Neutrino interaction modelling at T2K

Or, how is the sausage made?

Clarence Wret

NuFact 2021

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Outline

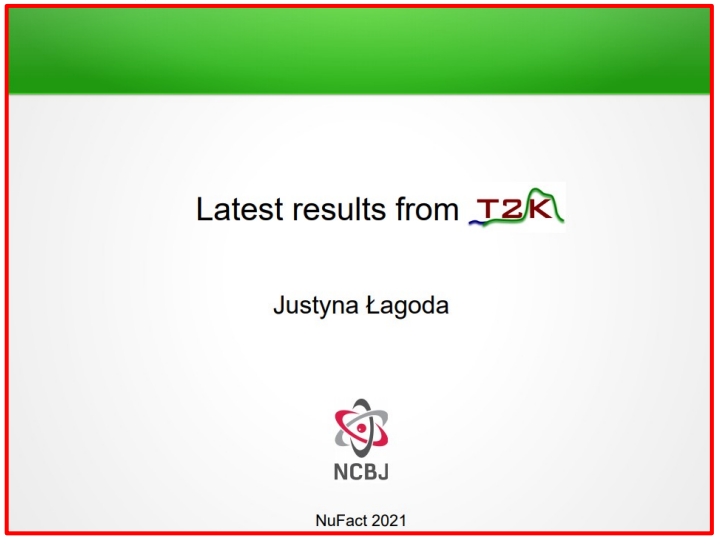
- Brief introduction to T2K
- 2020 analysis and approach to interactions
- 2021 analysis and looking to the future
- Summary

Introduction to T2K

For more info on T2K, see

Ciro's talk

Justyna's talk



Introduction to T2K

Clickable links

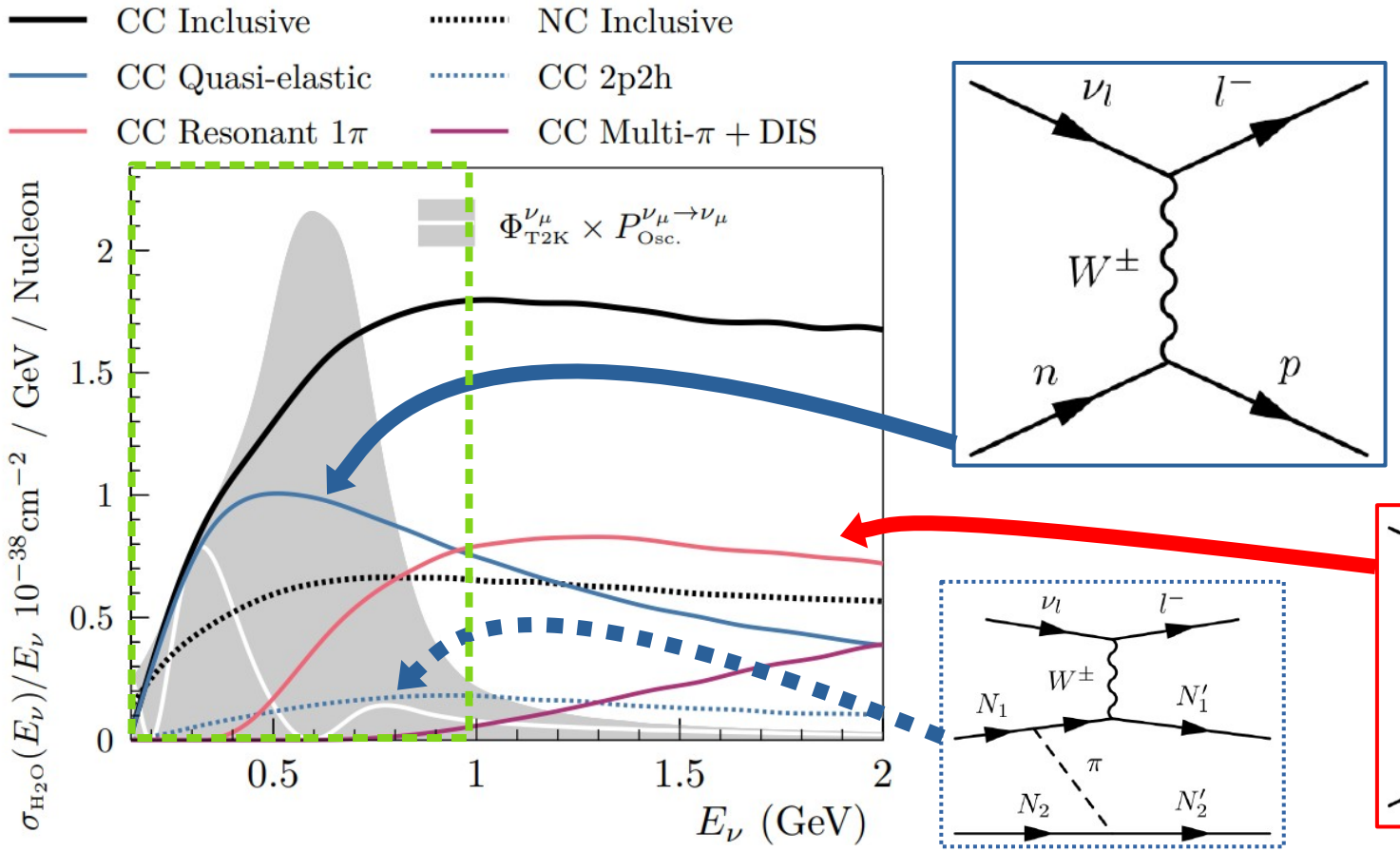
For more info on T2K, see

Ciro's talk

Justyna's talk

Introduction to T2K

- Long baseline neutrino oscillation experiment, in low GeV region (**0.6 GeV peak**), with physics-capable magnetised near-detector



For more info on T2K, see:

