Impact of neutrino interaction uncertainties on T2K physics measurements

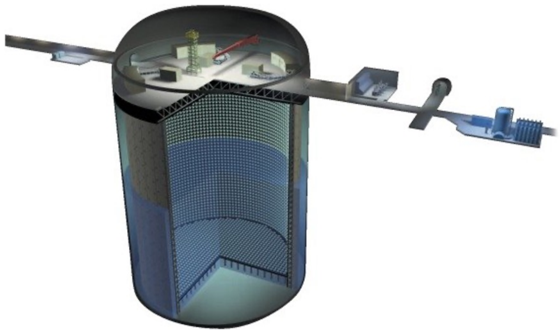
Laura Munteanu on behalf of the T2K experiment

NuInt 2024, São Paulo, Brazil

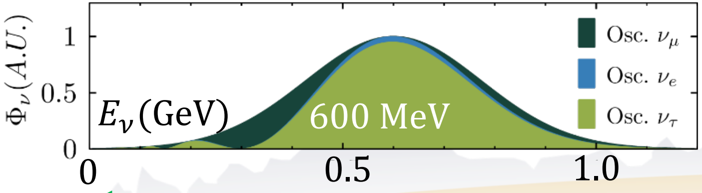
15 April 2024

The T2K Experiment

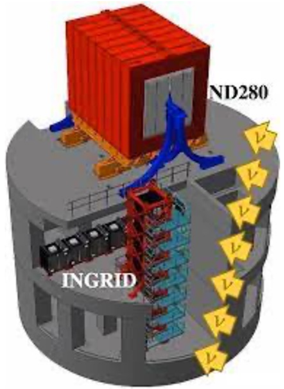
Far detector: Super-Kamiokande



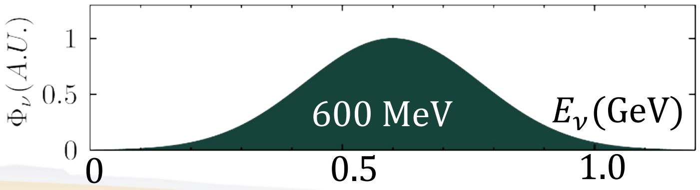
$$N_{\nu_{\mu/e}}(E_\nu) = P_{\nu_\mu \to \nu_{\mu/e}}(E_\nu)\Phi(E_\nu)\sigma(E_\nu)\epsilon(E_\nu)$$

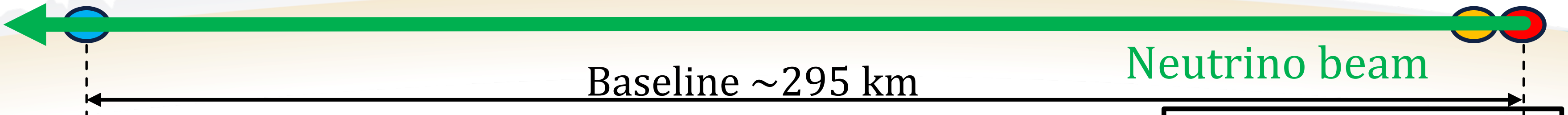


Near detector complex



$$N_{\nu_\mu}(E_\nu) = \Phi(E_\nu)\sigma(E_\nu)\epsilon(E_\nu)$$





See L. Machado's talk

T2K physics program

Neutrino oscillations

Nature 580, 339–344 (2020)

Eur. Phys. J. C **83**, 782 (2023)

Eur. Phys. J. C (2023) 83:782
https://doi.org/10.1140/epjc/s10052-023-11819-x

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Experimental Physics

Measurements of neutrino oscillation parameters from the T2K experiment using 3.6 × 10^{21} protons on target

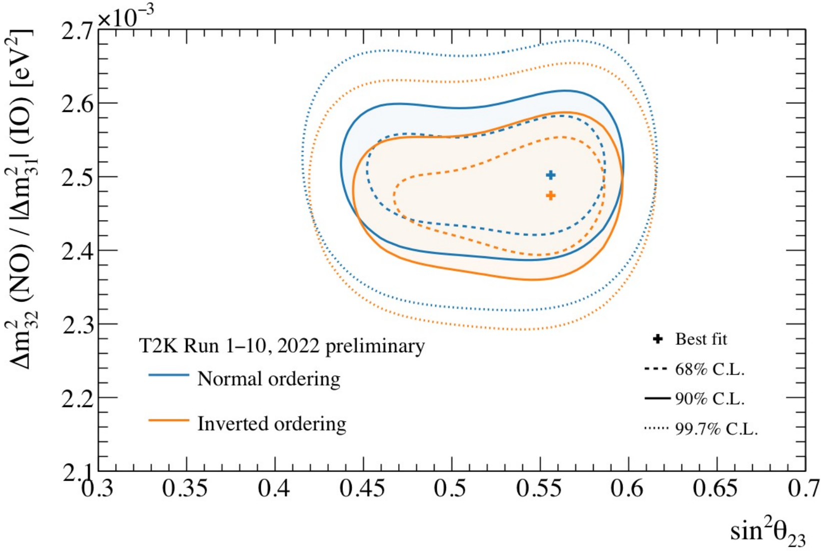
T2K Collaboration

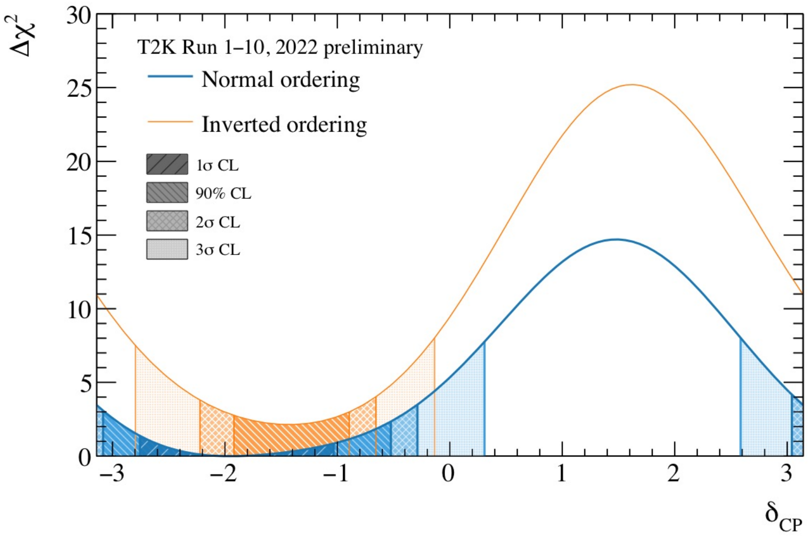
Exotic searches

Neutrino cross-sections

See talks by
S. Dolan
C. Jesús-Valls

Latest oscillation results





Measuring neutrino oscillations with T2K

- Oscillation parameters are inferred from event spectra **as a function of reconstructed neutrino energy**

Systematic uncertainties

$$N_{\nu_\beta}(E_\nu^{reco}) = P_{\nu_\mu \to \nu_\beta}(E_\nu^{true})\Phi(E_\nu^{true})\sigma(E_\nu^{true})\epsilon(E_\nu^{true})S(E_\nu^{true}, E_\nu^{reco}) \qquad \beta = e, \mu$$

Oscillation parameters

Neutrino flux

Interaction cross-section

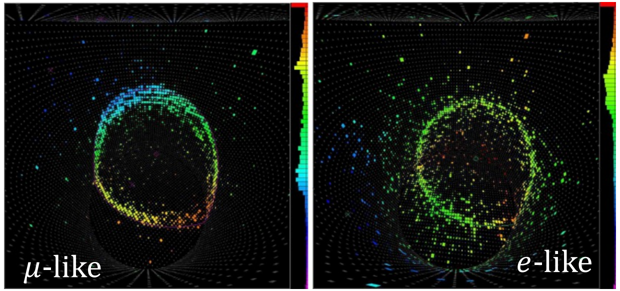
Detection efficiency

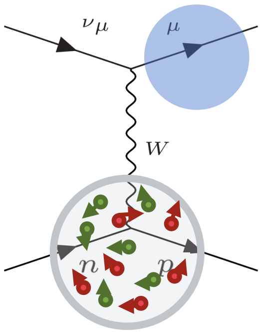
Energy smearing matrix

- Constrain systematics with **near detector**
- But **heavily rely on models** to predict near-to-far detector **extrapolation and neutrino energy smearing**

