27/10/22

Modelling Neutrino Interactions for the T2K experiment

Stephen Dolan
For The T2K Collaboration

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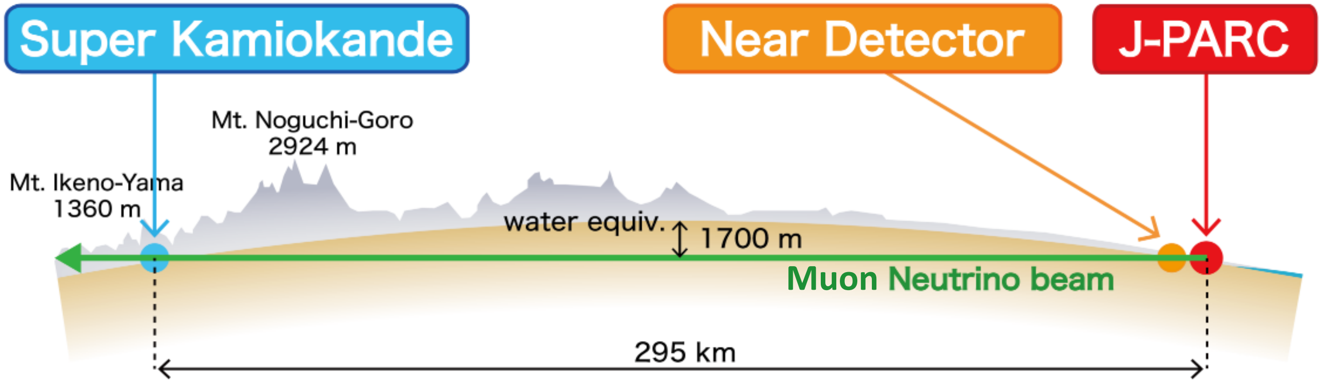
NuINT 2022

The 13th International Workshop on Neutrino-Nucleus Interactions in the Few GeV Regions

Outline

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

The T2K Experiment



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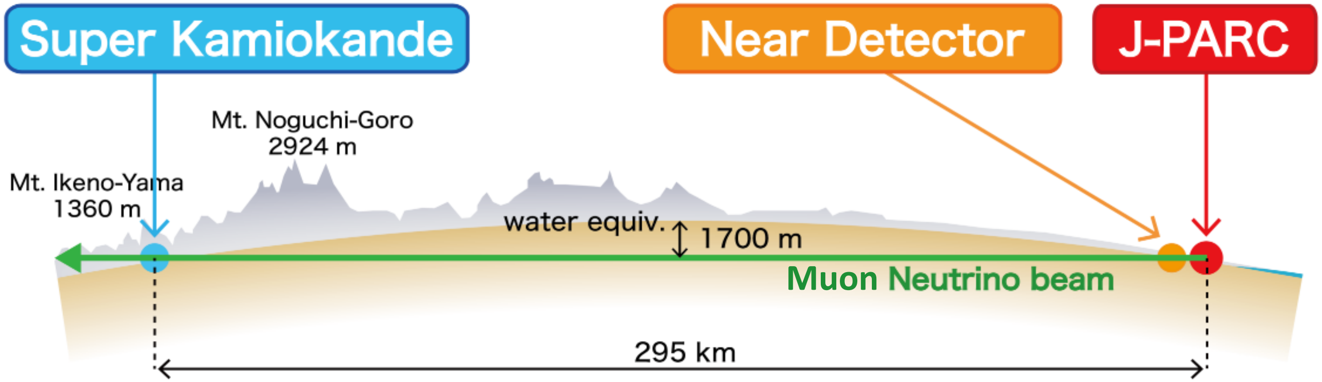
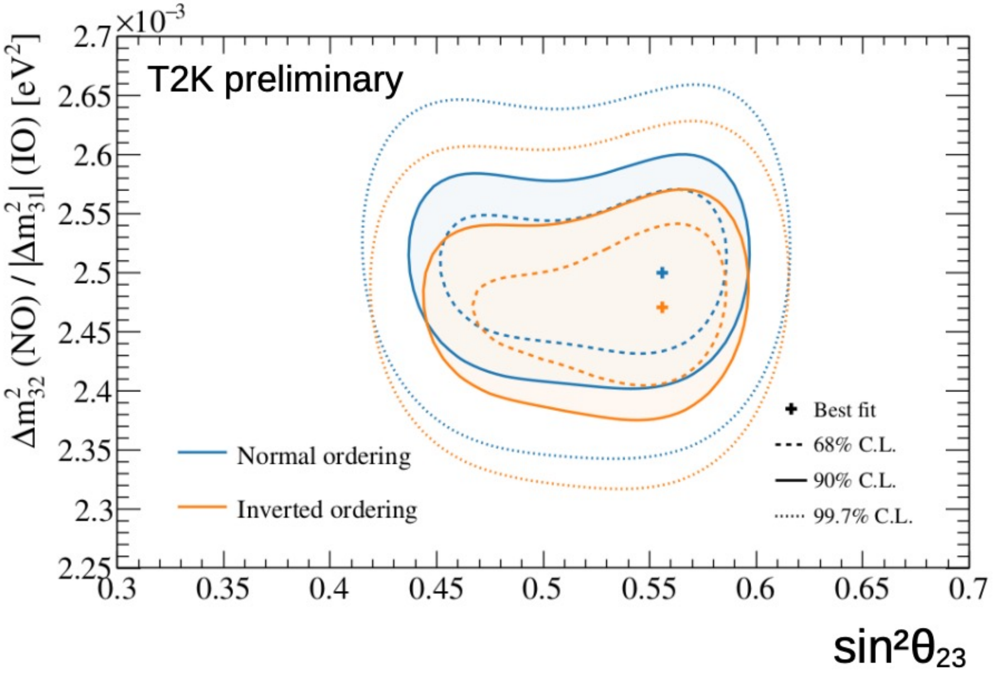
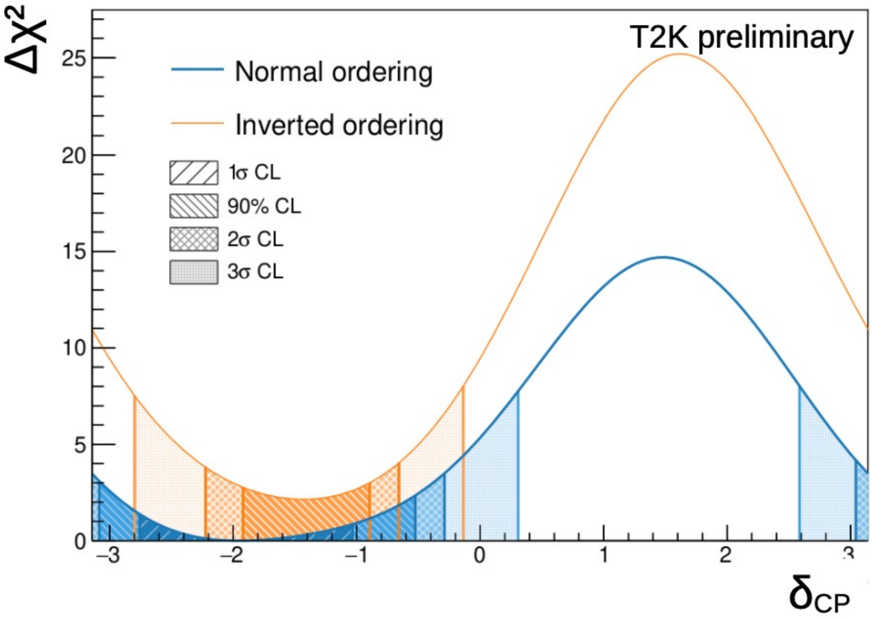


Neutrino oscillations at T2K





Neutrino Interactions at T2K

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

$N_\ell(\mathrm{E}_\nu)$ = Event rate

$P(\nu_{\ell'} \rightarrow \nu_\ell)(E_\nu)$ = Oscillation probability

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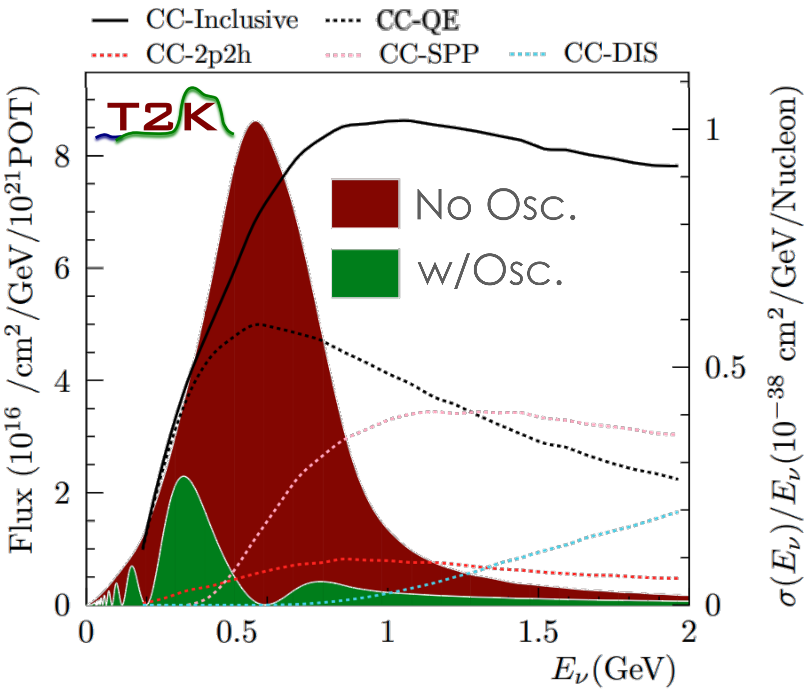
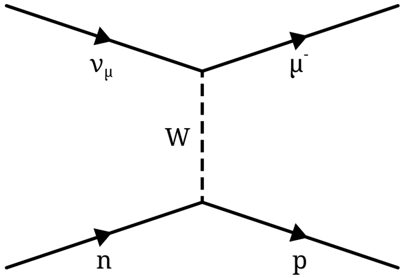


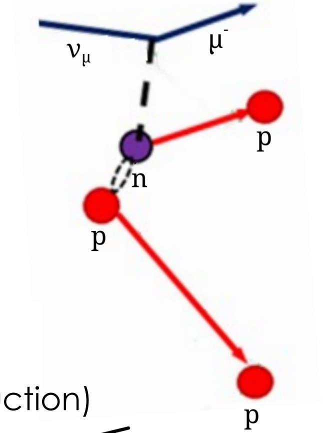
CC-QE

(Charged-Current Quasi-Elastic)



CC-2p2h

(2 particle, 2 hole)



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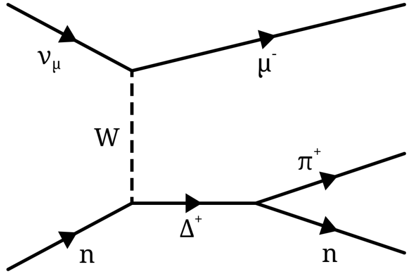
(Single Pion Production)



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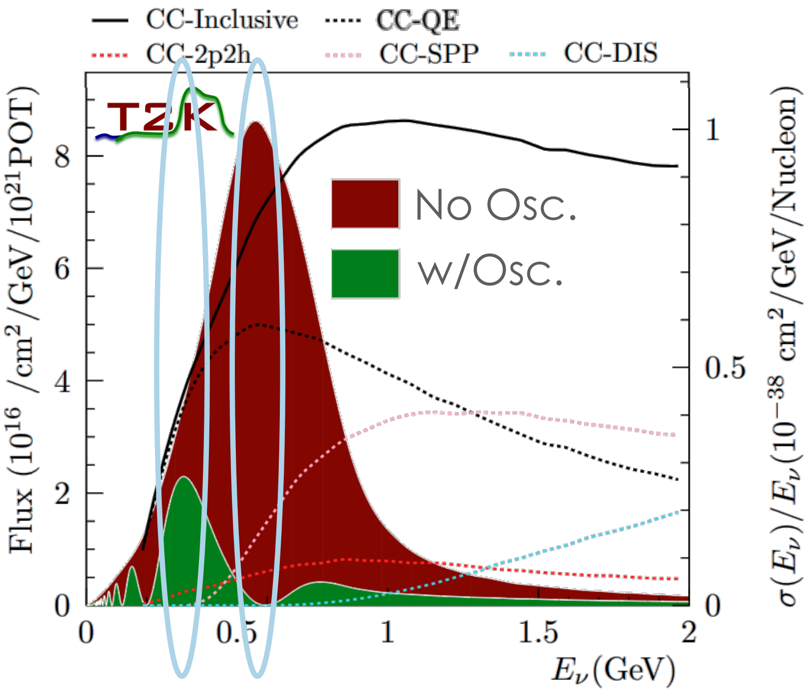

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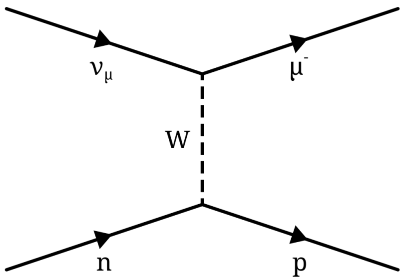

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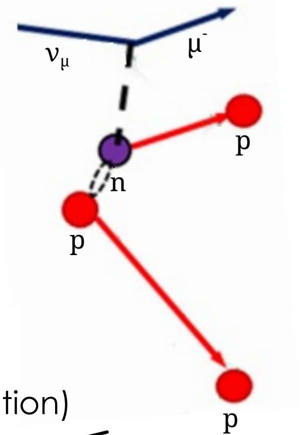

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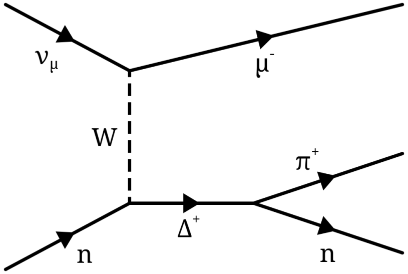

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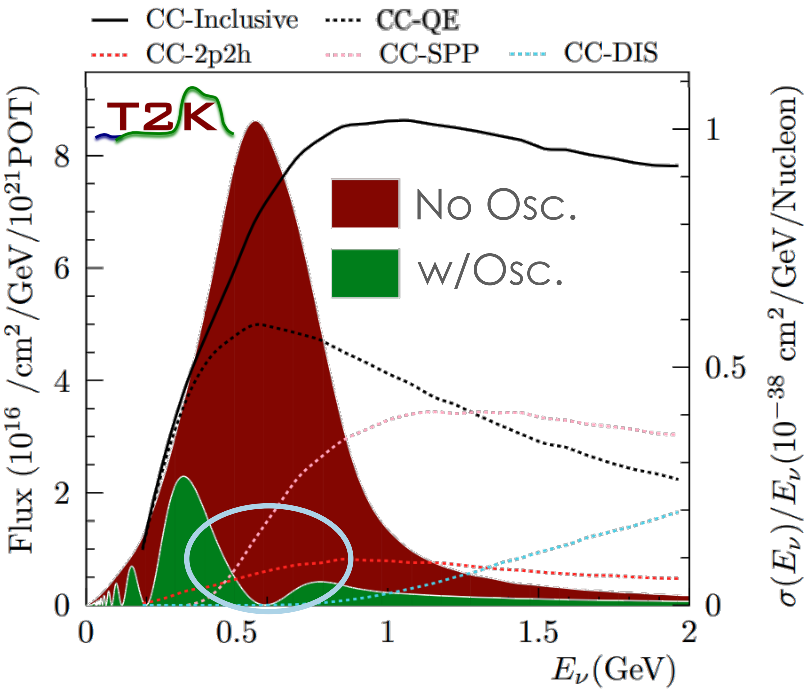

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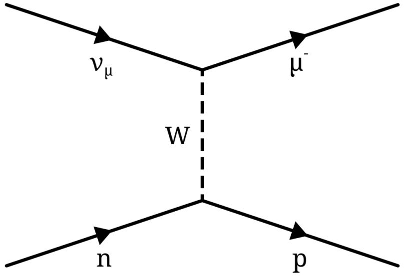

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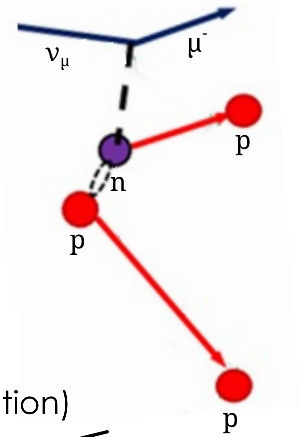

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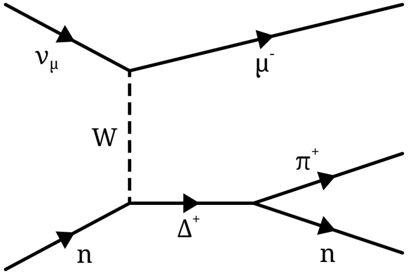
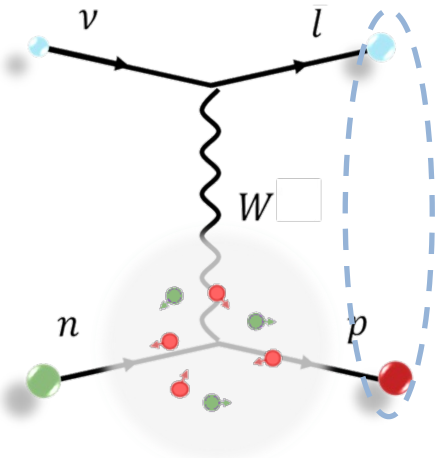
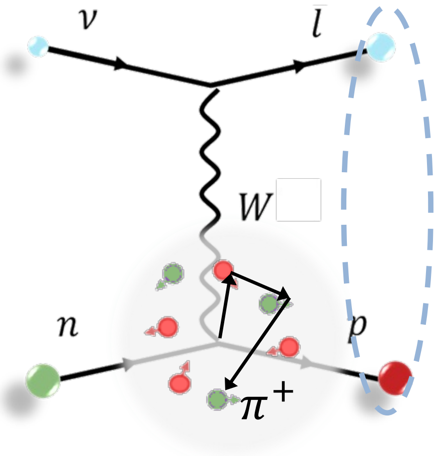


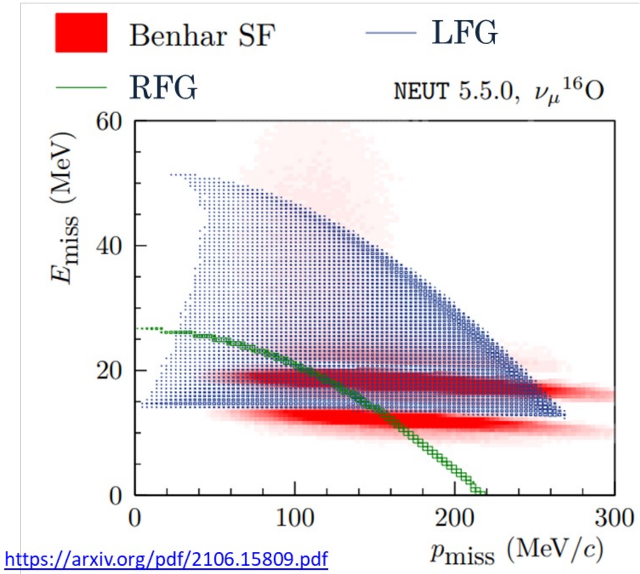
Neutrino Energy Reconstruction

CCQE (1p1h)