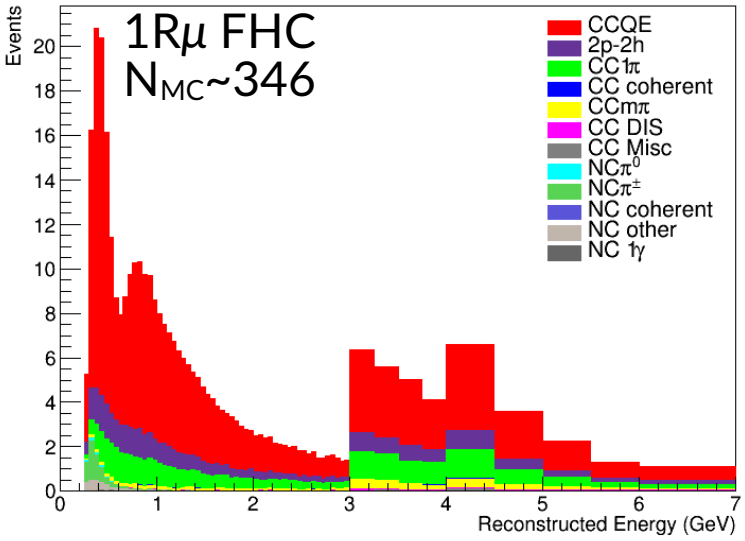
Ciro's talk

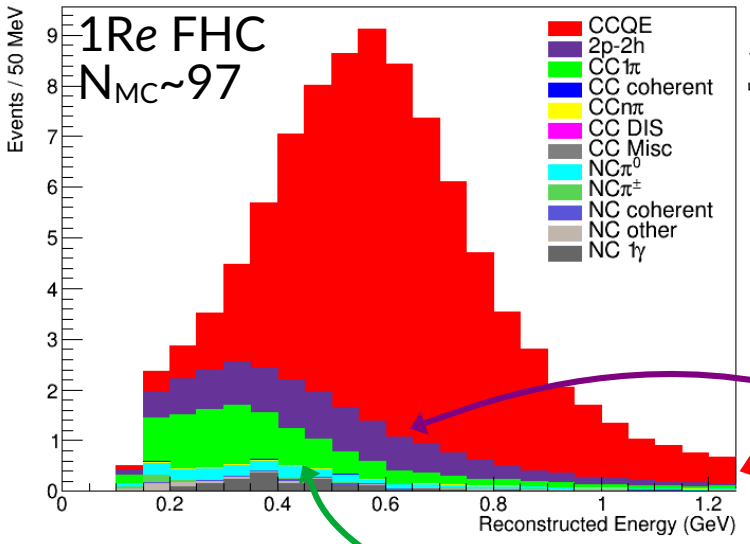
Justyna's talk

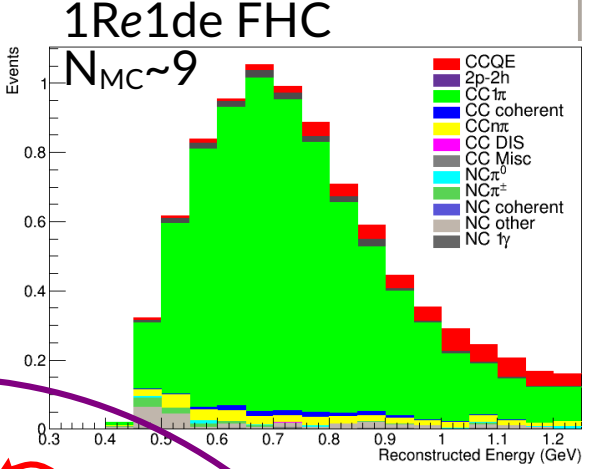
- Dominated by **CCQE** interaction, with 1π and 2p2h turning on
- NEUT generator: largely T2K, K2K and Super-K development (with commits from Nobel prize winner!) Hayato-san's talk Recent NEUT paper
  - Ability to run GENIE and NuWro for cross-section analyses; not in OA

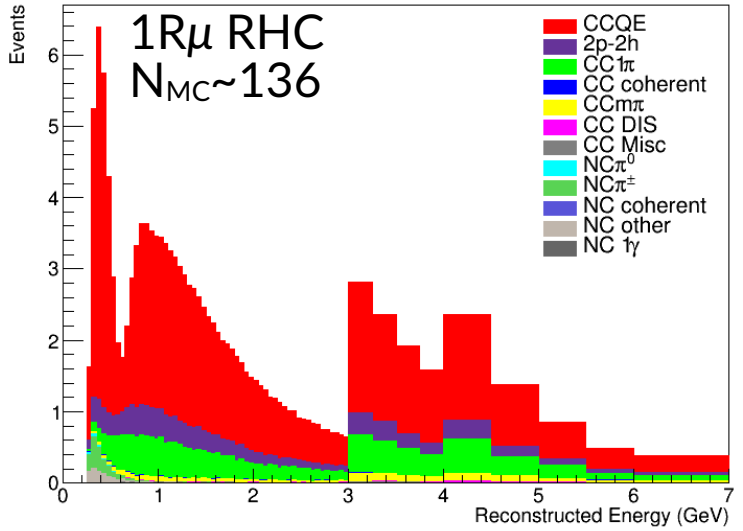
The SK selections

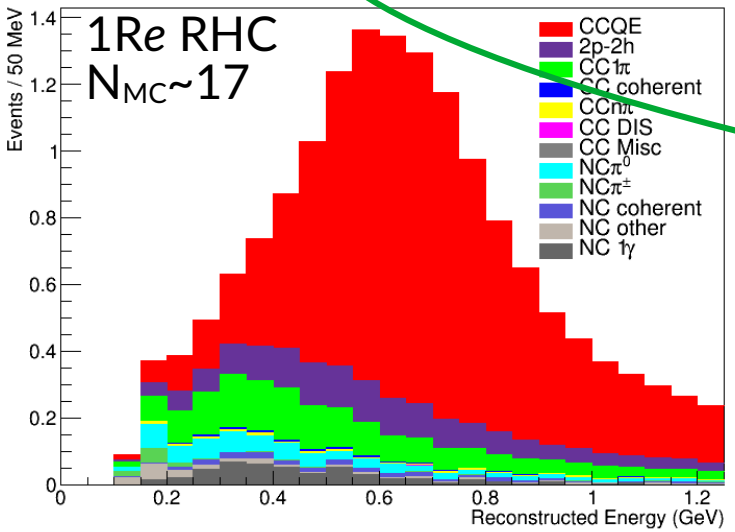
- Selections at the far-detector are **1e0π**, or **1μ0π** → further emphasise importance of CCQE interactions (limits 1π contrib.)