Measuring neutrino oscillations with T2K

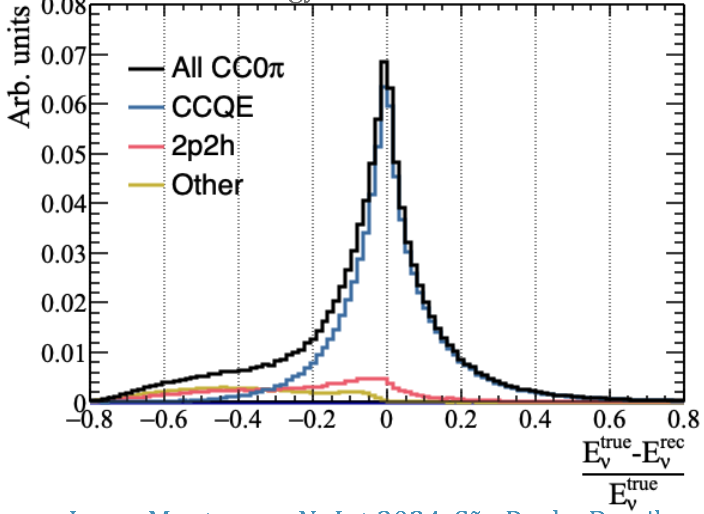
Oscillated neutrino event rates as a function of neutrino energy measured with SK – water Cherenkov detector





Infer neutrino energy using **lepton information** under 2-body reaction assumption

Neutrino energy bias



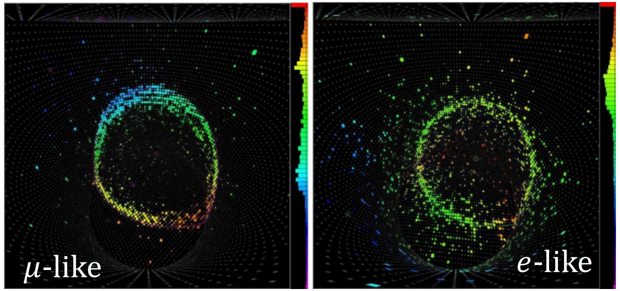
Need to control: (1st order)

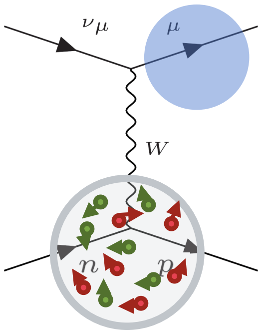
- Shape of **Fermi motion**
- Proportion of **QE vs non-QE** processes
- **Physics beyond PWIA**
- **Energy dependence** of the cross-section (due to oscillations)
- **A-scaling** (C and O)

PWIA: Plane Wave Impulse Approximation

Measuring neutrino oscillations with T2K

Oscillated neutrino event rates as a function of neutrino energy measured with SK – water Cherenkov detector





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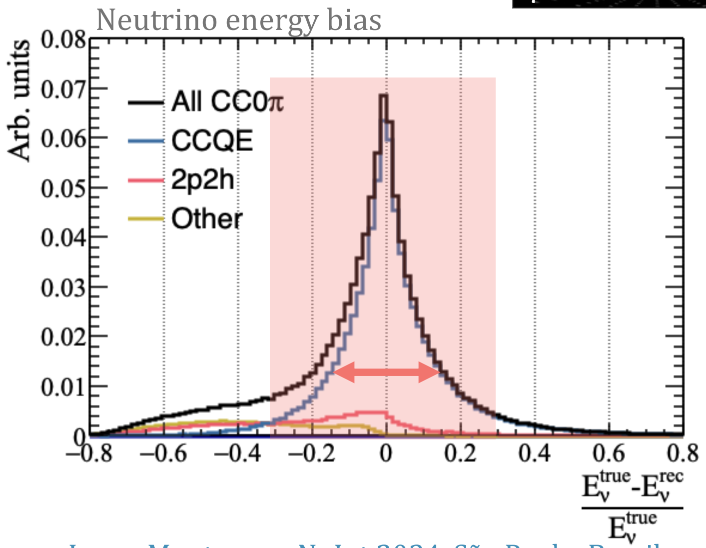

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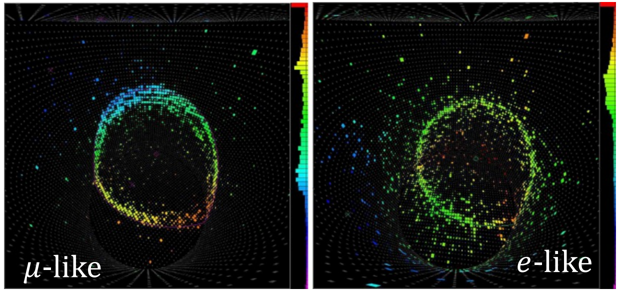

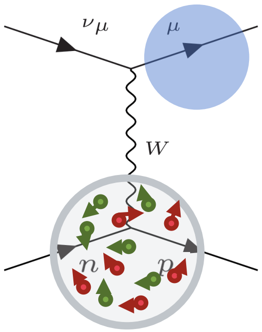

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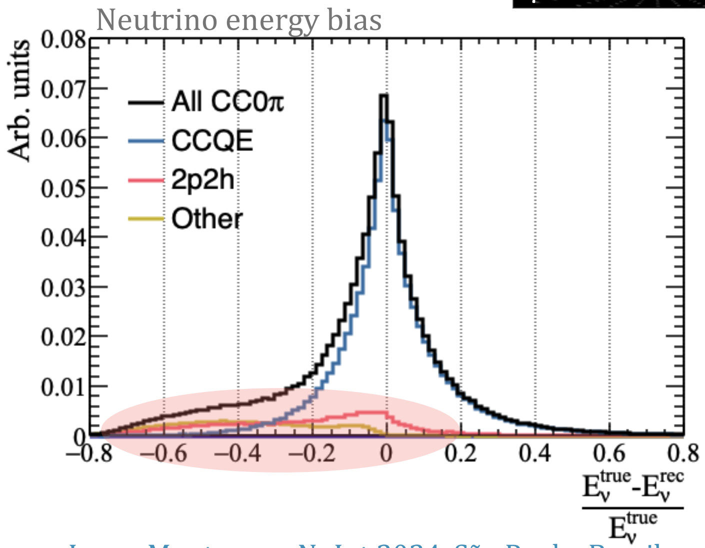

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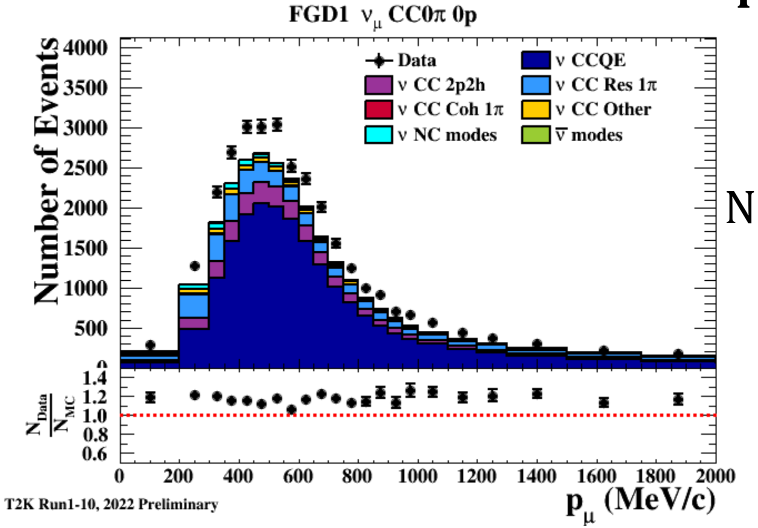
PWIA: Plane Wave Impulse Approximation

