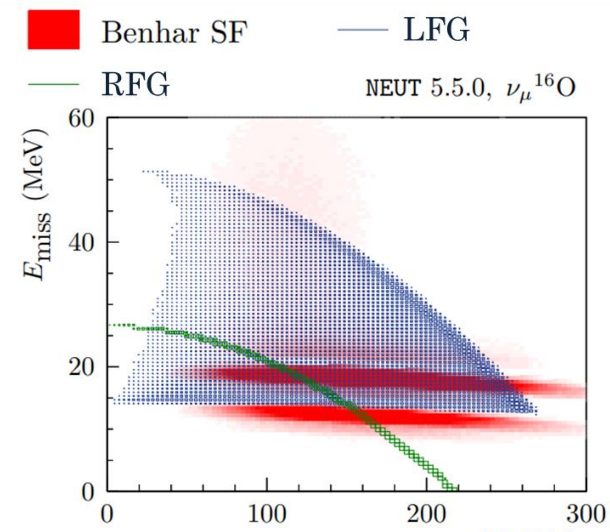
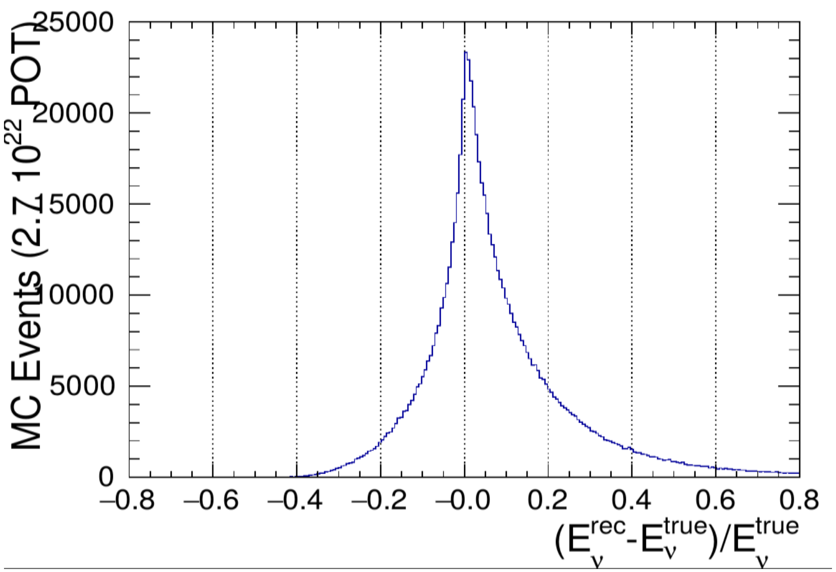




https://arxiv.org/pdf/2106.15809.pdf



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The energy loss in the nucleus (to extract the struck nucleon from its shell) introduces a **bias**

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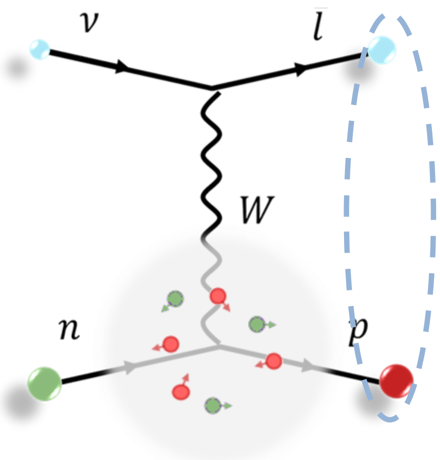
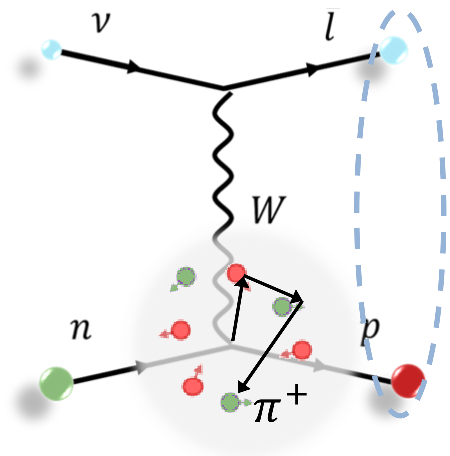
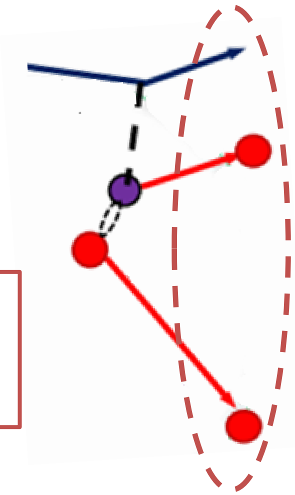


CCRES

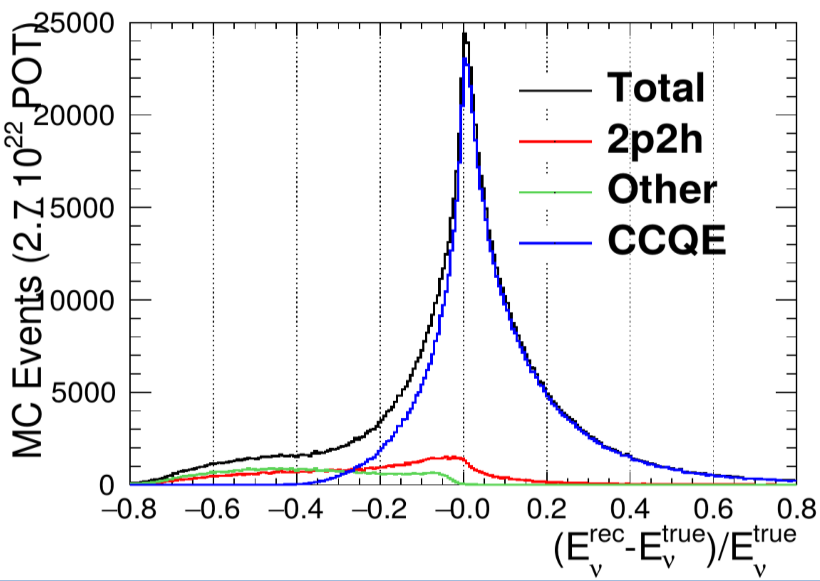


Final state interactions (FSI) can cause different interaction modes to have the same final state

2p2h



Interactions off a bound state of two nucleons can result in **2p2h** final states



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Not a good proxy for non-CCQE events: 2p2h and CC1π with pion abs. FSI

Three things we need to model

(a non exhaustive list)

1. Relative CC0π contribution of CCQE and other processes
   - *So we know how often we mis-reconstruct* E_ν

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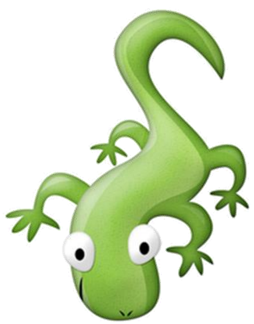

T2K uses the **NEUT neutrino nucleus interaction simulation** to model this

The European Physical Journal Special Topics **volume 230**, pages 4469–4481 (2021)

See our NuFact 2022 talk on NEUT for details!

The CCQE Model

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  - ✓ More sophisticated description of the nuclear ground state (i.e. **Fermi motion** and **removal energy**) than Fermi-gas (FG) models
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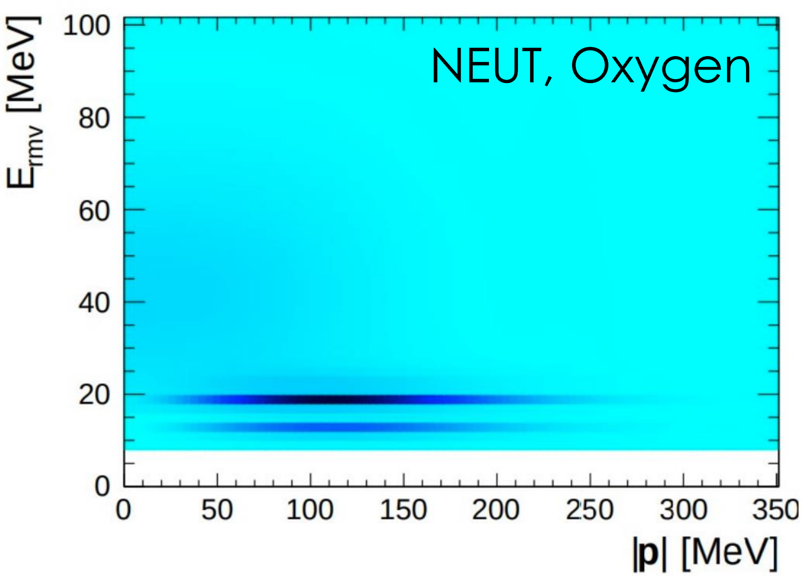
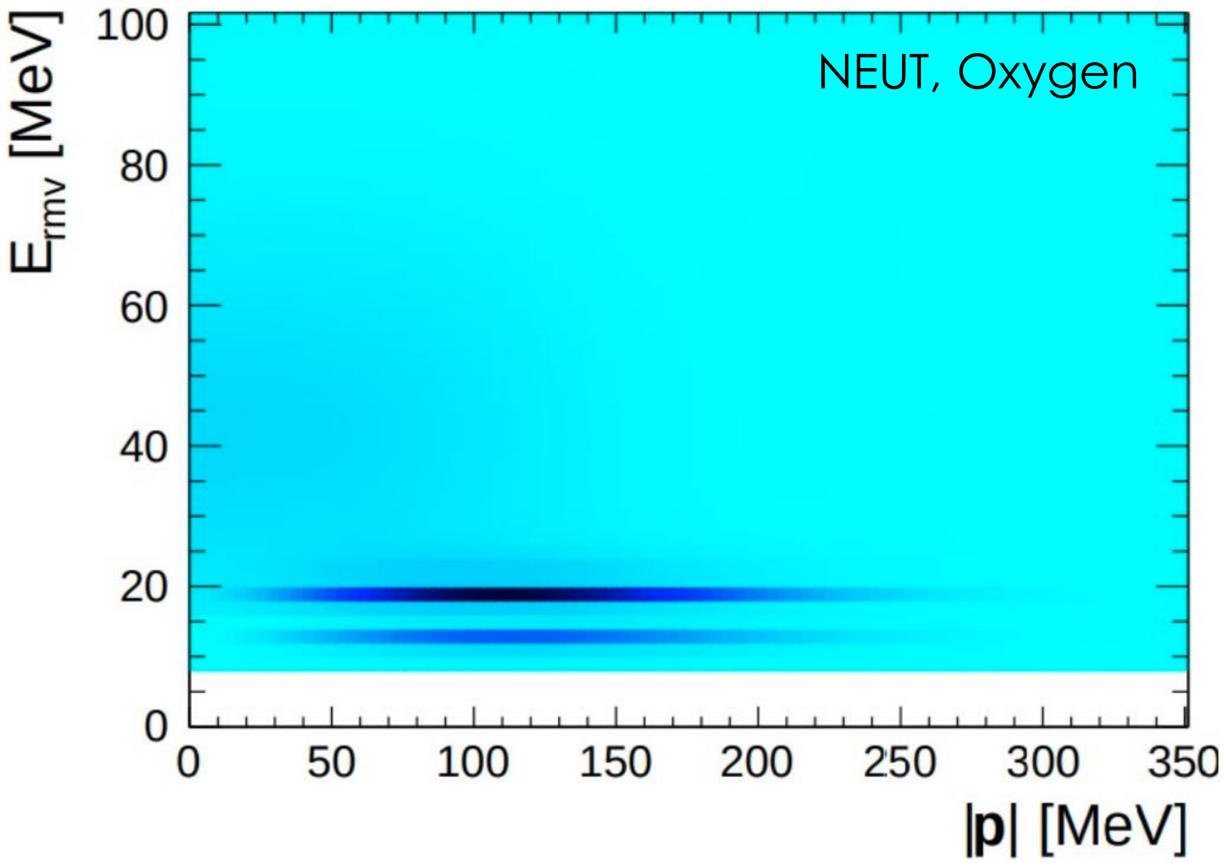


$$\frac{d^5\sigma_{\nu\ell}}{d\Omega(\hat{k}')d\Omega(p_N)\mathrm{d}E_{\ell}'} \sim S(E_m,\boldsymbol{p}_m)\mathrm{L}_{\mu\nu}\mathrm{W}^{\mu\nu}\delta(\omega+M-E_m-E_{p'})$$