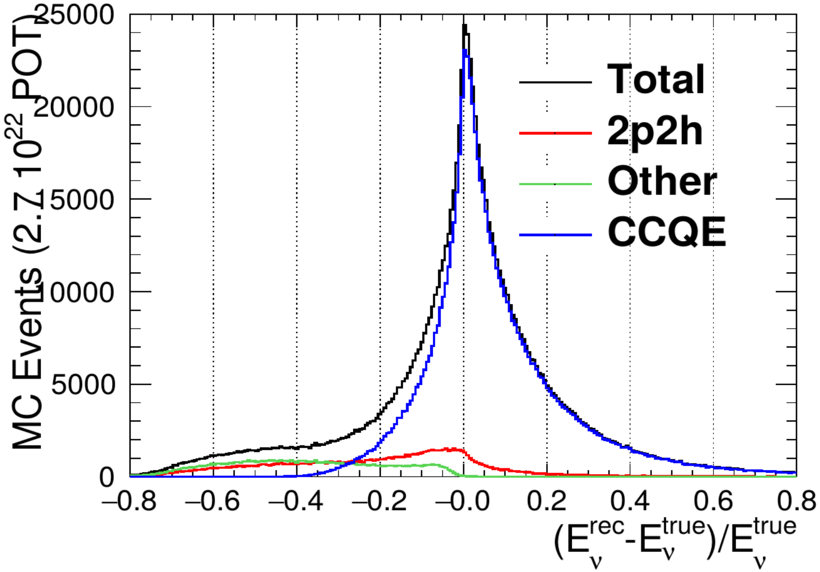


CCRES





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



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

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

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

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 contribution of CCQE and other processes in our far detector samples
    - *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 Luke's NEUT talk later at NuInt 2022

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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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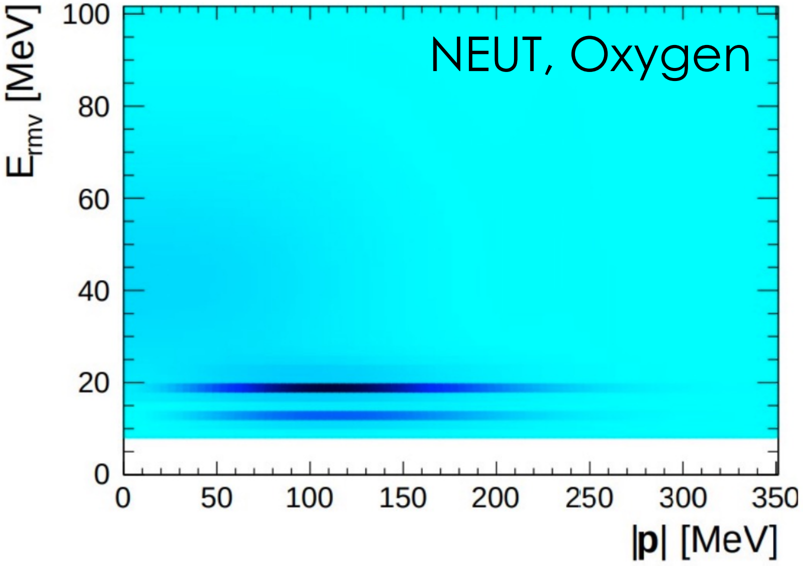

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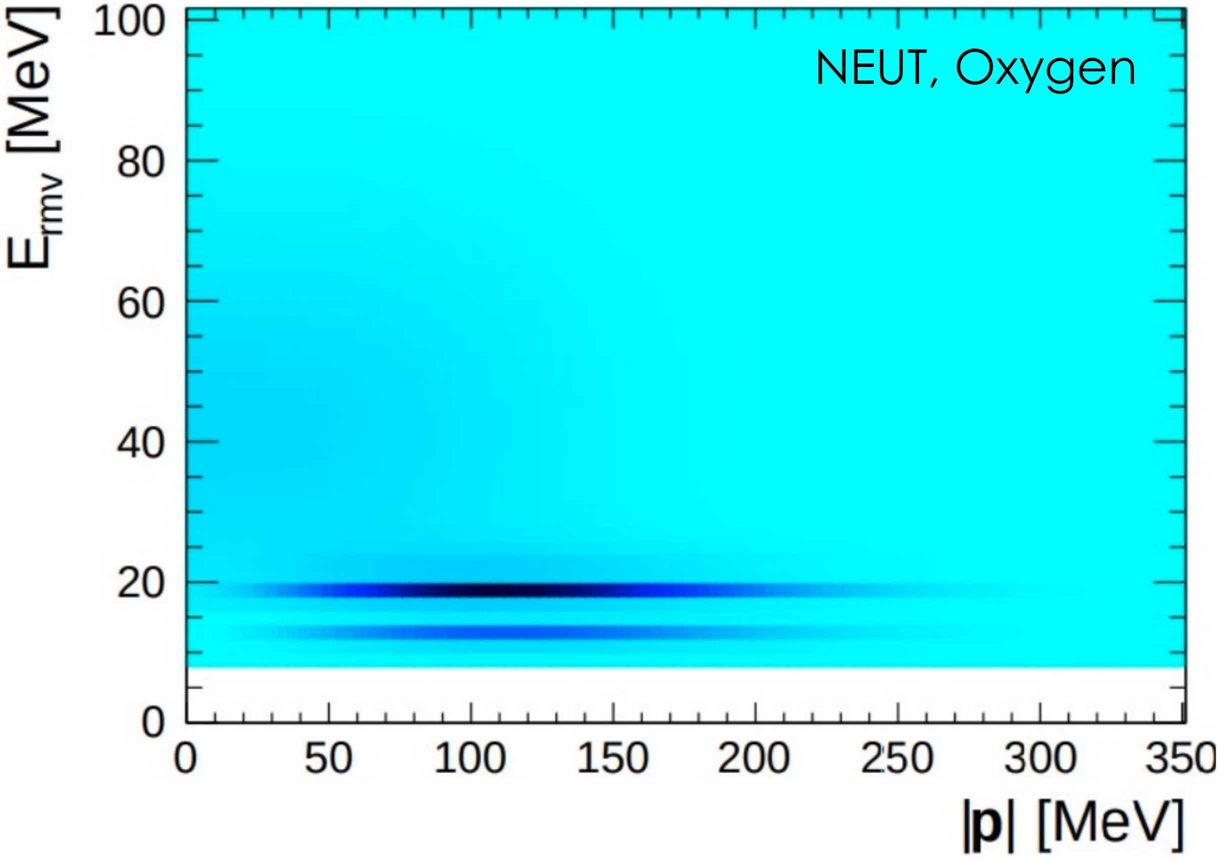
"Spectral Function"

Single nucleon tensor contraction
(no nuclear effects)

Identifying the natural d.o.f.



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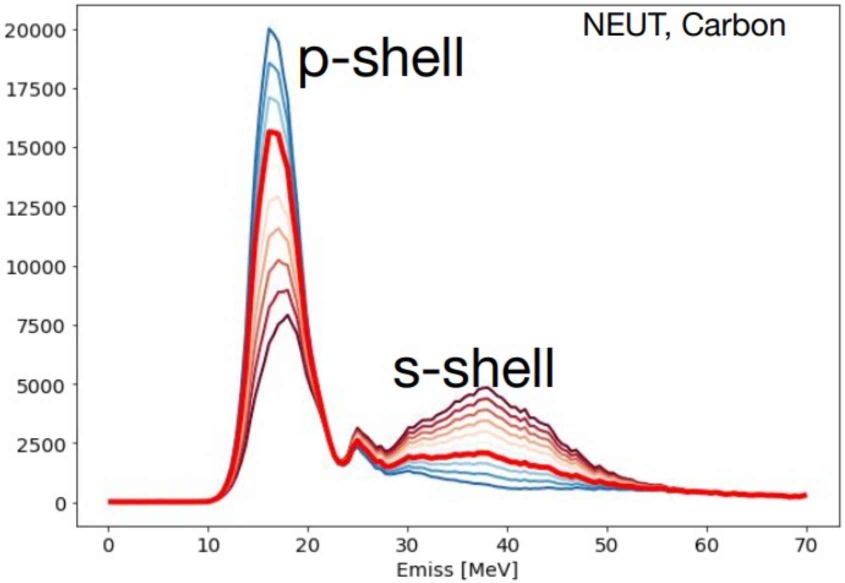
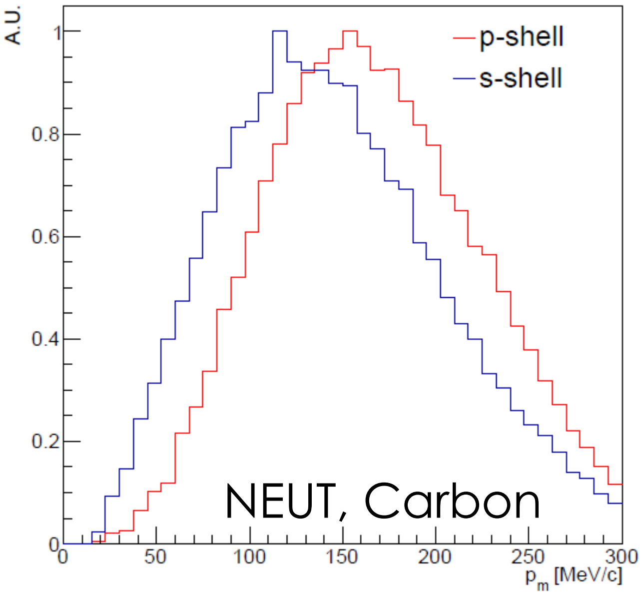
  - Change **relative occupancy** of the shells (2 shells for C, 3 for O)





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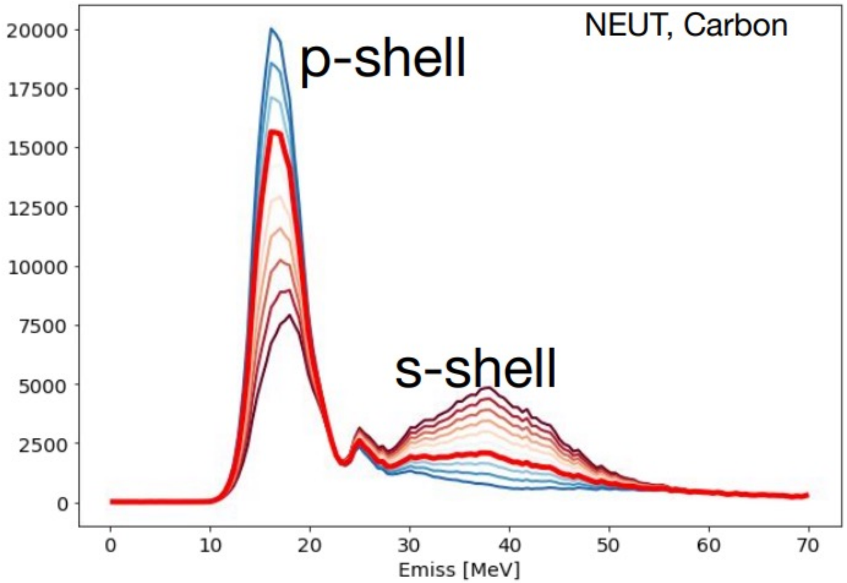

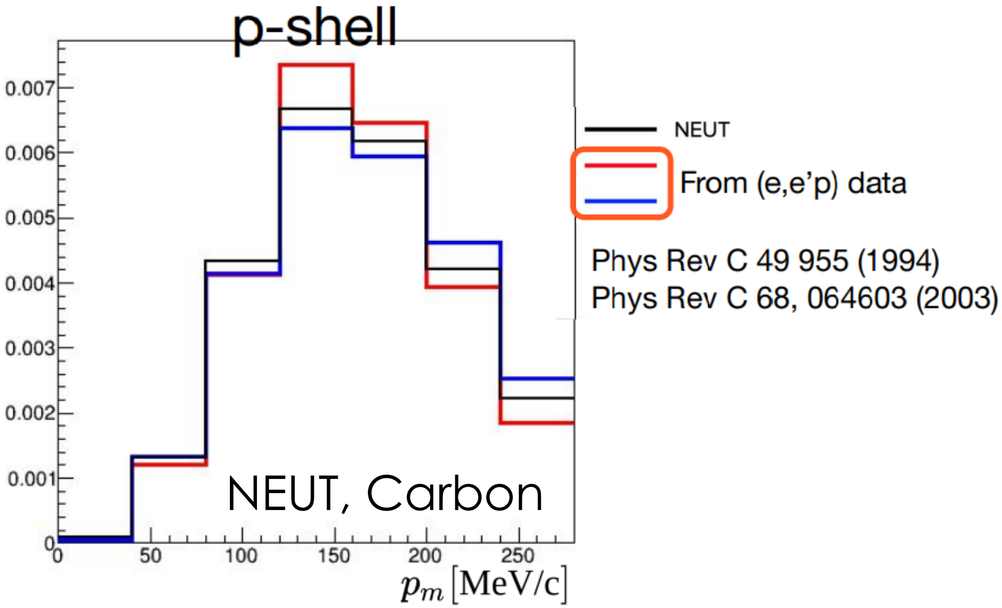

Phys Rev C 49 955 (1994)
Phys Rev C 68, 064603 (2003)

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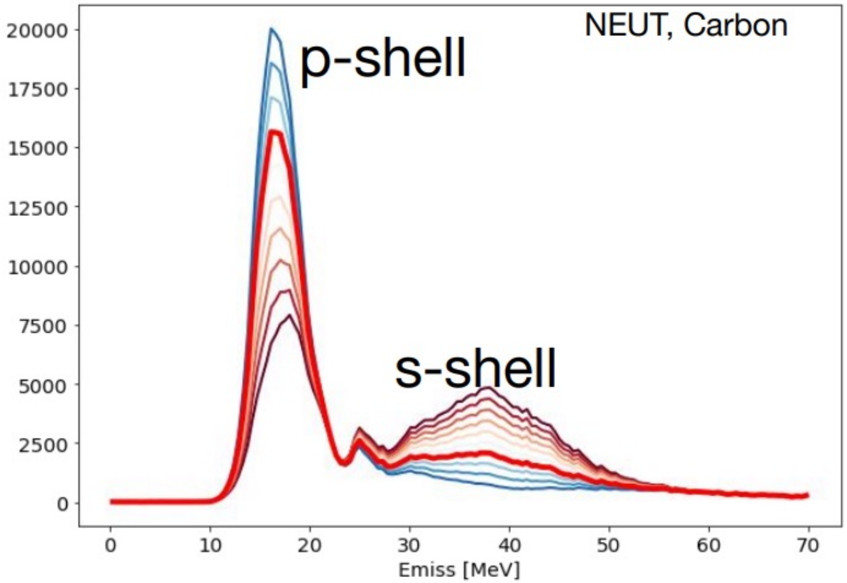

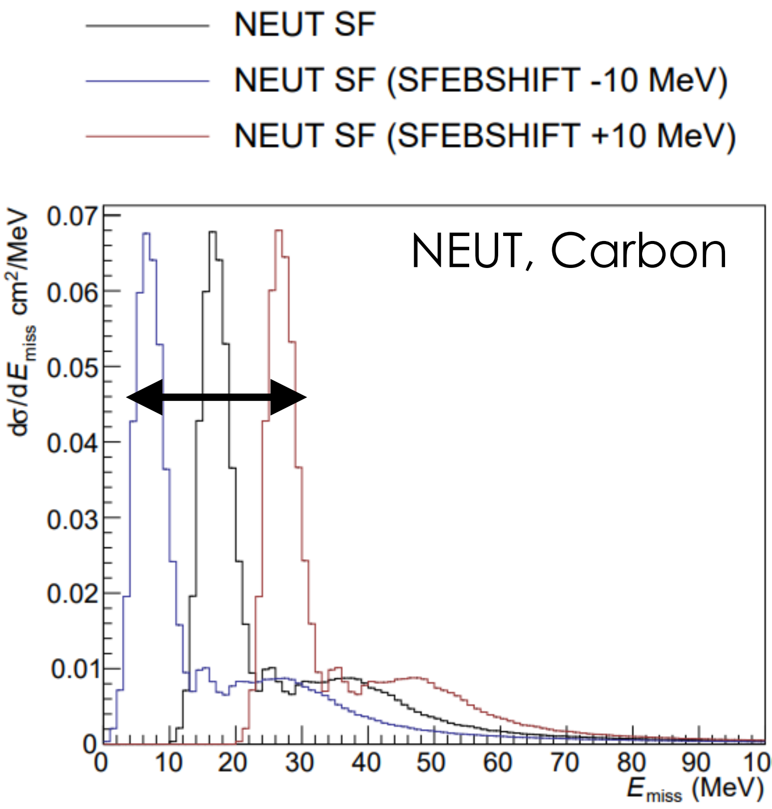

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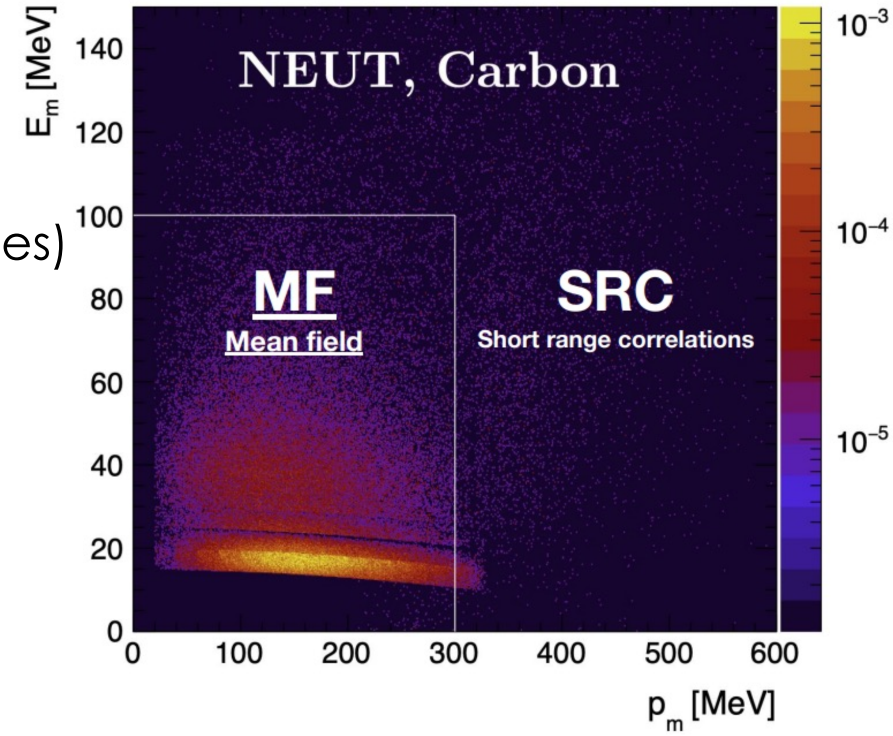
    - NEUT predicts 5%, other models predict closer to 20%