Constraining uncertainties with near detector data

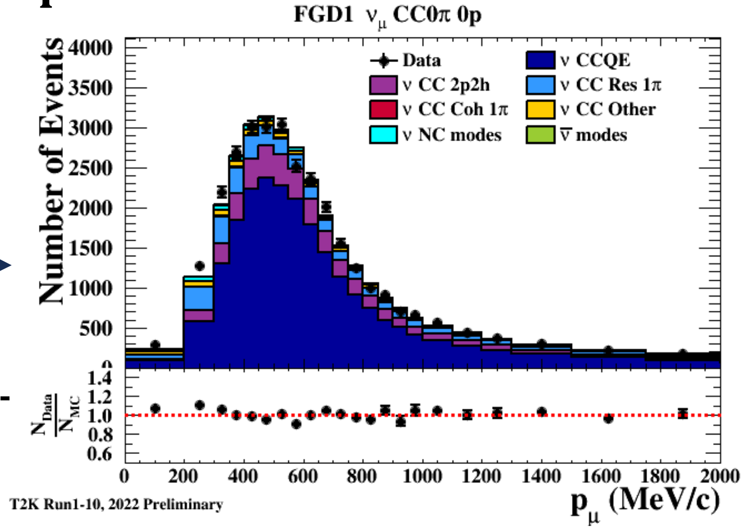
- 22 near detector samples
- 4000+ bins in $(p_\mu, cos\theta_\mu)$
- ~700 parameters (~70 for cross-section uncertainties)

Example: CC0π0p sample



Near detector fit

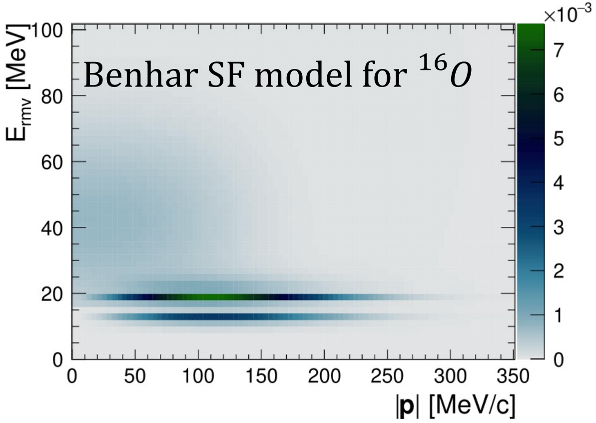
Varies parameters related to flux, detector and **cross-section model**

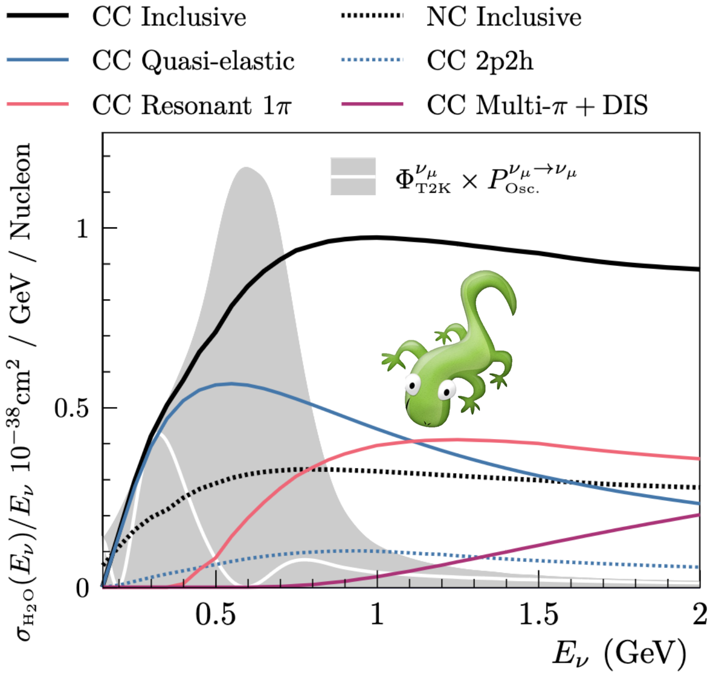


Baseline model and simulation

T2K uses the NEUT neutrino event generator

Process	Model
CCQE (1p1h)	Benhar Spectral Function (SF)
CC 2p2h	Nieves et al. 2p2h
CC Resonant	Rein Sehgal
Final State Interactions	NEUT cascade (based on Salcedo & Oset)





See talk by P. Stowell

CCQE uncertainties – intrinsic degrees of freedom

T2K is the first neutrino oscillation experiment to use a non-Fermi gas model

- ✓ Tuned to $ee'p$ data
- ✓ More powerful at predicting hadron kinematics than other available models
- ✓ Possibility to vary physically meaningful degrees of freedom

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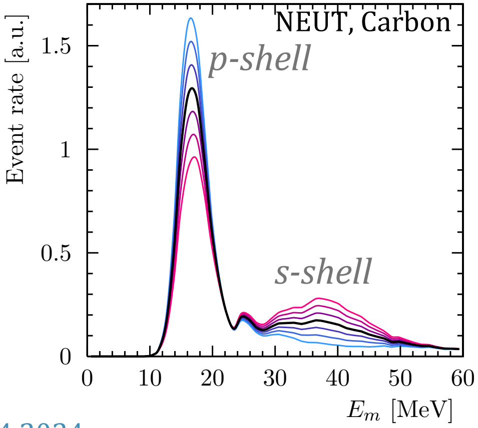
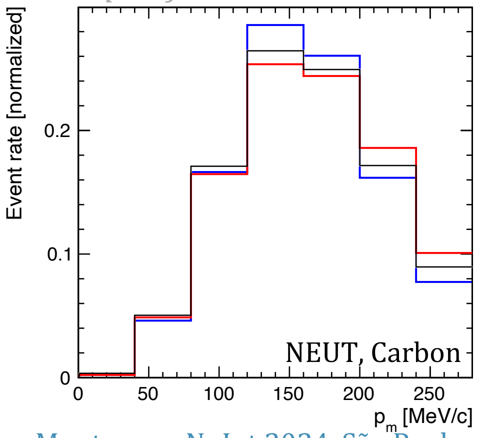
$*E_m, p_m$ – missing energy and momentum

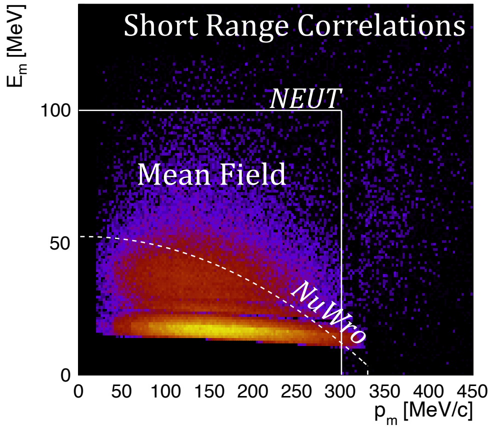
Relative shell occupancy



Shape of nucleon momentum



Relative fraction of MF vs SRC



CCQE uncertainties – intrinsic degrees of freedom

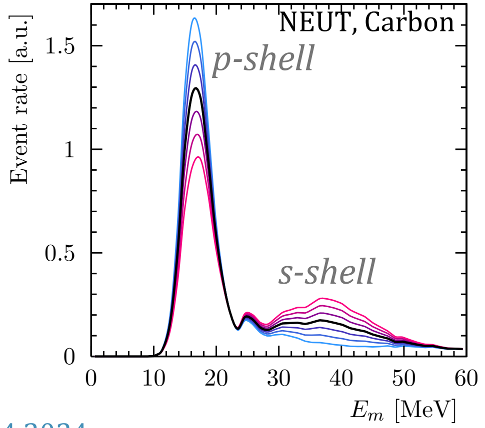
T2K is the first neutrino oscillation experiment to use a non-Fermi gas model