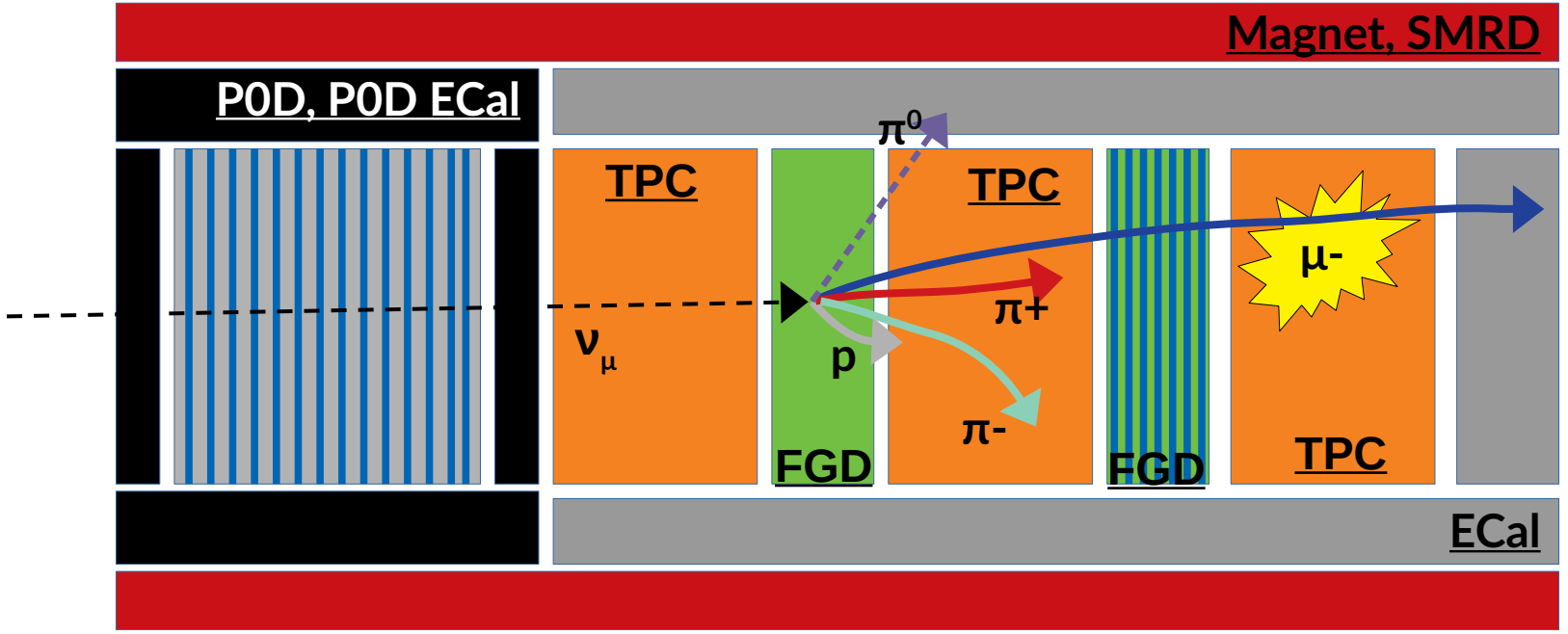
CCQE, 2p2h and 1π central to analysis

3.6x10^{21} POT (55:45 FHC:RHC; 2020 analysis), using PDG2019

The ND280 selections

- Use observable topology in detector as basis for selection: **pion multiplicity**, same as SK
- Want a selection of **CC0π** interactions: largely represents the far-detector selection and **constrains signal interaction** in OA
- Add background-enhanced selections, e.g. CC1$\mu^-1\pi^+$, or CC1$\mu^-0\pi$ in anti-ν_μ mode (wrong-sign): **constrain backgrounds** in OA

ND280 side-view



- Interaction model systematics **focus on 0π**, but also need adequate model of background contributions

Model building at T2K

- Choose a **baseline model** for the analysis production
  - Model needs to be implemented in NEUT
  - Justifiable uncertainties from theory, e.g.
    - M_A^{QE} has some uncertainty from bubble chambers: allow variation
    - 2p2h predictions from Martini, Nieves, SuSAv2 differ → introduce uncertainties to cover differences
  - Introduce extra uncertainties when have little theory guidance, or when we can't adequately model external data
    - e.g. MINERvA, MiniBooNE, T2K cross-section results
- Use **alternative models** as "simulated data" to see how OA constraint changes if nature is explained by alternative model
  - Model directly from theory: e.g. z-expansion axial form factor, 2p2h model by SuSAv2 or Martini et al, single pion production model by M. Kabirnezhad
  - Data-driven simulated data: e.g. compare pion momentum spectrum (not fitted) at ND280, and devise scaling so data at ND matches; what is effect on OA?
  - This procedure **inflates our uncertainties** on oscillation parameters

The 2020 interaction model

Paper in preparation

ΔN/N for SK selections after (before) fit to ND280 data

Selection		Flux	Error source (%) Int.	SK det.	Total (%)
1Rμ	ν_μ	2.9 (5.1)	3.1 (10.1)	2.1 (2.9)	3.0 (11.1)
	$\bar{\nu}_\mu$	2.8 (4.7)	3.0 (10.1)	1.9 (2.5)	4.0 (11.3)
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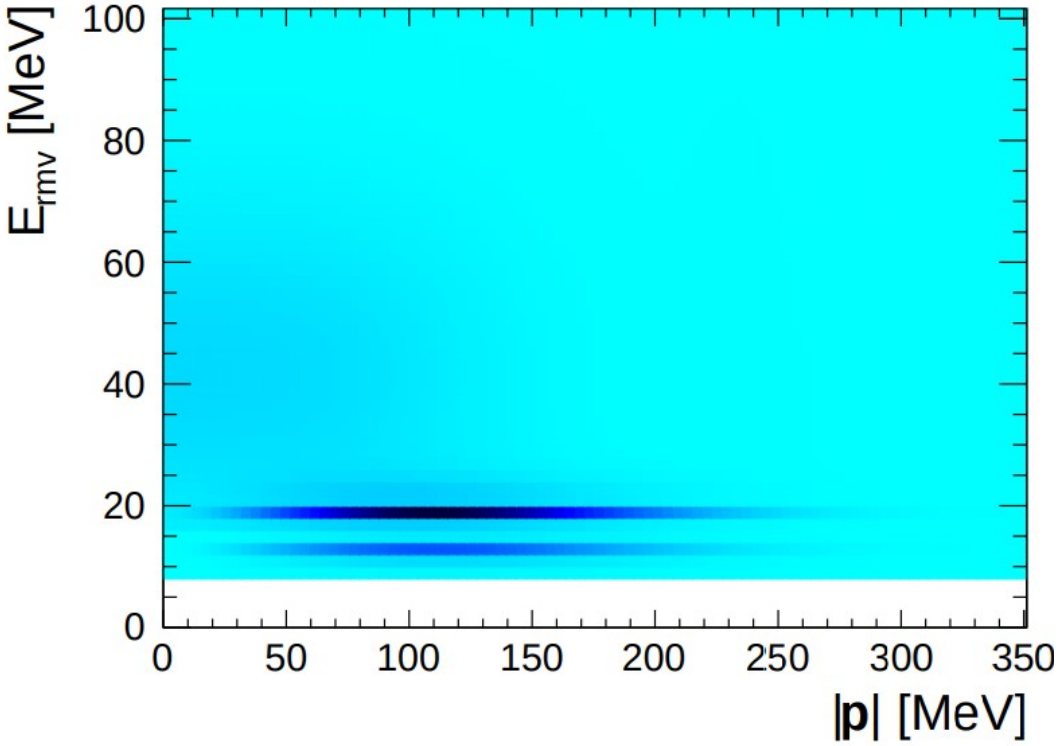
1Re1de	ν_μ	2.8 (4.9)	4.2 (12.0)	13.4 (13.4)	14.3 (18.7)

Don't add in quadrature to give total, see backups

CCQE model

- Start with CC0π model:
  - Initial state model, CCQE model and form factors, 2p2h model, final state interactions
- Benhar spectral function model: models shell features of nucleus