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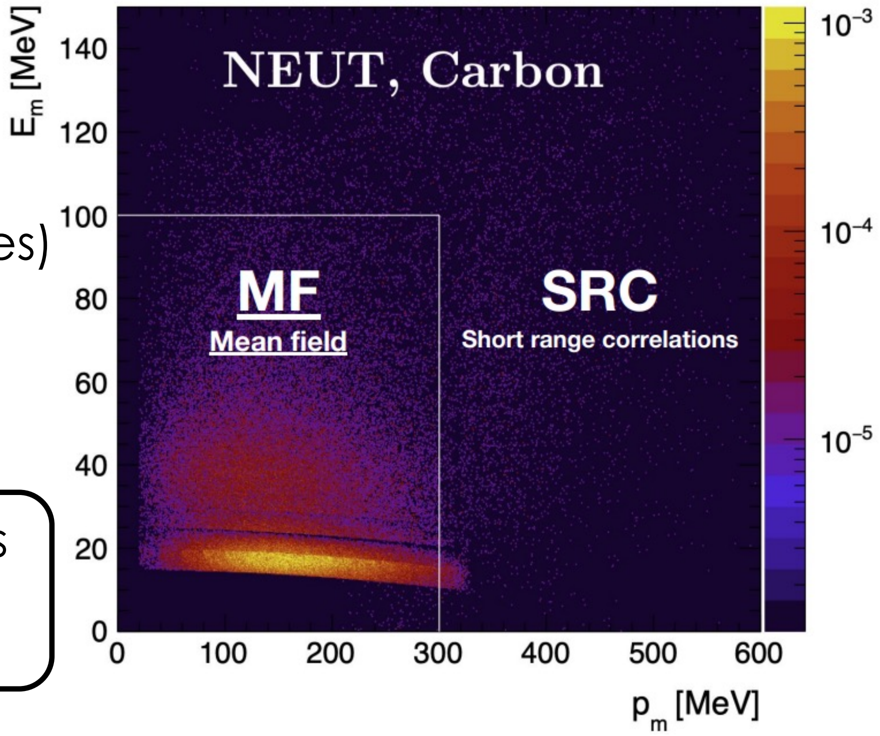
Crucial check: the parameter constraints from T2K's near detector are reasonable given electron scattering data



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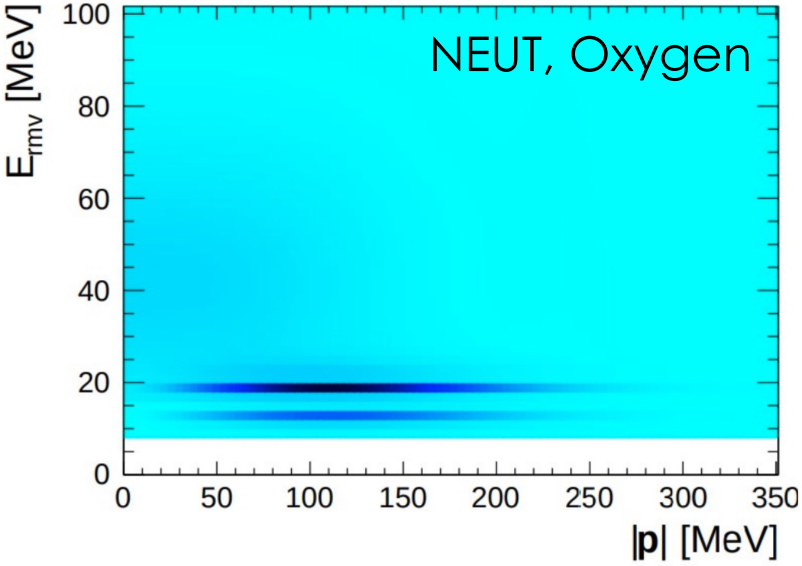

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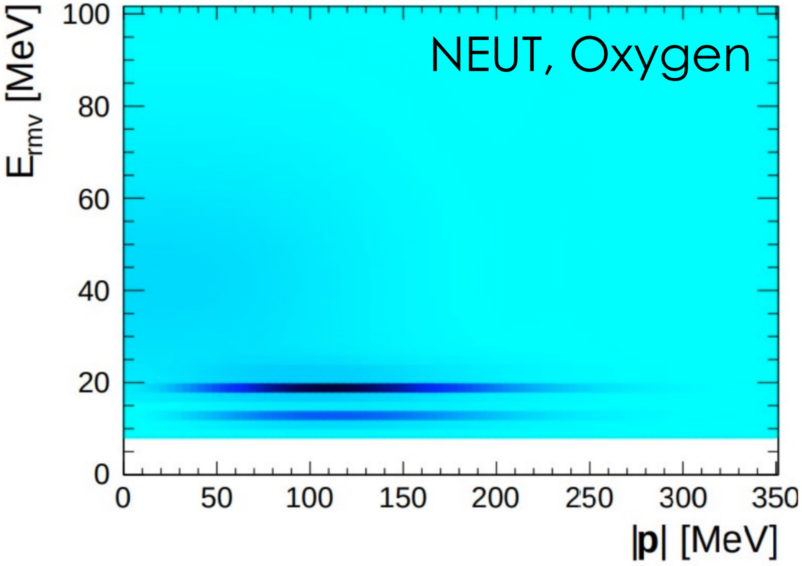
  - X Relies on "**factorization**", breaks down at low q_0, q_3 (~15% of events)
  - X **FSI effects** are not included on the outgoing lepton kinematics
  - X Simplistic approach to **Pauli Blocking** (also important at low q_0, q_3)



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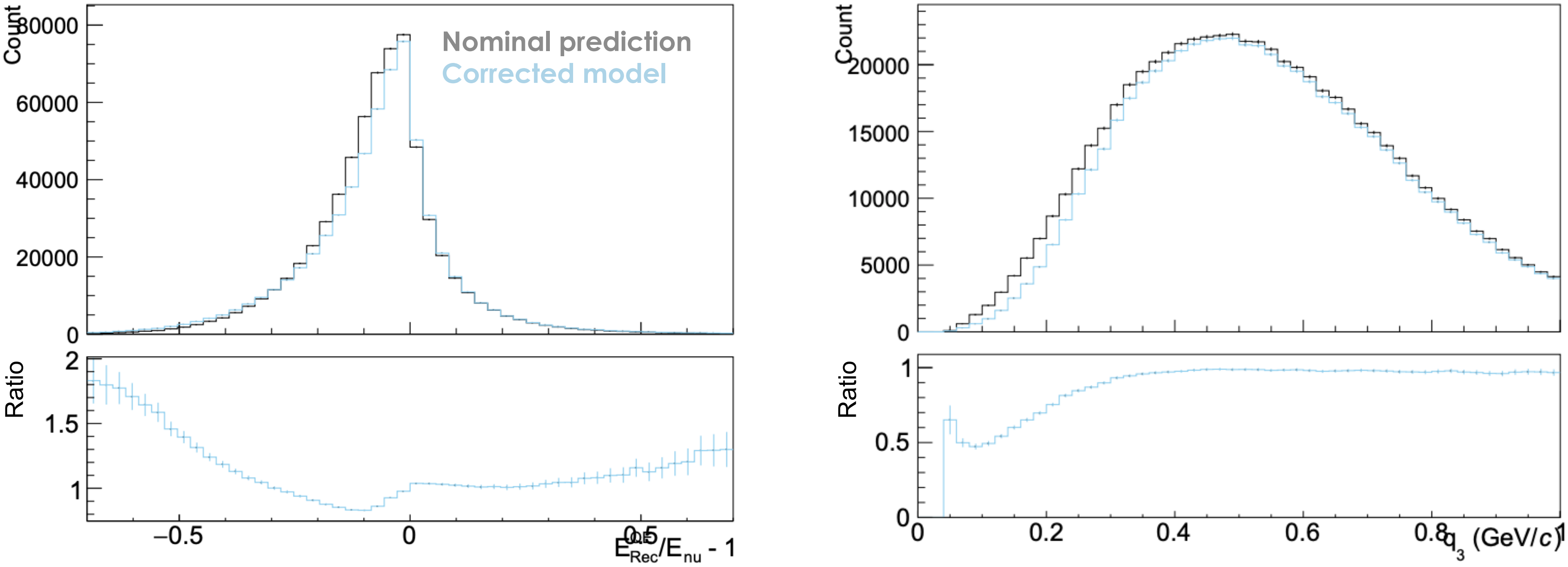
Beyond factorisation

- **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



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
- Some 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
- Model improvements will be required as we begin to use our significantly upgraded near detector
    - See Laura's talk

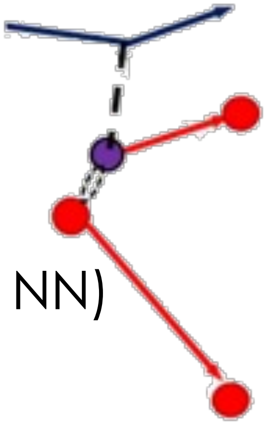
Uncertainties
2(3) shell occupancy uncertainites for C(O)
2 SRC normalisation uncertaintes (split for C/O)
Nucleon axial mass
3 Q^2 shape uncertainties*
4 removal energy shift uncertainies (split C/O, p/n)
4 Pauli blocking uncertainies (split C/O, p/n)
2 FSI correction uncertainties (split C/O)
q_3 depedent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

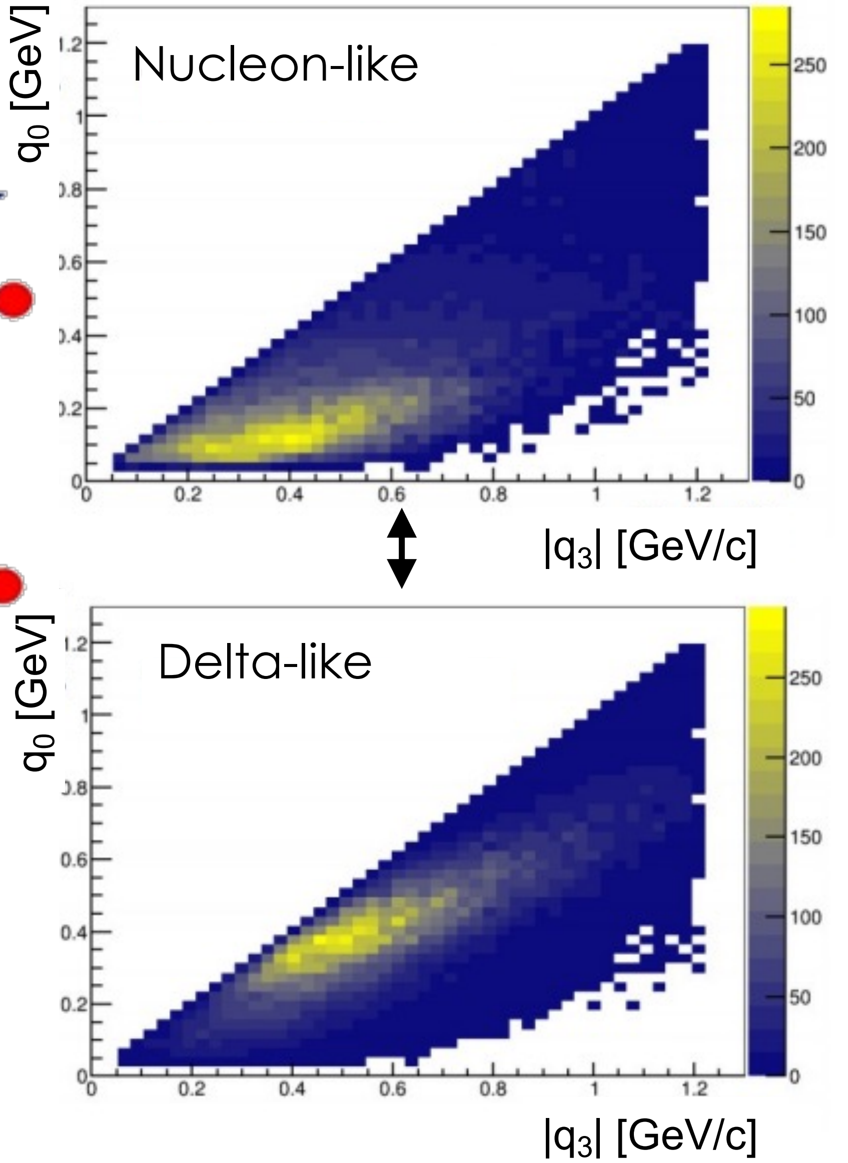
  Phys. Rev. C **83**, 045501



- 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)



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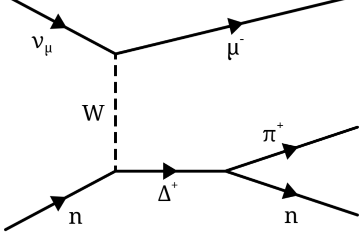
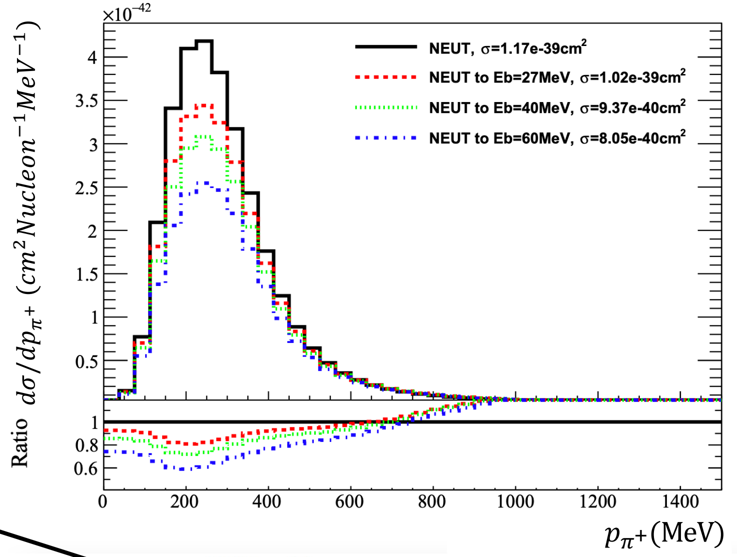
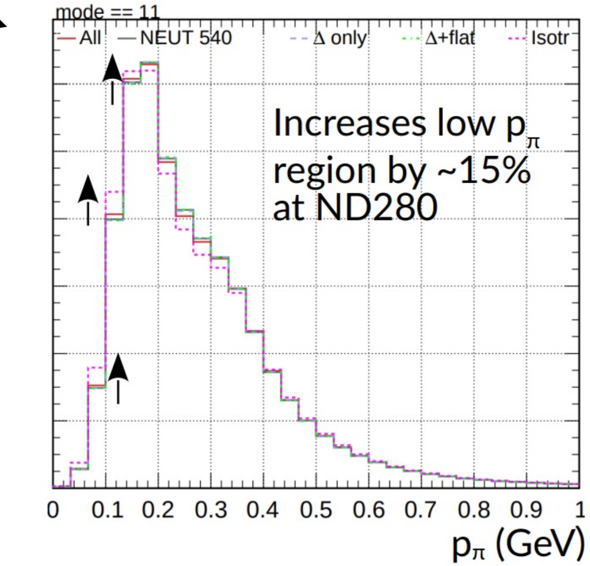


- Base model: **Rein-Sehgal with lepton mass corrections** (annals Phys. **133** (1981) 79–153)
- Parameters controlling:
  - Form factors (M_A^{RES}, C_A^5)
  - Non-resonant background
  - Channel normalisations
  - *Removal energy*
  - *Resonance decay kinematics*
- Particularly important to model well due to increased use of pion focussed samples at T2K's far detector
- Fairly complete set of nucleon-level uncertainties, but room for further variations of the pion kinematics
- Nuclear effect treatment is simplistic





Increases low p_π region by ~15% at ND280

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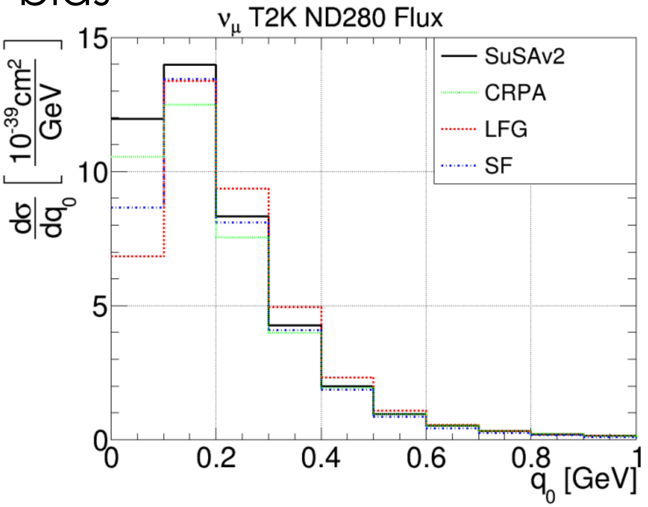
Examples (of 16 studies used for our latest analysis):

1. Swap the CCQE model to CRPA Phys. Rev. C 65, 025501, Phys. Rev. C 98, 054603
2. Use the Martini model for pion production Phys. Rev. C 65 81 045502
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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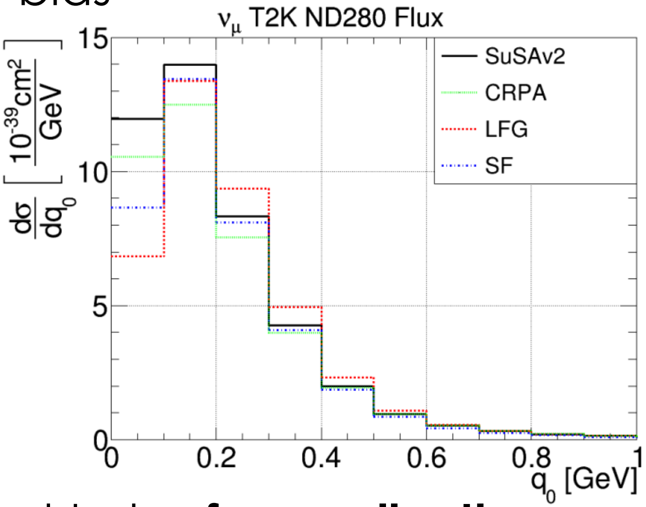
4. **Alter the CCQE/2p2h fractions based on ND280 data**
5. Simulate real photon emission via radiative corrections to CC interactions