"Spectral Function"

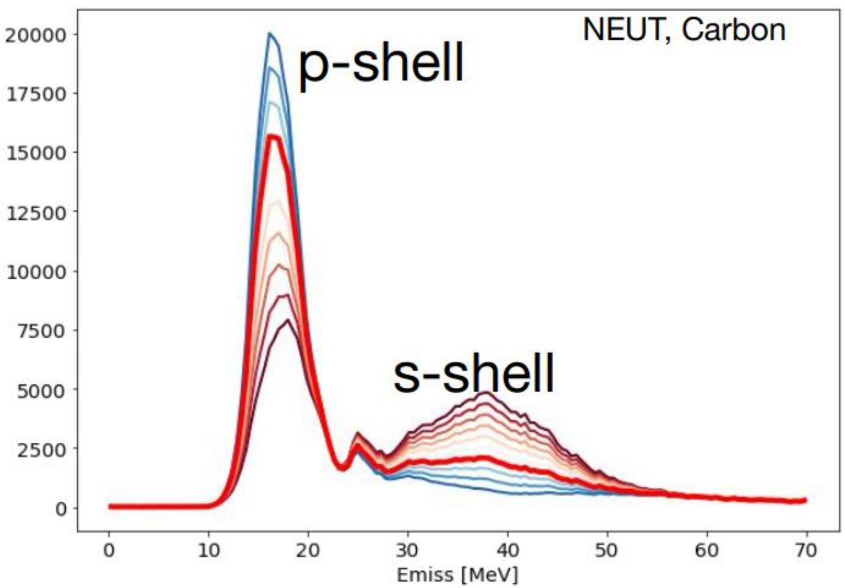
Single nucleon tensor contraction
(no nuclear effects)

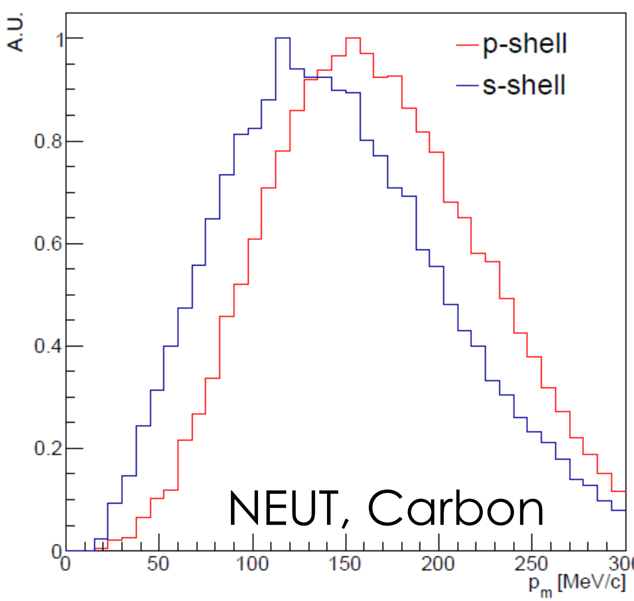
Identifying the natural d.o.f.



Identifying the natural d.o.f.

- **Fermi motion and removal energy** in the mean field region:
  - Change **relative occupancy** of the shells (2 shells for C, 3 for O)





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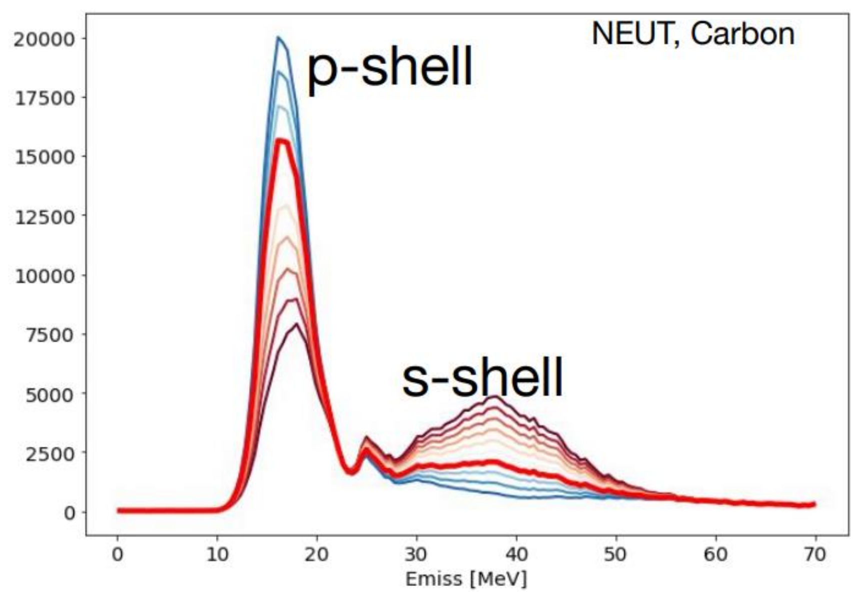

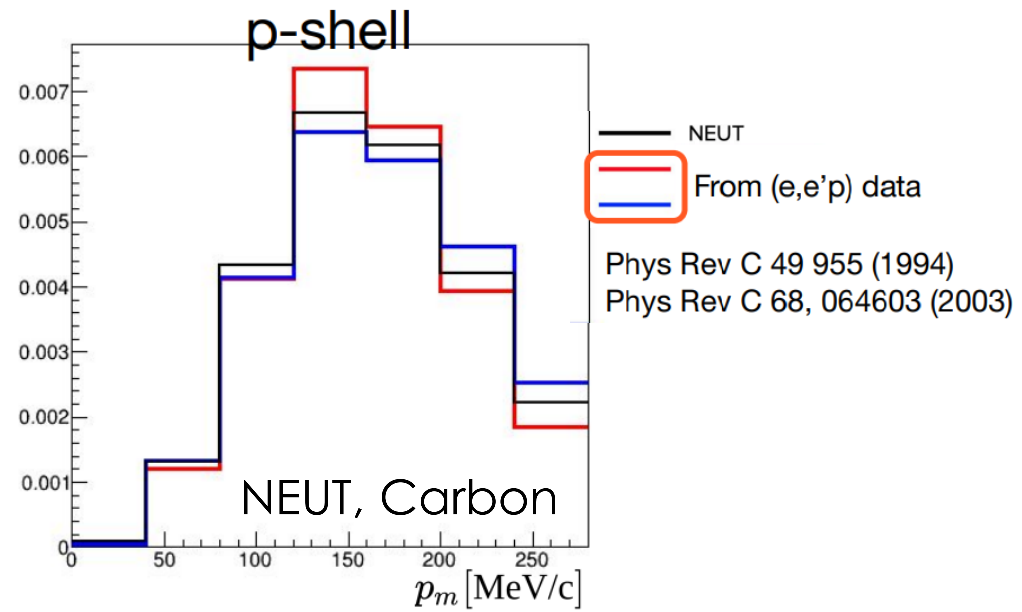

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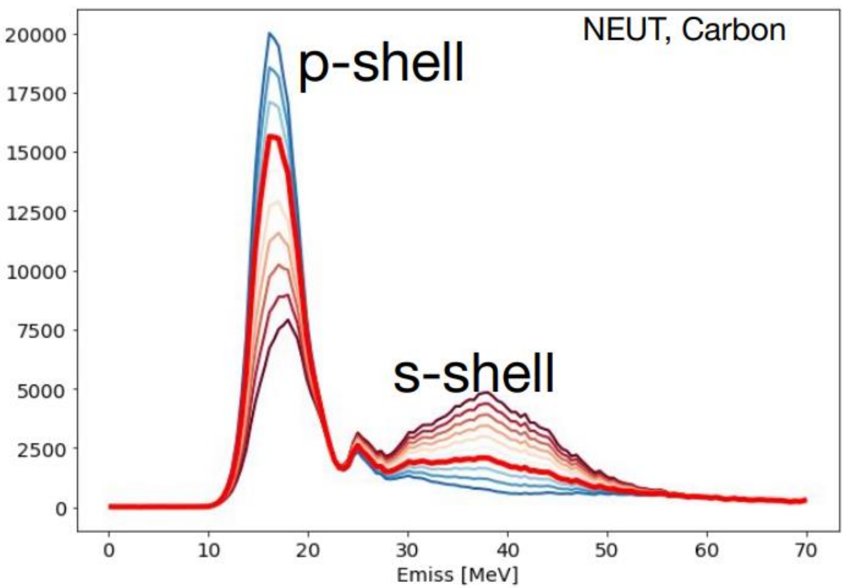

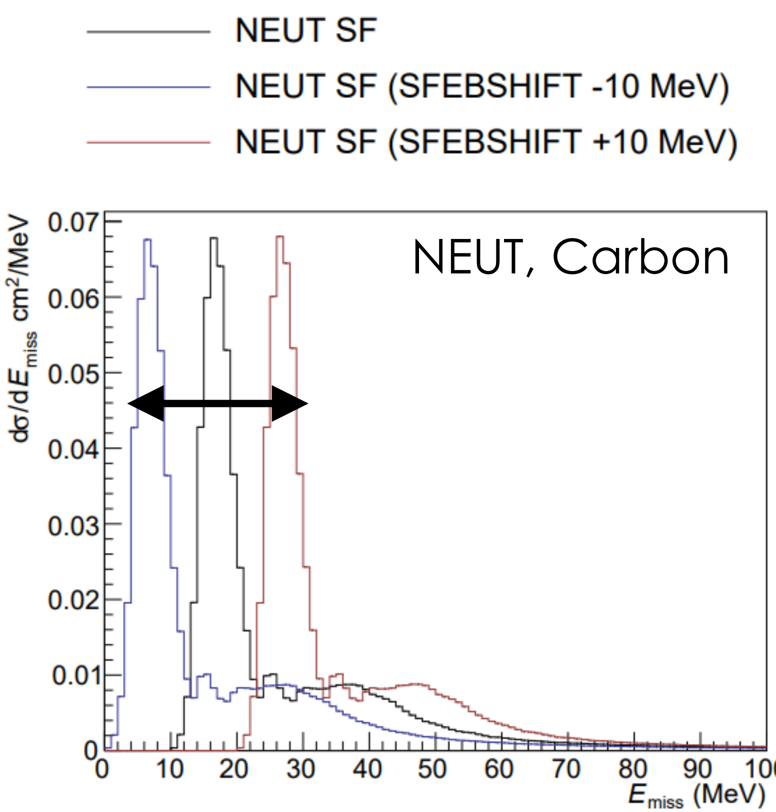

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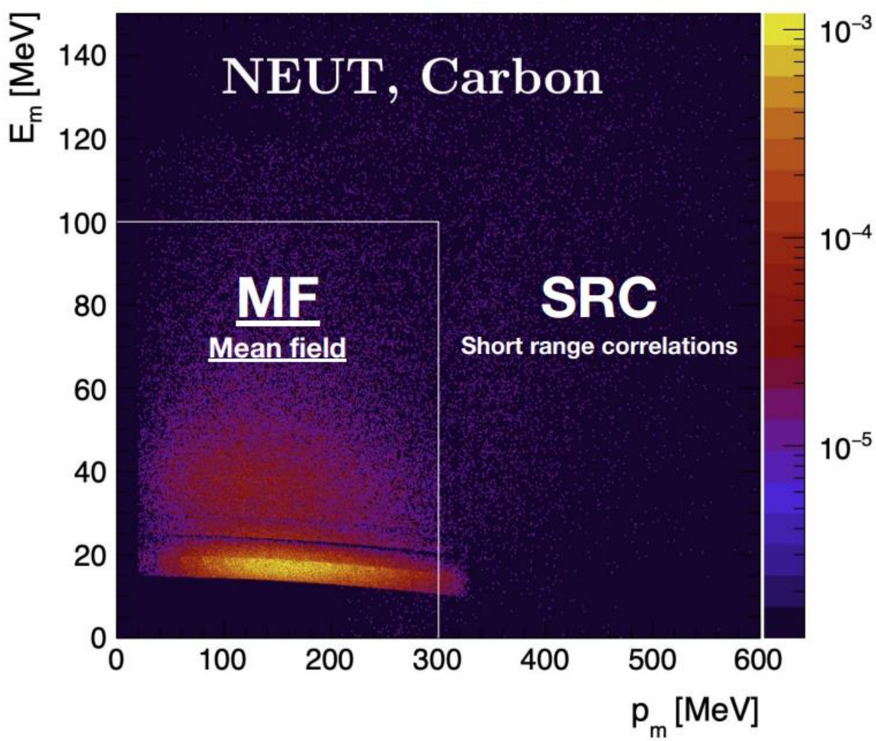
- **Short range correlations**:
  - **Normalisation of the SRC contribution** (high nucleon momentum tail, 2 nucleon final states)
  - NEUT predicts 5%, other models predict closer to 20%