Nucl. Phys. A, 579, 3–4



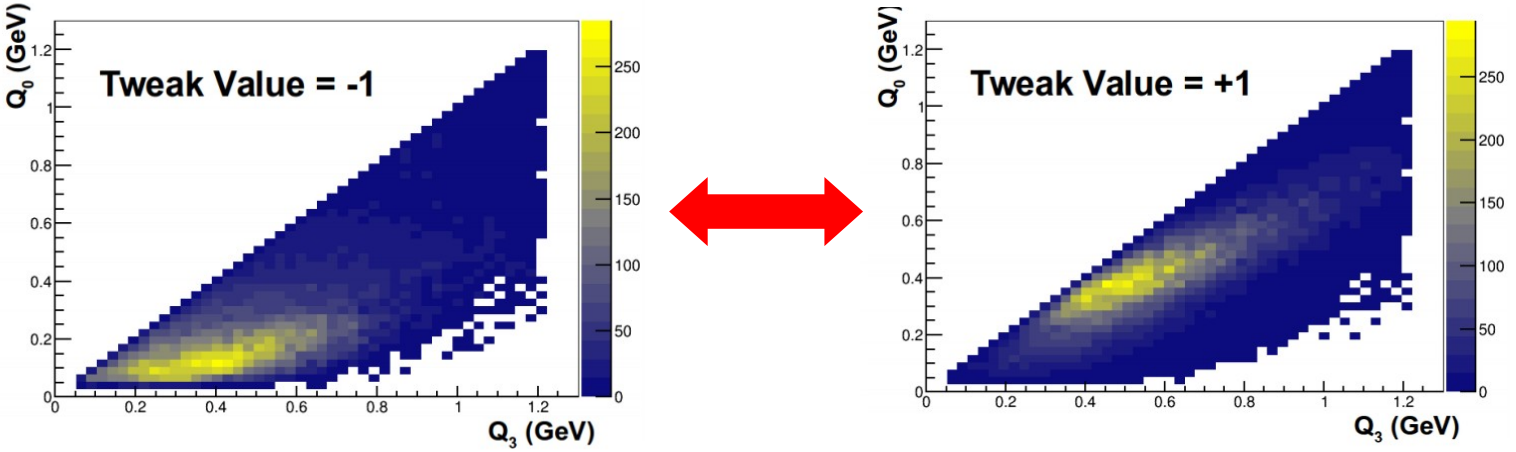
- Develop in-house binding energy treatment, allowing removal energy to vary
  - Directly affects outgoing lepton kinematics
- BBA05 vector form factors, and dipole axial form factor, tuned to ANL/BNL nucleon data

- CCQE Q^2 normalisation parameters: little guidance on low-Q^2 suppression, and adds flexibility to cover different axial form factors
  - Inform by comparing to external T2K and MINERvA CC0π data

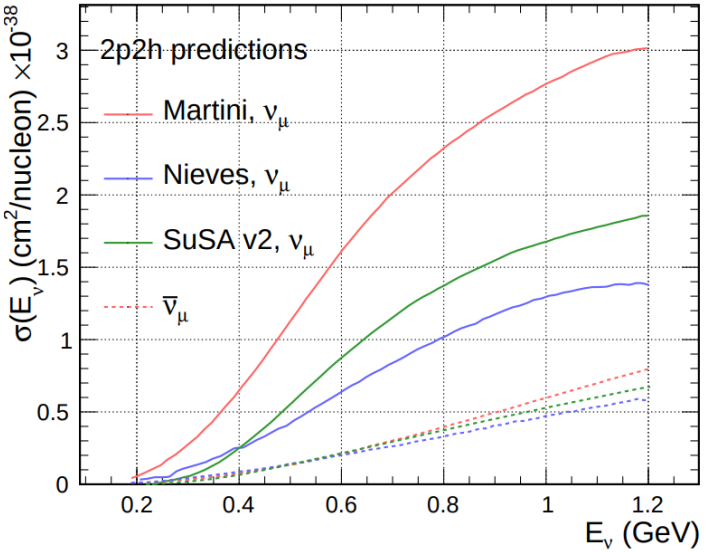
Phys. Rev. D 93, 112012 Phys. Rev. D 99, 012004

2p2h model

- Valencia model for 2p2h, with added uncertainties
  - Shape variation in (q_0,$|\mathbf{q}_3|$) for Δ and non-Δ dominated



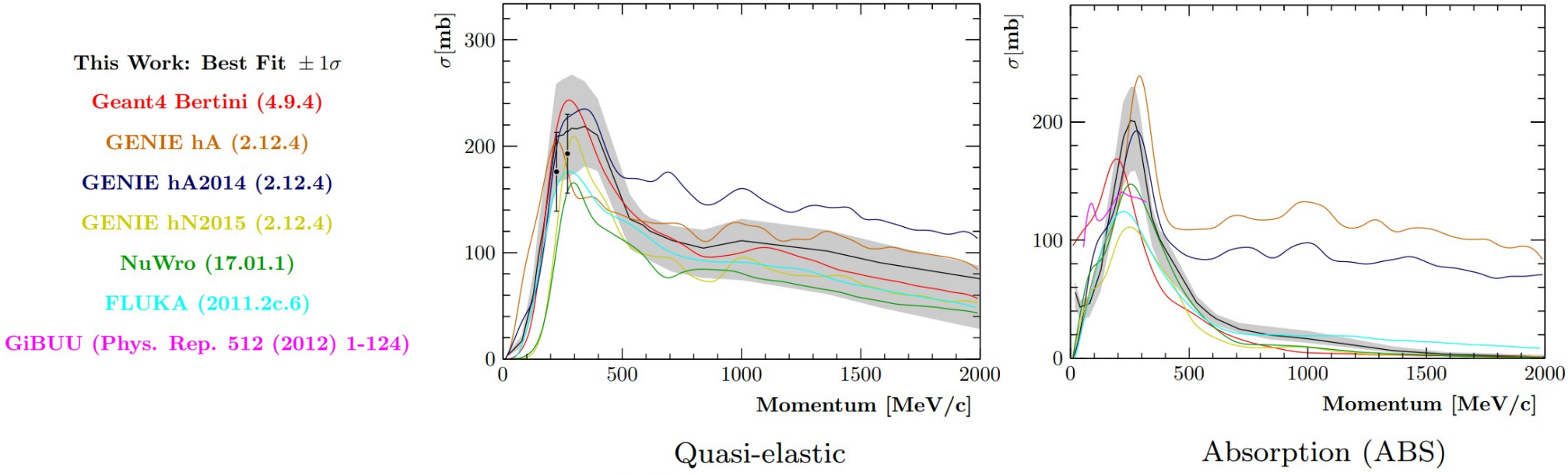
- Completely separate ν and anti-ν 2p2h normalisation parameters
- Allow additional 20% variation of norm. of 2p2h on ^{12}C vs ^{16}O
- Shape freedom from differences in Martini, Nieves and SuSAv2 2p2h predictions
  - Separated in low and high E_ν, ν and anti-ν



Phys. Lett. B, 707, 1
Phys. Rev. C 80, 065501
Phys. Rev. D 94, 093004

Pion model

- Pions enter CC0π by either absorbed in nucleus, or missed in detector
  - Resonance excitation modelled with Rein-Sehgal, with lepton mass corrections and Δ(1232)-focussed form-factors
  - In-house tune to ANL and BNL CC1π data, with error inflation to cover MiniBooNE and MINERvA CC1π data
- Pion final state interactions by Salcedo-Oset cascade, tuned to world π-A scattering data Phys. Rev. D 99, 052007 (2019)



- Multi-π and DIS model updated with new multiplicity uncertainty, Bodek-Yang on/off (40% effect at peak Q^2), overall scaling factors to match high E_ν CC-inclusive data for ν_μ and anti-ν_μ