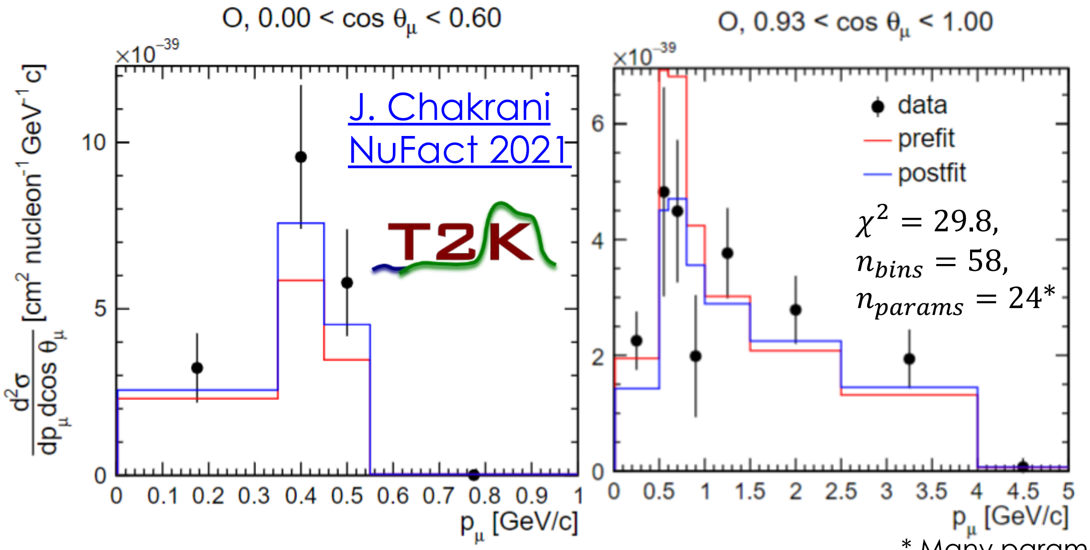
- The bias on oscillation parameters was usually found to be **far smaller than our systematic uncertainty** (which is smaller than the statistical uncertainty)
- One exception: the bias on Δm^2_{32} in studies 1 and 4 is comparable to the size of the systematic uncertainty (but less than half the total uncertainty).
  - An uncertainty inflation is made to account for this
  - Extends the Δm^2_{32} uncertainty by ~13%

Outline

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

Continued benchmarking

- Critically analysing the strengths and limitations of our uncertainty model is an essential part of improving it
- Ongoing work: fit T2K and MINERvA cross section measurements using the uncertainty model.
    - Quantitatively good description of T2K CC0π lepton kinematics on C+O



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$\chi^2 = 29.8,$
$n_{bins} = 58,$
$n_{params} = 24^*$

* Many parameters have tight prefit constraints

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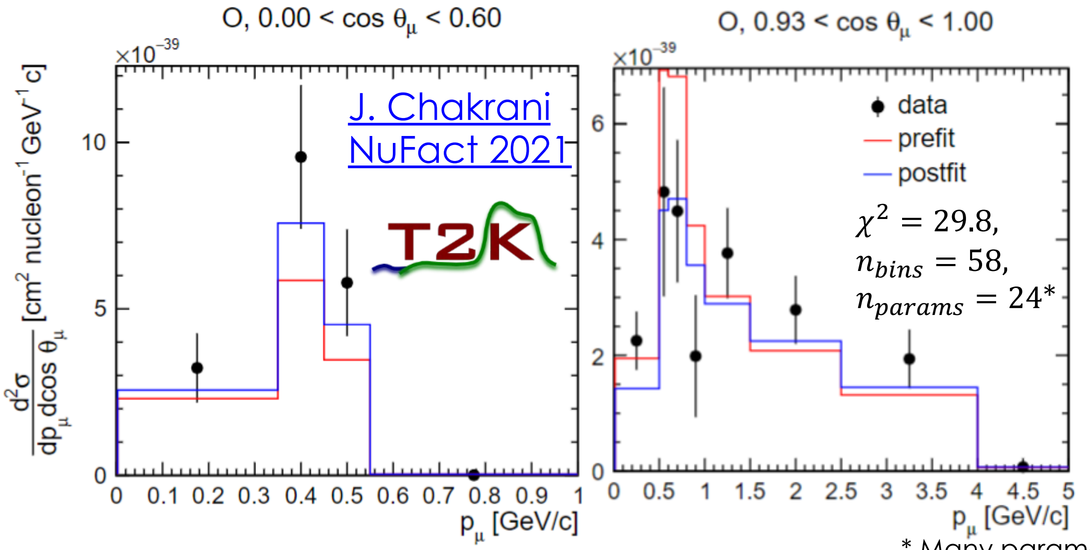

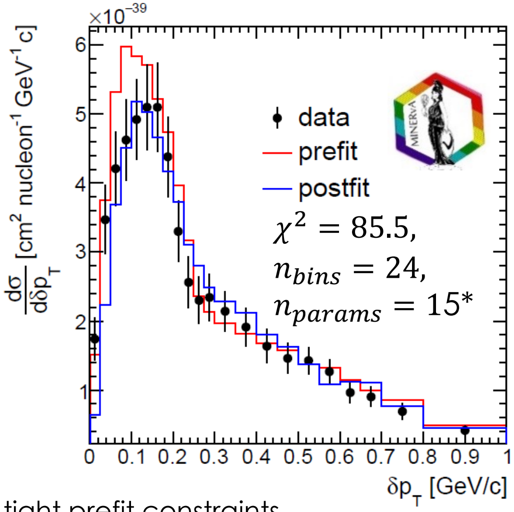

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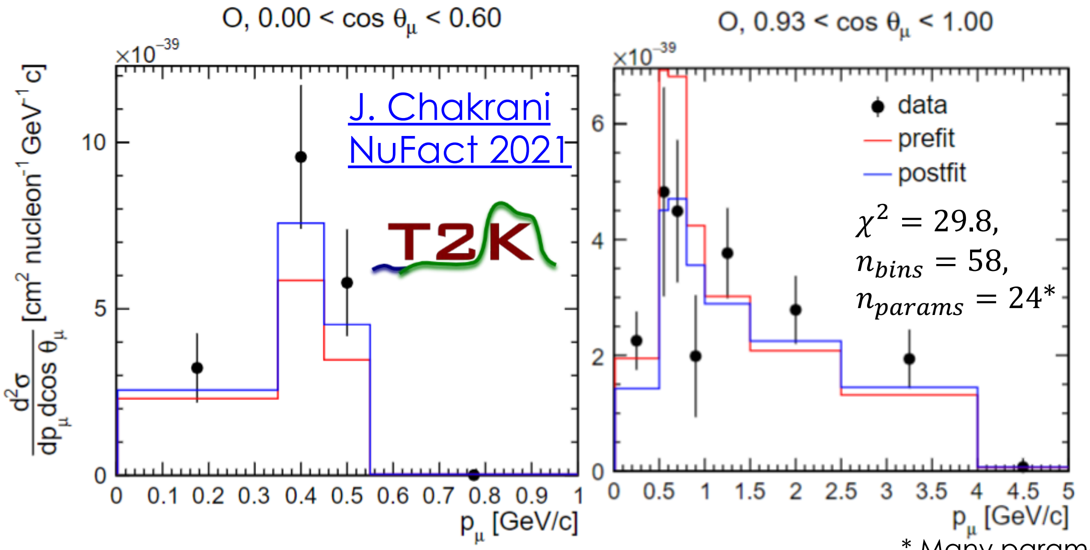
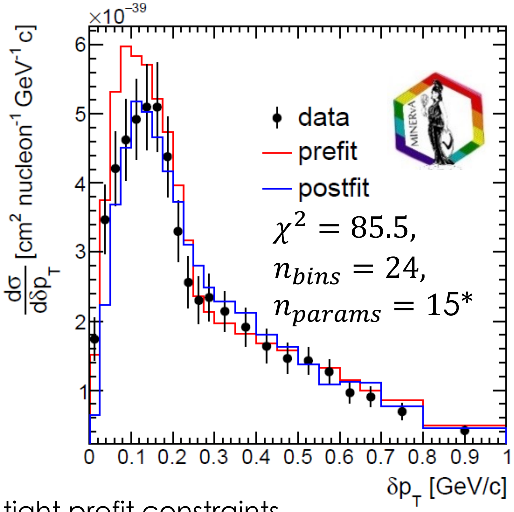
  - Poor description of MINERvA TKI measurements
  - Compare fit results to the constraints achieved in T2K's near detector fit
- Provides direction and priorities for model improvement work



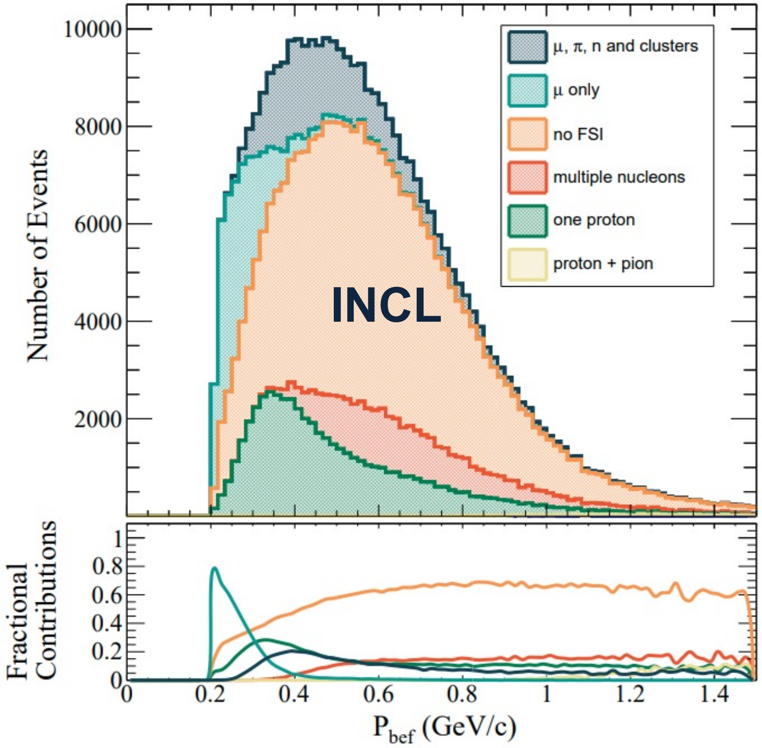


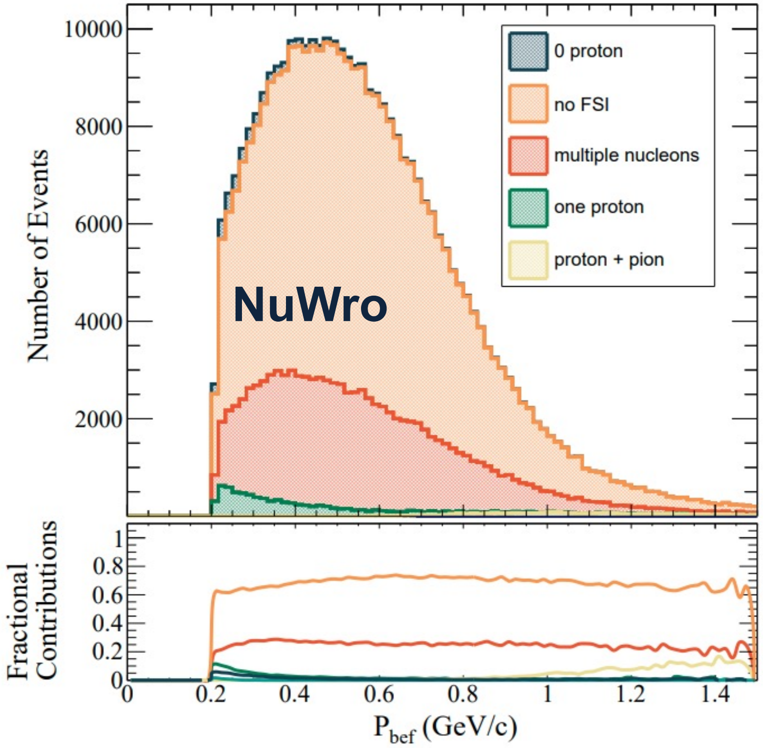
* Many parameters have tight prefit constraints

Advanced FSI cascades

Plots from
Ershova et al.,
Study of FSI of protons with INCL and NuWro cascade models
Phys. Rev. D **106**, 032009

- More advanced treatment of FSIs is available via the INCL model (Phys. Rev. C **87** 014606)





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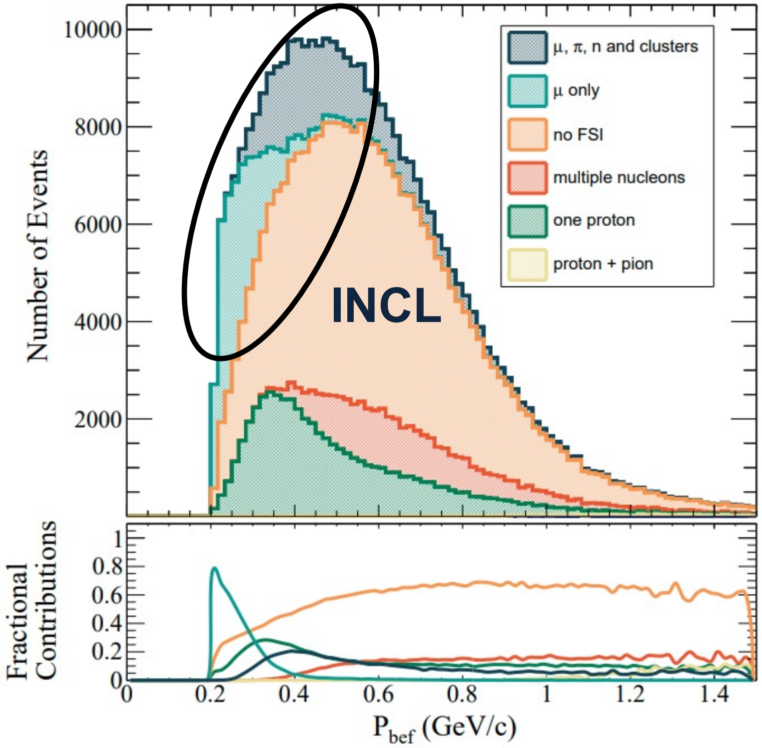
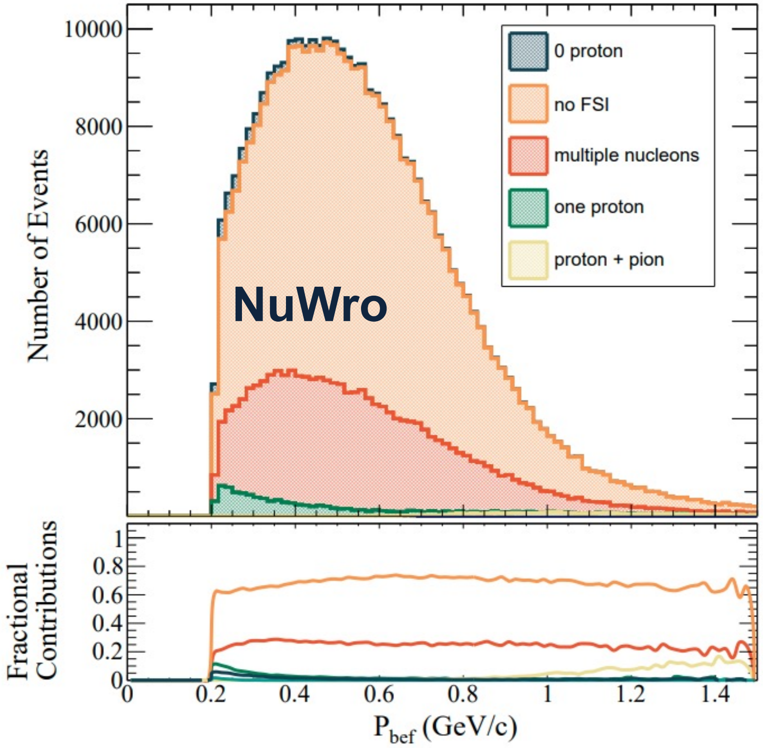
- More advanced treatment of FSIs is available via the INCL model (Phys. Rev. C **87** 014606)
- INCL's treatment of **nucleon absorption** and **nuclear cluster production** gives a different distribution of energy among outgoing hadrons
- Need new uncertainties to account for this if we want to make more use of nucleon kinematics in T2K analyses





FSI beyond the cascade

Plots from:
Franco-Patino et al.,
arXiv:2207.02086

See also:
Nikolakopoulos et al.,
Phys. Rev. C **105**, 054603

- Instead of cascades, FSI can be modelled via a distortion of the outgoing nucleon wave function by a nuclear potential

- Recent theory effort has allowed a calculation of exclusive observables with such treatments (although not all effects are accounted for, e.g. π-abs.)