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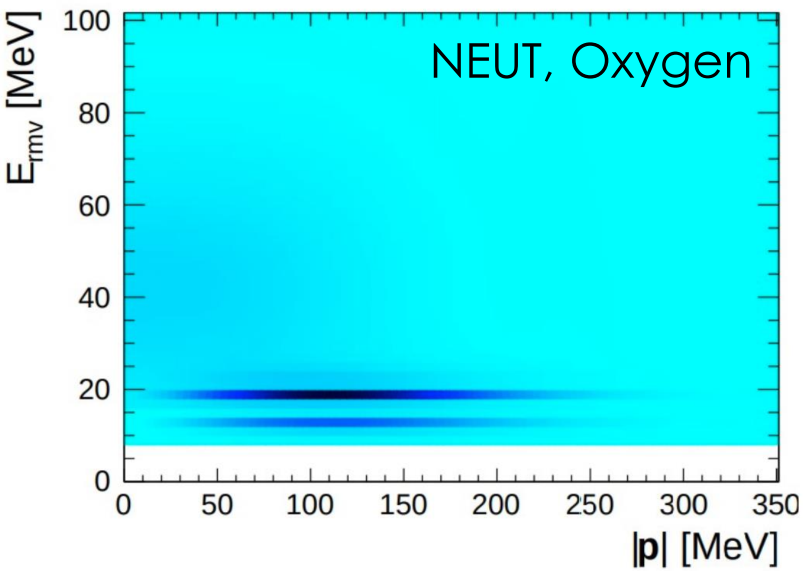

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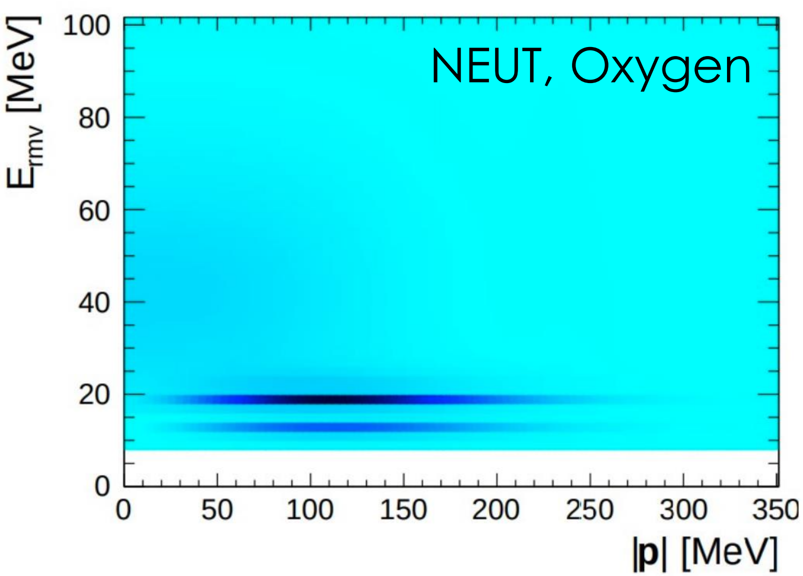
  - X Relies on "**factorization**", breaks down at low q_0, q_3 (~15% of events)
  - X **FSI effects** are not included on the outgoing lepton kinematics
  - X Simplistic approach to **Pauli Blocking** (also important at low q_0, q_3)



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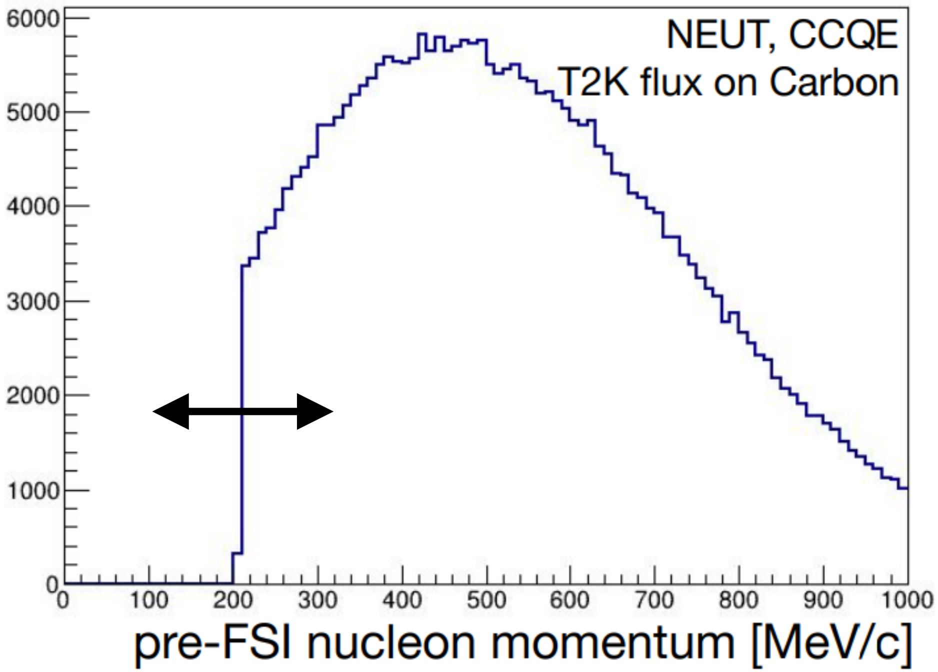
Beyond factorisation

- **Pauli blocking** in the NEUT SF takes an RFG treatment:
- Set xsec to 0 if the pre-FSI proton momentum is below a threshold
- Try moving the threshold to cover external data



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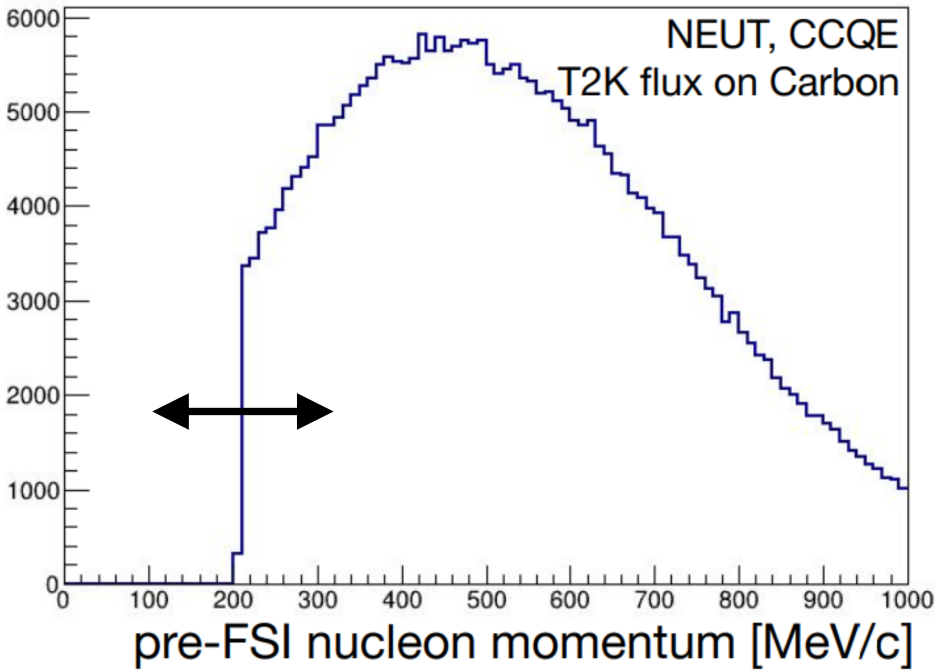
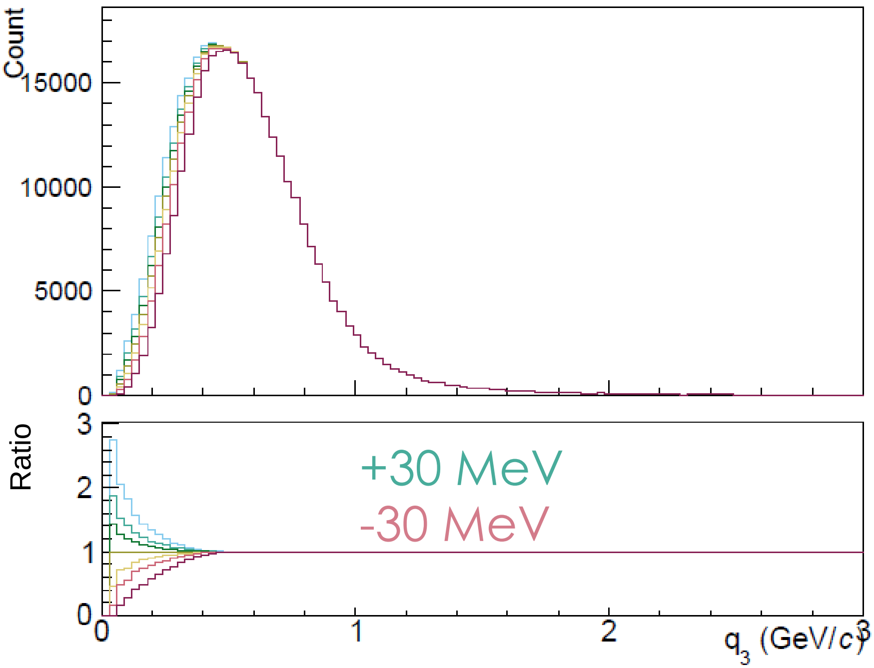
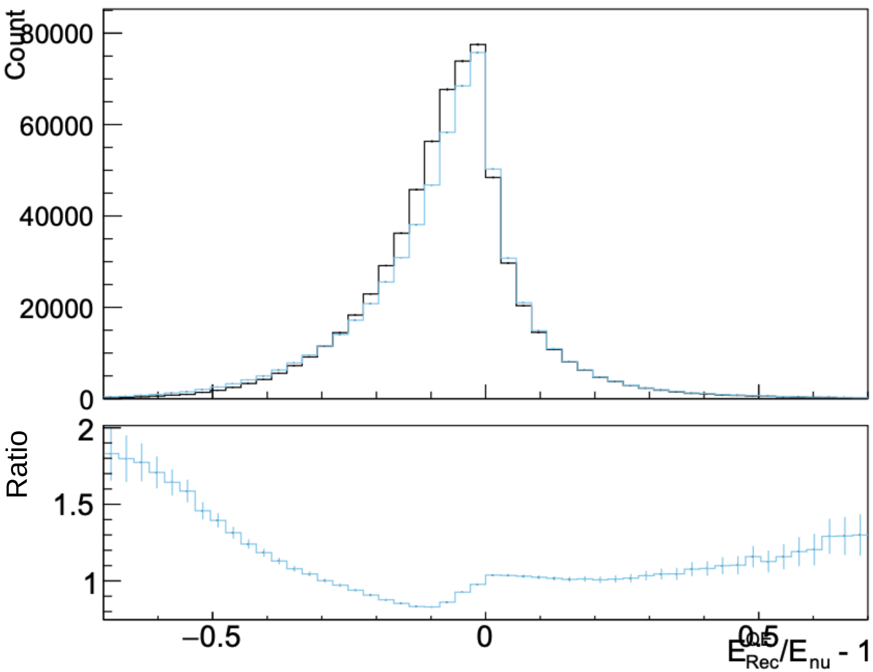
- Large impact at low energy and momentum transfer