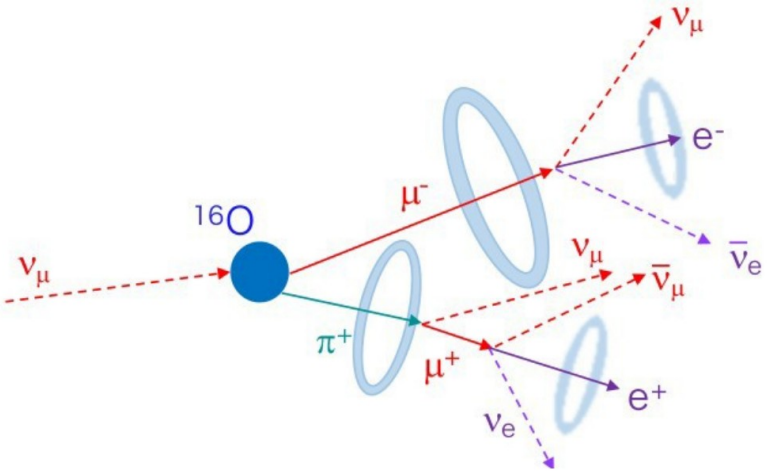
The 2021 interaction model

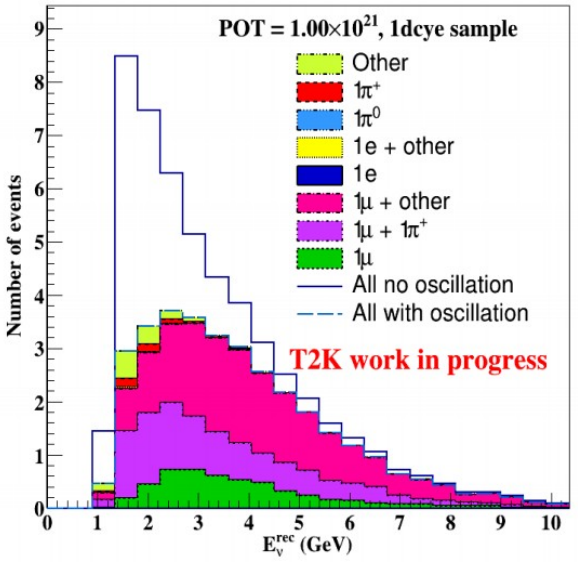
Responding to the 2021 T2K analysis improvements
by revisiting the 2020 interaction model

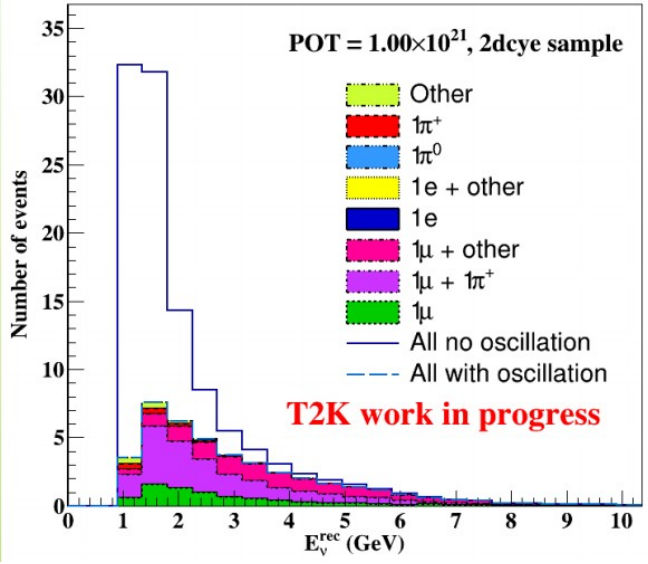
Analysis improvements

Justyna's talk
Kamil's poster

- Introducing **2-ring events** for muon selections in ν_μ-mode





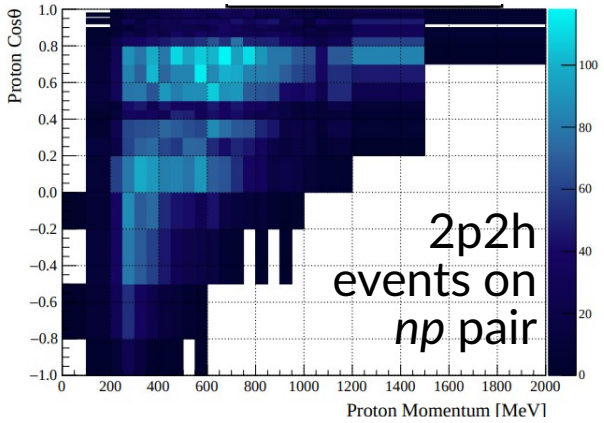


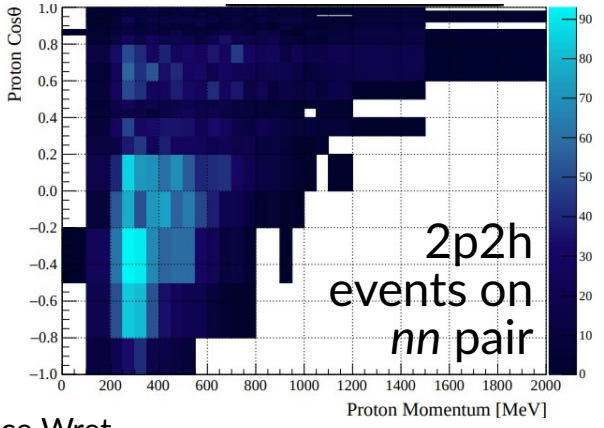
  - Requires developing new interaction systematics for pion production
- ND280 introducing **photon-tagged** selection to better separate multi-π and DIS from photon contributions (both used to be tagged in "CCOther" sample)
  - Updated multi-π and DIS uncertainties, and dedicated $CC1\pi^0/CC1\pi^+$ scaling parameter, informed by external data
- ND280 separating CC0π selection into **CC0π0p** and **CC0πNp**
  - Proton multiplicity systematics, like *pn*/*nn* fractions, Pauli blocking effects, Spectral Function systematics from s and p-shells, nucleon FSI