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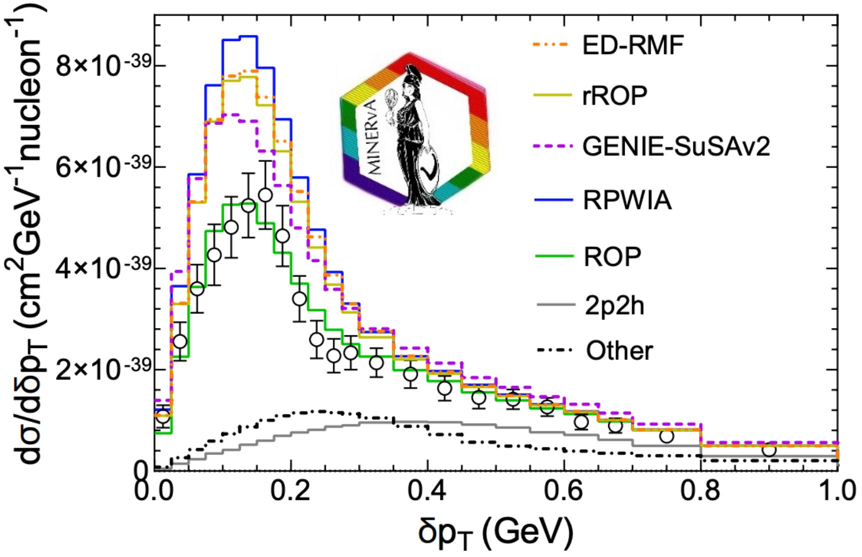

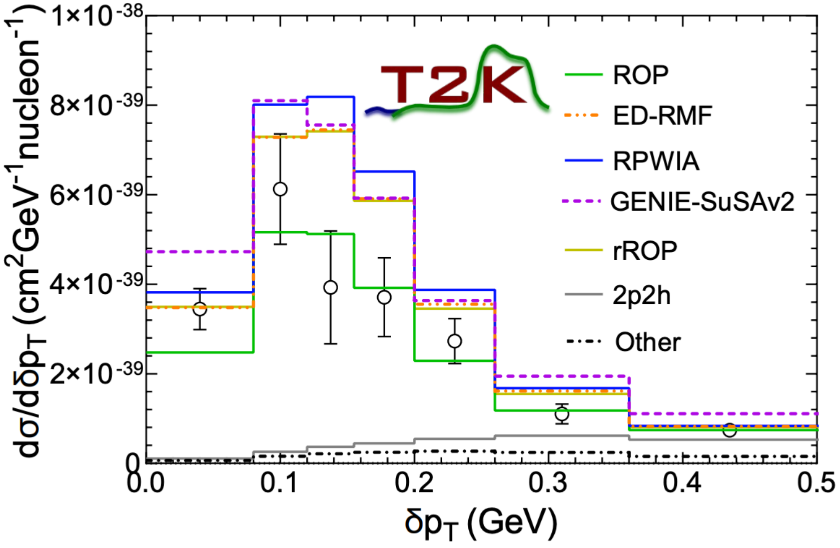

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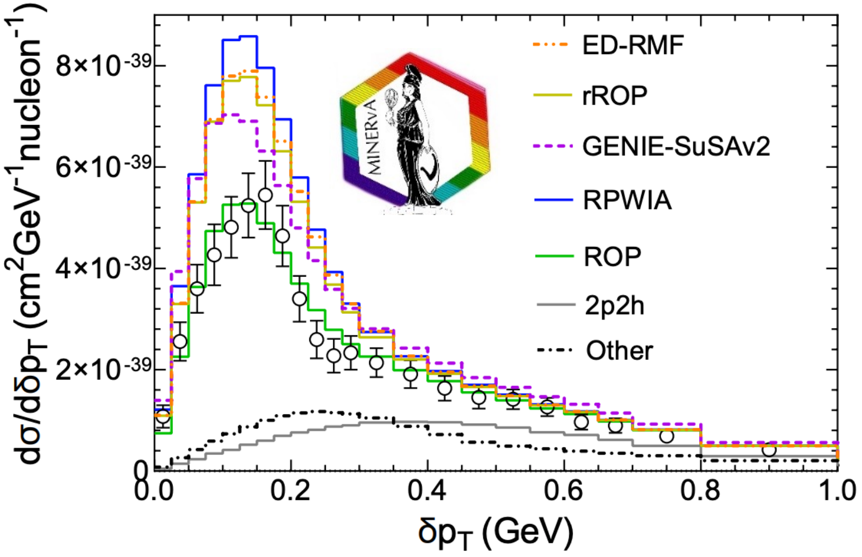
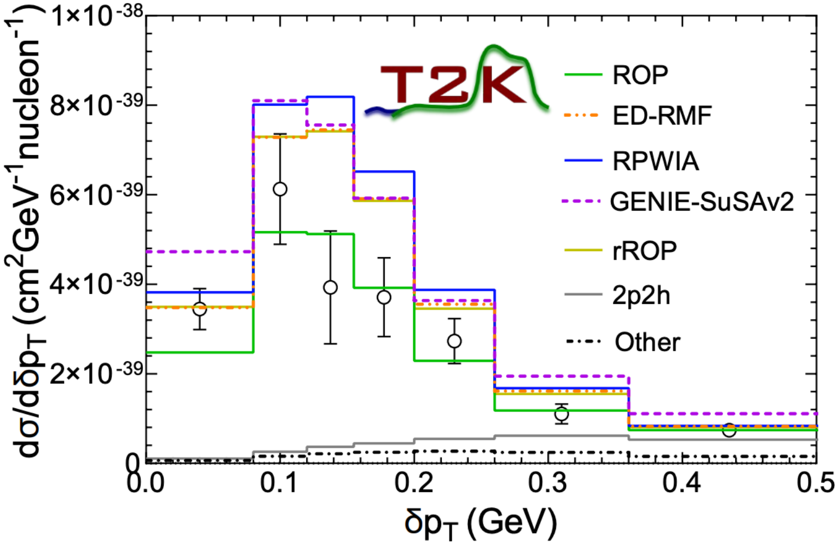
  - Example below: missing transverse momentum

- Key conclusions
  - Significant differences in predictions for different nuclear potentials
  - Sometimes all of these deviate strongly from the cascade approach
  - ***Clear indication for the need of freedoms beyond our existing FSI uncertainties***





Further future improvements

CCQE

- Improve sophistication of **low q_0, q_3 uncertainties** (see e.g. Phys.Rev.D 106, 7, 073001)
- **Increased use of e,e'p data** to constrain initial state uncertainties
- Further exploration of **correlations in carbon and oxygen** uncertainties
- *Longer term: move to an **unfactorized baseline model***

(see e.g. Phys. Rev. C 101, 015503)

2p2h

- New freedoms in nucleon ejection kinematics (motivated by studies within NuWro and MicroBooNE) (see e.g. Phys. Rev. D 105, 072001)

Single pion production

- Reimplementation of the **updated MK model** with associated overhaul of uncertainties (original model: Phys. Rev. D 102, 053009)
- Assessment of differences between baseline model and the newly implemented **DCC model** (Phys. Rev. D 92, 074024)
- *Longer term: develop a consistent treatment of nuclear effects*

Other

- Continue **updating the DIS/SIS NEUT model** (See Christophe's talk)
- Implementation of photons from **radiative corrections**

(See Nature Communications, 13, 5286 and Oleksandr's talk)

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 bias 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 new samples 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
- Plenty of **scope for model improvement**, which can be benchmarked by lepton scattering measurements
- **Cross-experiment collaboration** and **engagement with the theory community** will be essential to ensure the construction of an uncertainty model suitable for future measurements

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

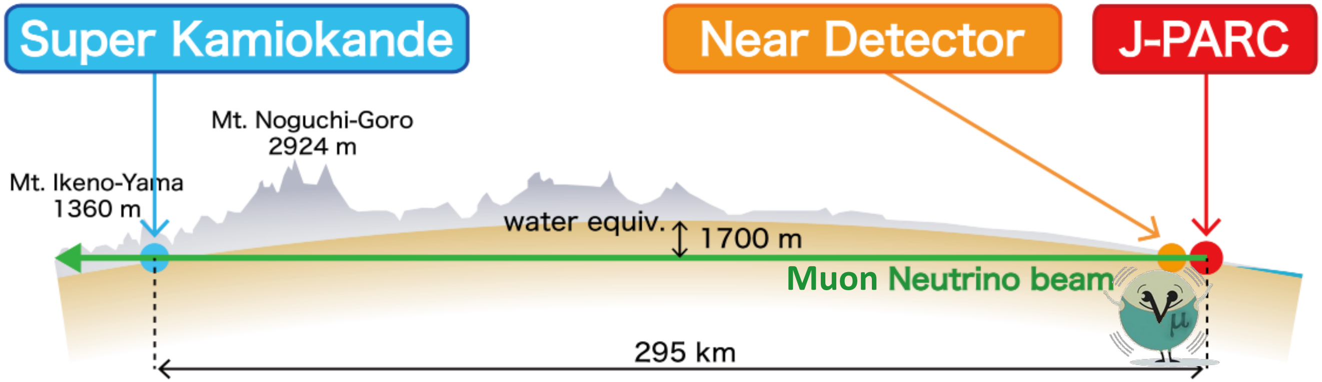
Shallow and Deep Inelastic (SIS and DIS)

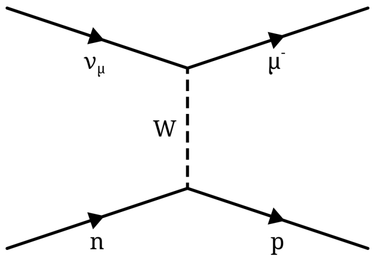
- **GRV98 PDF with optional corrections from *Bodek and Yang***
- **Hadron multiplicity by *PYTHIA v5.72* (W > 2 GeV) or a custom model (W < 2 GeV)**

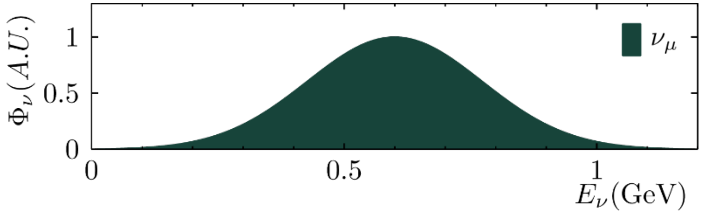
Final State Interactions (FSI)

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

The T2K Experiment







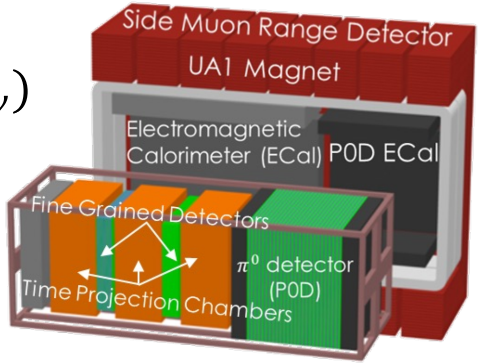
$$N_\mu(E_\nu) = \sigma(E_\nu)\Phi_\nu(E_\nu)\epsilon(E_\nu)$$

Interaction cross section

Neutrino flux

Detector effects

Near Detector
ND280



(Mostly Hydrocarbon Scintillator)

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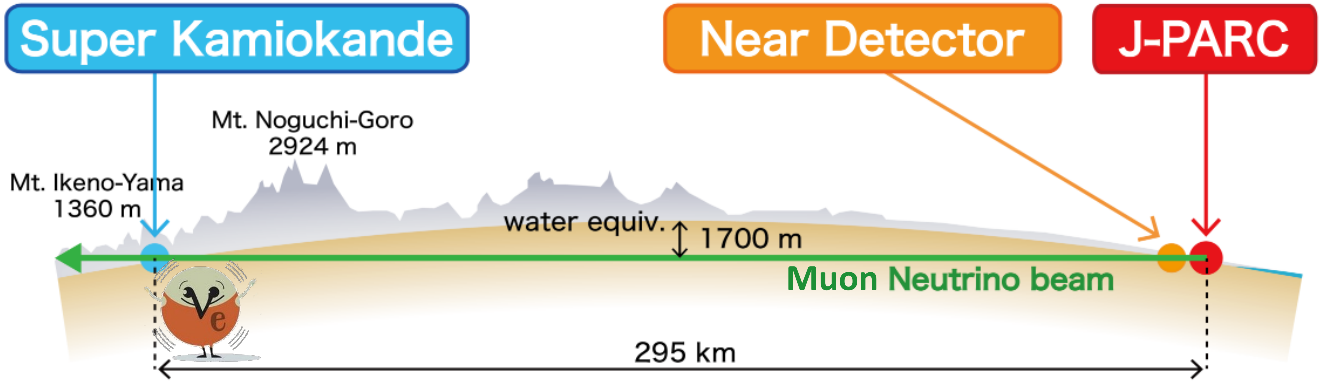
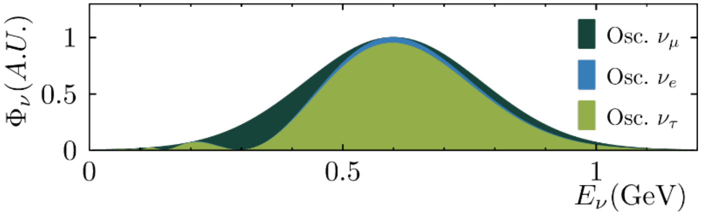
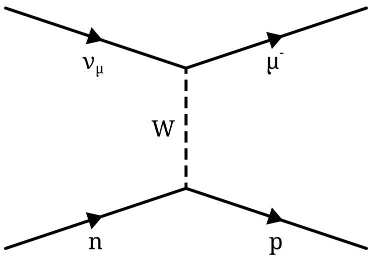
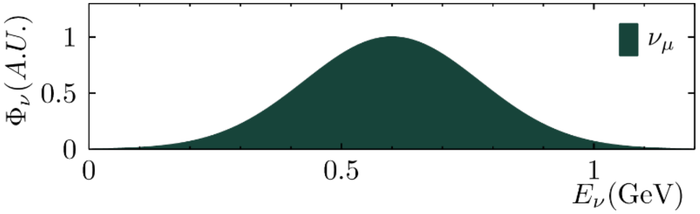


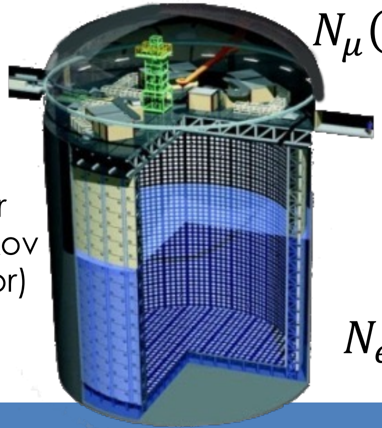


Far Detector
Super-Kamiokande





Near Detector
ND280



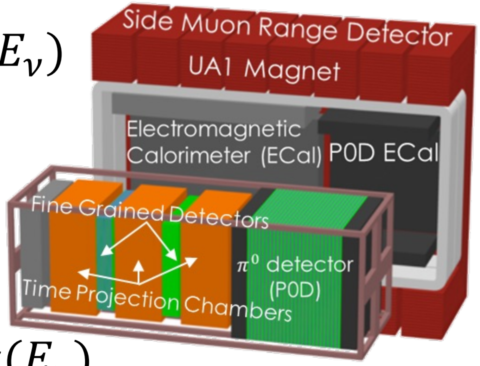
(Water Cherenkov Detector)

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

Oscillation probability

PMNS Mixing
δ_{CP} θ_{13}
Δm^2_{32} θ_{23}

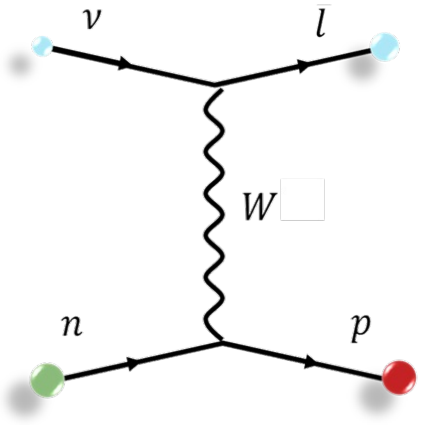
$$N_e(E_\nu) = P(\nu_\mu \to \nu_e)\sigma(E_\nu)\Phi_\nu(E_\nu)\epsilon(E_\nu)$$

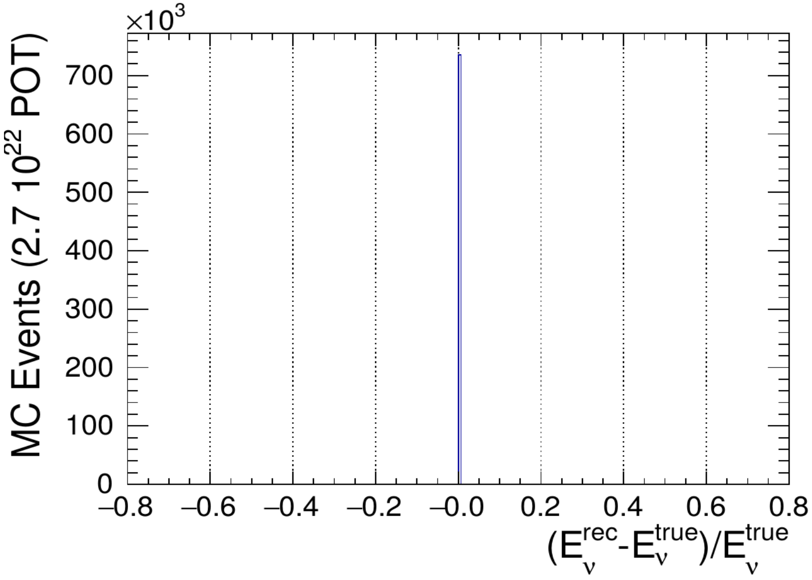


(Mostly Hydrocarbon Scintillator)

Neutrino Energy Reconstruction

CCQE (1p1h)

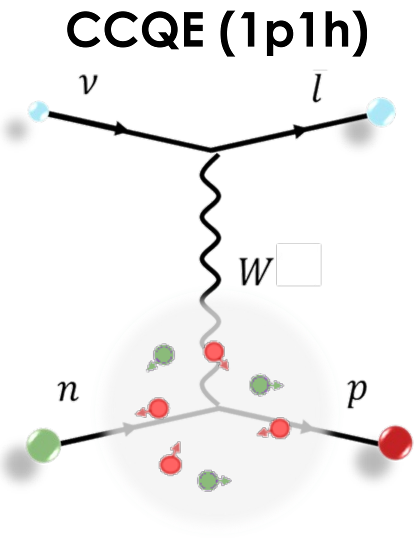


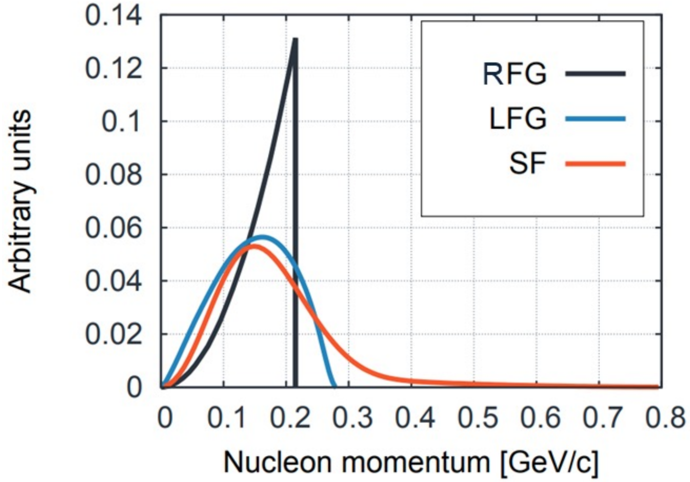


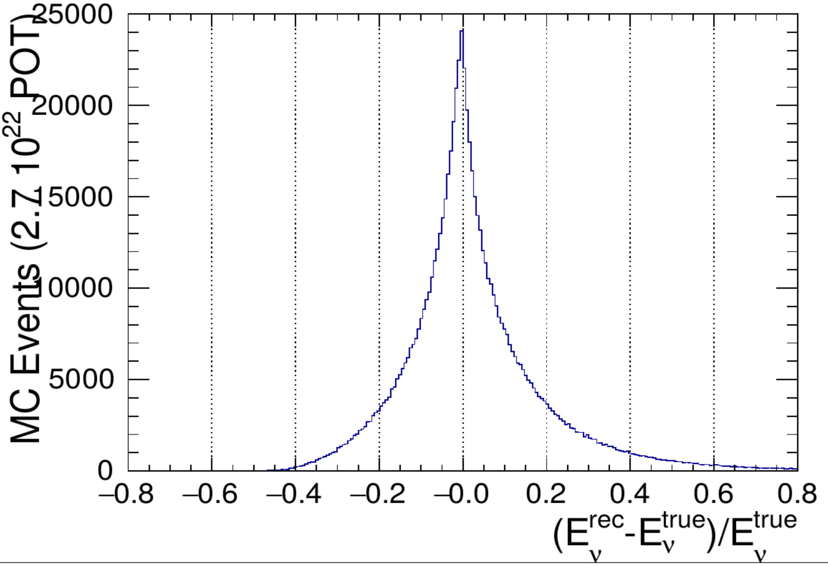
$$E_\nu = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu cos\,\theta_\mu)}$$