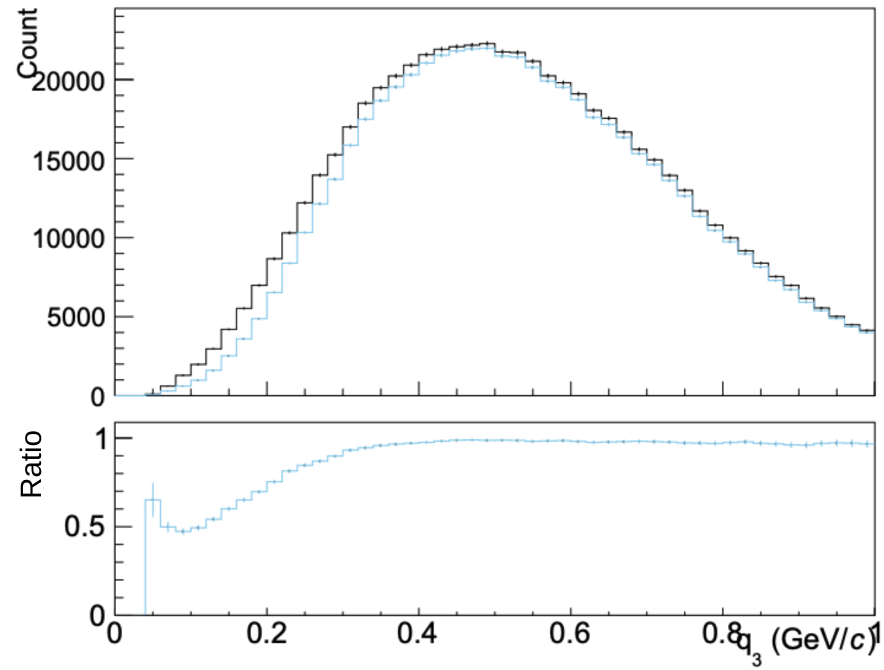




Beyond factorisation

- **Impact of FSI on the outgoing lepton** can be added using the method proposed in Phys. Rev. D **91**, 033005
- Build templates to apply this correction, interpolate between "on" and "off" to create a parameter.
- Important impact on neutrino energy reconstruction
- Impact largest at low momentum and energy transfer



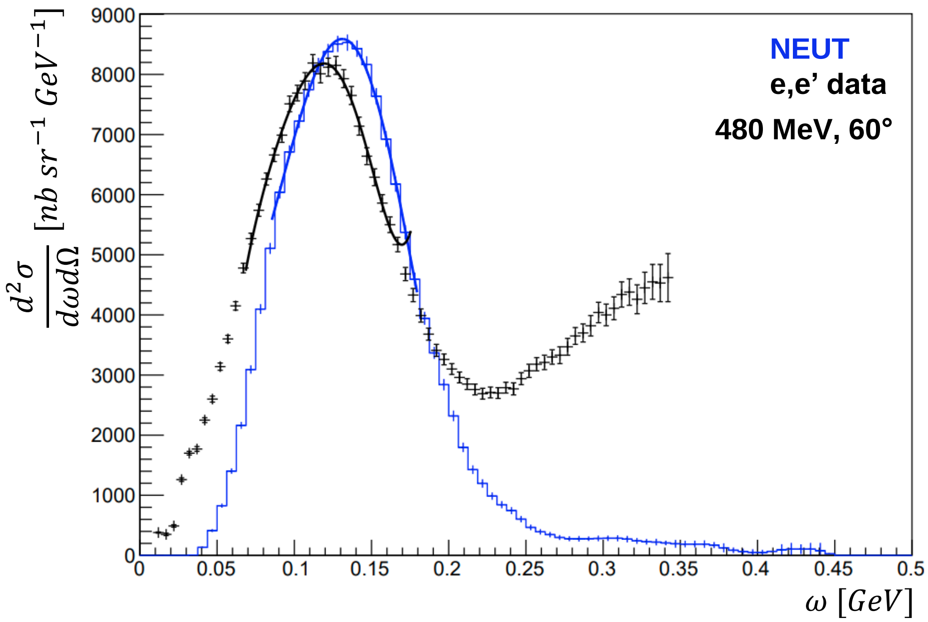


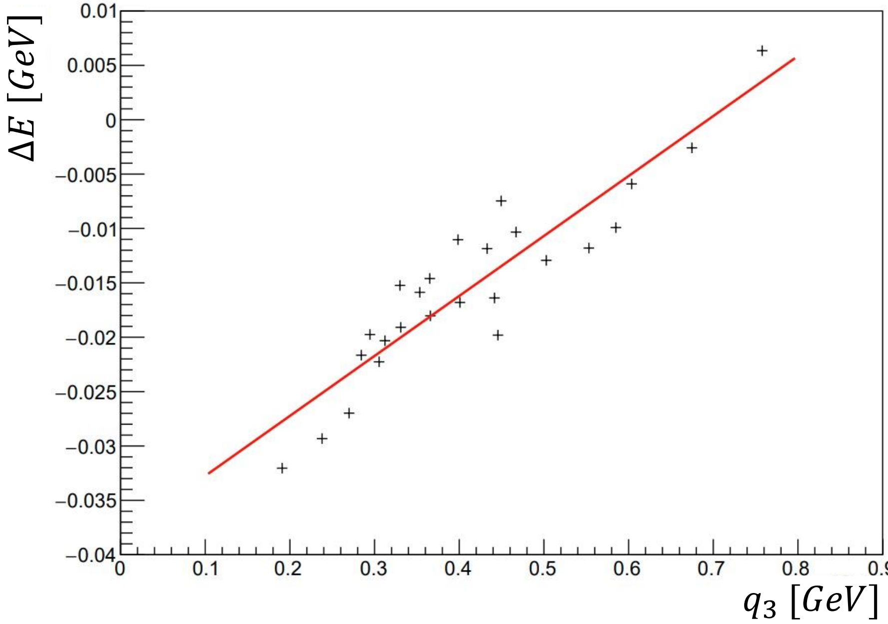
Beyond factorisation

- **q_3 dependent removal energy:** factorised models can be made to better match inclusive (e, e') data by making the removal energy dependent on the momentum transfer [Eur. Phys. J. C. (2019) 79: 293, G. Megias PhD thesis]
- A sort of simple breaking of factorization
- Compared NEUT SF to (e, e') data to derive a q_3 dependence

J. McElwee, NuFact 2021

See talk on the NEUT generator developments for more details





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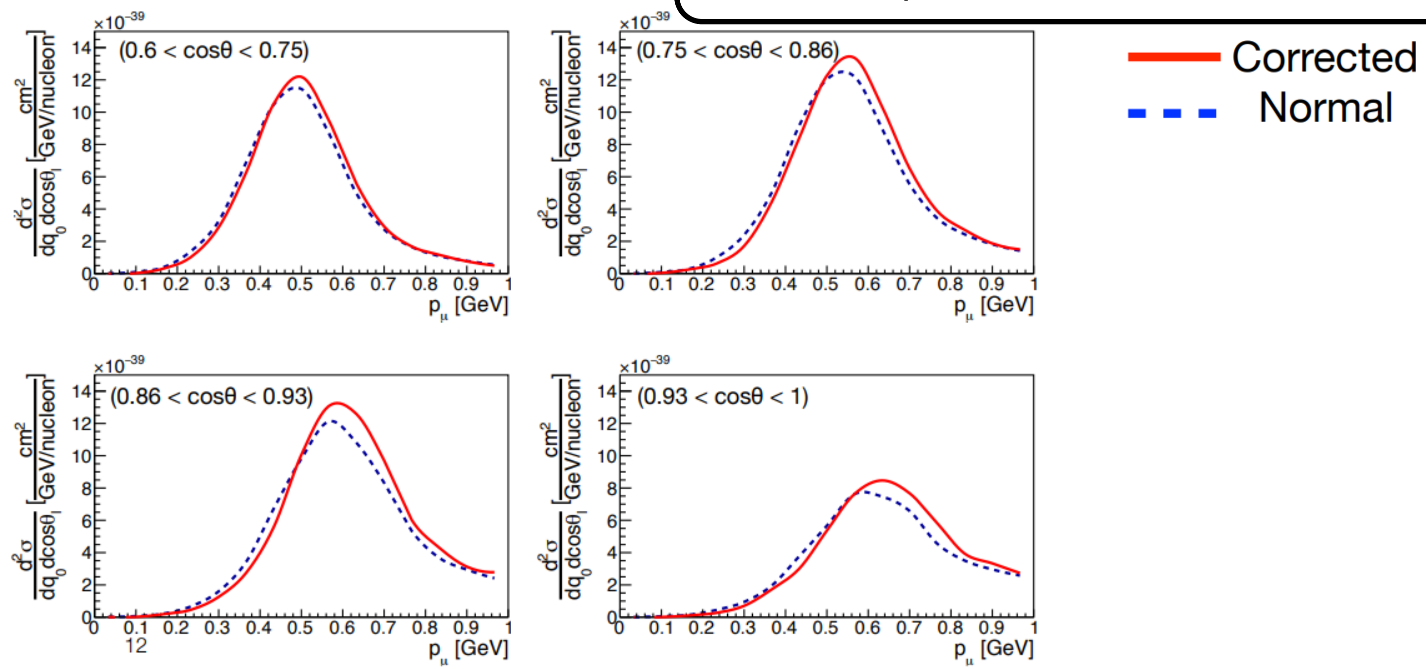
- A sort of simple breaking of factorization
- Compared NEUT SF to (e, e') data to derive a q_3 dependence
- Largest impact is, again, at low energy and momentum transfer

J. McElwee, NuFact 2021

See talk on the NEUT generator developments for more details



CCQE Uncertainties

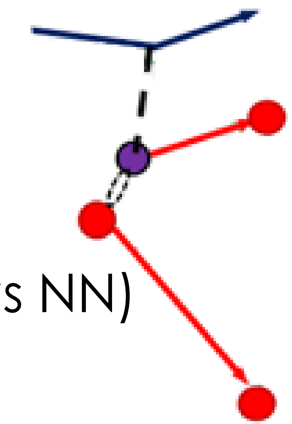
- Fairly complete set of (22) uncertainties for altering both lepton and nucleon kinematics
- The uncertainties are split between carbon and oxygen where required
- Lots of degeneracies due to model limitations (Pauli Blocking, FSI effects and q_3-dependent removal energy do similar things)
- Ideally would like to move to an unfactorised model for future analyses

Uncertainties
2(3) shell occupancy uncertainites for C(O)
2 SRC normalisation uncertaintes (split for C/O)
Nucleon axial mass
3 Q^2 shape uncertainties*
4 removal energy shift uncertainies (split C/O, p/n)
4 Pauli blocking uncertainies (split C/O, p/n)
2 FSI correction uncertainties (split C/O)
q_3 depedent removal energy uncertainty

*These are designed to cover physics beyond the dipole parametrisation of the axial form factor. See backup slides for details.