CCQE and 2p2h improvements

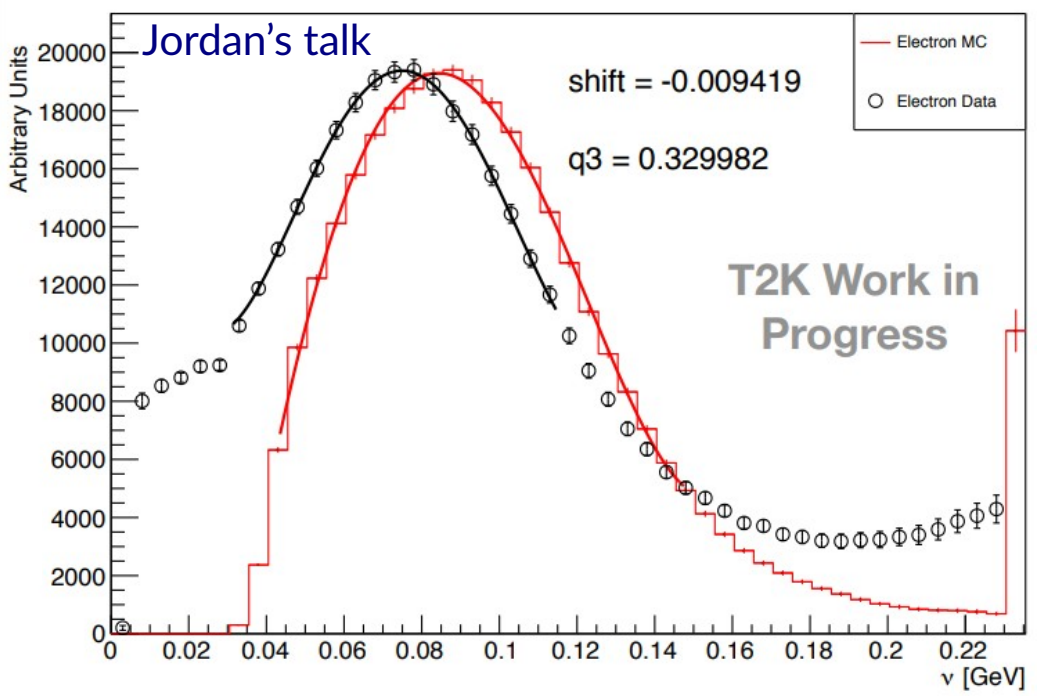
- New $|\mathbf{q_3}|$-dependent **removal energy** treatment from comparing NEUT to electron scattering data

- 2p2h interactions on ***np*** **or** ***nn*** pairs has significant impact on proton kinematics, so also the detection capability of 0p/Np

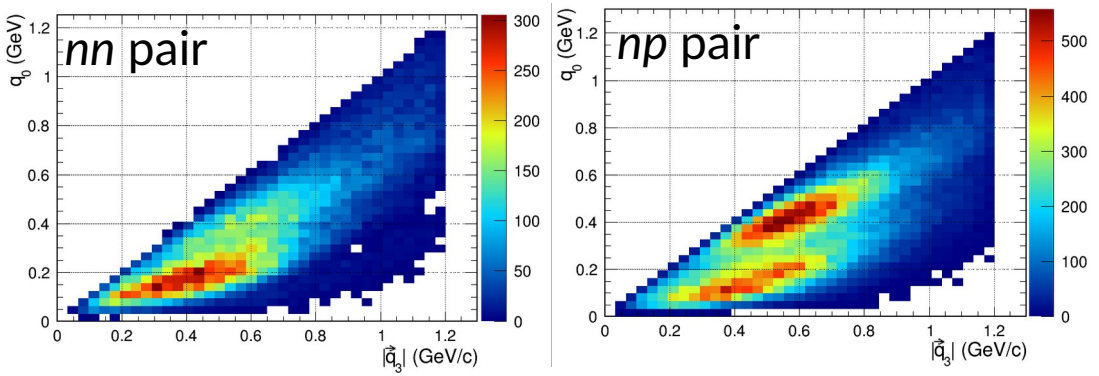




Highest mom. proton cand.



- Split old 2p2h shape parameter into ***np*** **and** ***nn*** contributions, since (q_0, $|\mathbf{q_3}|$) population is different

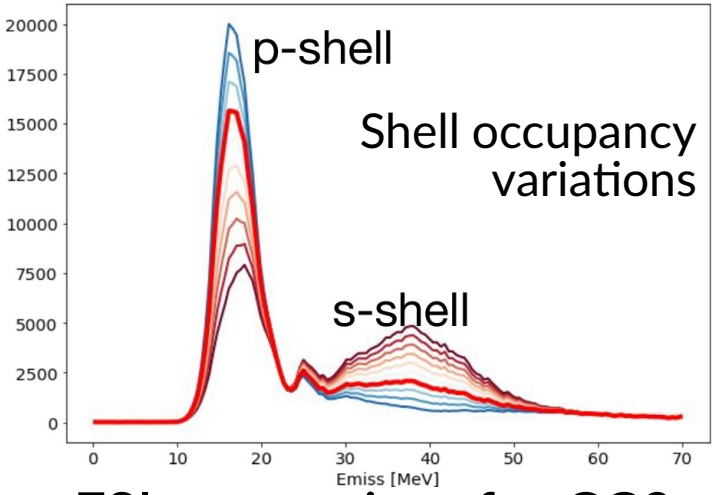


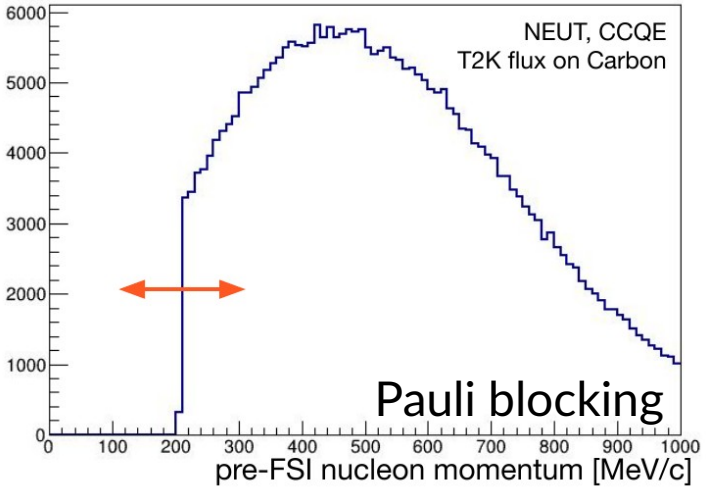
CCQE and 2p2h improvements

- Removing the empirical low Q^2 suppression in favour of theory motivated uncertainties

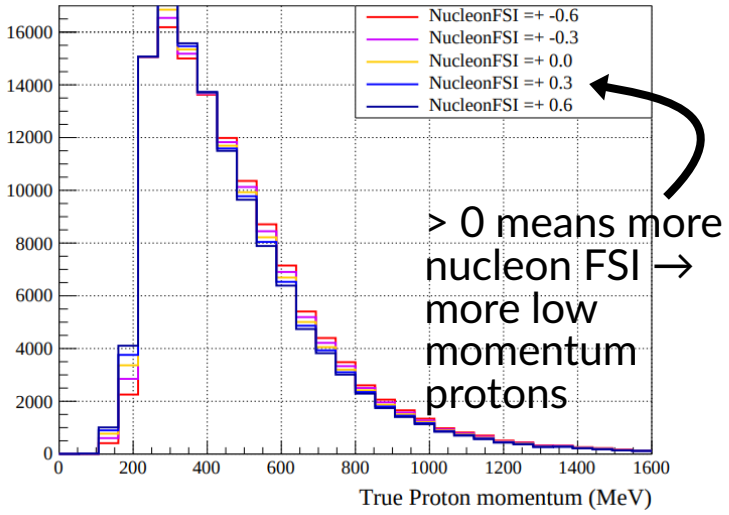
  Jaafar's talk
  Recent ND280 upgrade physics paper