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

Neutrino Energy Reconstruction







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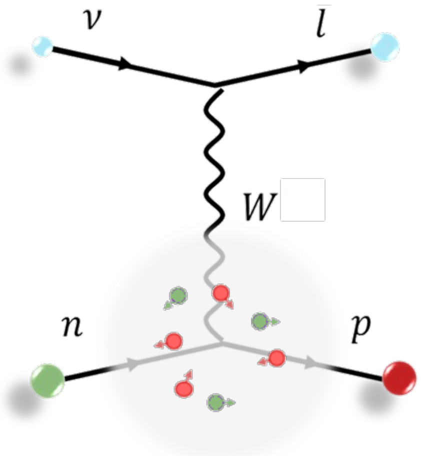
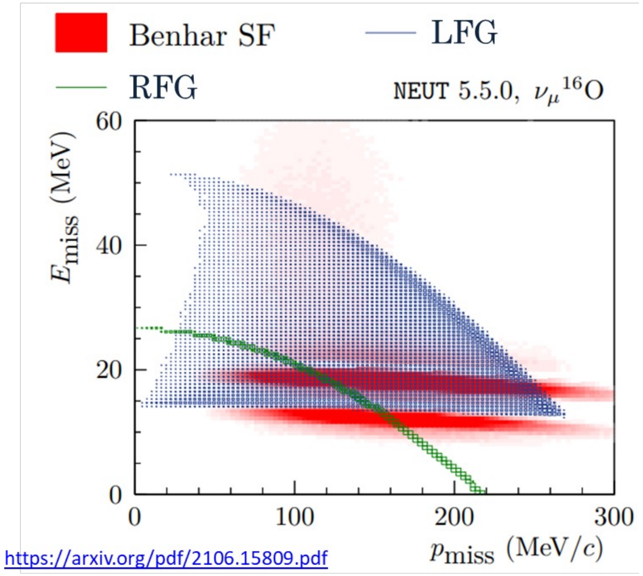
The motion of the nucleons inside the nucleus (*Fermi motion*) causes a **smearing** on E_ν

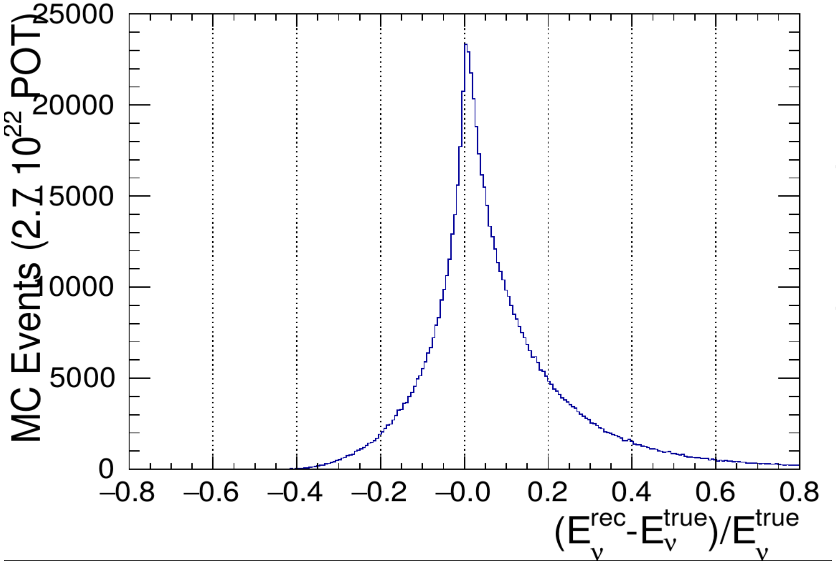
Neutrino Energy Reconstruction

CCQE (1p1h)





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



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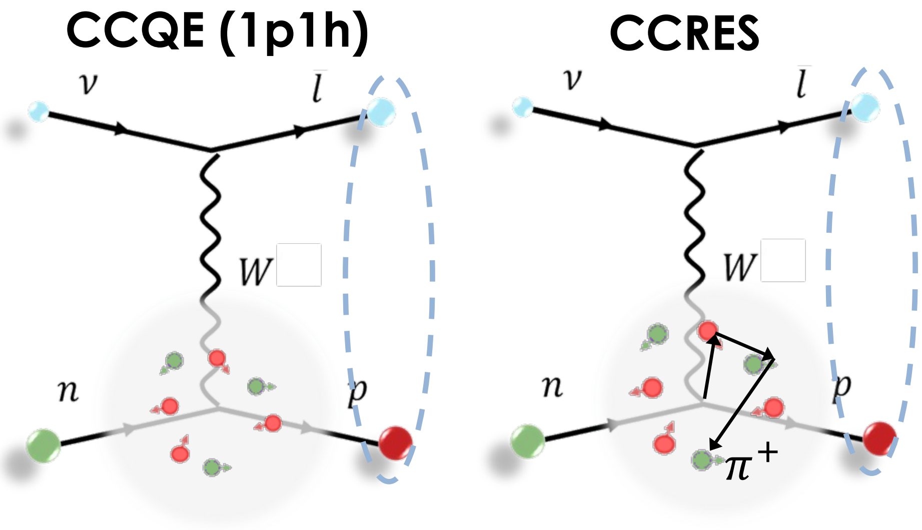
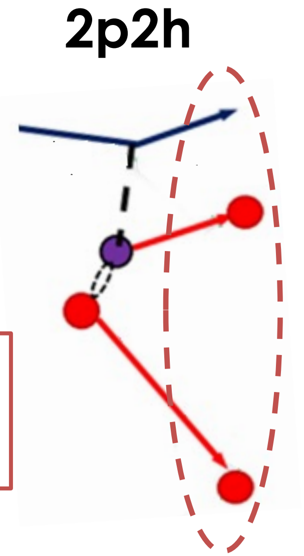
The motion of the nucleons inside the nucleus (*Fermi motion*) causes a **smearing** on E_ν

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

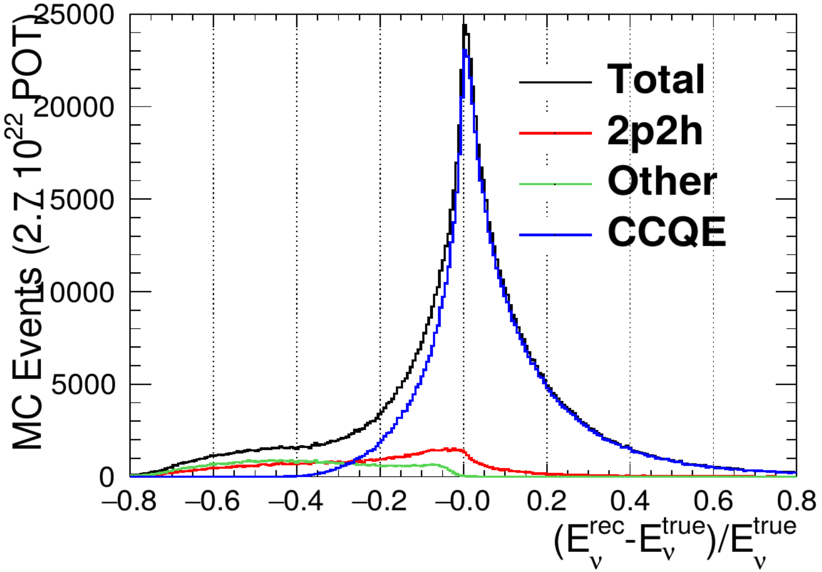
Neutrino Energy Reconstruction



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



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



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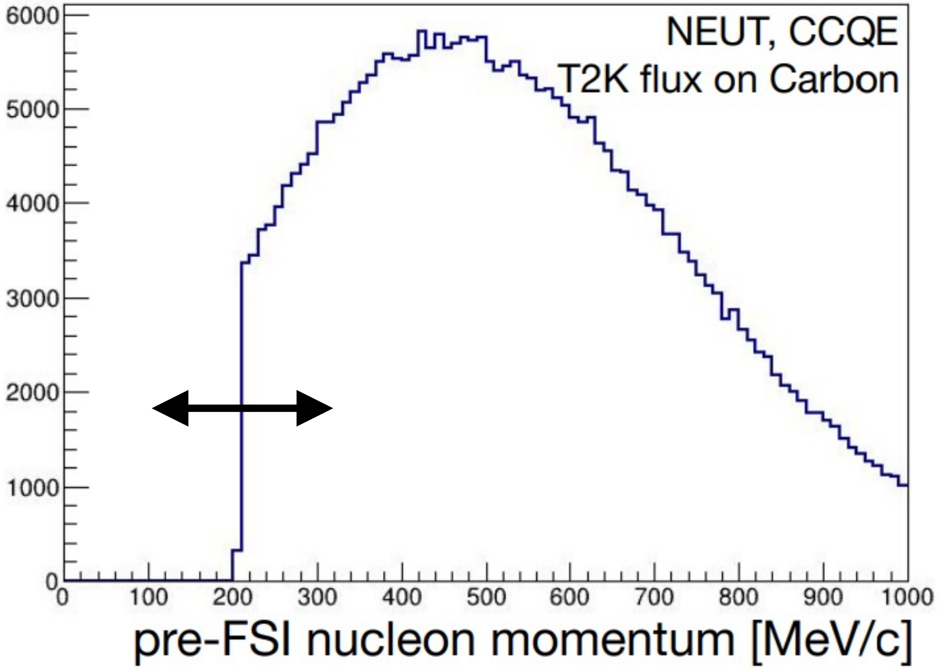
The motion of the nucleons inside the nucleus (*Fermi motion*) causes a **smearing** on E_ν

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

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

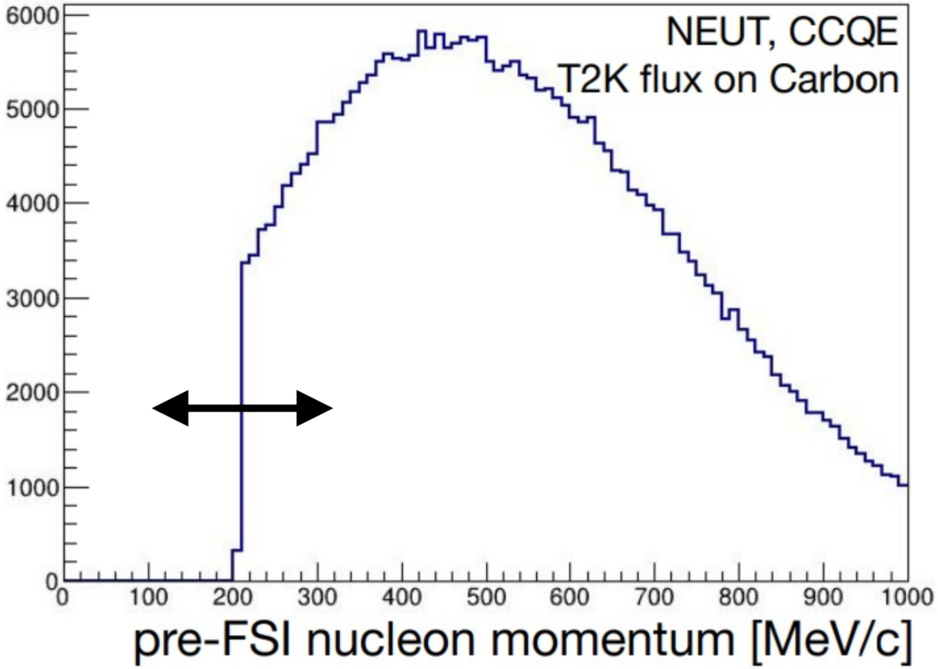
Beyond factorisation

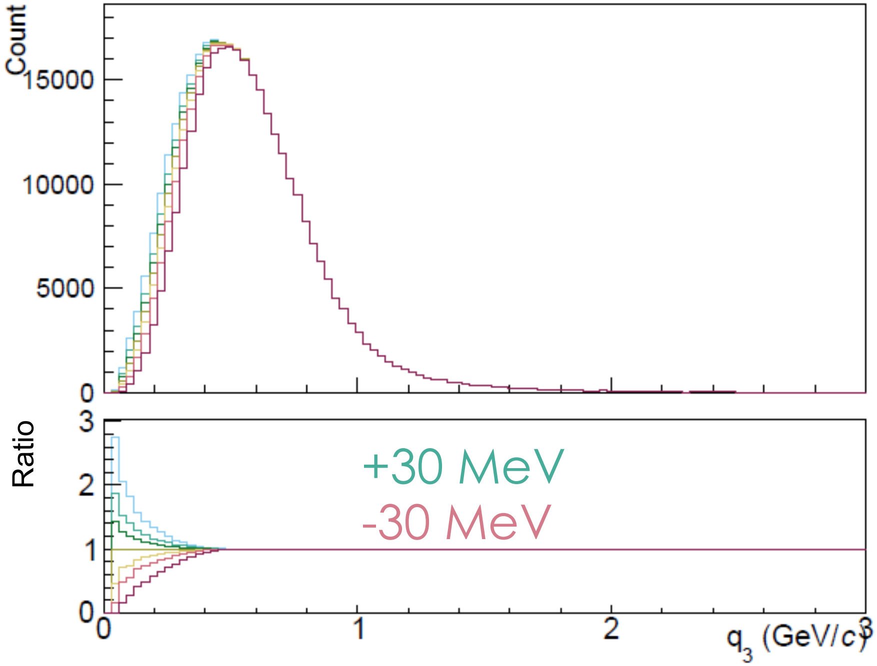
- **Pauli blocking** in the NEUT SF takes an RFG treatment:
- Set xsec to 0 if the pre-FSI proton momentum is below a threshold
- Try moving the threshold to cover external data



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
- Large impact at low energy and momentum transfer