2p2h

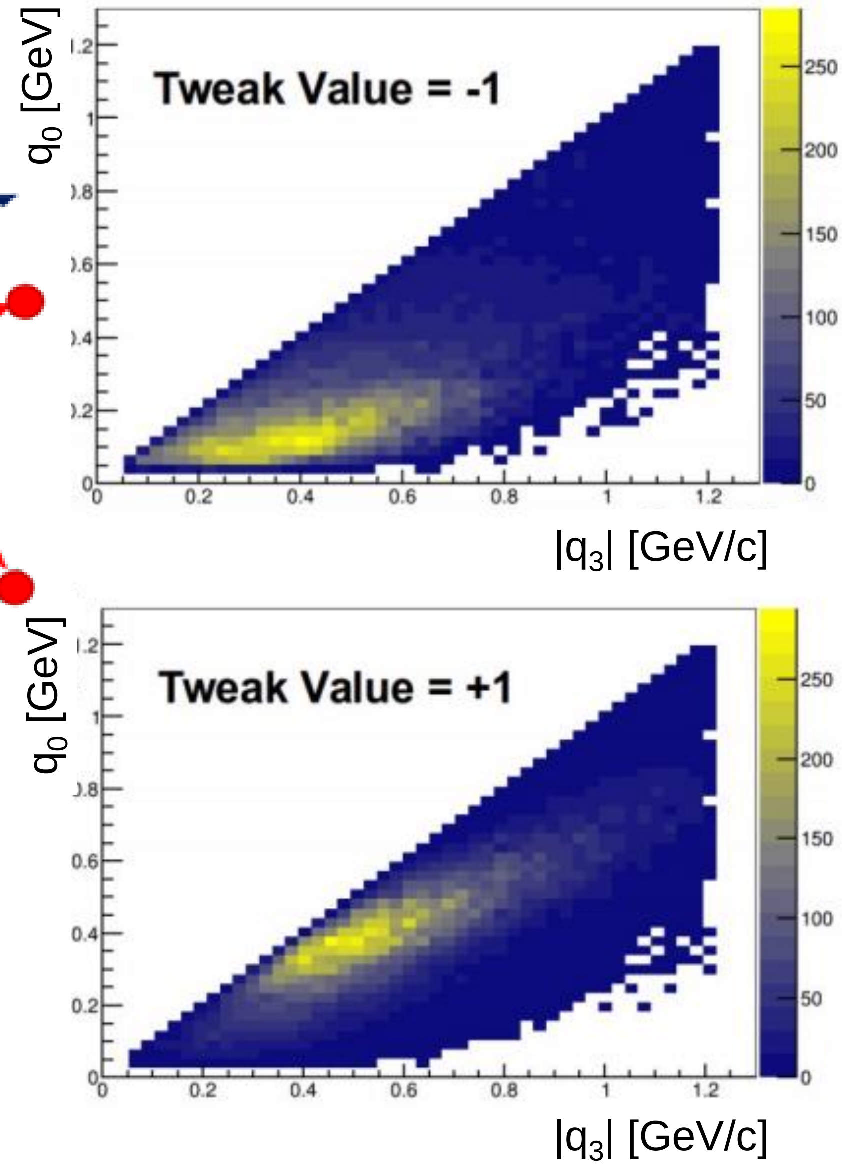
- Base model: **Valencia 2p2h**
  Phys. Rev. C **83**, 045501



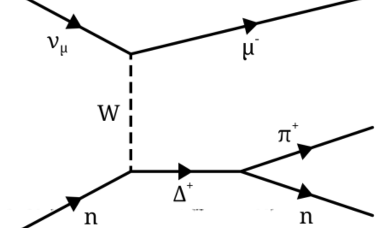
- Parameters controlling:
  - Normalisation
  - Shape
  - Pair contributions (pN vs NN)
  - Energy dependence

- Fairly complete set of variations for the lepton kinematics

- Lacking freedom to fully cover plausible variations in nucleon kinematics (which T2K doesn't need so much)



Single Pion Production

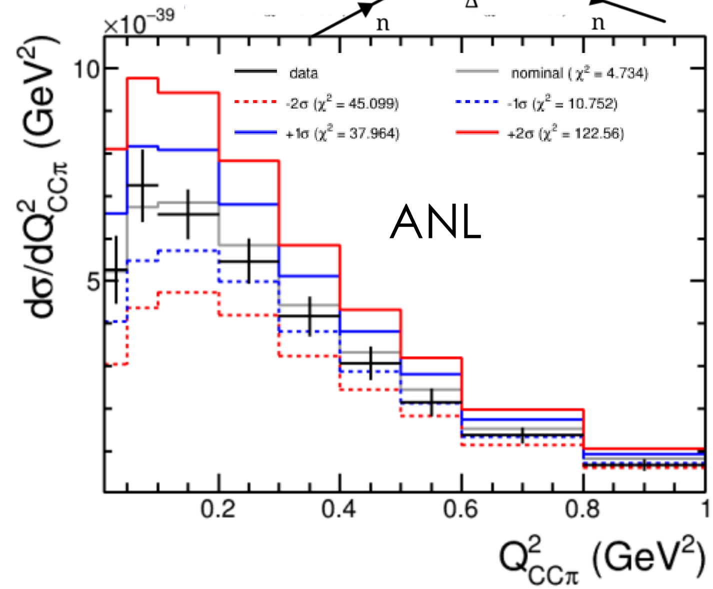


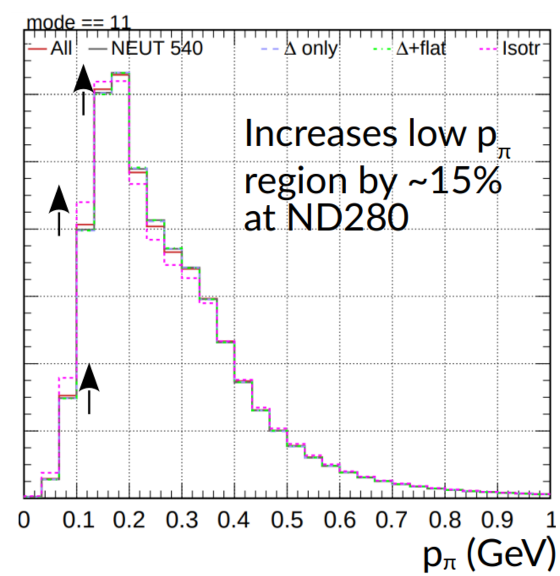
- Base model: **Rein-Sehgal with lepton mass corrections**
  Annals Phys. **133** (1981) 79–153

- Parameters controlling:
  - Form factors (M_A^{RES}, C_A^5)
  - Non-resonant background
  - Some channel normalisations
  - Removal energy
  - Resonance decay kinematics

- Fairly complete set of nucleon-level uncertainties, but room for further variations of the pion kinematics

- Nuclear effect treatment is currently rather simplistic





Robustness checks

The T2K uncertainty model is far from complete

- Thanks to nuclear theory developments and creative cross-section measurements, **we have a good idea of what we may be missing**
- We test the robustness of our analyses via studies where we **treat an alternative model as if it was data** and assess the bias

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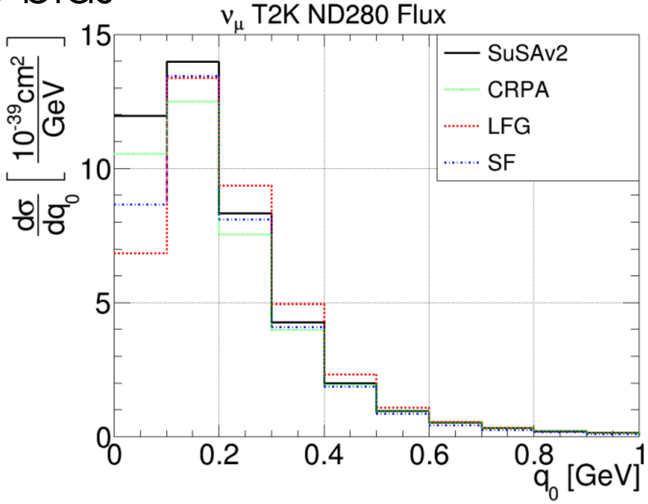

Examples (of 16 studies used for our latest analysis):

1. Swap the CCQE model to CRPA
2. Use the Martini model for pion production
3. Change pion kinematics based on MINERvA data
4. Alter the CCQE/2p2h fractions based on ND280 data
5. Simulate real photon emission via radiative corrections to CC interactions

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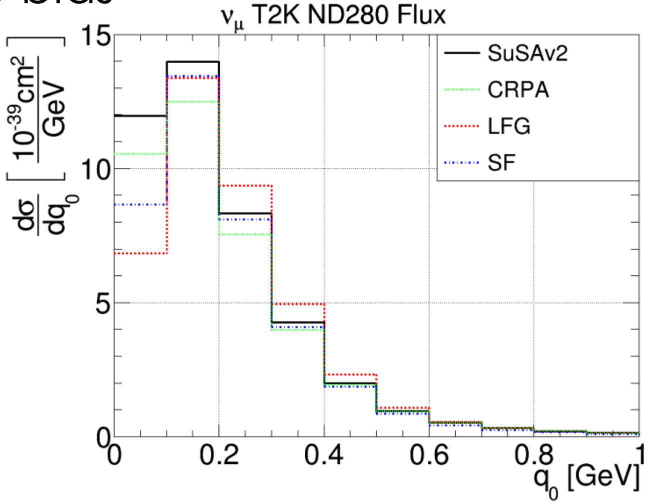


- The bias on oscillation parameters was usually found to be **far smaller than our systematic uncertainty** (which is smaller than the statistical uncertainty)
- One exception: the bias on Δm^2_{32} in studies 1 and 4 is comparable to the size of the systematic uncertainty (but less than half the total uncertainty).
  - An uncertainty inflation is made to account for this

Summary

- A **robust modelling of neutrino interactions** becomes increasingly critical as neutrino experiments gather more data
- T2K has **made significant improvements to its uncertainty model**, targeting the physics that is most likely to induce bias in oscillation analyses
- An **overhaul of CCQE uncertainties** gives better theory grounding for our model and improved predive power for nucleon kinematics
- Further **improvements in 2p2h and pion production modelling** gives us confidence in our use of hadron kinematics in analyses at the near and far detectors
- The model is not perfect, but we are able to **test the impact of its imperfection** via dedicated robustness checks.