- ✓ Tuned to $ee'p$ data
- ✓ More powerful at predicting hadron kinematics than other available models
- ✓ Possibility to vary physically meaningful degrees of freedom

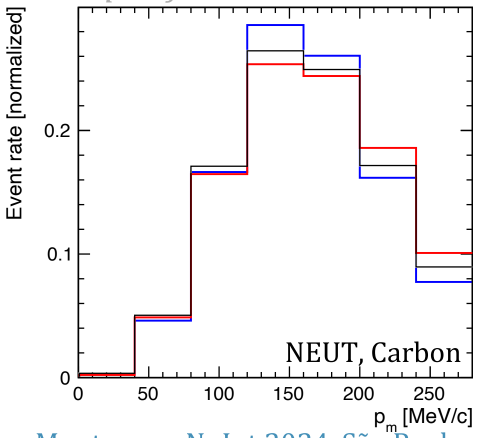
- ✗ Relies on factorization approach
- ✗ Does not include FSI effects on the lepton
- ✗ Simplistic description of Pauli blocking

***E_m, p_m – missing energy and momentum**

Relative shell occupancy



Shape of nucleon momentum



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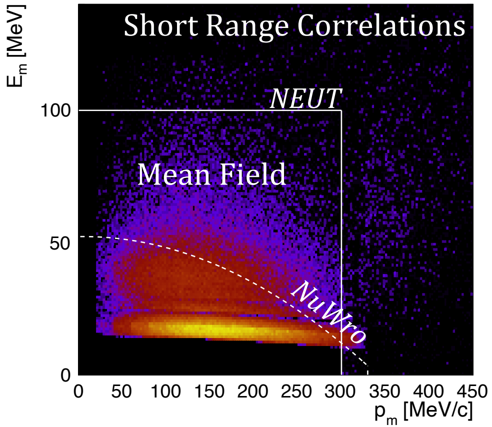
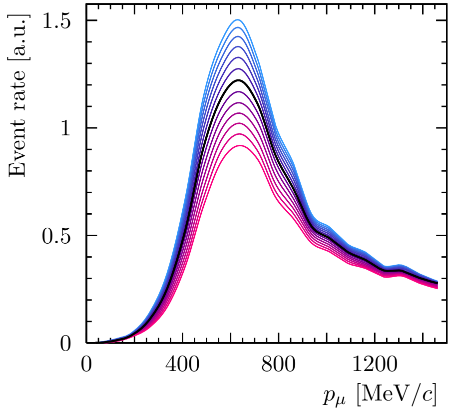


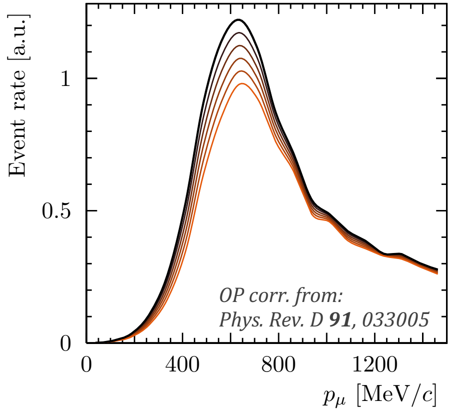
CCQE uncertainties – effective degrees of freedom

Current near detector fit is performed as a function of **lepton kinematics only**
→Include **effective** d.o.f. which alter the shape of lepton kinematic distributions

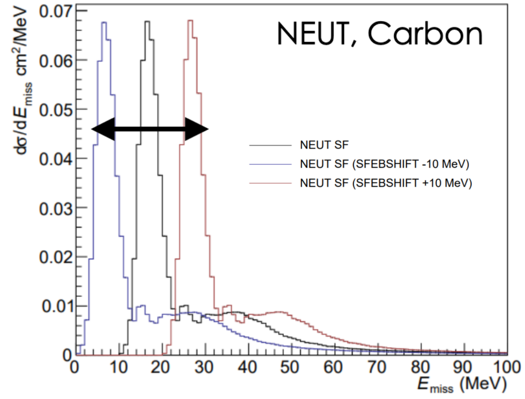
Pauli blocking



Optical potential



Shift in removal energy distribution



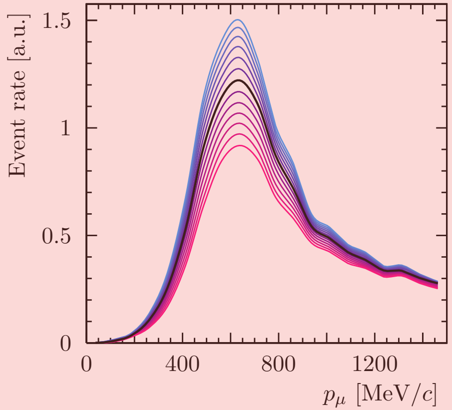
CCQE uncertainties – effective degrees of freedom

Current near detector fit is performed as a function of **lepton kinematics only**
→Include **effective** d.o.f. which alter the shape of lepton kinematic distributions

Target low-ω region (~15% of CCQE events) where effects beyond PWIA are important

PWIA: Plane Wave Impulse Approximation

Pauli blocking



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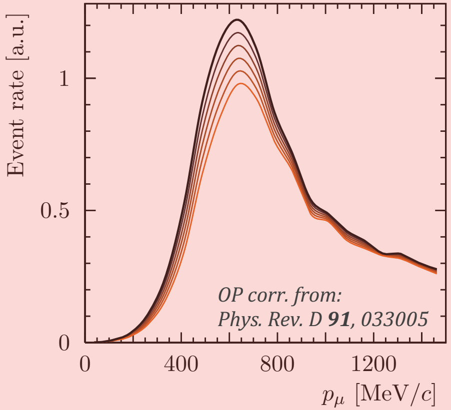

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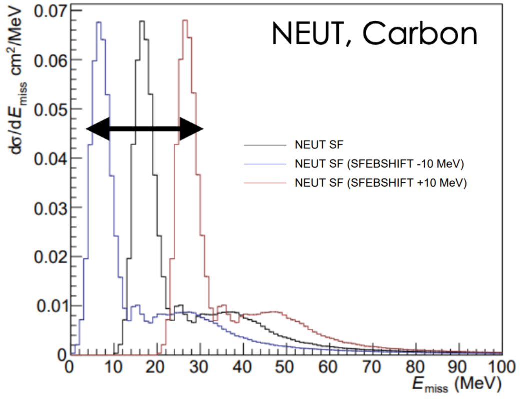
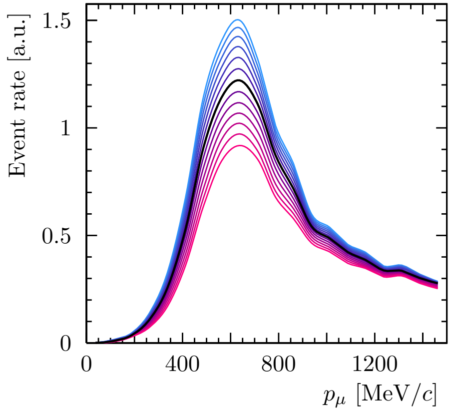


CCQE uncertainties – effective degrees of freedom

Current near detector fit is performed as a function of **lepton kinematics only**
→Include **effective** d.o.f. which alter the shape of lepton kinematic distributions

Account for uncertainties in shell positions
Previously dominant source of systematic uncertainty on Δm^2_{32}
(now subdominant thanks to use of SF model and $ee'p$ constraints)