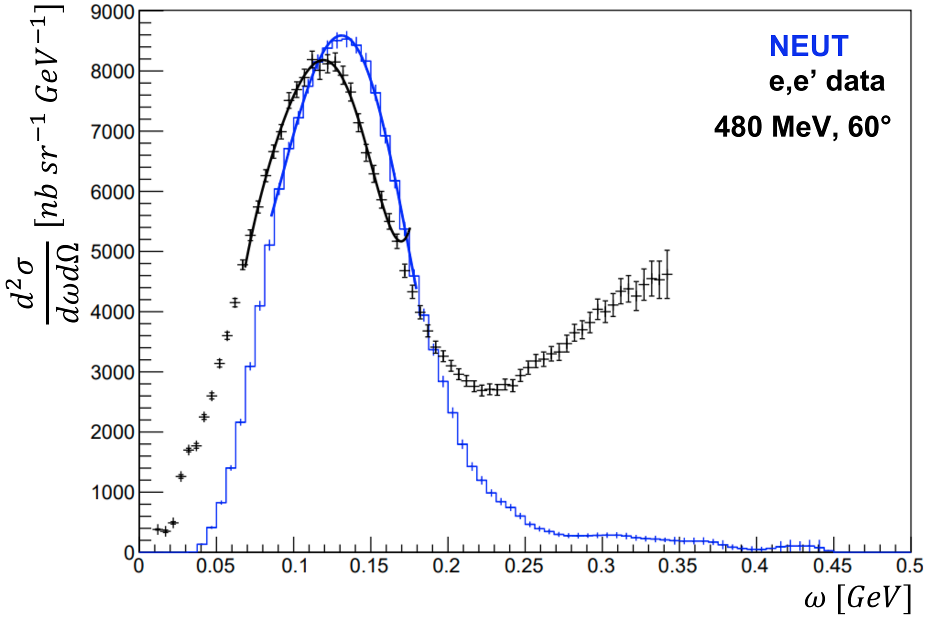


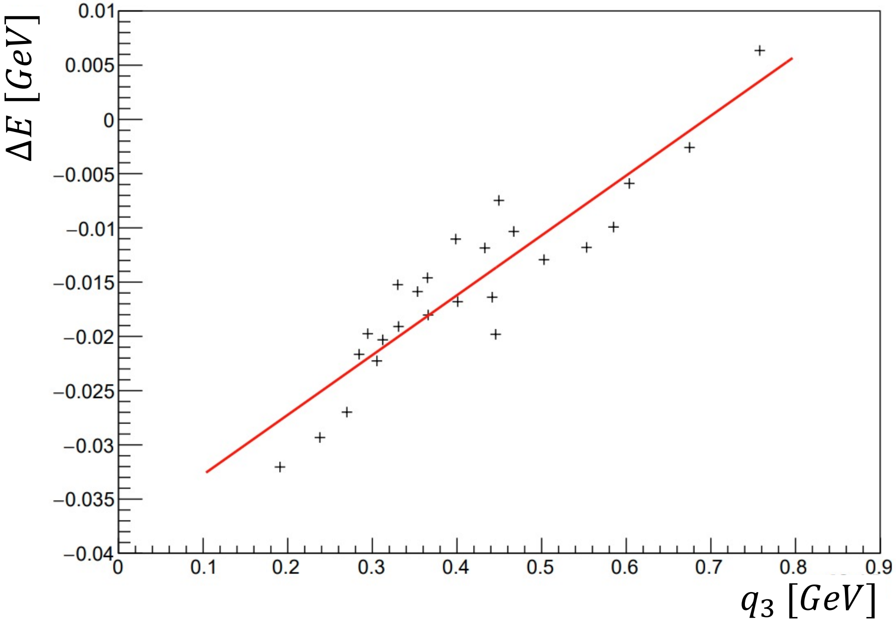


Beyond factorisation

- **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





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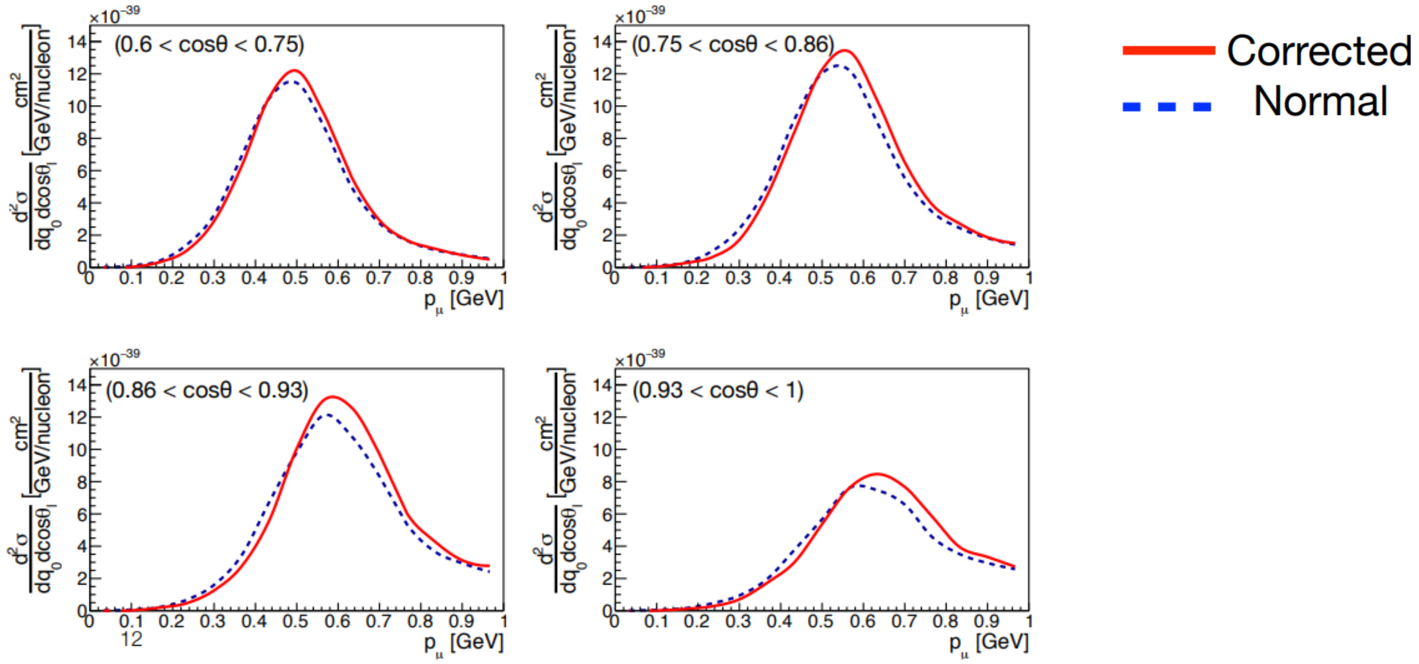
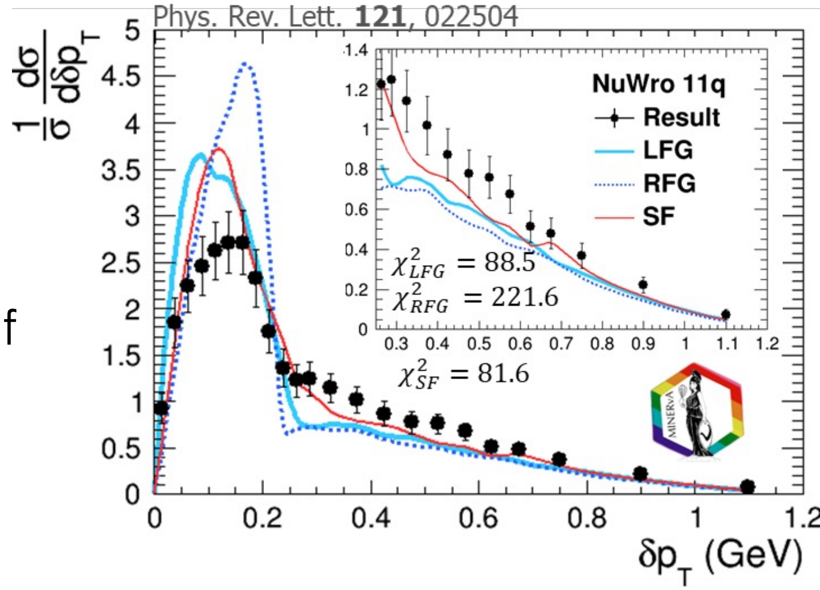
- A sort of simple breaking of factorization
- Compared NEUT SF to (e, e') data to derive a q_3 dependence
- Largest impact is, again, at low energy and momentum transfer

J. McElwee, NuFact 2021

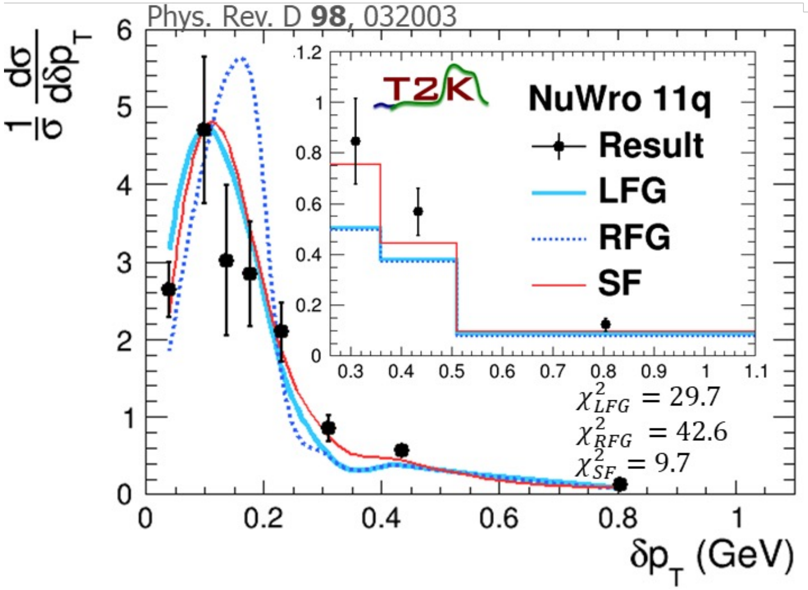


An apology to theorists

- 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!



Phys. Rev. Lett. **121**, 022504



Phys. Rev. D **98**, 032003

Final State Interactions

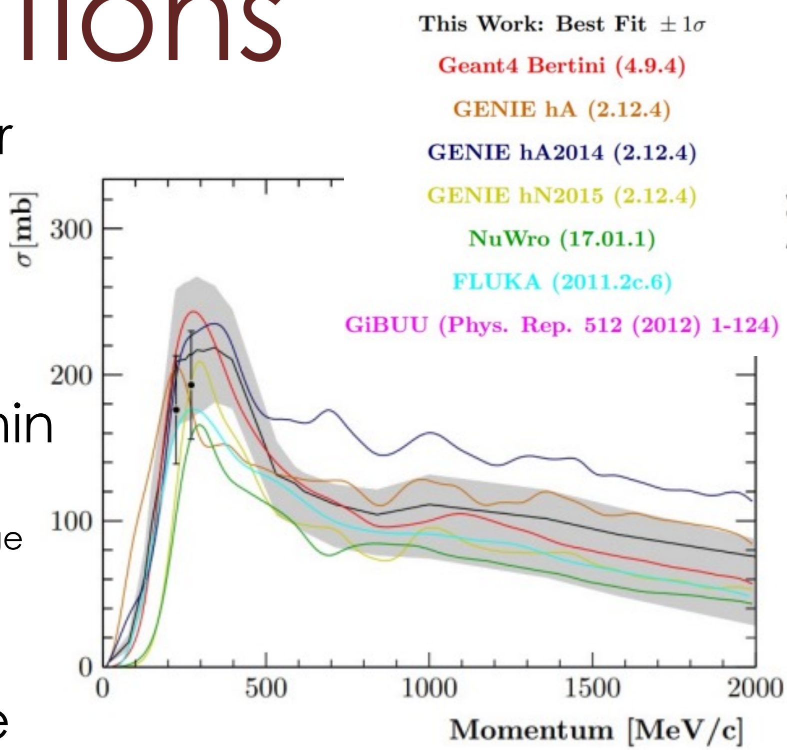
- Base model: Salcedo-Oset cascade for pions, analogous model for nucleons

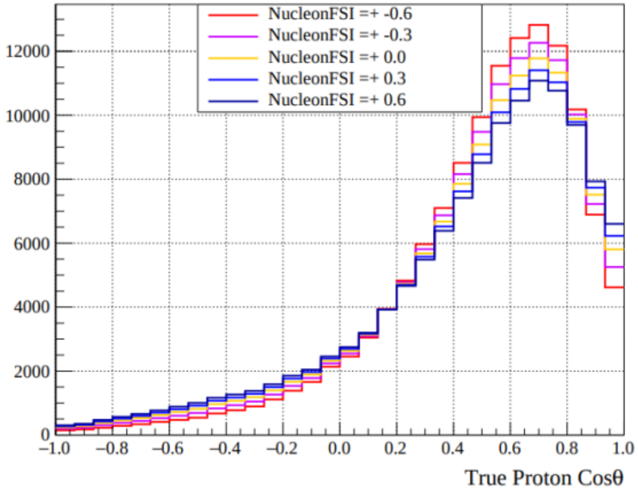
  Phys. Rev. D **99**, 052007

- 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



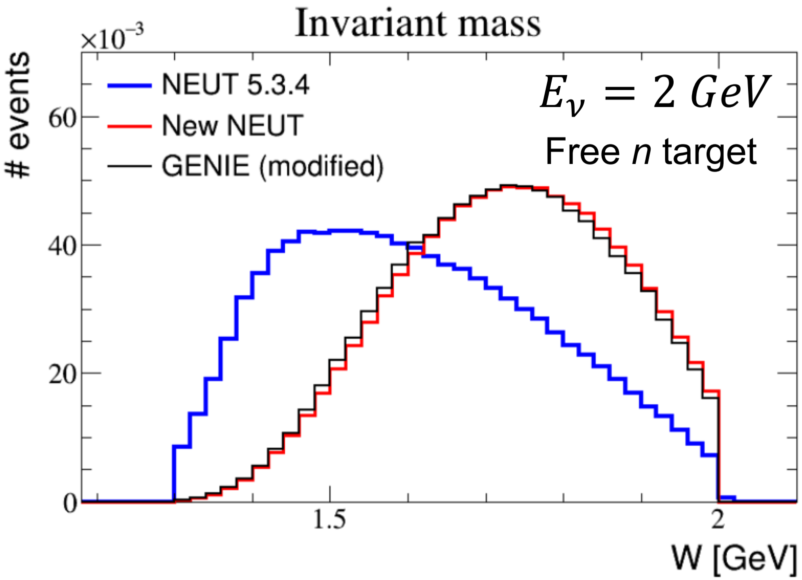


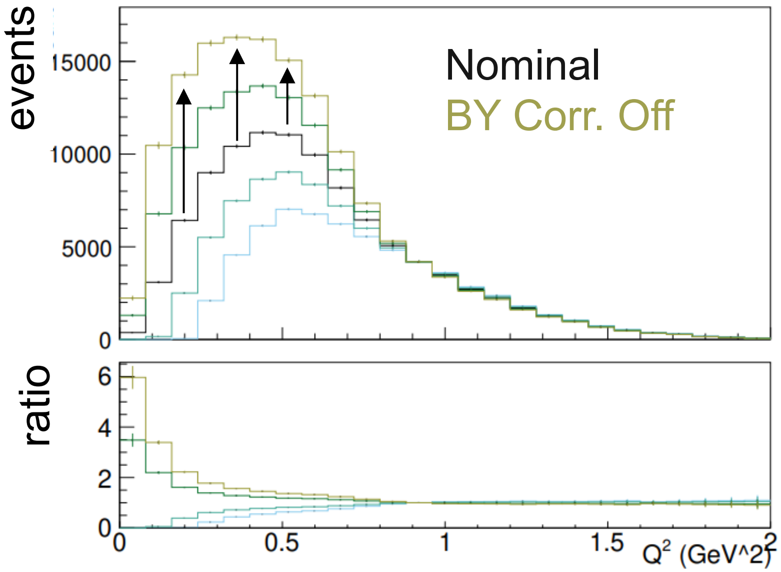
Deep/Shallow inelastic scattering

- 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





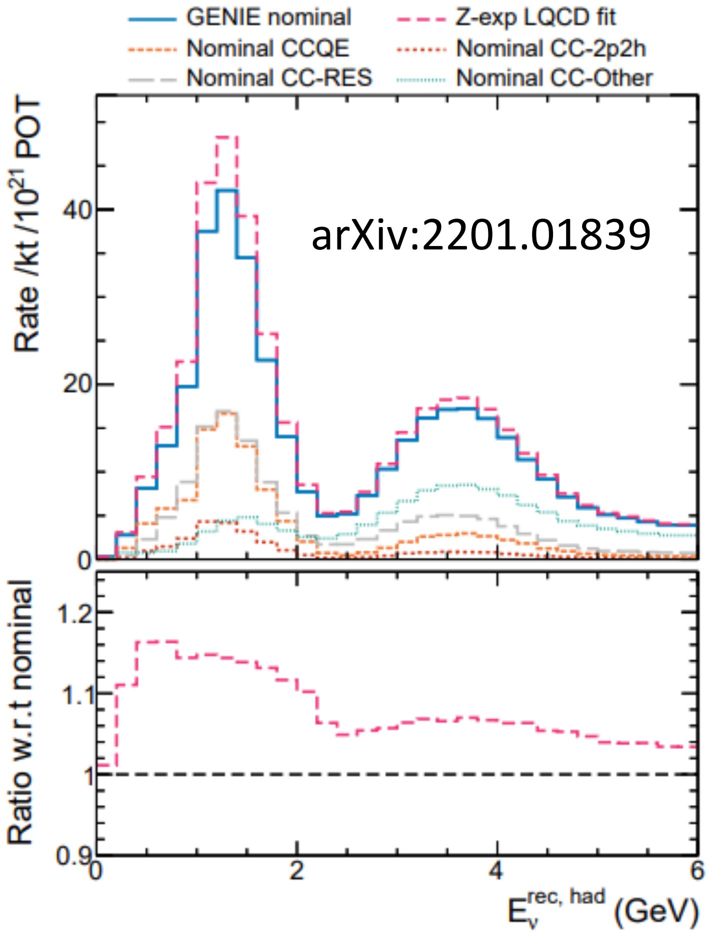
Five things we need to model

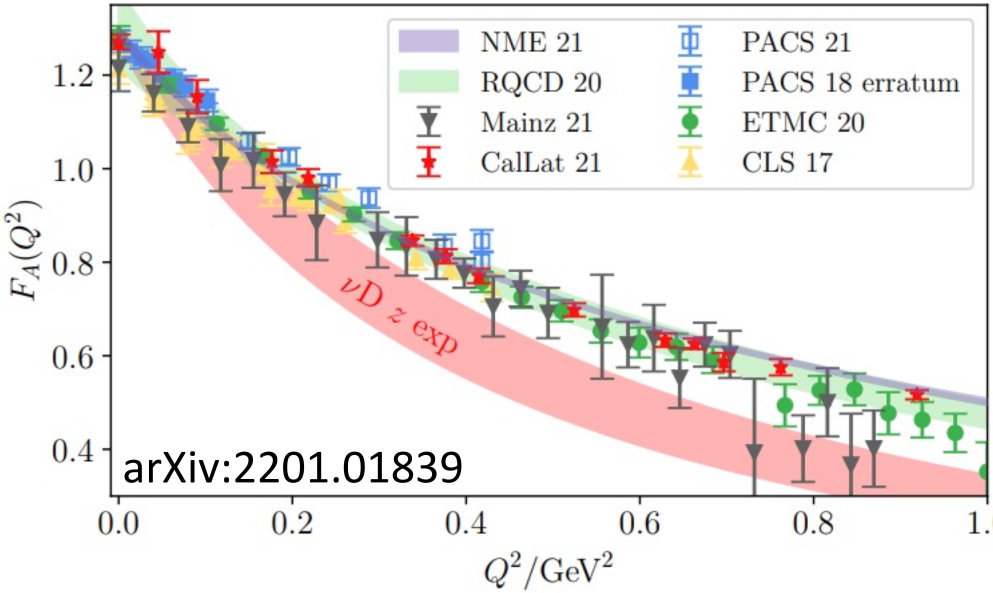
(a non exhaustive list)

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


arXiv:2201.01839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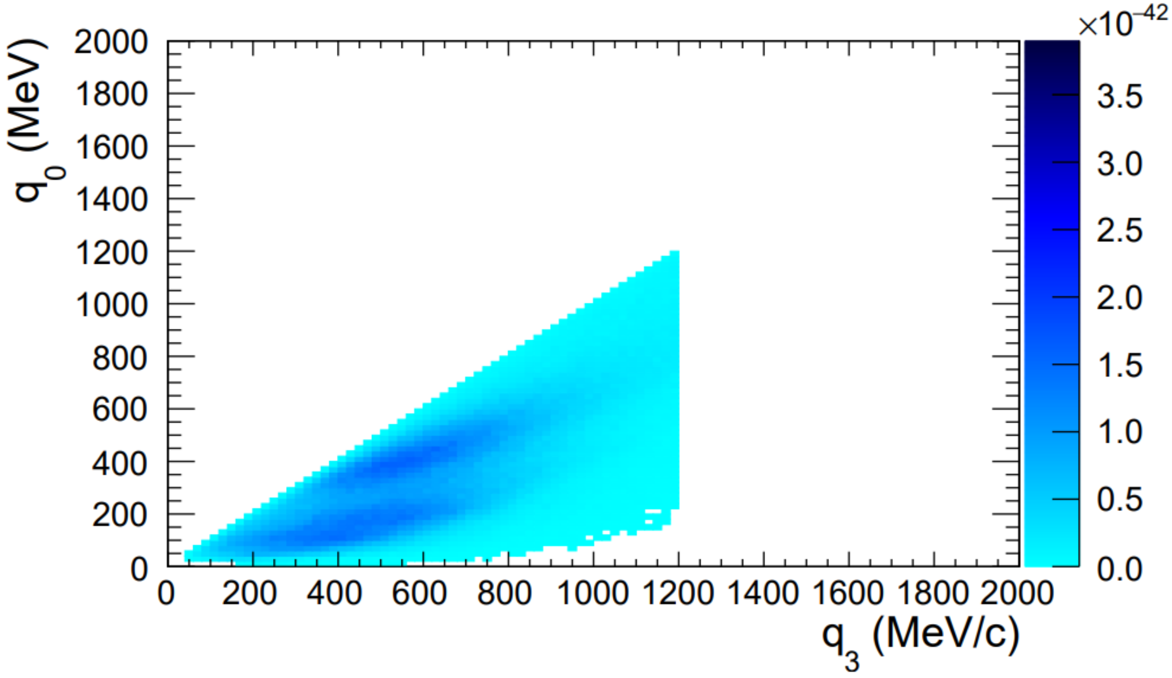
2p2h Model + Uncertainties