BACKUP

NEUT Models

Bold text indicates the base models used for the latest T2K oscillation analysis

Quasi Elastic Scattering (QE/1p1h)

- Smith-Moniz Relativistic Fermi Gas
- *Nieves et al.* Local Fermi Gas (with RPA and *Bourguille et al.* removal energy treatment)
- ***Benhar et al.* Spectral Function**
- SuSAv2 and HF-CRPA via reweighting of Spectral Function

Multi-Nucleon Interactions (2p2h)

- ***Nieves et al.*** (with optional *Bourguille et al.* removal energy modifications)

Single Meson Production (RES and Coh)

- ***Rein-Segal* resonant model (with optional Berger-Segal lepton mass corrections)**
- Preliminary version of *M. Kabirnezhad* single pion production model
- *Berger-Segal* and *Rein-Segal* coherent scattering models
- *Rein* diffractive pion production

Shallow and Deep Inelastic (SIS and DIS)

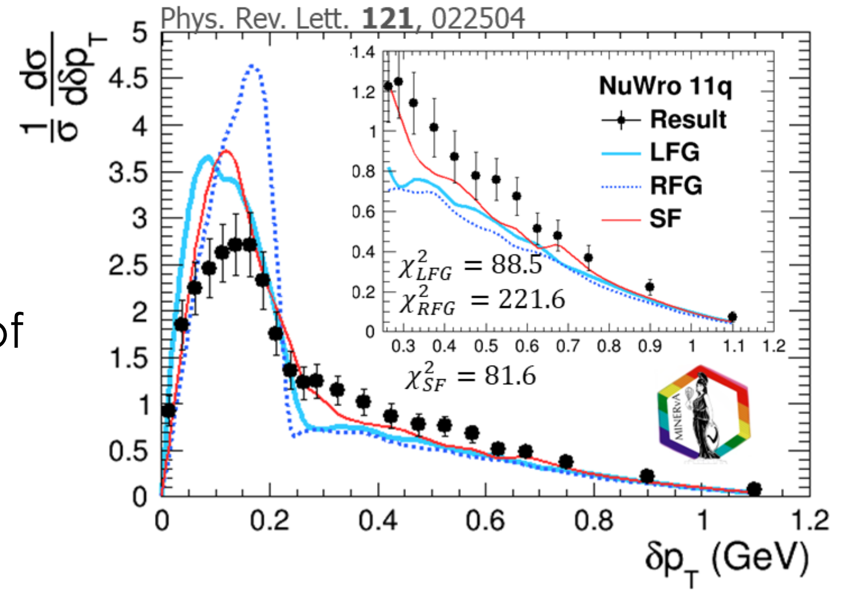
- **GRV98 PDF with optional corrections from *Bodek and Yang***
- **Hadron multiplicity by *PYTHIA v5.72* (W > 2 GeV) or a custom model (W < 2 GeV)**

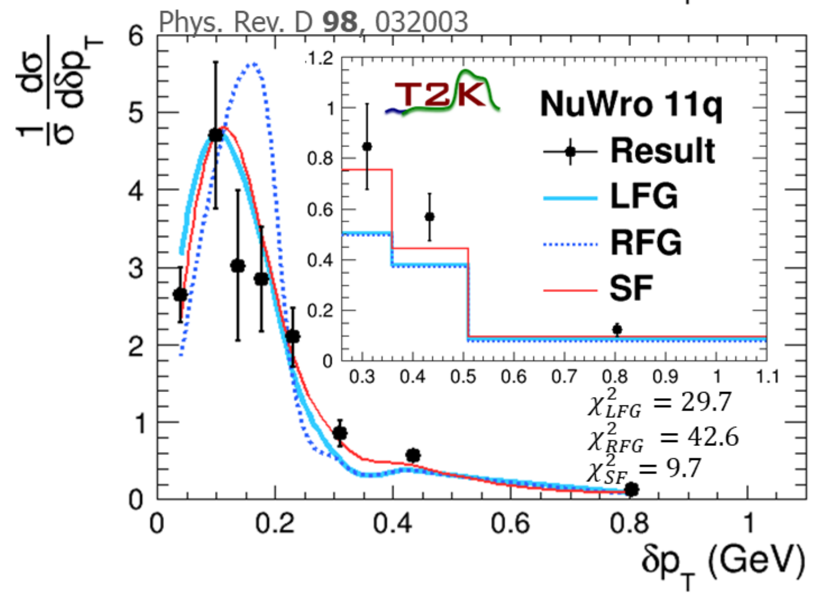
Final State Interactions (FSI)

- **Pion FSI uses the *Salcedo et al.* cascade model**
- **Nucleon FSI uses a cascade model based on the work of *Bertini et al.***

An apology to theorists

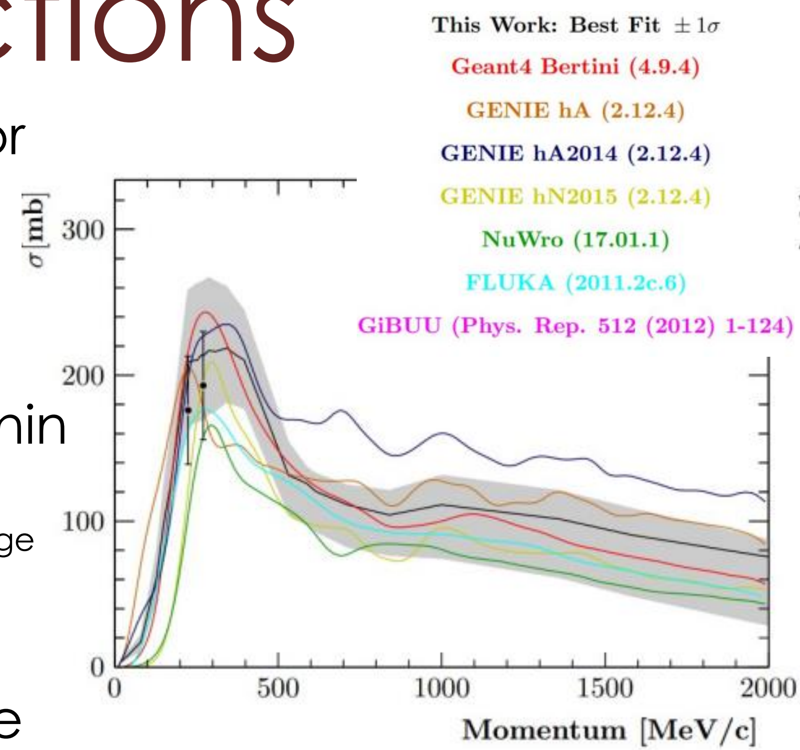
- It's crucial that our uncertainties are able to cover all physics that could bias our oscillation analysis
- We can start by varying natural degrees of freedom within our base model …
- … but we know that no base model can describe pertinent cross-section data
- Often need to exaggerate or invent uncertainties to cover differences between models or data discrepancies
- Get ready for some Franken-models!

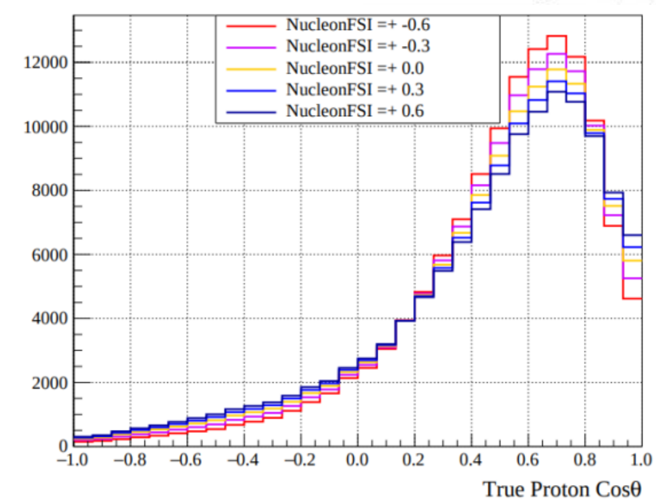




Final State Interactions

- Base model: Salcedo-Oset cascade for pions, analogous model for nucleons
  Phys. Rev. D **99**, 052007
- Parameters controlling:
  - Probability for interaction types within the pion cascade.
    - Quasi-elastic, Inelastic, Absorption, Charge exchange
  - Further split into low and high pion energy regions
  - One nucleon FSI dial to change the overall interaction probability
- Plenty of freedom to change FSI interaction types, but not the kinematics of scatters within the cascade
- Future analyses using more hadronic information may demand a more sophisticated treatment



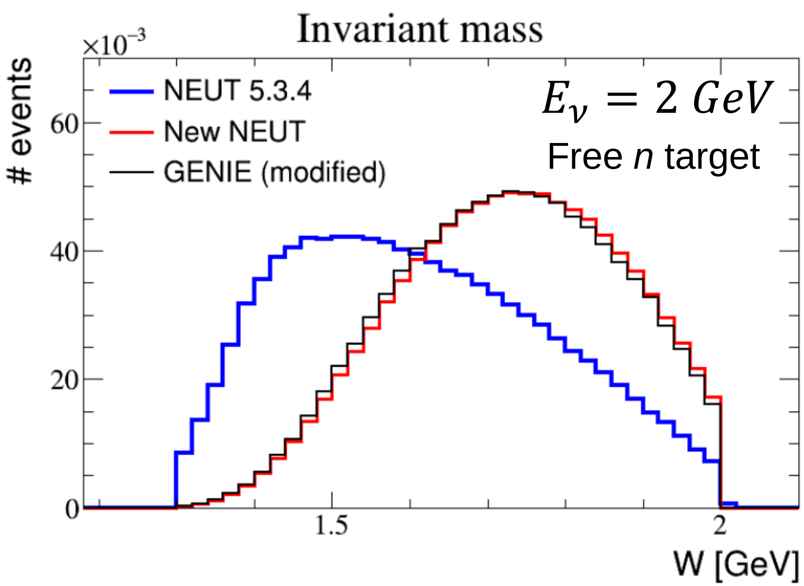


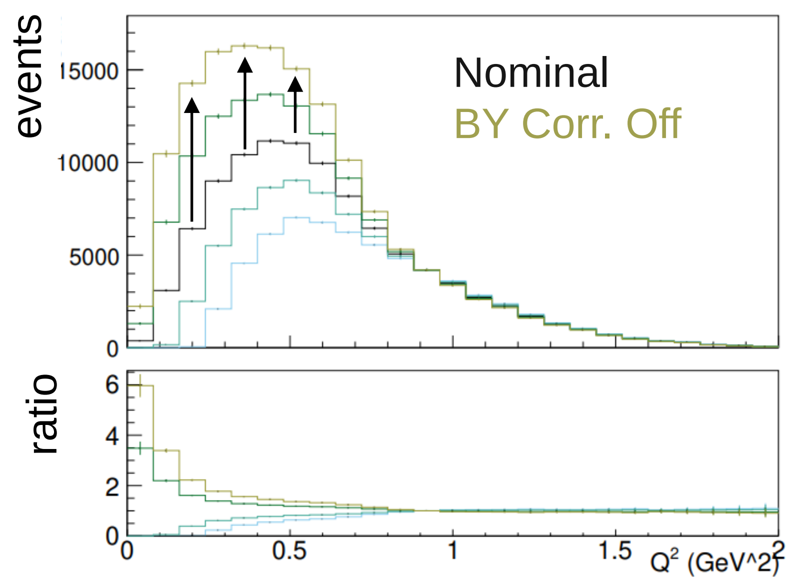
Deep/Shallow inelastic scattering

- Base model: GRV98 + Bodek-Yang
- Hadronization (W>2GeV): PYTHIA 5.72
- Hadronization (W<2GeV): Custom model
  - Based on hadron multiplicity bubble chamber data

- Parameters controlling:
  - Normalisations
  - Bodek-Yang corrections
  - Particle multiplicity

- Provides sufficient freedom to cover T2K's very limited contributions from DIS or SIS





Five things we need to model

(a non exhaustive list)

1. Relative CC0π contribution of CCQE and other processes
   - *So we know how often we mis-reconstruct* E_ν

2. Initial state nucleon momentum and energy
   - *So we know how wide (and biased) our CCQE* E_ν *reconstruction is*

3. Neutrino energy dependence of cross sections and their differences on Carbon and Oxygen
   - *So we know how to extrapolate from our ND to our FD*