Pauli blocking



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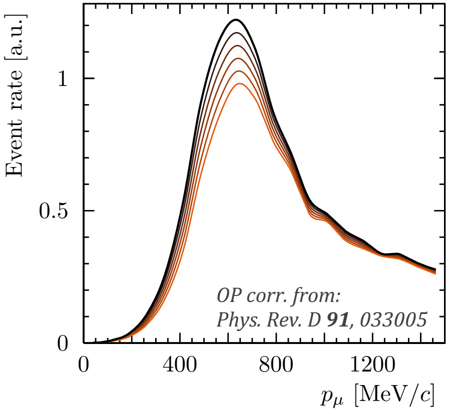

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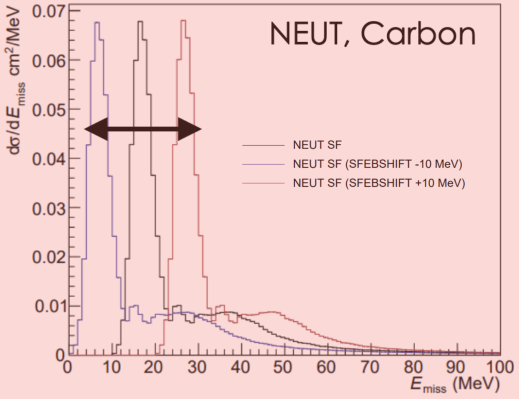


CCQE uncertainties – effective degrees of freedom

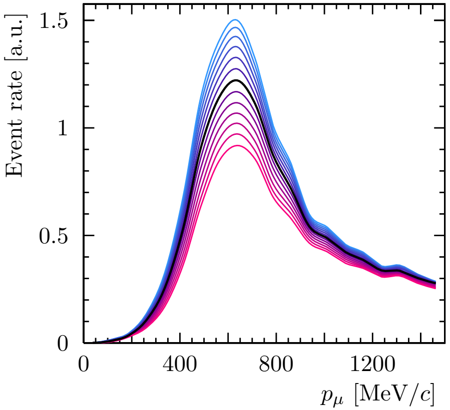
Current near detector fit is performed as a function of **lepton kinematics only**

→Include **effective** d.o.f. which alter the shape of lepton kinematic distributions

+Effective Q^2 shape freedom for deviations from dipole M_A prediction

Will need revisiting once we include hadron kinematics in the ND analysis

Pauli blocking



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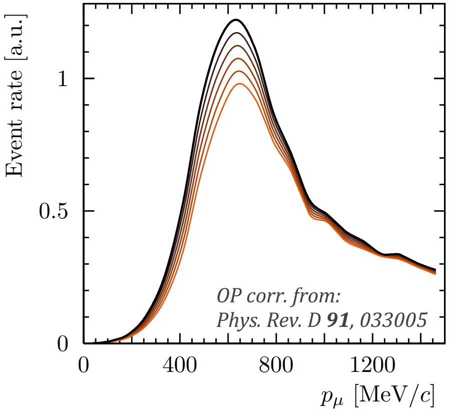

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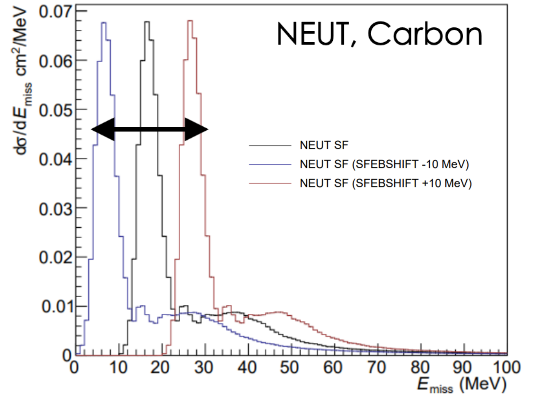
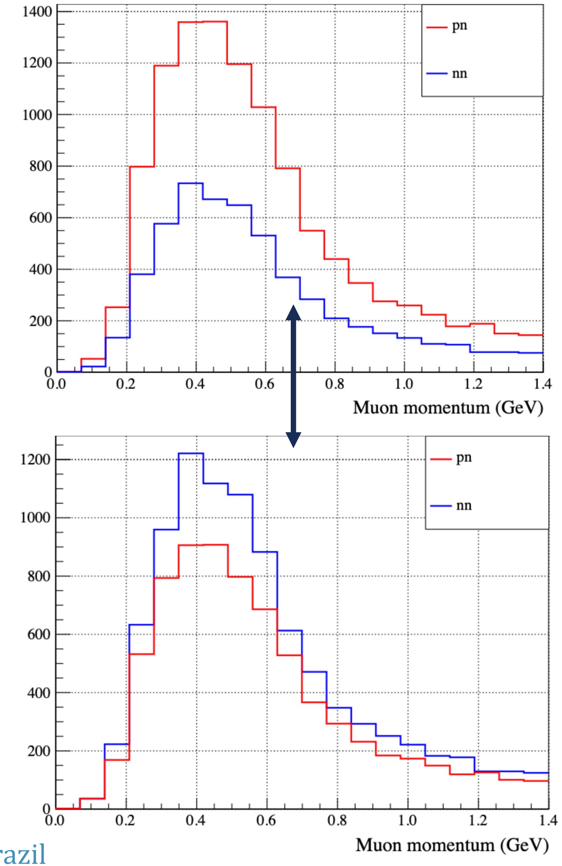


2p2h uncertainties

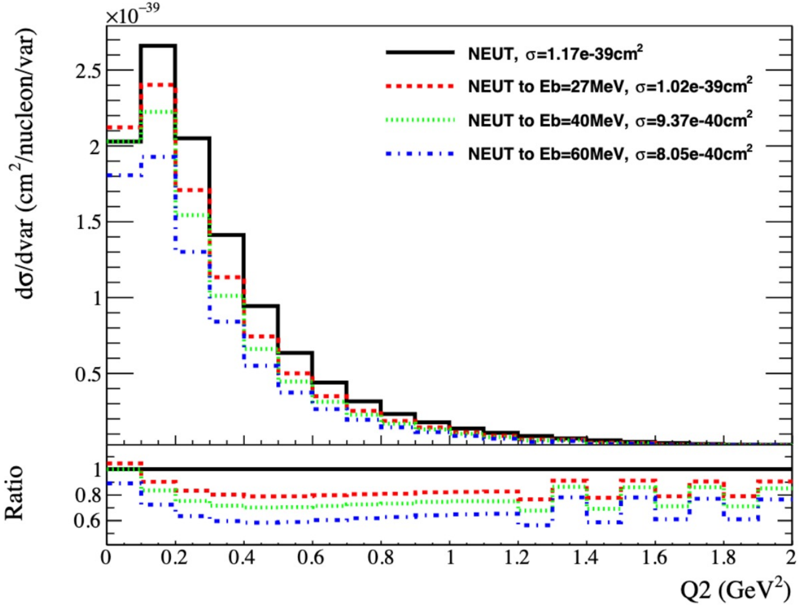
- Dominant non-QE contrib. in CC0π samples
- Simulated using Nieves et al. 2p2h model
- Freedoms include:
  - Normalization
  - Shape (Δ vs non-Δ components)
  - nn vs np pair fractions
  - Energy dependence of different models
- Lacking freedom in nucleon kinematics
  - Not very impactful for current analyses
  - But will become critical in future analyses

Impact of varying the fraction of 2p2h nn and np initial states



Pion production uncertainties

- Baseline model: Rein-Sehgal + Graczyk-Sobczyk form factors
- Dominated by Δ resonance, but 17 resonances + interferences included
- Non-resonant pion production but no interference with resonant production
- Parameters which control:
  - Form factors (M_{RES}^{A} and C_5^A) – newly tuned
  - Non-resonant contributions
  - Removal energy in π-production events
  - Resonance decay kinematics