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

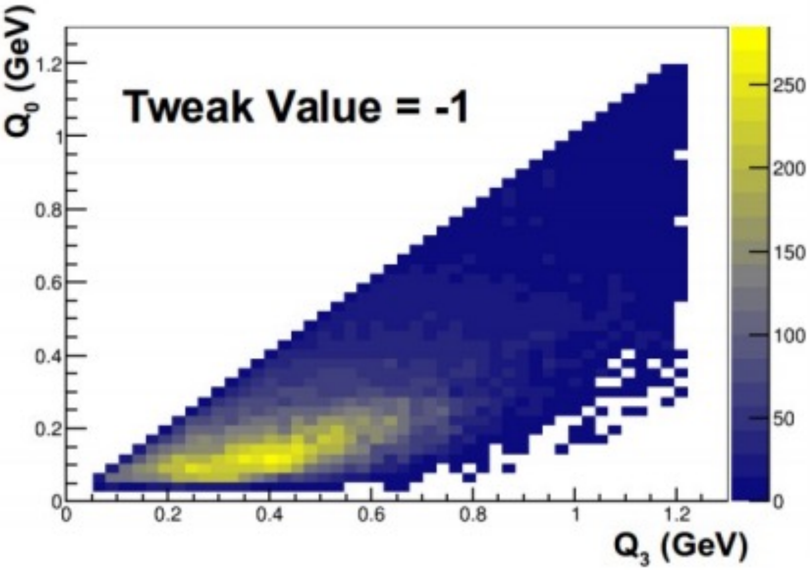


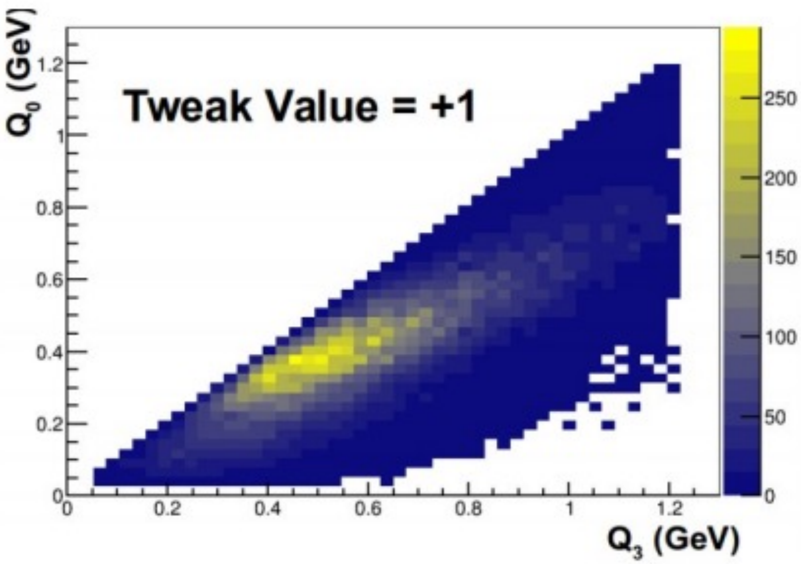
2p2h Model + Uncertainties

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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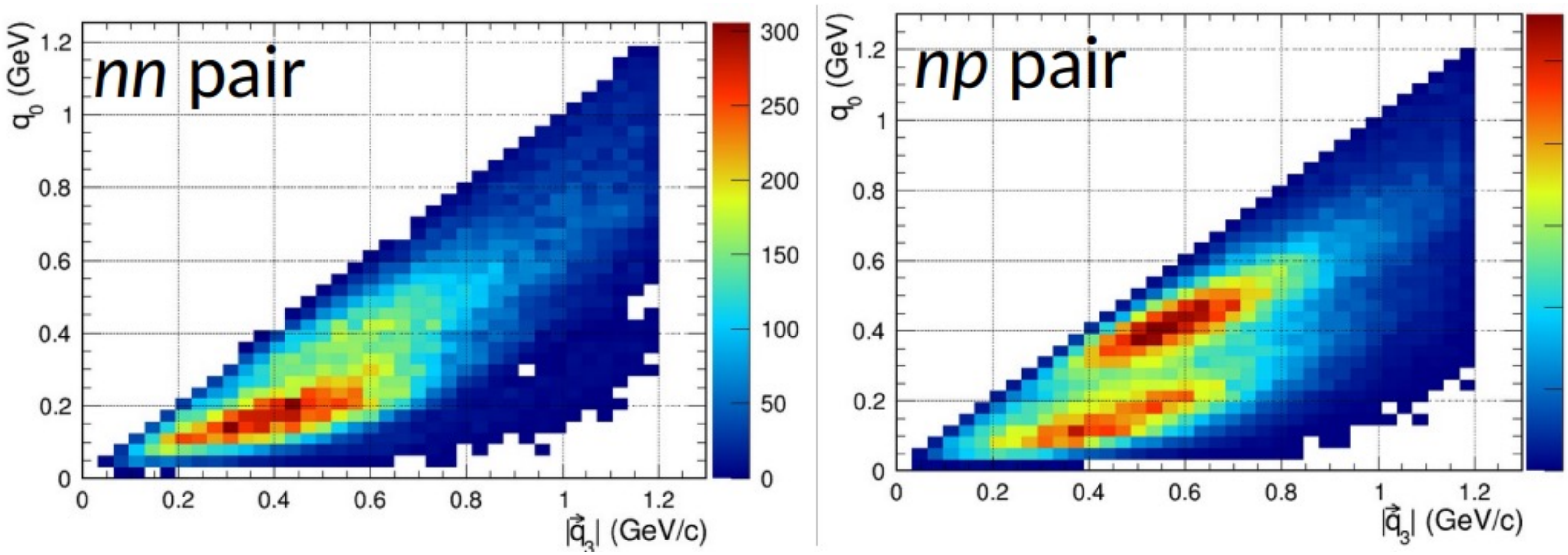
- Split the variations also by the pair type (NN vs Np)

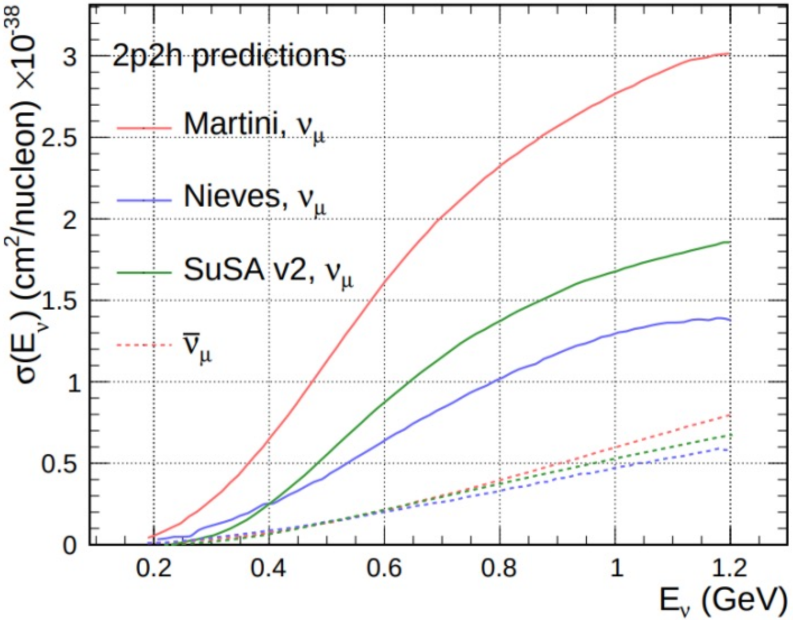


2p2h Model + Uncertainties

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

Assign uncertainties on:

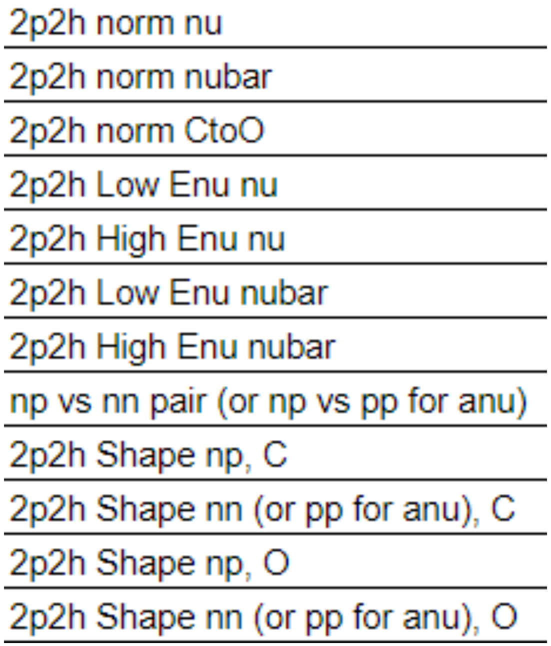
- The normalisation (separate parameters for C, O, $\nu, \bar{\nu}$)
- The shape in energy and momentum transfer (relative contribution of Δ-like and not Δ-like)
- Split the variations also by the pair type (NN vs Np)
- The neutrino energy dependence (span Martini and SuSAv2-MEC)



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)



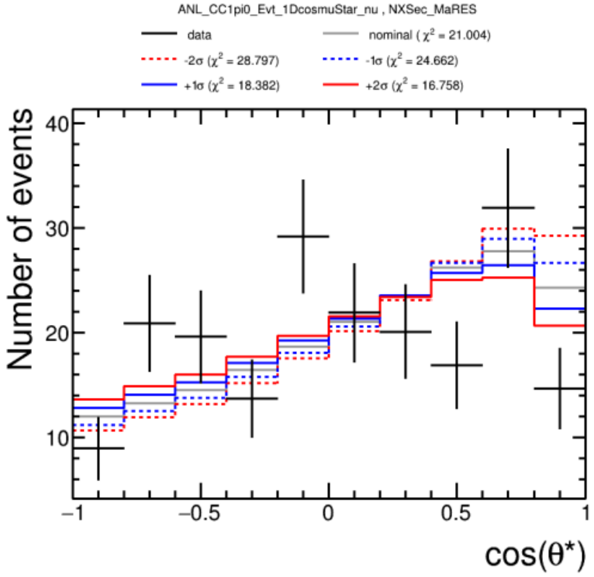
2p2h norm nu
2p2h norm nubar
2p2h norm CtoO
2p2h Low Enu nu
2p2h High Enu nu
2p2h Low Enu nubar
2p2h High Enu nubar
np vs nn pair (or np vs pp for anu)
2p2h Shape np, C
2p2h Shape nn (or pp for anu), C
2p2h Shape np, O
2p2h Shape nn (or pp for anu), O

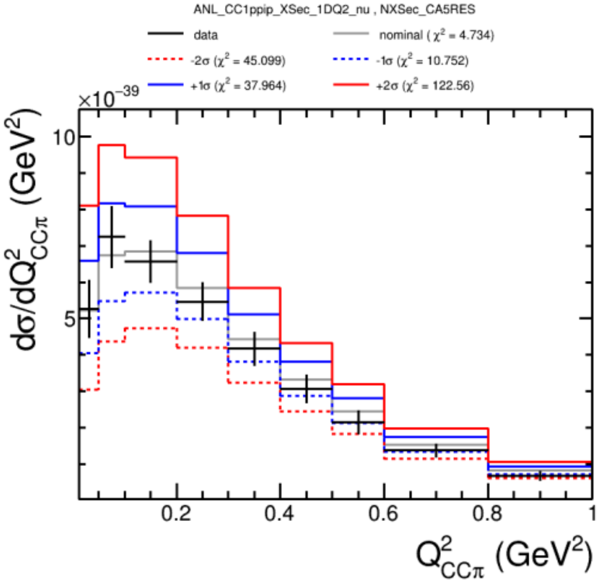
Single Pion Production

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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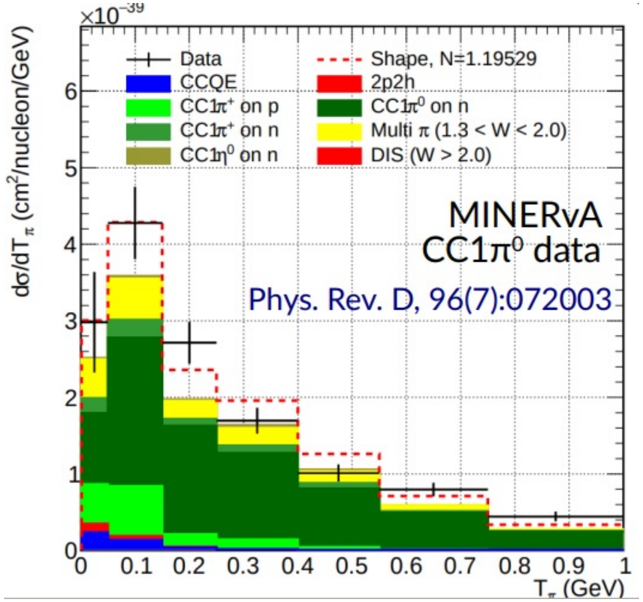
- Additional freedom for CC1π^0 normalisation based on external data



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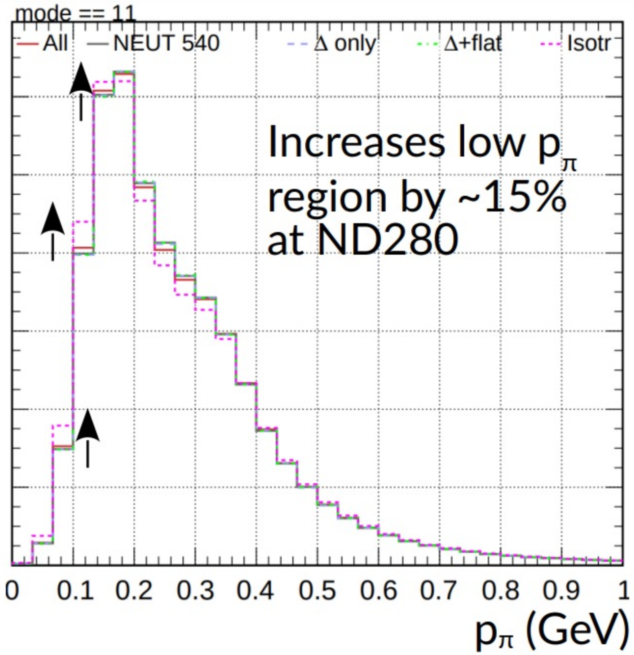
- Removal energy in CC1π (RFG-like)
- Uncertainty affecting only pion kinematics from altering the treatment of $N^* \rightarrow \pi + N$



Increases low p_π region by ~15% at ND280

Single Pion Production

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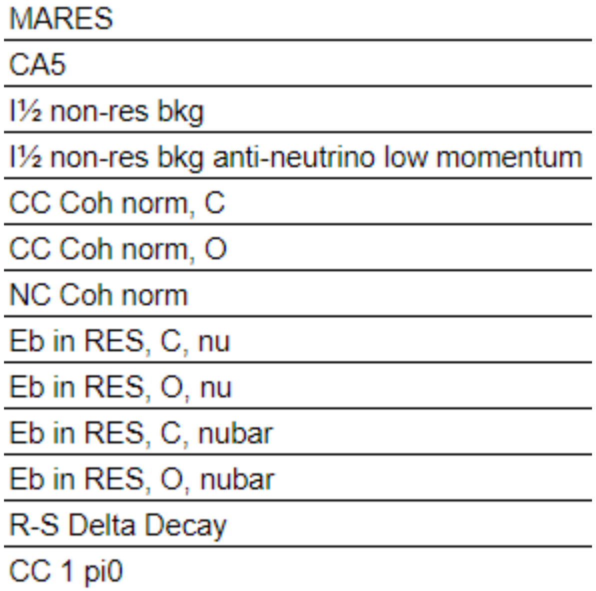
- Non resonant background normalisation
- Additional *ad-hoc* freedom for low momentum pions (<200 MeV/c)
- Additional freedom for CC1π^0 normalisation based on external data
- Removal energy in CC1π (RFG-like)
- Uncertainty affecting only pion kinematics from altering the treatment of $N^* \rightarrow \pi + N$
- 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

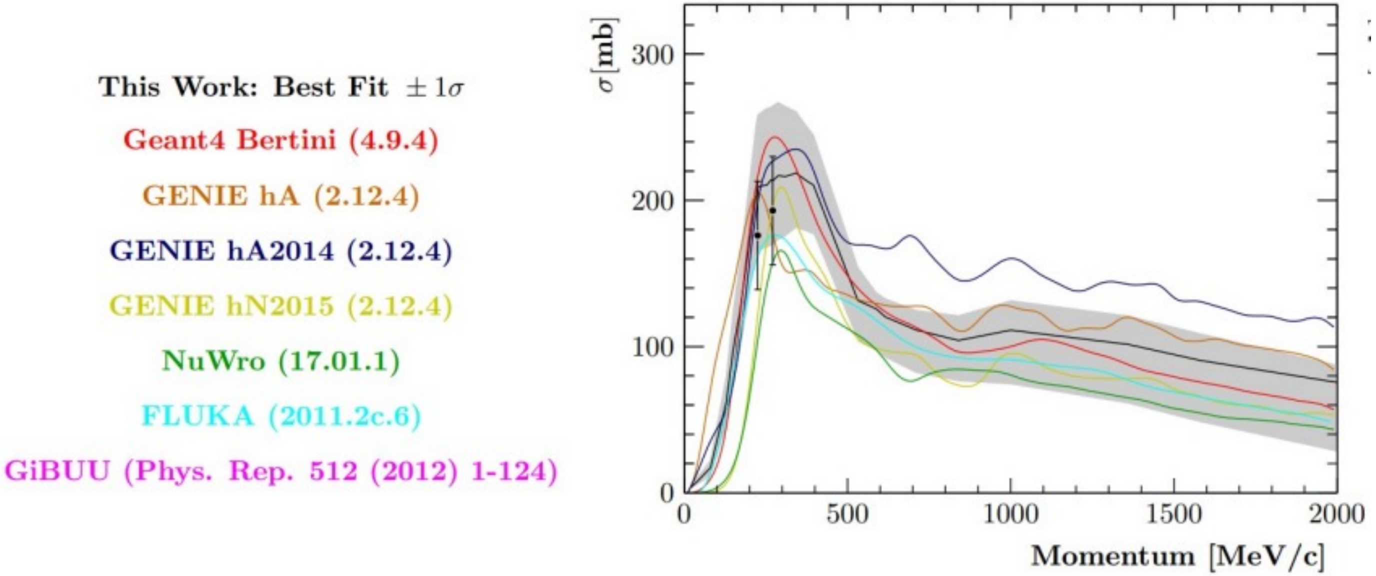


MARES
CA5
I½ non-res bkg
I½ non-res bkg anti-neutrino low momentum
CC Coh norm, C
CC Coh norm, O
NC Coh norm
Eb in RES, C, nu
Eb in RES, O, nu
Eb in RES, C, nubar
Eb in RES, O, nubar
R-S Delta Decay
CC 1 pi0

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

Final State Interactions

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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