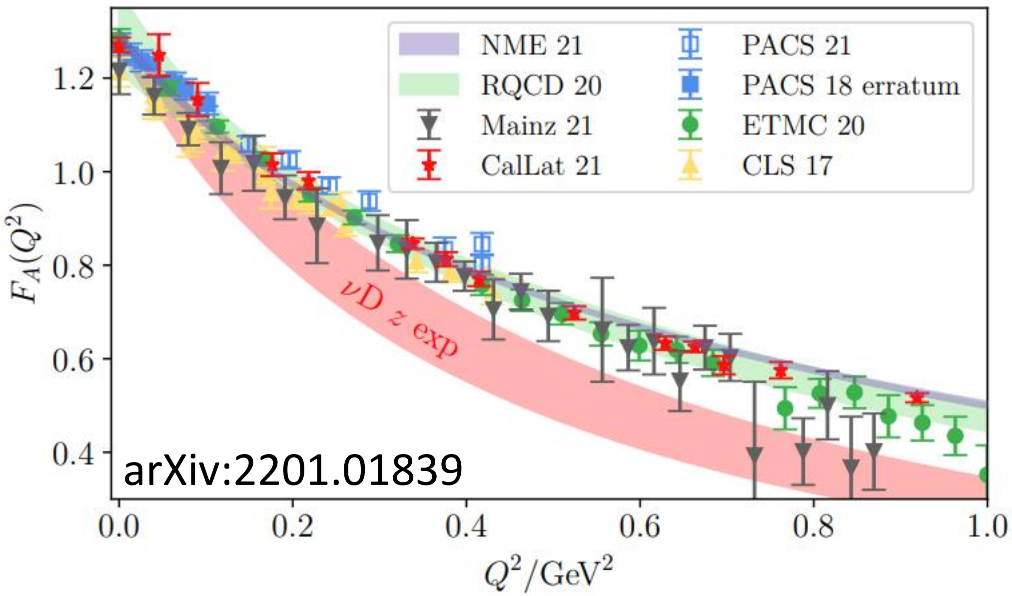
4. Differences in $\nu/\bar{\nu}$ cross sections
   - *So we know when* $\nu/\bar{\nu}$ *differences imply CP-violation*

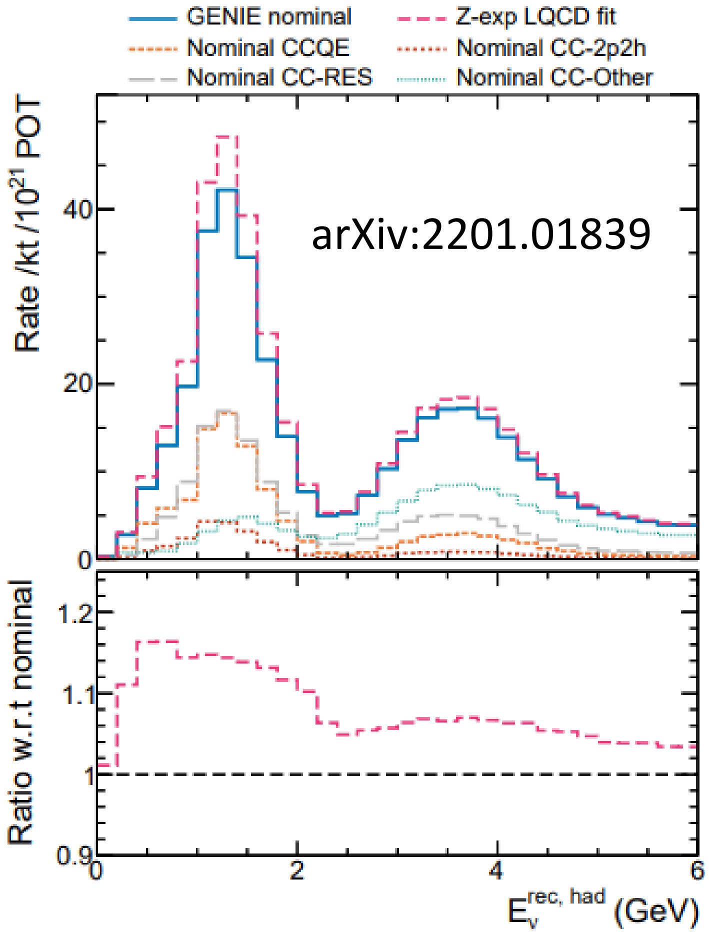
5. Differences in ν_e/ν_μ cross sections
   - *So we know how to use our ND constraints on* ν_μ *in* ν_e *app. analyses*

Beyond the dipole

- The latest and greatest LQCD calculations suggest serious issues with dipole (or even usual z-exp) axial form factor parametrisations

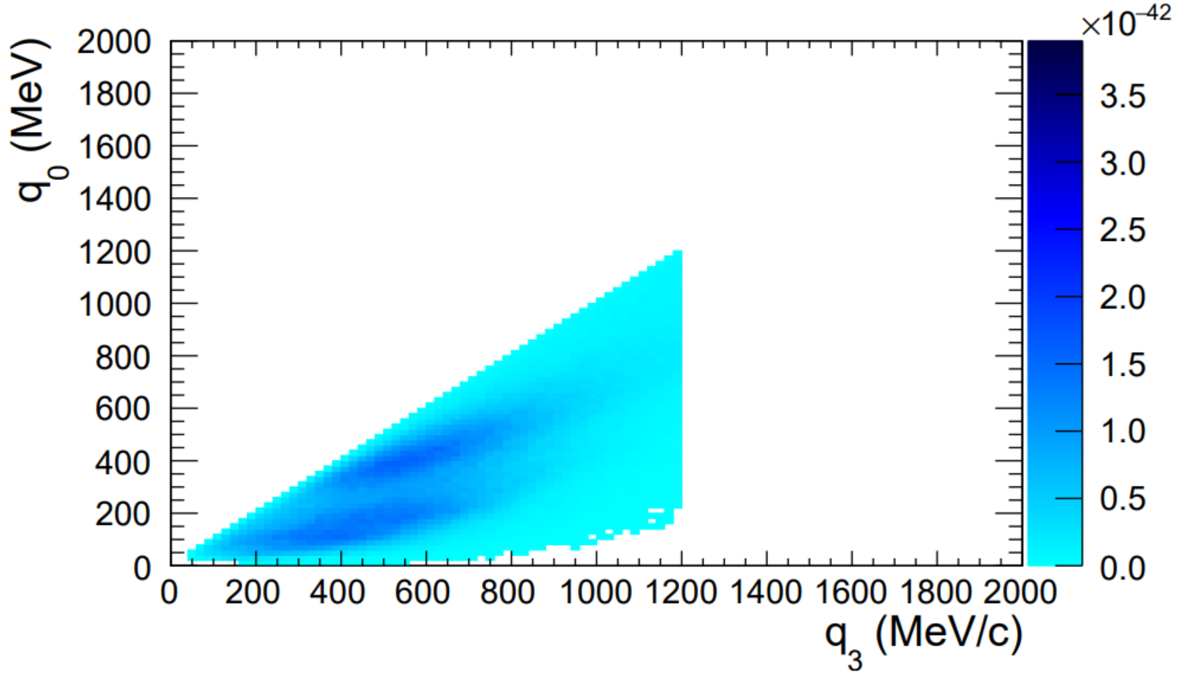
- T2K's simplistic approach: Add binned normalisation uncertainties in problematic regions of Q^2
  - Test robustness with mock data studies





2p2h Model + Uncertainties

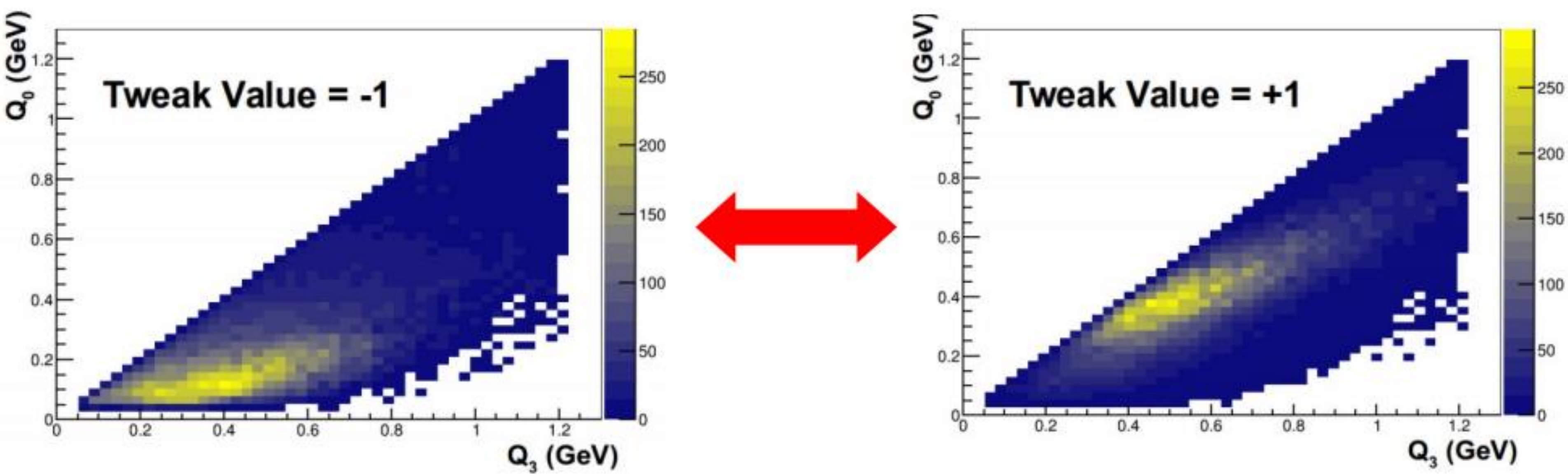
T2K uses the familiar **Valencia 2p2h** model



2p2h Model + Uncertainties

T2K uses the familiar **Valencia 2p2h** model
Assign uncertainties on:

- The normalisation (separate parameters for C, O, $\nu, \bar{\nu}$)
- The shape in energy and momentum transfer (relative contribution of Δ-like and not Δ-like)



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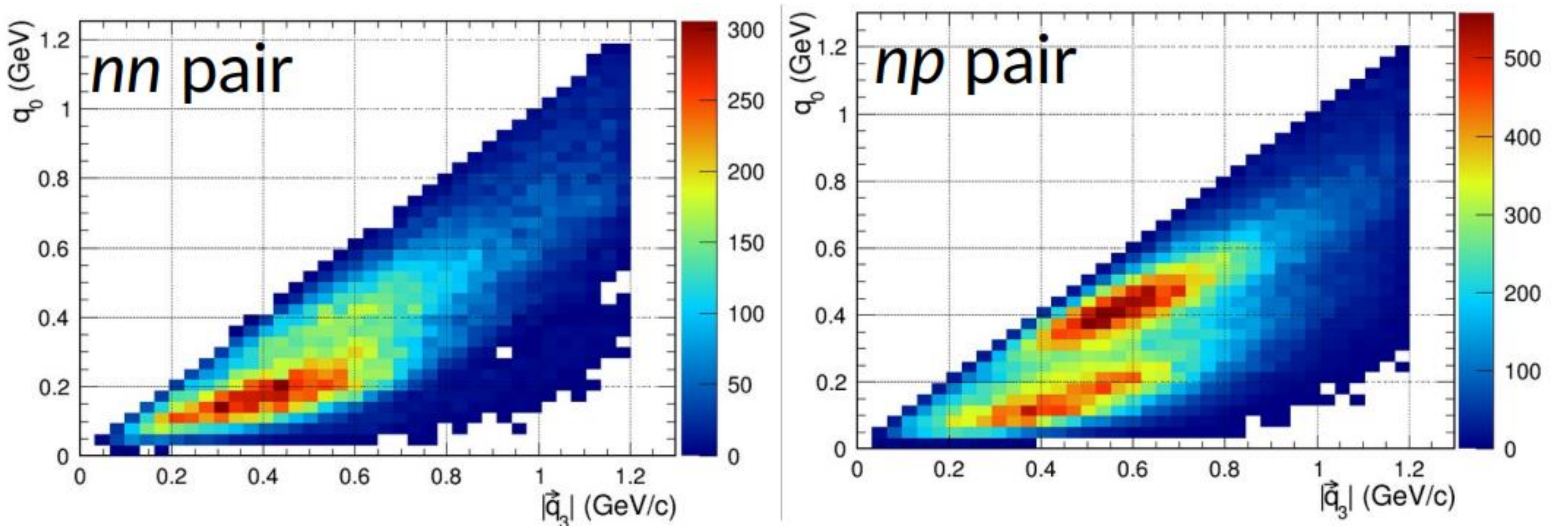