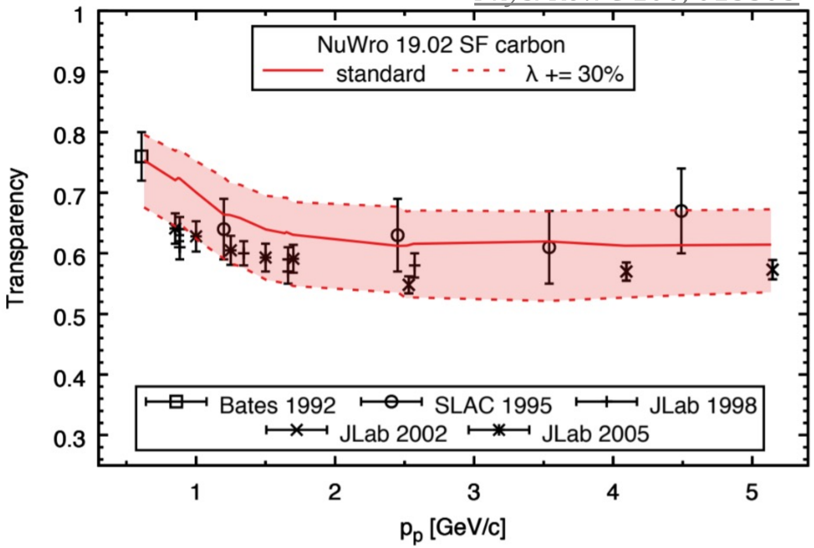


Impact of varying the removal energy for π-production events

Final State Interactions

- Salcedo-Oset intra-nuclear cascade
  - 6 meson FSI parameters tuned to π-C and π-O scattering data *Phys. Rev. D* ***99****, 052007*
- Simple parameter to control probability of proton FSI

Phys. Rev. C 100, 015505



Robustness studies

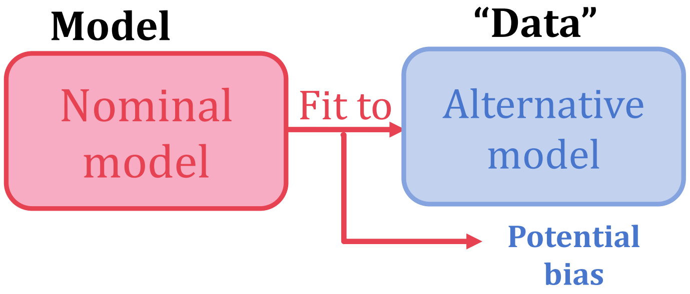
Our uncertainty model is not complete due to
→unknown unknowns
→lack of theoretical guidance
→lack of tools/challenges in propagating some effects

We test the robustness of our analysis by assessing its performance against alternative models or tunes

Examples: (non-exhaustive, **16 total tests**)

1. Alternative CCQE models (LFG, CRPA)
2. Varying the proportion of non-QE events
3. Alternative π-production models (e.g. Martini 1π)
4. Hard photon emission

Principle:

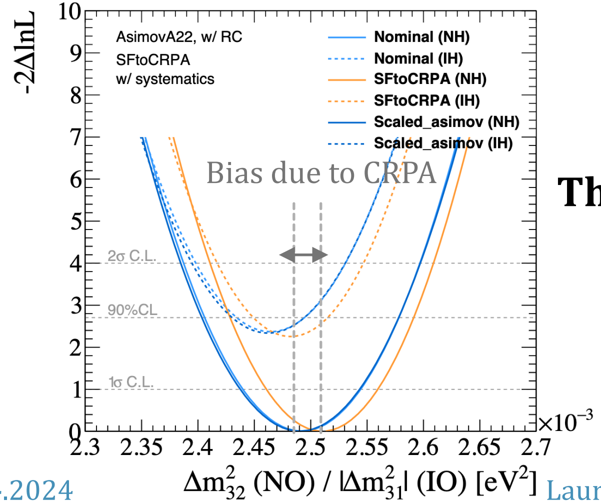


Robustness studies

- All robustness checks show deviations which are far below the *total* uncertainty on oscillation parameters

But notable cases where sizable deviations were seen:

1. **CRPA** alternative model shows a bias comparable to the size of the total systematic uncertainty on Δm^2_{32}
2. Attributing the data-MC discrepancy to **non-QE** events only shows a bias of ~70% of the systematic uncertainty on Δm^2_{32}



Accounted for by applying an additional smearing to Δm^2_{32}

This smearing is the dominant systematic uncertainty on Δm^2_{32}

Highlights aspects of the model which need improvement

Robustness studies

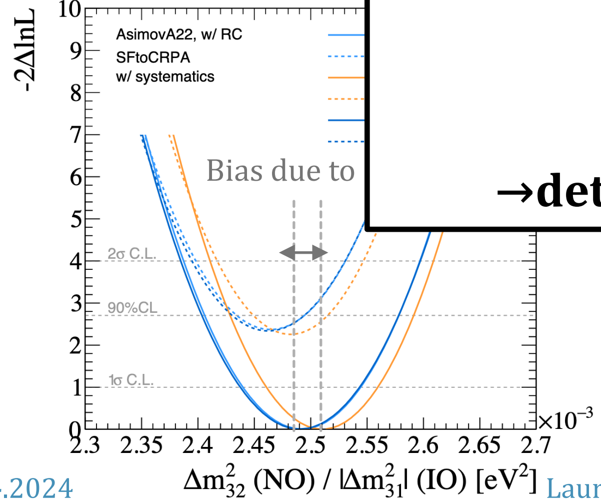
- All robustness checks show deviations which are far below the *total* uncertainty on oscillation parameters

But notable cases where sizable deviations were seen:

1. **CRPA** alternative m … atic uncertainty on Δm^2_{32}
2. Attributing the data … 0% of the systematic uncertainty on Δm…

… nal smearing to Δm^2_{32}

… **tic uncertainty on Δm^2_{32}**



For a full description of
- full baseline model
- uncertainty model
- robustness studies
- near detector fit

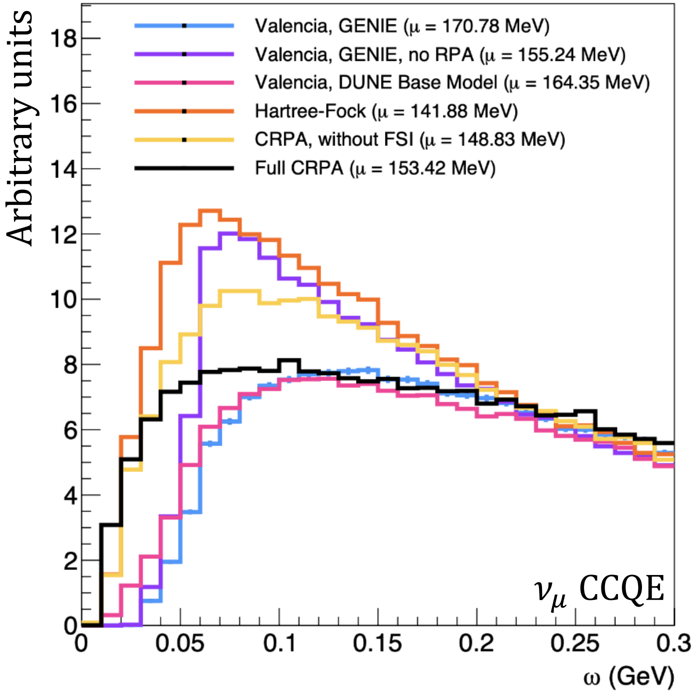
→**detailed paper in preparation**

Highlights aspects of the model which need improvement

Lessons learned – towards the next analysis

- **Low-ω physics** (RPA, optical potential, Pauli blocking…) are the **dominat source of systematic uncertainty on atmos. parameters for T2K** (and T2K+SK atmospheric) oscillation analyses
  - Currently developing new freedoms to target these effects
- Lacking freedom in **nucleon kinematics**
  - Ok for now but unacceptable once we include hadron kinematics in the analysis
  - Next analysis will include freedom to control SRC pair fractions & cascade nucleon FSI
  - Ongoing work to even better describe nucleon FSI
- Emission of **radiative photons** now simulated in NEUT for next analysis