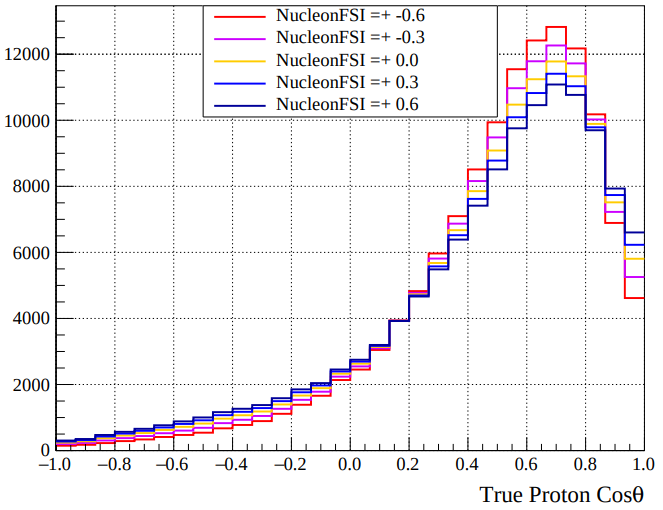
  - p-shell, s-shell occupancy, optical potential, short range correlations, Pauli blocking uncertainties





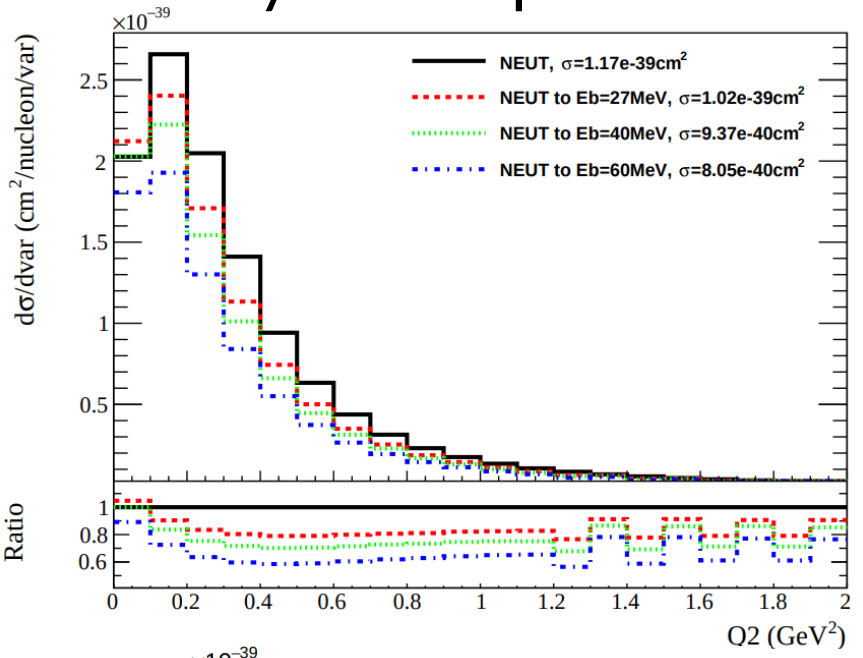
- Nucleon FSI uncertainty for CC0π0p/Np split

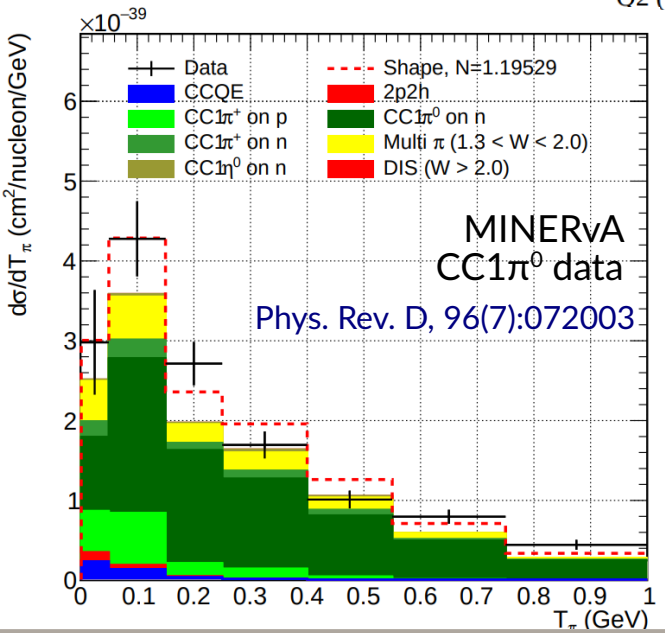




CC1π improvements

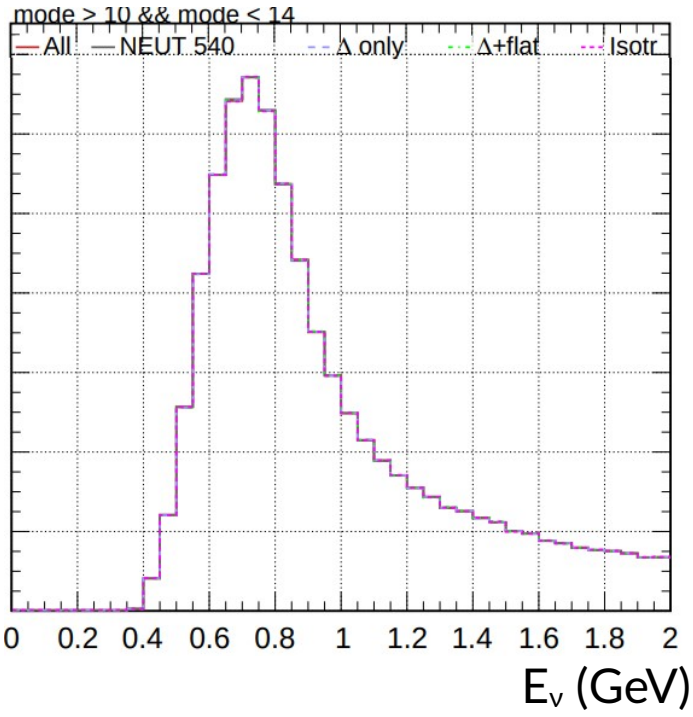
- Effect of binding energy in Relativistic Fermi Gas gauged from NuWro comparisons: dedicated uncertainty developed
- Studied effect of Pauli blocking, which was much smaller than binding energy: no dedicated uncertainty
- Survey of global CC1π^0, CC1π^+ and CC1π^- data showed CC1π^0 often under-estimated in NEUT
  - Concern that ND photon sample could be driven by CC1π^+ data
  - Much better described when allowing a relative CC1π^0 normalisation parameter
  - Physics origin could be Rein-Sehgal, or FSI, or nuclear effects, or all? Empirical parameter for now