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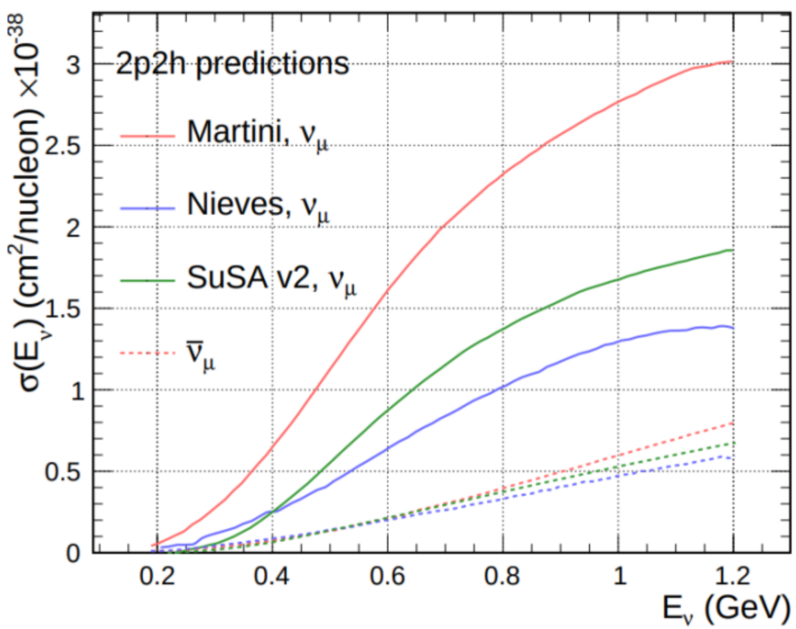
- The normalisation (separate parameters for C, O, $\nu, \bar{\nu}$)
- The shape in energy and momentum transfer (relative contribution of Δ-like and not Δ-like)
- Split the variations also by the pair type (NN vs Np)
- The neutrino energy dependence (span Martini and SuSAv2-MEC)



2p2h Summary

- Parameters controlling:
  - Normalisation
  - Shape
  - Pair contributions
  - Energy dependence

- Fairly complete set of variations for the lepton kinematics, but lacking freedom to fully cover plausible variations in nucleon kinematics (which T2K doesn't need so much)

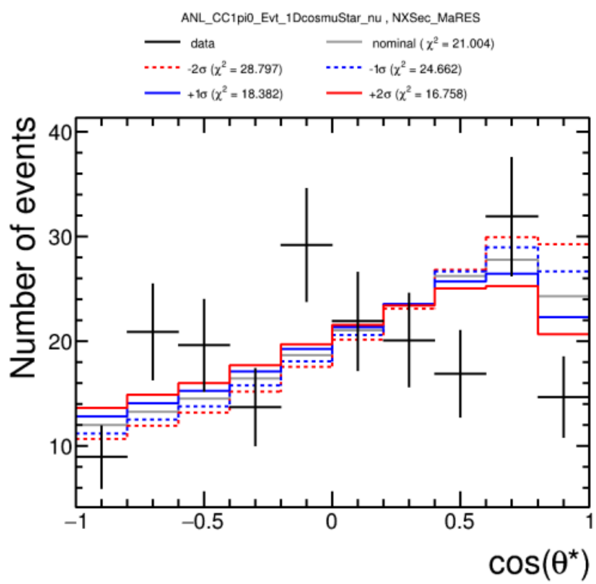
2p2h norm nu
2p2h norm nubar
2p2h norm CtoO
2p2h Low Enu nu
2p2h High Enu nu
2p2h Low Enu nubar
2p2h High Enu nubar
np vs nn pair (or np vs pp for anu)
2p2h Shape np, C
2p2h Shape nn (or pp for anu), C
2p2h Shape np, O
2p2h Shape nn (or pp for anu), O

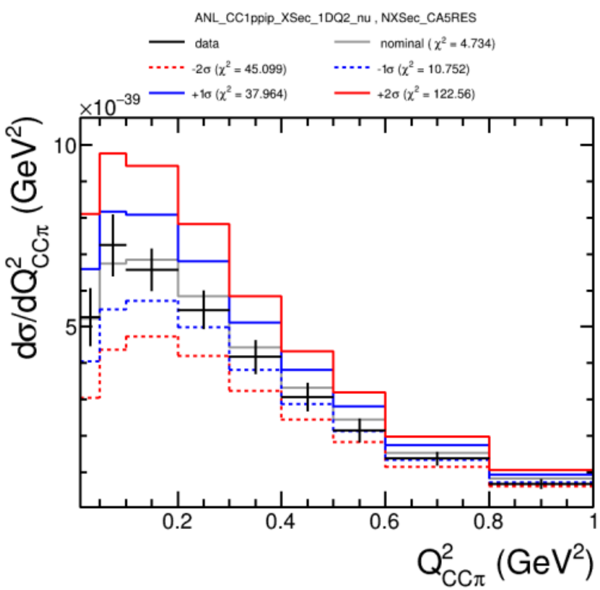
Single Pion Production

T2K uses the familiar **Rein-Sehgal** model, with lepton mass corrections and an in-house tuning to ANL+BNL data

Uncertainties:

- Form factors: M_A^{RES} and C_A^5
- Non resonant background normalisation
- Additional *ad-hoc* freedom for low momentum pions (<200 MeV/c)





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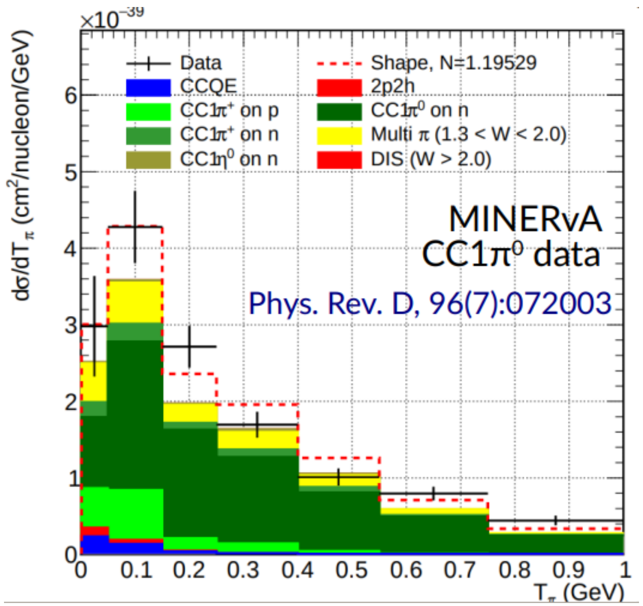
- Additional freedom for $CC1\pi^0$ normalisation based on external data



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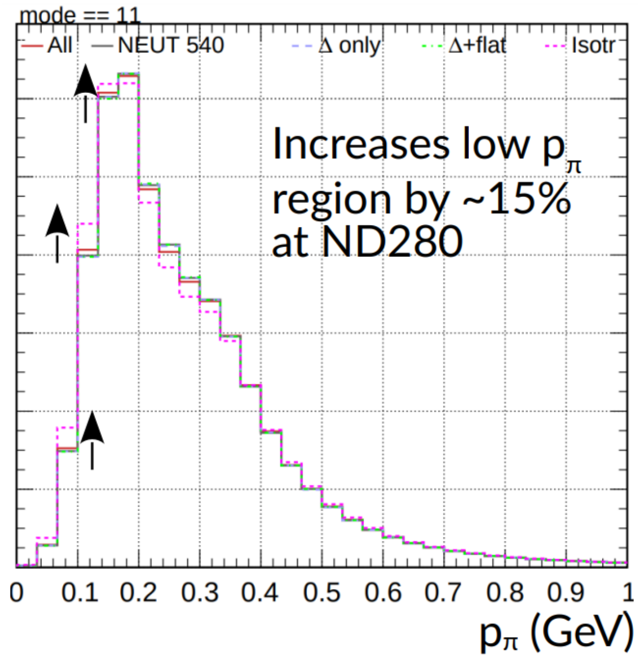
- Removal energy in CC1π (RFG-like)
- Uncertainty affecting only pion kinematics from altering the treatment of $N^* \rightarrow \pi + N$



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- Extra uncertainties for Coh normalisation

Single Pion Production

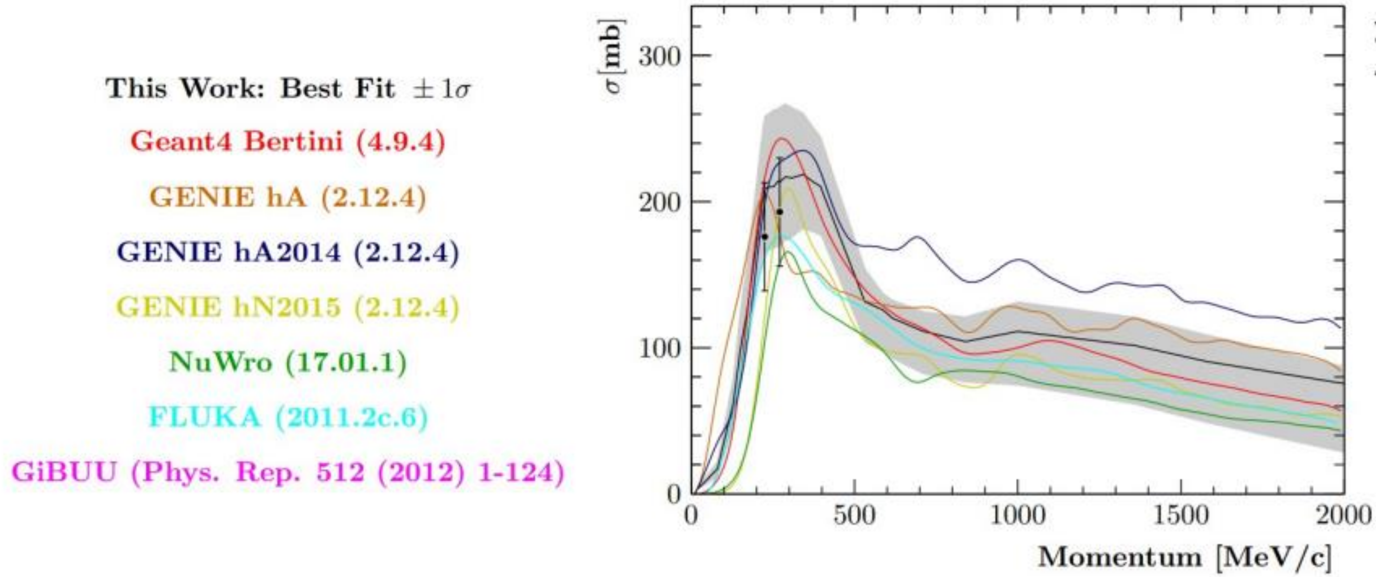
- Parameters controlling:
  - Form factors
  - Non-RES background
  - Some mode normalisations
  - Removal energy
  - Resonance decay
- Fairly complete set of nucleon-level uncertainties, although there's scope for further variations of the pion kinematics
- Nuclear effect treatment is currently rather simplistic

MARES
CA5
I½ non-res bkg
I½ non-res bkg anti-neutrino low momentum
CC Coh norm, C
CC Coh norm, O
NC Coh norm
Eb in RES, C, nu
Eb in RES, O, nu
Eb in RES, C, nubar
Eb in RES, O, nubar
R-S Delta Decay
CC 1 pi0

Final State Interactions

T2K uses NEUT's cascade model (similar to GENIE "hN").

- **Pion final state interactions** by Salcedo-Oset cascade, tuned to world π-A scattering data [Phys. Rev. D 99, 052007 (2019)]
- This tuning provides uncertainties on the probability for different interactions to occur within the cascade



Quasi-elastic

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- This tuning provides uncertainties on the probability for different interactions to occur within the cascade

- **Nucleon final state interactions** do not yet have such a detailed treatment, but these are also less crucial for T2K analyses.
- Just one parameter to control the total FSI probability