Work of T. Holvey



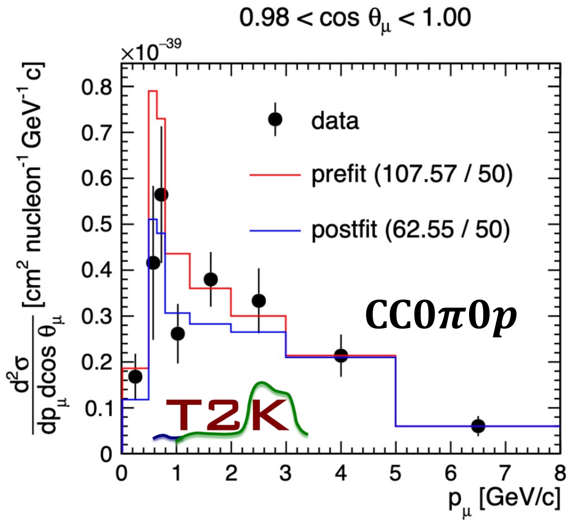
Additional future improvements

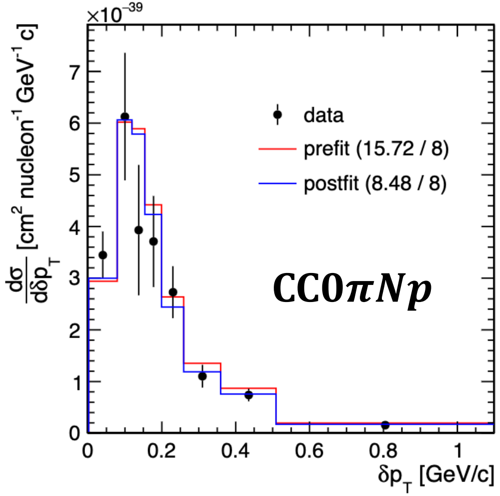
- Ongoing (very promising!) implementation of ED-RMF model in NEUT
  - Opens up the possibility of physically motivated uncertainties relatable to a **fully microscopic model**
- Addition of new freedoms for **hadron kinematics in 2p2h processes**
  - E.g. inclusion of MicroBooNE-inspired decay angle freedom for 2p2h events
- Wider phase space of **robustness studies**
  - 2p2h alternative models
  - Pion multiplicities
- ...and many more!

Benchmarking with cross-section measurements

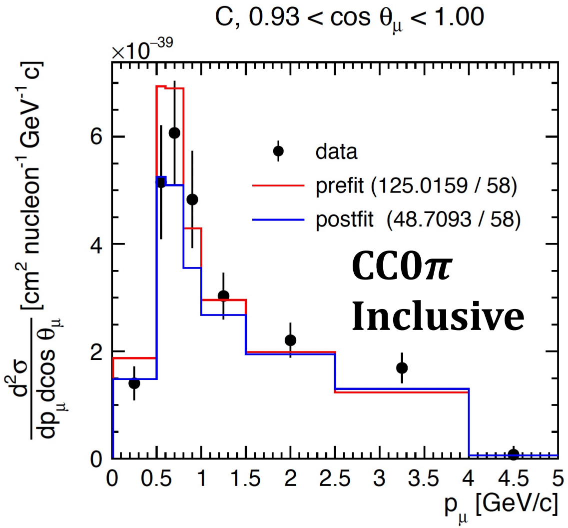
The T2K uncertainty model has enough freedom to describe T2K inclusive and some semi-inclusive measurements

Fits performed using





Measurement from Phys. Rev. D 98, 032003 (2018)



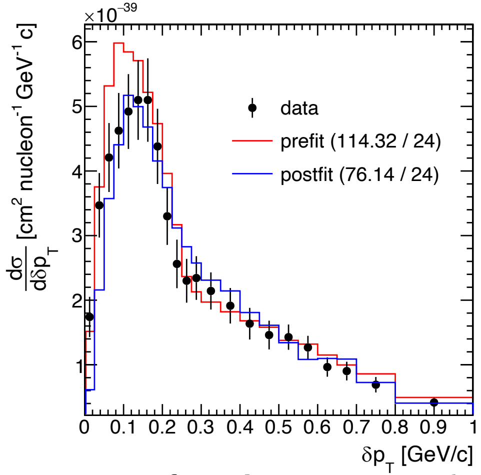
Measurement from Phys. Rev. D 101, 112004 (2020)

Benchmarking with cross-section measurements

The T2K uncertainty model has enough freedom to describe T2K inclusive and some semi-inclusive measurements

Fits performed using

…improves agreement with MINERvA measurements but doesn't describe it quantitatively



Measurement from Phys.Rev.Lett. 121 (2018) 2, 022504

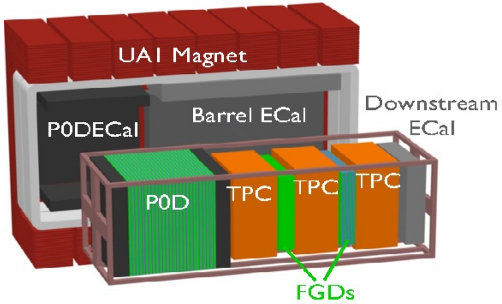
Possible lacking freedoms:

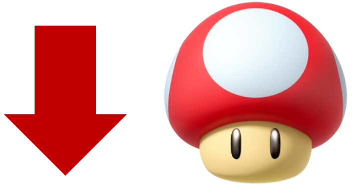
- Energy dependence
- Hadron kinematics
- Nucleon FSI
- Resonant pion production

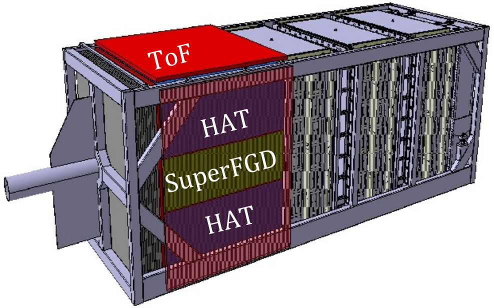
Summary & prospects

See talk by U. Virginet

- T2K has developed a sophisticated neutrino interaction uncertainty model for its oscillation analyses
- **~70 d.o.f. for relevant effects**
- Robustness of the model is assessed through dedicated studies
  - **Dominant source of systematic uncertainty on atmos. parameters** currently related to **beyond-PWIA effects**
  - Help identify shortcomings of the model which we are currently addressing
- Iterative work currently done in preparation for the first data with the new **Upgraded ND280**
  - Will open up a world of possibilities for new and robust measurements
  - Needs dedicated, new uncertainties **for including hadronic observables** in the oscillation analysis

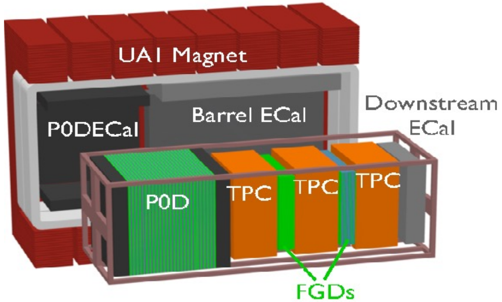


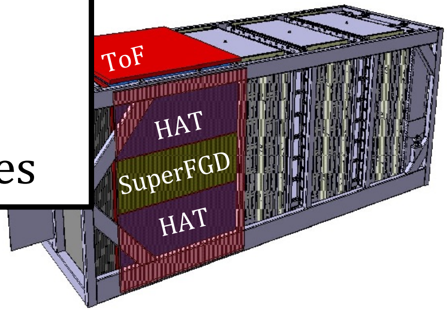




Summary & prospects

See talk by U. Virginet





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- **~70 d.o.f. for relevant effects**
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  - I ... mings of the model which we are currently a...
- Itera... data w...
  - Will open... measurer...
  - Needs de... **observables** in the oscillation analysis