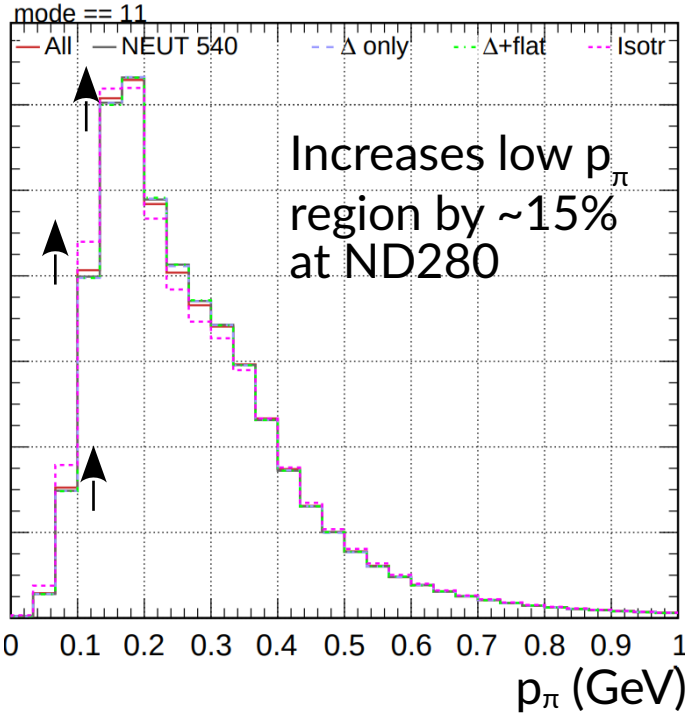




CC1π improvements

- Another survey of global data found no low-Q^2 suppression required, with the exception of MINERvA CC1π^0
  - Study effect of low Q^2 suppression through simulated data study
- Shape of pion kinematics barely changes under 2020 systematics
  - Developed uncertainty from treatment of $N^* \rightarrow \pi$+N, including no resonances (flat), $\Delta(1232)$-only, and multiple resonances





  - Invariant in lepton variables and cross-section constant → lepton kinematics can't constrain pion kinematics

Summary

- T2K's interaction model has been iterated on for every analysis the last four oscillation analyses
  - Adding new selections at ND280 and SK can mean stronger constraints, but have to carefully evaluate our related systematics to avoid over-fitting
  - Grateful to neutrino interaction community for model guidance and advice as we move towards precision oscillation measurements
- Interaction model challenges grow as the selections become more sophisticated (e.g. multi-ring ν_e), joint fits are pursued (e.g. T2K-SK, T2K-NOvA brings in higher E_ν), and our statistics increase
- Presented overview of T2K's approach, and outlined the models in the finalised 2020 analysis, and the maturing 2021+ analysis
- NEUT seeing multiple improvements in near future
  - SuSAv2 CCQE and multi-nucleon model, Nieves 1p1h model, Kabirnezhad single pion model updates, Sato et al. single pion model
  - Model development central to T2K: predictive semi-inclusive models, and low Q^2 (q_0) physics, especially for Quasi-Elastic-like events
  - (anti-)ν_e/ν_μ differences: currently large conservative systematic

Hayato-san's talk

Recent NEUT paper

Thank you!

More details at NuFact 2021:

Jaafar's talk: Parametrising CCQE uncertainties in the Spectral Function model for neutrino oscillation analyses

Jordan's talk: Is T2K missing energy? Searching the electron-scattering data archives for robust removal energy uncertainties

Hayato-san's talk: NEUT strategy

Kamil's poster: Expanding T2K near detector fit by adding proton information

Viet's poster: Physics studies for the ND280 upgrade in the T2K experiment

Ciro's talk: Results from T2K

Justyna's talk: Latest results from T2K

Backups

Correlations after fit to ND data

- Near detector fit considerably correlates flux and interaction parameters, meaning the error sources don't add in quadrature

Selection		Error source (%) Flux	Int.	SK det.	Total (%)
1Rμ	ν_μ	2.9 (5.1)	3.1 (10.1)	2.1 (2.9)	3.0 (11.1)
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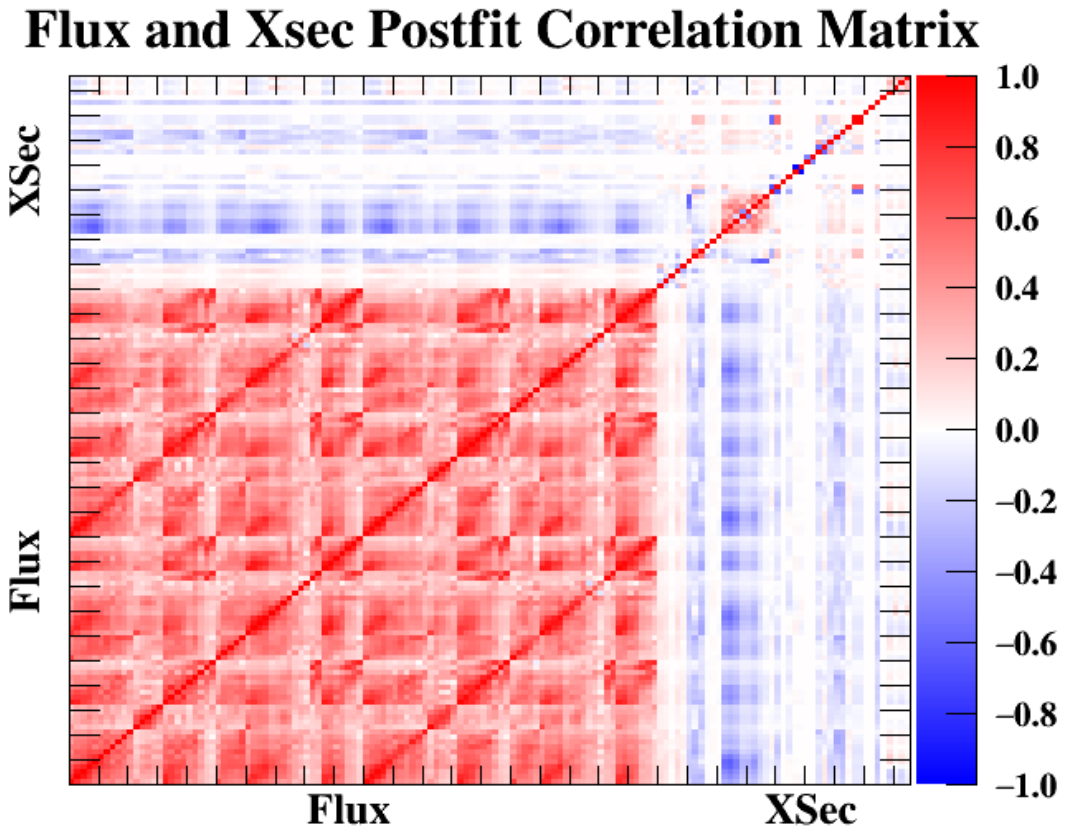

T2K Preliminary

Dedicated ν_e uncertainties

- Separate normalisation for ν_e and anti-ν_e, with a correlated part, from Phys. Rev., D86:053003, 2012; 2.8% with -0.5 correlation
- Also have a Coulomb screening effect, which shifts the reconstructed momentum by

Target	μ^-	μ^+
Carbon	-3.6 MeV	+2.6 MeV
Oxygen	-4.3 MeV	+3.3 MeV

and does not apply to electrons