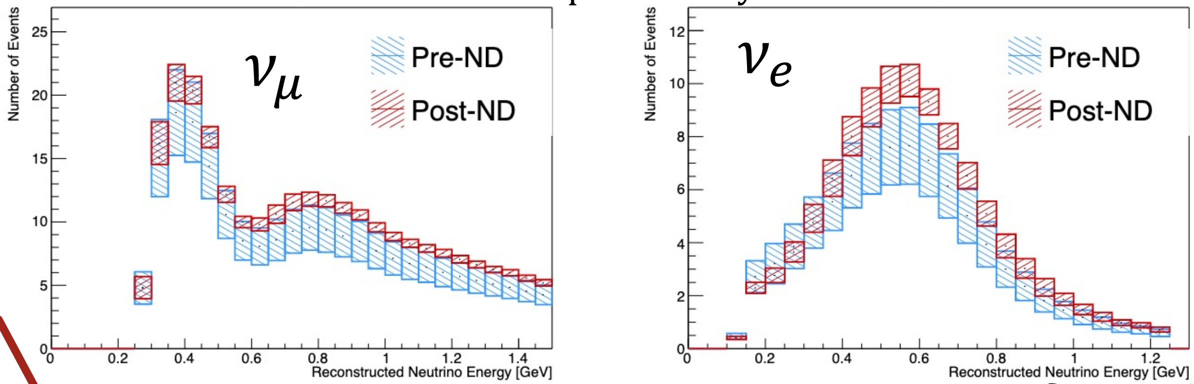
Key challenges:

- C/O correlations
- Nucleon kinematics in 2p2h interactions
- Nuclear effects in pion production processes

Supplementary material

Impact of ND constraint on FD spectra and errors

T2K preliminary



Systematic errors

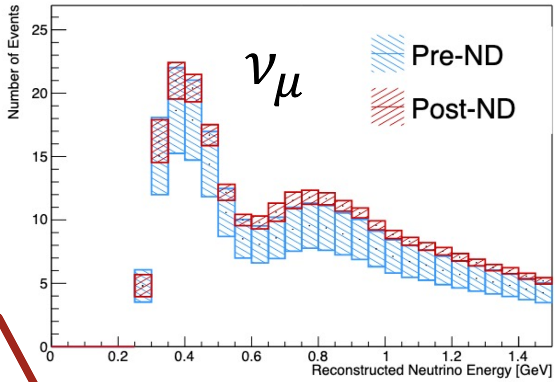
Before ND fit

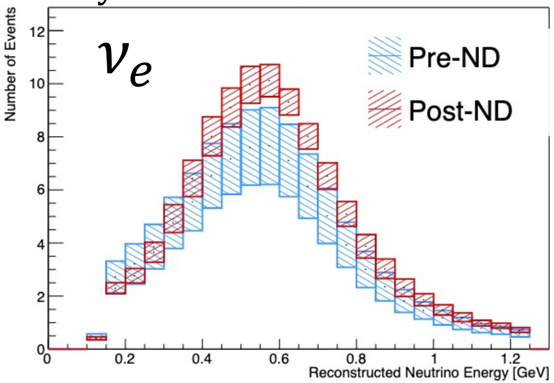
Error source (units: %)	1R FHC	1R RHC	MR FHC CC1π^+	1Re FHC	1Re RHC	1Re FHC CC1π^+	1Re FHC/RHC
Flux	5.0	4.6	5.2	4.9	4.6	5.1	4.5
Cross-section (all)	15.8	13.6	10.6	16.3	13.1	14.7	10.5
SK+SI+PN	2.6	2.2	4.0	3.1	3.9	13.6	1.3
Total All	16.7	14.6	12.5	17.3	14.4	20.9	11.6

T2K Run 1-10, preliminary

Impact of ND constraint on FD spectra and errors

T2K preliminary





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Error source (units: %)	1R FHC	1R RHC	MR FHC CC1π^+	1Re FHC	1Re RHC	1Re FHC CC1π^+	FHC/RHC
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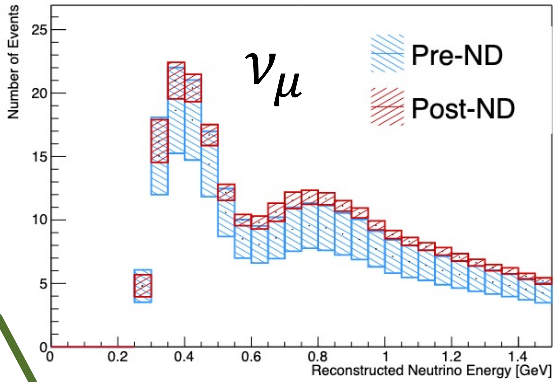
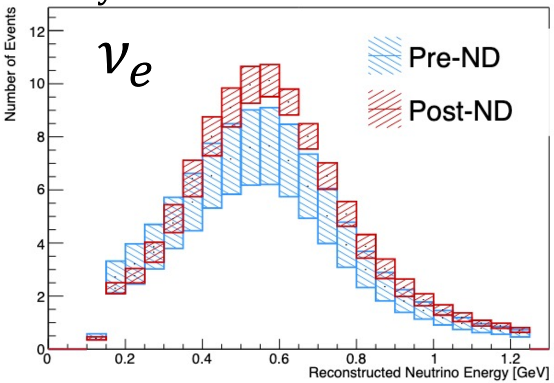




After ND fit

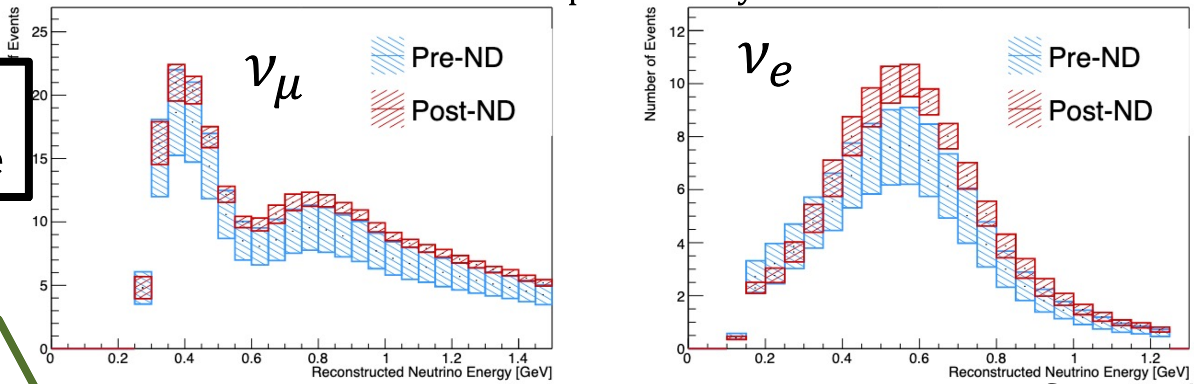
Systematic errors

	1R		MR	1Re			
Error source (units: %)	FHC	RHC	FHC CC1π^+	FHC	RHC	FHC CC1π^+	FHC/RHC
Flux	2.8	2.9	2.8	2.8	3.0	2.8	2.2
Xsec (ND constr)	3.7	3.5	3.0	3.8	3.5	4.1	2.4
Flux+Xsec (ND constr)	2.7	2.6	2.2	2.8	2.7	3.4	2.3
Xsec (ND unconstr)	0.7	2.4	1.4	2.9	3.3	2.8	3.7
SK+SI+PN	2.0	1.7	4.1	3.1	3.8	13.6	1.2
Total All	3.4	3.9	4.9	5.2	5.8	14.3	4.5

T2K Run 1-10, preliminary

Impact of ND constraint on FD spectra and errors

T2K preliminary



But also tuned spectrum shape

After ND fit

Systematic errors

Error source (units: %)	1R FHC	1R RHC	MR FHC CC1π^+	1Re FHC	1Re RHC	1Re FHC CC1π^+	FHC/RHC
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T2K Run 1-10, preliminary